OES-ENVIRONMENTAL

2020
State of the Science Report

ENVIRONMENTAL EFFECTS OF MARINE RENEWABLE ENERGY DEVELOPMENT AROUND THE WORLD

OES-ENVIRONMENTAL

2020 State of the Science Report

ENVIRONMENTAL EFFECTS OF MARINE RENEWABLE ENERGY DEVELOPMENT AROUND THE WORLD

SEPTEMBER 2020

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

SUGGESTED CITATION
The suggested citation for this report is: Copping, A.E. and Hemery, L.G., editors. 2020. OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). doi:10.2172/1632878

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

Operating Agent
Samantha Eaves, Ph.D., U.S. Department Of Energy

Authors

Pacific Northwest National Laboratory (United States)
Andrea E. Copping, Ph.D.
Lenaïg G. Hemery, Ph.D.
Jonathan M. Whiting, PE
Lysel Garavelli, Ph.D.
Mikaela C. Freeman
Robert J. Cavagnaro, Ph.D.
Robert P. Mueller
Alicia M. Gorton, Ph.D.

Aquatera Limited and **Nova Innovation Limited** (United Kingdom)
Kate Smith, Ph.D.

Centre for Environment, Fisheries and Aquaculture Science (United Kingdom)
Andrew B. Gill, Ph.D.
Marieke Desender, Ph.D.

Dalhousie University (Canada)
David R. Barclay, Ph.D.

European Marine Energy Centre (United Kingdom)
Caitlin Long

Fundy Ocean Research Center for Energy (Canada)
Daniel J. Hasselman, Ph.D.

Independent Researcher (United States)
Louise P. McGarry

Integral Consulting Inc. (United States)
Grace Chang, Ph.D.

MaREI, University of College Cork (Ireland)
Anne Marie O'Hagan, Ph.D.
Célia Le Lièvre, Ph.D.

SMRU Consulting (United Kingdom)
Carol E. Sparling, Ph.D.

Sustainable Marine Energy, Ltd. (Canada)
Craig Chandler

University of Alaska Fairbanks (United States)
Andrew C. Seitz, Ph.D.

University of the Highland and Islands (United Kingdom)
Elizabeth Masden, Ph.D.
Benjamin J. Williamson, Ph.D.

University Of St. Andrews (United Kingdom)
Carol E. Sparling, Ph.D.
Douglas M. Gillespie, Ph.D.
Gordon D. Hastie, Ph.D.

University of Washington (United States)
Brian Polagye, Ph.D.
Christopher Bassett, Ph.D.
Emma Cotter, Ph.D.
John K. Horne, Ph.D.
James Joslin, Ph.D.

Contributors

U.S. Department of Energy
Samantha Eaves, Ph.D.

Pacific Northwest National Laboratory
Deborah J. Rose
Hayley K. Farr
Dorian M. Overhus
Levy G. Tugade
Garrett J. Staines
Susan Ennor

Aquatera Limited
Ian Hutchison
Jennifer Fox

University of the Highland and Islands
Natalie Isaksson

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

Copping, A.E. and Hemery, L.G., editors. 2020. OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). doi:10.2172/1632878

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

Section A – Introduction

Chapter 1

Marine Renewable Energy and Ocean Energy Systems

Copping, A.E. 2020. Marine Renewable Energy and Ocean Energy Systems. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 2-17). doi:10.2172/1632879

Chapter 2

Marine Renewable Energy: Environmental Effects and Monitoring Strategies

Copping, A.E 2020. Marine Renewable Energy: Environmental Effects and Monitoring Strategies. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 18-26). doi:10.2172/1632880

Section B – Current Knowledge of Key Device Interactions with the Marine Environment

Chapter 3

Collision Risk for Animals Around Turbines

Sparling, C.E., A.C. Seitz, E. Masden, and K. Smith. 2020. Collision Risk for Animals around Turbines. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 28-65). doi:10.2172/1632881

Chapter 4

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

Polagye, B. and C. Bassett. 2020. Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 66-85). doi:10.2172/1633082

Chapter 5

Risk to Animals from Electromagnetic Fields Emitted by Electric Cables and Marine Renewable Energy Devices

Gill, A.B. and M. Desender. 2020. Risk to Animals from Electromagnetic Fields Emitted by Electric Cables and Marine Renewable Energy Devices. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 86-103). doi:10.2172/1633088

Chapter 6

Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices

Hemery, L.G. 2020. Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 104-125). doi:10.2172/1633182

Chapter 7

Changes in Oceanographic Systems Associated with Marine Renewable Energy Devices

Whiting, J.M. and G. Chang. 2020. Changes in Oceanographic Systems Associated with Marine Renewable Energy Devices. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 126-145). doi:10.2172/1633183

Chapter 8

Encounters of Marine Animals with Marine Renewable Energy Device Mooring Systems and Subsea Cables

Garavelli, L. 2020. Encounters of Marine Animals with Marine Renewable Energy Device Mooring Systems and Subsea Cables. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 146-153). doi:10.2172/1633184

Chapter 9

Social and Economic Data Collection for Marine Renewable Energy

Freeman, M.C. 2020. Social and Economic Data Collection for Marine Renewable Energy. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 154-174). doi:10.2172/1633195

Section C – Environmental Monitoring

Chapter 10

Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines

Hasselman, D.J., D.R. Barclay, R.J. Cavagnaro, C. Chandler, E. Cotter, D.M. Gillespie, G.D. Hastie, J.K. Horne, J. Joslin, C. Long, L.P. McGarry, R.P. Mueller, C.E. Sparling, and B.J. Williamson. 2020. Environmental Monitoring Technologies and Techniques for Detecting interactions of Marine Animals with Turbines. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 176-212). doi:10.2172/1633202

Section D– Strategies for Accelerating Permitting/Consenting

Chapter 11

Marine Spatial Planning and Marine Renewable Energy

O'Hagan, A.M. 2020. Marine Spatial Planning and Marine Renewable Energy. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 214-241). doi:10.2172/1633204

Chapter 12

Adaptive Management Related to Marine Renewable Energy

Le Lièvre, C. 2020. Adaptive Management Related to Maritime Renewable Energy. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 242-261). doi:10.2172/1633206

Chapter 13

Risk Retirement and Data Transferability for Marine Renewable Energy

Copping, A.E., M.C. Freeman, A.M Gorton, and L.G. Hemery. 2020. Risk Retirement and Data Transferability for Marine Renewable Energy. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 262-278). doi:10.2172/1633208

Section E – Looking Ahead

Chapter 14

Summary and Path Forward

Copping, A.E. 2020. Summary and Path forward. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 280-292). doi:10.2172/1633209

AVAILABILITY OF REPORT

A PDF file of this report is available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

ACKNOWLEDGEMENTS

The U.S. Department of Energy and Ocean Energy Systems provided financial support for this effort. Partner nations contributed in-kind resources. We want to thank and acknowledge all of the researchers and developers who have contributed information to the OES-Environmental metadata collection effort.

We would also like to acknowledge support of the OES-Environmental initiative by Mary Boatman and Erin Trager, Bureau of Ocean Energy Management (U.S.), and Candace Nachman, National Oceanic and Atmospheric Administration (U.S.).

We also thank Kelly Cunningham, Ryan Hull, and Matt Sturtevant at Pacific Northwest National Laboratory for their work on developing and maintaining the *Tethys* and OES-Environmental knowledge base, in addition to Mikaela Freeman, Hayley Farr, Dorian Overhus, Deborah Rose, Levy Tugade, Amy Woodbury, Cailene Gunn, Julia Indivero, Heidi Stewart, and Kailan Mackereth for assisting with the *Tethys* knowledge base content curation.

Finally, we would like to thank those who provided the many helpful suggestions and review comments we used to improve this manuscript.

Design and production: Robyn Ricks

Illustrations: Rose Perry

OES-ENVIRONMENTAL COUNTRY REPRESENTATIVES

- **Australia:** Mark Hemer, CSIRO
- **Canada:** Anna Redden, Acadia University, Dan Hasselman, FORCE
- **China:** Qiwei Zhao, National Ocean Technology Center
- **Denmark:** Hans Chr Soerensen, Wave Dragon
- **France:** Nolwenn Quillien, Morgane Lejart, France Énergies Marines
- **India:** Purnima Jalihal, National Institute of Ocean Technology
- **Ireland:** Anne Marie O'Hagan, MaREI, University College Cork
- **Japan:** Daisuke Kitazawa, Takero Yoshida, University of tokyo
- **Norway:** Lars Golmen, Norwegian Institute for Water Research
- **Portugal:** Teresa Simas, WavEC – Offshore Renewables
- **Spain:** Juan Bald, AZTI-Tecnalia
- **Sweden:** Jan Sundberg, Uppsala University
- **United Kingdom:** Caitlin Long, European Marine Energy Centre
- **United States:** Andrea Copping, Pacific Northwest National Laboratory

ABBREVIATIONS AND ACRONYMS

°C	degrees Celsius
2D	two-dimensional
3D	three-dimensional
µPa	micropascal(s)
µT	microtesla(s)
µV	microvolt(s)
AC	alternating current
ADCP	acoustic Doppler current profiler
ADV	Acoustic Doppler Velocimeter
AM	adaptive management
AMC	Adaptive Management Committee
AMP	Adaptive Management Plan or Adaptable Monitoring Package
amp	ampere(s)
amp hr	ampere hour(s)
AMT	Adaptive Management Team
AZFP	Acoustic Zooplankton and Fish Profiler
BACI	before-after-control impact
B-field	magnetic field
BACI	before-after-control-impact
BMP	best management practice
BOEM	Bureau of Ocean Energy Management
Ca2+	Calcium
CCTV	closed-circuit television
CI	confidence interval
cm	centimeter(s)
COTS	commercial off-the-shelf
CTD	conductivity-temperature-depth
CW	continuous wave
dB	decibel(s)
dB re 1 µPa	decibel(s) in relation to one micro pascal
DC	direct current
DCENR	Department of Communications, Energy and Natural Resources, Northern Ireland
DEFRA	Department for Environment, Food & Rural Affairs
DELWP	Department of Environment, Land, Water and Planning
DGRM	Direção-Geral de Recursos Naturais, Segurança e Serviços Marítimos (Directorate-General for Natural Resources, Safety and Maritime Services)
DIDSON	Dual-Frequency Identification Sonar
DOE	U.S. Department of Energy
DOEIMS	Development of an Ocean Energy Impact Monitoring System
DRIP	Data-Rich Information Poor
DVR	digital video recorder
EERE	Energy Efficiency and Renewable Energy
E-field	electric field
EIA	environmental impact assessment
EIS	environmental impact statement
EMEC	European Marine Energy Centre
EM	electromagnetic
EMF	electromagnetic field
EMP	Environmental Monitoring Plan
EnFAIT	Enabling Future Arrays in Tidal
ESA	European Space Agency
ETIP	European Technology and Innovation Platform
ETI	Energy Technologies Institute
EwE	Ecopath with Ecosim (modeling approach)
EWTEC	European Wave and Tidal Energy Conference
FAST	Fundy Advanced Sensor Technology
FERC	Federal Energy Regulatory Commission
FLOWBEC	Flow, Water Column and Benthic Ecology
FORCE	Fundy Ocean Research Centre for Energy
GIS	geographic information system
GMF	geomagnetic field
GPS	global positioning system
GW	gigawatt(s)
GWh	gigawatt-hour(s)
HF	high frequency
hr	hour(s)
HV	high voltage
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
Hz	hertz
I/O	input/output
IBM	individual based modeling
ICES	International Council for the Exploration of the Sea
ICOE	International Conference on Ocean Energy
IEA	International Energy Agency
IEC	International Electrotechnical Commission

IEC TC 114	IEC Technical Committee 114
iE-field	induced electric field
IMP	Integrated Monitoring Pod
inSTREAM	in Situ Turbulence Replication Evaluation and Measurement
IR	infrared
ISO	International Organization for Standardization
kHz	kilohertz
km	kilometer(s)
kV	kilovolt(s)
kW	kilowatt(s)
LED	light-emitting diode
LiDAR	light detection and ranging
m	meter(s)
m/s	meter(s)/second
mA	milliampere(s)
MaREI	Marine Renewable Energy, Ireland
MaRVEN	Marine Renewable Energy, Vibration, Electromagnetic Fields and Noise
MCT	Marine Current Turbines (installation)
MHK	marine hydrokinetic
mm	millimeter(s)
MMO	Marine Management Organisation
MMO	Marine Mammal Observer
MPA	Marine Protected Area(s)
MRE	marine renewable energy
MSP	marine spatial planning
mT	millitesla(s)
mV/m	millivolt(s) per meter
MW	megawatt(s)
MWh	megawatt(s)-hour(s)
nm	nanometer(s)
NMFS	National Marine Fisheries Service
NMPF	National Marine Planning Framework
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
nT	nanotesla(s)
OCS	Outer Continental Shelf
OES	Ocean Energy Systems
OGP	oil and gas platform
OPT	Ocean Power Technology
OREC	Ocean Renewable Energy Conference
ORJIP Ocean Energy	Offshore Renewable Joint Industry Programme for Ocean Energy
ORPC	Ocean Renewable Power Company
OSU	Oregon State University
OTEC	Ocean Thermal Energy Conversion
OWF	offshore wind farm
PAM	passive acoustic monitoring
PBR	Potential Biological Removal
PEMP	project environmental monitoring plan
PNNL	Pacific Northwest National Laboratory
PPE	Programmations Pluriannuelles de l'Énergie (French Strategy for Energy and Climate Multi-Annual Energy Plan)
PWP	Pelamis Wave Power
RD&D	research, development, and demonstration
ReDAPT	Reliable Data Acquisition Platform for Testing
RITE	Roosevelt Island Tidal Energy
RMEE	RITE Monitoring of Environmental Effects
ROV	remotely operated vehicle
s	second(s)
SAC	Special Area of Conservation
SDK	software development kit
SEMLA	Swedish Electromagnetic Low-Noise Apparatus
SIA	social impact assessment
SME	Sustainable Marine Energy
SMRU	Sea Mammal Research Unit
SNR	signal-to-noise ratio
SPL	sound pressure level
Sv	mean volume backscattering strength
TB	terabyte(s)
TGU	turbine generator unit
UAV	unmanned aerial vehicle
UK	United Kingdom
UNESCO	United Nations Educational, Scientific and Cultural Organization
U.S.	United States
V	volt(s)
VDC	volts direct current
V/m	volt(s) per meter
VC	video camera
W	watt(s)
WEC	wave energy converter
WETS	Wave Energy Test Site

CONTENTS

FIGURES, TABLES, AND BOXES

FIGURES

TABLES

BOXES

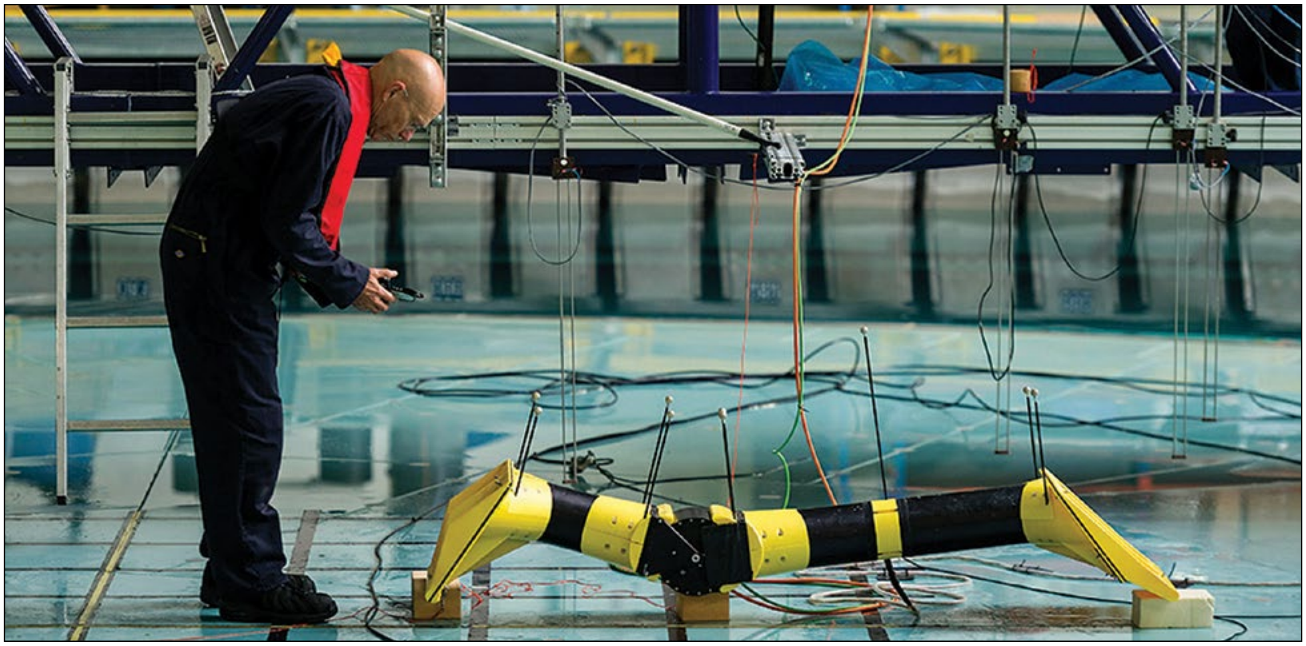
Executive Summary

Executive Summary

This report summarizes the state of the science of environmental effects of marine renewable energy and serves as an update and a complement to the *2016 Annex IV report*, which can be found at *http://tethys.pnnl.gov/publications/state-of-the-science-2016*.

Marine renewable energy (MRE) is harvested from ocean waves, tides, and currents, as well as ocean temperature and salinity gradients, and from the flow of large rivers (which use technologies similar to those that capture tidal energy). This report focuses on the potential environmental effects from the generation of power from waves using wave energy converters (WECs), tides using tidal turbines, and large rivers using river turbines. Lessons learned from other offshore industries, including offshore wind, oil and gas, and power and communication cables, are included, where appropriate.

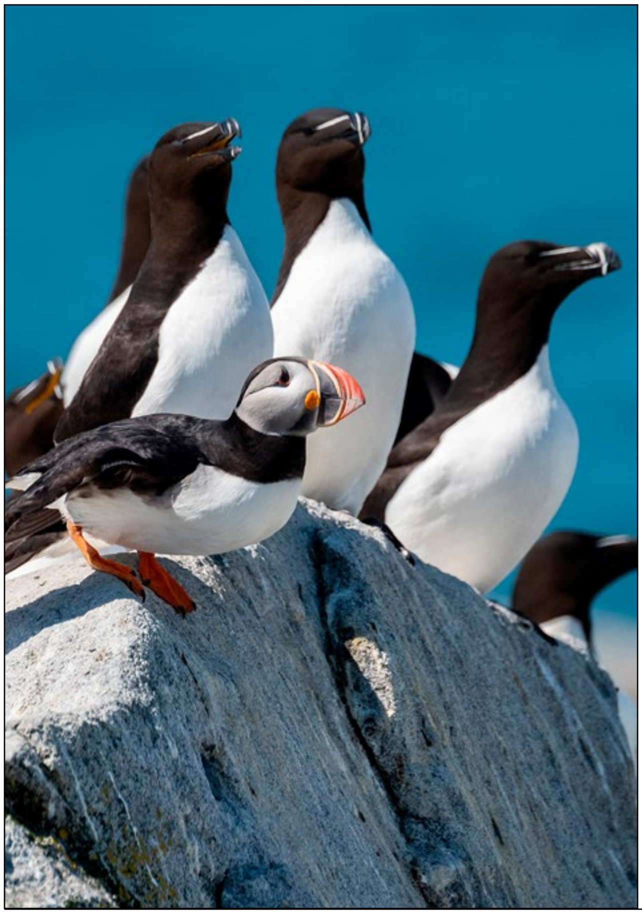
The *2020 State of the Science* report was produced by the Ocean Energy Systems (OES)-Environmental initiative (formerly Annex IV), under the International Energy Agency's OES-Environmental collaboration (*https://www.ocean-energy-systems.org*). Under OES-Environ-



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

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

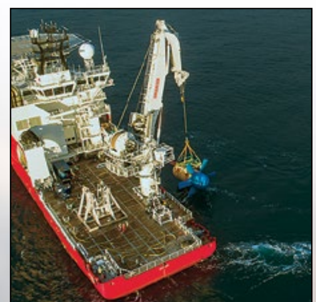
The information reviewed and synthesized for this report relates to the potential risks that MRE devices pose to marine animals, habitats, and the environment, and may be of value to MRE stakeholders including researchers, regulators, device and project developers, and others. This body of knowledge can inform science-based decision-making for international regulators, and support developers in project siting, engineering design, operational strategies, and monitoring program design. Most particularly, this report should help the research community connect with the latest thinking about MRE interactions, identify scientific collaborators, and assist with adding to the growing body of knowledge. When used in conjunction with site-specific information, this report can help streamline consenting of MRE devices. While most monitoring activity around MRE devices is limited to single devices or very small arrays, much of this research and monitoring will be useful as the industry grows. The information synthesized in the *2020 State of the Science* report represents the state of knowledge derived from studies and monitoring, built on publicly available peer-reviewed scientific literature and reports published by researchers, developers, and government agencies, seen through the lens of many of the best researchers in the field. The analyses and conclusions drawn in this report are not meant to take the place of site-specific analyses or studies used to make project siting decisions or to direct consenting actions.



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

MRE is an emerging industry that has had a limited number of small deployments and no full-scale commercial deployments to date. As a result, the paucity of baseline and post-installation data continues to drive a level of uncertainty among regulators and stakeholders that increases the perception of risk for many potential interactions between MRE devices and marine animals, habitats, and the environment. This lack of data continues to confound our ability to differentiate between actual and perceived risks. Ultimately, the risk to marine animals, habitats, and the environment is a function of the attributes of the MRE device (static or dynamic), type of device (wave, tidal, or riverine), and the spatial scale of a particular installation (single device or array). Risk is defined as the interaction of the probability or likelihood of a deleterious outcome, with the consequences, if such an outcome occurs.

As the MRE industry advances, the body of knowledge surrounding potential environmental effects of MRE development will continue to grow, informing our perception of risk. It is possible that as additional data are collected, we may retire or set a lower priority for certain risks. The evidence base for risk retirement will be informed by our growing knowledge about the nature of specific stressor-receptor interactions, helping to determine which interactions have sufficient evidence to retire those risks, and where significant uncertainties remain. However, risk to marine animals, habitats, and the wider environment may continue to present challenges to consenting commercial development.



BENEFITS OF MARINE RENEWABLE ENERGY

The acceleration of MRE research and development around the world contributes to locally-derived secure energy sources that have the potential to create significant benefits, including positive impacts on local communities, local infrastructure and services, local employment and businesses, and the export of products and services. In addition, MRE development has the potential to combat the effects of climate change, including ocean acidification and increasing ocean temperatures. Deleterious effects of climate change are already affecting many marine and coastal resources, and will continue to affect marine animals and habitats as well as eroding beneficial human uses from the harvest and aquaculture of seafood organisms, coastal protection from storms and erosion of shorelines.

COLLISION RISK FOR ANIMALS AROUND TURBINES

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

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

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

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

Evidence suggests that underwater noise emitted from operational MRE devices is unlikely to significantly alter behavior or cause physical harm to marine animals.

RISK TO ANIMALS FROM ELECTROMAGNETIC FIELDS EMITTED BY ELECTRIC CABLES AND MARINE RENEWABLE ENERGY DEVICES

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

The evidence base to date suggests that the ecological impacts of EMFs emitted from power cables from single MRE devices or small arrays are likely to be limited, and marine animals living in the vicinity of MRE devices and export cables are not likely to be harmed by emitted EMFs.

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

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

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

CHANGES IN OCEANOGRAPHIC SYSTEMS ASSOCIATED WITH MARINE RENEWABLE ENERGY DEVICES

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

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

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

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

SOCIAL AND ECONOMIC DATA COLLECTION FOR MARINE RENEWABLE ENERGY

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

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

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

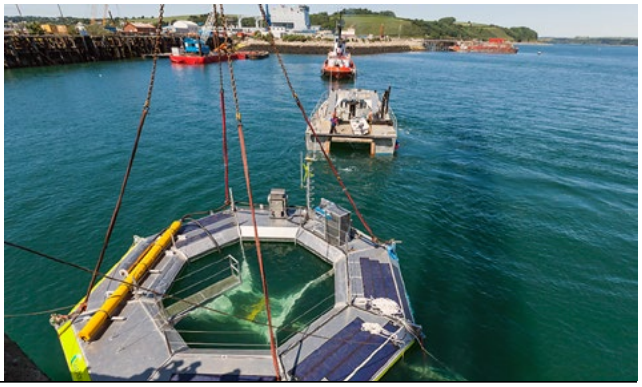
The interaction of marine animals with tidal and river turbines remains the least understood aspect of potential MRE effects and has been hampered by the inability to observe these interactions. These challenges require the design of monitoring equipment that can survive in harsh marine environments,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

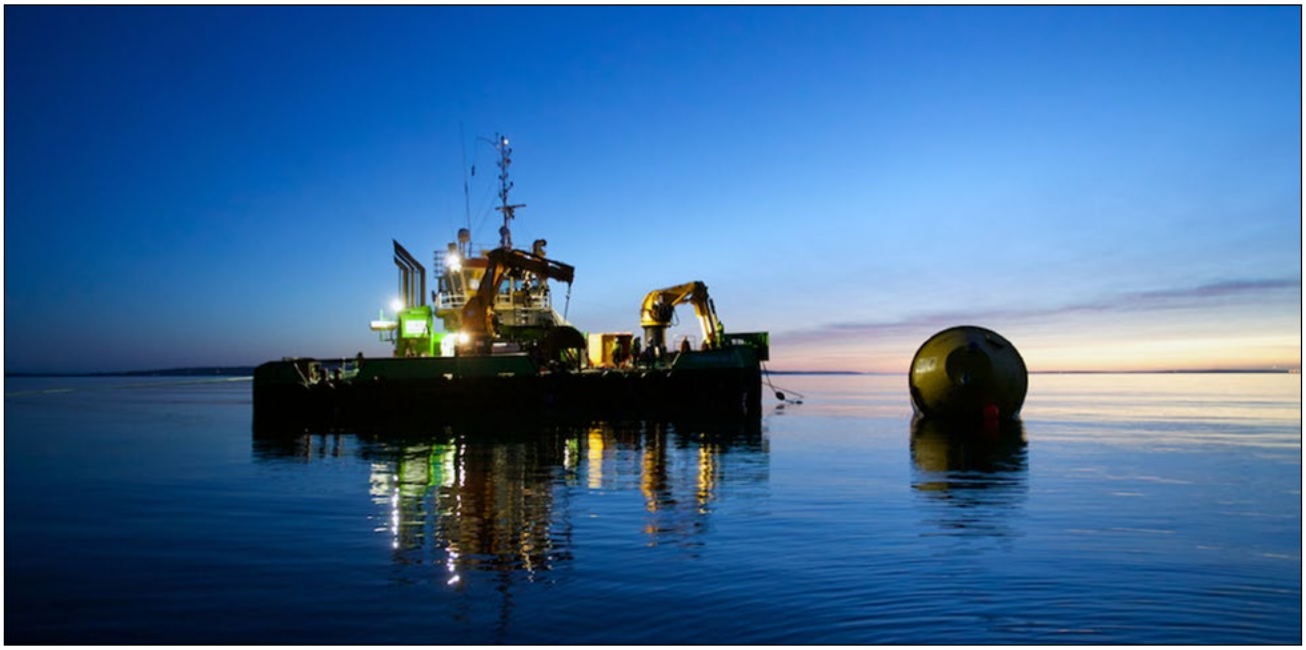
The most common instruments used to observe interactions of marine animals with MRE devices are passive and active acoustic instruments and optical cameras. Passive acoustic monitoring uses hydrophones measure underwater sound including vocalizing marine mammals. Active acoustic systems generate sound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

MARINE SPATIAL PLANNING AND MARINE RENEWABLE ENERGY

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

The 15 nations of the OES-Environmental initiative were surveyed about their MSP practices in relation to MRE development. Their practices varied widely from intentional inclusion of MRE in MSP processes, to application of MSP principles without a formal MSP plan, to the lack of MSP used in MRE development.





ADAPTIVE MANAGEMENT AND MARINE RENEWABLE ENERGY

Adaptive management (AM) has the potential to support the sustainable development of the MRE industry by enabling projects to be deployed incrementally in the face of uncertainty about potential effects, and to assist in closing knowledge gaps through rigorous monitoring and review. AM is an iterative process, also referred to as "learning by doing," that seeks to reduce scientific uncertainty and improve management through periodic review of decisions in response to the knowledge gained from monitoring.

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

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

RISK RETIREMENT AND DATA TRANSFERABILITY FOR MARINE RENEWABLE ENERGY

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

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

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

PATH FORWARD FOR MARINE ENERGY MONITORING AND RESEARCH

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

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

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

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at: *https://tethys.pnnl.gov/publications/state-of-the-science-2020*

CONTACT

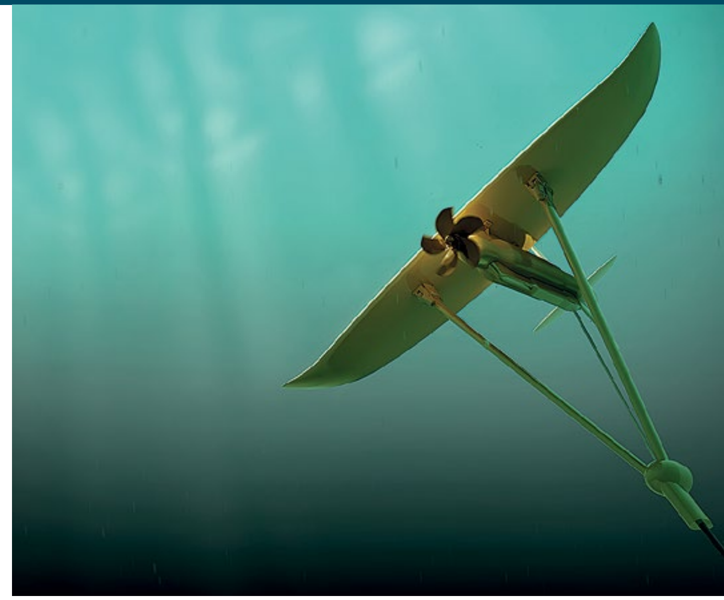
Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

Section A

Introduction

1.0



Chapter author: Andrea E. Copping

Marine Renewable Energy and Ocean Energy Systems

Research, development, and deployment of marine renewable energy (MRE) conversion technologies that harvest all forms of ocean renewable resources are being advanced around the world. The potential benefits derived from capturing the abundant energy of tides, waves, ocean currents, as well as thermal and salinity gradients, continue to drive the development of the emerging MRE industry. Stakeholder understanding of the potential benefits of MRE as a renewable energy source is informed by increased science-based understanding of the potential effects of MRE installations worldwide. The international Ocean Energy Systems (OES)-Environmental collaboration continues to promote global technology cooperation and information exchange to accelerate environmentally acceptable development of viable ocean energy systems.

1.1.
BENEFITS OF MARINE RENEWABLE ENERGY

The range of benefits that may be provided by the development and operation of MRE devices include the availability of a local secure energy source, potential economic development for local communities and regional supply chains, as well as mitigation for climate change. Additional detail on these benefits are explained further in Chapter 9 (Social and Economic Data Collection for Marine Renewable Energy), and some of the benefits of MRE in relation to other uses can be found in Chapter 11 (Marine Spatial Planning and Marine Renewable Energy). Other beneficial uses are sometimes considered, including improved ecological services and improvements to habitats.

Significant economic benefits can accrue from MRE development at a commercial scale, including the potential to enhance portions of coastal economies by creating high-paying skilled jobs in areas where other industries are not prevalent (Marine Energy Wales 2020; Smart and Noonan 2018).

Because MRE devices must be fully marinized, they may require relatively less maintenance compared to offshore wind turbine parts in air, although MRE devices may be placed farther offshore and in less hospitable regions, including in high latitudes and remote locations, which may increase the difficulty of maintenanc (Copping et al. 2018; LiVecchi et al. 2019). Relatively small MRE devices can be placed offshore to serve many different types of ocean observation platforms on the sea surface and at depth. This placement of devices alleviates the need for a surface presence and frequent costly vessel cruises to replenish batteries. It may also provide energy for emerging offshore aquaculture farms. These offshore devices could potentially provide a stepping stone to electrification of commercial shipping and passenger vessel trips (Copping et al. 2018; LiVecchi et al. 2019).

MRE has the potential to add to the renewable energy portfolios of many countries to meet low-carbon renewable energy standards (Copping et al. 2018; Thresher and Musial 2010) and to address the need for climate change mitigation (IRENA 2019; UN General Assembly 2012). Like solar and wind energy, MRE does not require that generation technologies be replenished with fossil fuels, which reduces risk to waterways or habitats from spills during transport or power generation, and does not cause air quality degradation. While the manufacture and other elements of the MRE life cycle will generate carbon emissions, these emissions are expected to be similar to those of other renewable technologies, which are accounted for in life cycle carbon budgets. However, processes for studying life cycle analyses for MRE are not well developed. Power generated from waves and tides is more predictable, consistent, and continuous than either wind or solar power.

Like other renewable energy forms, a driving motivation behind MRE development is the mitigation of climate change by reducing greenhouse gas (GHG) emissions through the expansion of non-carbon generating sources. Marine animals and plants are subject to the deleterious effects of GHG emissions-related ocean acidification (e.g., Doney et al. 2009; Fabry et al. 2008; Harley et al. 2006) and ocean warming (e.g., Cheung et al. 2013; Stachowicz et al. 2002; Wernberg et al. 2011), and nearshore habitats that support many commercially important and endangered species are affected by rising sea levels (e.g., Bigford 2008; Yang et al. 2015). The potential benefits to marine animals and habitats of mitigating climate change through renewable power generation far outweigh the potential impacts of MRE development, if projects are sited and scaled in an environmentally responsible manner (Copping et al. 2016). However, the scale of MRE development will need to be greatly accelerated in order to have a measurable effect on climate change mitigation and other benefits to marine life.

The placement of all wave and tidal devices developed to date requires contact with the seabed to hold them in place, either by gravity foundations placed on the seafloor, or some form of anchor or holdfast driven into the sea bottom. This placement will alter the immediate deployment location to some extent, but may also create new habitat types that may be in short supply in the immediate region. MRE devices (particularly wave energy converters [WECs]) can be sited offshore in ways that avoid rare rocky reef or deep-sea sponge/coral habitats, and they can be preferentially placed in soft-bottom habitats that are extensive on the continental shelves and slopes of the world's oceans. Adding an MRE foundation or anchor may create new hard-bottom habitat, providing shelter and access to food for benthic organisms (e.g., Callaway et al. 2017), including commercially important species like crab and lobster (Hooper and Austen 2014; Langhamer and Wilhelmsson 2009).

Typically, environmental statutes and regulations do not have mechanisms to enable consideration of beneficial uses of MRE devices—such as habitat creation (e.g., Callaway et al. 2017)—to offset potential deleterious effects. However, the creation of *de facto* marine reserves around MRE projects is likely to benefit local communities of fish and other organisms, as stressors associated with human activities, such as fishing, and disturbance are removed (Inger et al. 2009).

1.2. BALANCING CONCERNS WITH BENEFITS FOR MRE DEVELOPMENT

When considering the benefits of marine energy, one must also consider its potential negative effects. In every location where MRE development is being considered, it is important to determine potential effects on marine animals, habitats, and the oceanographic systems that support them, and to use every effort to minimize or mitigate such damage. Many of the animal populations that reside in the energy-rich areas of the ocean are already under considerable stress from other human activities including shipping, fishing, waste disposal, and shoreline development (Crain et al. 2009). To achieve sustainable development it is important that the MRE industry not cause additional environmental stress and related damage. It is the examination of these stresses, their potential risks to the marine environment, and how these risks might be understood, placed in context, managed, and minimized, that are the major focuses of this report.

1.3. *2020 STATE OF THE SCIENCE* REPORT

This report builds on and serves as an update and a complement to the 2013 Final Report for Phase 1 of OES-Environmental (Copping et al. 2013) and the *2016 State of the Science* report (Copping et al. 2016). Its content reflects the most current and pertinent published information about interactions of MRE devices and associated infrastructure with the animals and habitats that make up the marine environment. It has been developed and reviewed by over 60 international experts and scientists from around the world as part of an ongoing effort supported by the OES collaboration that operates within the International Technology Cooperation Framework of the International Energy Agency (IEA).

The term MRE is used throughout this report to describe power generated by the movement and gradients of seawater and the run of the river flows of large rivers. Generating power from the ocean includes the use of other technologies, including offshore wind turbines, but this report is focused on devices that generate energy from seawater and from large rivers. Lessons learned from bottom-fixed or floating offshore wind development and discussions of similar environmental effects also are included when appropriate.

1.3.1. SOURCES OF INFORMATION

Information used for the *2020 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—all of which represent the state of knowledge for the industry. Report topics include monitoring, baseline assessments, and investigations of environmental effects for specific MRE projects; research studies that support specific MRE projects or address environmental interactions broadly; and guidance and assessments commissioned by governments and regulatory bodies to assist with the responsible development of the industry. The chapter authors all have expertise in these fields and have considered the available information to create a coherent view of the state of evidence and knowledge, using their own expert judgment to interpret the work.

1.3.2. USES OF THE INFORMATION

The information gathered and analyzed for the *2020 State of the Science* report was compiled to help inform regulatory and research investigations about potential risks to marine animals, habitats, and oceanographic processes from tidal and wave installations. This information can also be used to assist MRE developers when considering design 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 consent/permit (hereafter consent) deployments—from single devices through commercial arrays. The information brought together for analysis represents readily available, reliable information about environmental interactions with MRE devices. However, the analyses and the conclusions drawn are not meant to take the place of site-specific analyses and studies, direct consenting actions, or influence siting considerations in specific locations.

1.3.3 REPORT PURPOSE AND SCOPE

This report summarizes the current state of knowledge, science, and understanding related to the potential environmental effects that MRE devices and systems placed in the ocean may have on the marine animals that live there and the habitats that support them. MRE development worldwide is mostly focused on the generation of power from waves, tides, and some large rivers, but MRE also includes generation from ocean currents and from temperature and salinity gradients.

This report describes the potential interactions of MRE devices with the marine environment and the methods and approaches used to evaluate the level of risk and uncertainty associated with these potential interactions. It provides insights into management approaches that have the potential to facilitate the MRE industry's ability to establish this new renewable energy source while also protecting the marine environment and the people who rely on it for their livelihoods.

This report summarizes and facilitates access to the best available scientific evidence on the environmental effects of MRE. The value of this information will be realized as it is applied to consenting processes to enable increased and responsible deployment of devices. For some low risk stressors, consenting of single devices and small arrays should be possible based on the information provided in this report, including information from consented or deployed projects, from related research studies or from evidence from analogous offshore industries. For higher risk stressors, further evidence will be needed.

This report does not specifically address tidal barrages or tidal lagoons, which generate power from the change in water flow from high to low tides and back. Dam-like tidal barrages generally consist of turbines installed across the mouths of tidal rivers and bays that capture power as the tide ebbs and floods. This method of energy capture tends to cause widespread environmental damage to river mouths and estuaries (e.g., Retiere 1994). Tidal lagoons resemble tidal barrages but are placed in bays away from the mouths of rivers. Little is known about the potential environmental effects of tidal lagoons (e.g., Elliott et al. 2019). To date a number of tidal lagoon projects have been proposed but there are no active projects under development in Europe or North America.

This report is limited to the in-water and nearshore aspects of MRE development and does not address the potential effects of shoreside components, including cable landings, electrical infrastructure, and connections to national grids.

1.3.4. REPORT CONTENT AND ORGANIZATION

The *2020 State of the Science* report on the environmental effects of MRE development begins with a set of environmental questions that define investigations (Chapter 2) and continues with specific information about stressor/receptor interactions of importance (Chapters 3–9), delves into technologies for monitoring interactions with marine animals (chapter 10), addresses a series of management and planning measures that may assist with responsible MRE development (Chapters 11–13), and concludes with a potential path forward (Chapter 14). The chapter topics are summarized in Table 1.1.

Throughout the report, numerous wave, tidal, and river current projects and test sites are discussed. Offshore wind sites are also mentioned when the environmental information from those sites informs MRE issues. The physical location of each of these projects is shown in Figure 1.1 and additional site information is provided in Table 1.2.

1.4. OCEAN ENERGY SYSTEMS

Founded in 2001, OES[1] is an intergovernmental collaboration between countries that operates within a framework established by the 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 protec-

1 *https://www.ocean-energy-systems.org/*
2 *https://www.iea.org*

Table 1.1. Description of the chapter topics in the *2020 State of the Science* report.

Chapter	Chapter Title	Topic
2	Marine Renewable Energy: Environmental Effects and Monitoring Strategies	Defining stressors and receptors, potential environmental effects, and approaches to monitoring marine renewable energy (MRE) interactions.
3	Collision Risk for Animals around Turbines	Research on collision risk for marine mammals, fish, and seabirds around turbines.
4	Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices	Research on the effects of underwater noise produced by operation of MRE devices on marine mammals and fish.
5	Risk to Animals from Electromagnetic Fields Emitted by Electric Cables and Marine Renewable Energy Devices	Research on the effects of electromagnetic fields produced by operation of MRE devices and transmission cables on sensitive marine species.
6	Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices	Research on the physical and biological changes to benthic and pelagic habitats caused by MRE devices.
7	Changes in Oceanographic Systems Associated with Marine Renewable Energy Devices	Research on the potential of MRE devices to change flow patterns, remove energy, and affect wave heights.
8	Encounters of Marine Animals with Marine Renewable Energy Device Mooring Systems and Subsea Cables	Research on the potential of marine animals to physically encounter, get entangled, or entrapped in mooring systems or cables from MRE devices.
9	Social and Economic Data Collection for Marine Renewable Energy	Data collection needs for addressing social and economic effects of MRE development for consenting.
10	Environmental Monitoring Technologies and Techniques for Detecting Interactions of Animals with Turbines	Research on existing environmental monitoring technologies and lessons learned from monitoring programs for turbines.
11	Marine Spatial Planning and Marine Renewable Energy	Marine spatial planning (MSP) interactions with MRE and possibilities for integrating MSP in planning and developing the MRE industry.
12	Adaptive Management Related to Marine Renewable Energy	Use of adaptive management in consenting MRE devices.
13	Risk Retirement and Data Transferability for Marine Renewable Energy	Potential for risk retirement and data transfer for consenting MRE devices, and a proposed pathway to streamline consenting processes.
14	Summary and Path Forward	Summary of the report and concluding remarks for a path forward.

tion. 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.

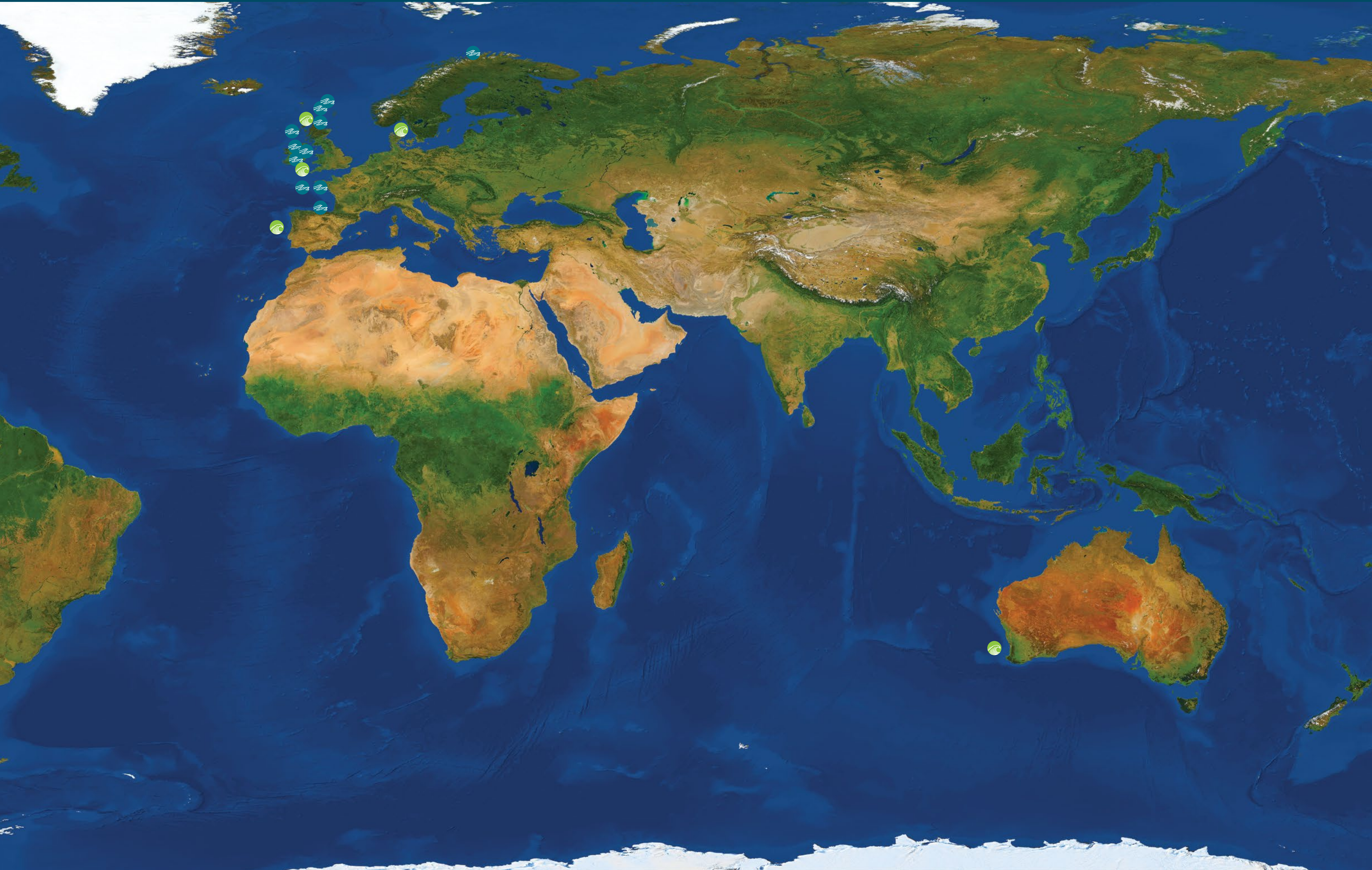
Under the OES Initiative, countries, through international cooperation and information exchange, advance research, development, and deployment of conversion technologies to convert energy from all forms of ocean renewable resources, including tides, waves, currents, temperature gradients (ocean thermal energy conversion), and salinity gradients for electricity generation, as well as for other uses, such as desalination. OES comprises 24 member countries and the European Commission (as of May 2020), each of which is represented by a Contracting Party. The Contracting Party 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 research and development analysis, and information exchange related to ocean energy systems. Work is conducted on diverse research topics that are specified as tasks of the Implementing Agreement (the OES agreement among nations). Each task is managed by an Operating Agent, usually the member nation that proposes the initiative and undertakes a set of planned activities, engaging the other participating nations in all aspects of the work.

Figure 1.1. Tidal, wave, river current, and offshore wind sites mentioned in the various chapters of the report. See Table 1.2 for corresponding site information.

Legend

Tidal Wave River Offshore wind




Alaska
1
Western United States
2
3
4
Hawaii
5
Eastern United States and Canada
6
7
8
9
10
Australia
26
United Kingdom
17
18
19
20
21
22
23
24
25
North Western Europe
11
12
Western Europe
13
14
15
16
Legend
Tidal
Wave
River
Offshore wind
Abandoned or decommissioned

Table 1.2. Wave, tidal, river current, and offshore wind sites mentioned in the various chapters of the report.

Site #	Site Name	Location	Technology	Project Name	Status
1	Kvichak River/Iguigig	Alaska, United States (U.S.)	River	ORPC RivGen	Operational
2	Race Rocks Ecological Reserve	British Columbia, Canada	Tidal	Clean Current's Tidal Current Generator	Decommissioned
3	Admiralty Inlet, Puget Sound	Washington, U.S.	Tidal	Admiralty Inlet Pilot Tidal Project	Abandoned
4	Reedsport	Oregon, U.S.	Wave	Reedsport OPT Wave Park	Abandoned
5	WETS	Hawaii, U.S.	Wave	Fred Olsen Lifesaver at WETS	Operational
6	Bay of Fundy	Nova Scotia, Canada	Tidal	FORCE test site, Cape Sharp Tidal Venture	Operational
7	Cobscook Bay	Maine, U.S.	Tidal	ORPC TidGen	Under Development
8	Grand Passage, Nova Scotia	Nova Scotia, Canada	Tidal	PLAT-I	Operational
9	Block Island	Rhode Island, U.S.	Offshore Wind	Rhode Island Ocean Special Area Management Plan	Operational
10	East River	New York, U.S.	Tidal	Roosevelt Island Tidal Energy (RITE)	Operational
11	Kvalsund	Norway	Tidal	Kvalsun Tidal Turbine Prototype (Hammerfest Strøm)	Decommissioned
12	Lysekil	Sweden	Wave	Lysekil Wave Energy Site	Operational
13	La Rance	France	Tidal Barrage	La Rance Tidal Barrage	Operational
14	Paimpol-Bréhat	France	Tidal	OpenHydro Paimpol-Bréhat Demonstration Project	Decommissioned
15	SEENOH Test Site	France	Tidal	Site Expérimental Estuarien National pour l'Essai et l'Optimisation Hydrolienne (SEENOH)	Operational
16	Aguçadoura	Portugal Wave Farm	Wave	Pelamis Wave Power Aguçadoura	Decommissioned
17	Bluemull Sound, Shetland	Scotland, United Kingdom (UK)	Tidal	Nova Innovation Shetland Tidal Array	Operational
18	Fall of Warness, Orkney	Scotland, UK	Tidal	EMEC test site	Operational
	Fall of Warness, Orkney	Scotland, UK	Tidal	OpenHydro at EMEC	Decommissioned
	Fall of Warness, Orkney	Scotland, UK	Tidal	EMEC test site: Deepgen, Alstrom	Decommissioned
19	Blllia Croo	Scotland, UK	Wave	EMEC test sit	Operational
20	Inner Sound, Pentland Firth	Scotland, UK	Tidal	MeyGen	Operational
21	Kyle Rhea	England, UK	Tidal	Kyle Rhea Tidal Stream Array	Abandoned
22	Strangford Lough	Northern Ireland, UK	Tidal	SeaGen	Decommissioned
	Strangford Lough	Northern Ireland, UK	Tidal	Minesto Powerkite	Decommissioned
	Schottel	Northern Ireland, UK	Tidal	Queen's University Belfast Tidal Test Site	Decommissioned
23	Holyhead Deep	Wales, UK	Tidal	Minesto Deep Green	Operational
24	Ramsey Sound	Wales, UK	Tidal	DeltaStream Pembrokeshire	Abandoned
25	FaBTest	Cornwall, UK	Wave	Fred Olsen Lifesaver at FaBTest	Decommissioned
26	Garden Island	Western Australia	Wave	Perth Wave Energy Project	Decommissioned

1.4.1. THE OES-ENVIRONMENTAL (FORMERLY ANNEX IV) TASK

The formation of the OES-Environmental[3] task or initiative, which is focused on the potential environmental impacts of MRE, was initiated by the United States and Canada in 2006 in response 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).[4] After a meeting of experts in late 2007, the United States developed a proposal for the formalization of OES-Environmental (at that time called Annex IV), which was submitted to and approved by the OES Executive Committee in 2008. The proposal noted the need to compile and disseminate information about the environmental effects of MRE and to identify methods of monitoring for such effects. OES-Environmental was proposed to focus primarily on ocean wave, tidal, and current energy development. The phases of task activities and participation in OES-Environmental task since its initiation are described in Table 1.3. The task has been led by the United States with the U.S. Department of Energy acting as the Operating Agent and Pacific Northwest National Laboratory (PNNL) implementing the task on behalf of the United States.

1.4.2. OES-ENVIRONMENTAL PHASE 3

The workplan for OES-Environmental Phase 3 (2016–2020) built on the tasks carried out during Phases 1 and 2, and the current status of these plans is described in Table 1.4.

OES-Environmental also hosted several workshops during Phase 3, bringing together experts to advance understanding of key interactions and to work toward consensus on how research and monitoring information can help inform consenting processes and help to move the MRE industry forward. The workshops are listed in Table 1.5 below.

The culmination of Phase 3 of OES-Environmental is the preparation of this document, the *2020 State of the Science* report.

Table 1.3. Ocean Energy Systems (OES)-Environmental task phases, timeline, and participating countries. Information about OES-Environmental activities during Phases 1 and 2 are detailed in the *2016 State of the Science* report (Copping et al. 2016). The UUnited States (U.S.) has led all three phases of the task, with the U.S. Department of Energy acting as the Operating Agent and Pacific Northwest National Laboratory implementing the task.

Phase	Timeline	Nations and Partners Committed
Phase 1	2009 - 2012	Seven participating nations (Canada, Ireland, New Zealand, Norway, South Korea, Spain, and the United States [U.S.]) supported the Ocean Energy Systems (OES)-Environmental task by formalizing their commitments to the effort and developing a work plan and budget for the task. Cooperating U.S. federal agencies during this phase included the Federal Energy Regulatory Commission (FERC), the Bureau of Ocean Energy Management (BOEM), and National Oceanic and Atmospheric Administration (NOAA). Pacific Northwest National Laboratory (PNNL) was assisted by the Wave Energy Centre in Portugal and the University of Plymouth in the United Kingdom (UK).
Phase 2	2013 - 2016	Thirteen nations (Canada, China, Ireland, Japan, New Zealand, Nigeria, Norway, Portugal, South Africa, Spain, Sweden, the UK, and the U.S.) participated in Phase 2. Cooperating U.S. federal agencies during this phase included BOEM and NOAA. PNNL was assisted by Aquatera Ltd. in the UK.
Phase 3	2016 - 2020	Fifteen nations (Australia, Canada, China, Denmark, France, India, Ireland, Japan, Norway, Portugal, South Africa, Spain, Sweden, the UK, and the U.S.) participated in this phase. The leadership and implementation of the task remained the same as those during Phase 2.

3. OES-Environmental was known as Annex IV until August 2019, at which time the name was changed to be more in line with other OES tasks. The organization, mission, and management of the task has not changed.

4. National Renewable Energy Laboratory (U.S.) and Natural Resources Canada (Canada). October 18, 2007. Potential Environmental Impacts of Ocean Energy Devices: Meeting Summary Report.

Table 1.4. Workplan for Ocean Energy Systems (OES)-Environmental Phase 3 (2016-2020).

Task #	Task	Task Description	Status and Progress (as of May 2020)
1	Expand *Tethys* collection	Populate the publicly available knowledge management system *Tethys* (*https://tethys.pnnl.gov*) with scientific information about the environmental effects of marine energy.	◆ 6262 documents (of which 2996 are peer-reviewed) that address environmental effects of marine renewable energy (MRE) development on *Tethys*. ◆ Documents are continually added to *Tethys* as they become available.
2	Outreach and engagement	Outreach and engagement with the MRE community, with emphasis on researchers, regulators, and device developers.	Key activities pursued during this phase included the following: ◆ A biweekly electronic newsletter, *Tethys* Blast, has been sent to the Ocean Energy Systems (OES)-Environmental community of approximately 1800. All *Tethys* Blasts are archived on *Tethys* at *http://tethys.pnnl.gov/tethys-blasts*. ◆ Webinars with experts on environmental effects of MRE feature advances in research. All webinars have been archived on *Tethys* at: *https://tethys.pnnl.gov/environmental-webinars.* ◆ Expert forums are held to discuss difficult technical questions that are common to more than one jurisdiction and that are hindering consenting of MRE. Presentations and audio files are available on *Tethys* at: *http://tethys.pnnl.gov/expert-forums*.
3	Metadata forms on environmental monitoring	Compile information from environmental data collection and monitoring around deployed MRE devices and related research studies.	◆ 107 metadata forms related to marine energy deployments ◆ 106 metadata descriptions of research studies
4	Supporting international conferences	Partner with international conferences on MRE to raise the profile of environmental research on MRE.	◆ Environmental Interactions of Marine Renewables (EIMR) 2016, Edinburgh, United Kingdom (UK) February 2016. ◆ European Wave and Tidal Energy Conference (EWTEC) 2017, Cork, Ireland, September 2017. ◆ EIMR 2018, Orkney UK, April 2018. ◆ EWTEC 2019, Napoli, Italy, September 2019.
5	*State of Science*	Develop *2020 State of the Science* report for environmental effects of MRE.	◆ Research, write, and integrate extensive reviews for report. ◆ Release report as public draft, June 2020. ◆ Release final report, September 2020.

Table 1.5. Workshops held by Ocean Energy Systems (OES)-Environmental during Phase 3.

Title	Location	Date
Management Measures Workshop *https://tethys.pnnl.gov/events/management-measures*	Glasgow, United Kingdom (UK)	May 9, 2017
Exploring the State of Understanding and Practice used to Assess Social and Economic Risks and Benefits of Marine Renewable Energy Development *https://tethys.pnnl.gov/events/exploring-state-understanding-practice-used-assess-social-economic-risks-benefits-marine*	Cork, Ireland	Aug 31, 2017
Case Studies on Social and Economic Effects around MRE Developments *https://tethys.pnnl.gov/events/case-studies-social-economic-effects-around-mre-development*	Kirkwall, UK	Apr 23, 2018
Data Transferability and Collection Consistency Workshop (ICOE) *https://tethys.pnnl.gov/events/annex-iv-data-transferability-collection-consistency-icoe*	Cherbourg, France	Jun 12, 2018
Addressing Collision Risks from Tidal and River Turbines *https://tethys.pnnl.gov/events/addressing-collision-risks-tidal-and-river-turbines*	Edinburgh, UK	Feb 26, 2019
Retiring Risks of MRE Environmental Interactions to Support Consenting/Permitting *https://tethys.pnnl.gov/events/retiring-risks-mre-environmental-interactions-support-consentingpermitting*	Napoli, Italy	Sep 5, 2019
Retiring Risk for MRE Projects to Support Permitting *https://tethys.pnnl.gov/events/oes-environmental-workshop-retiring-risk-mre-projects-support-permitting*	Portland, Oregon, United States	Sep 11, 2019
Environmental Effects and Risk Retirement for MRE *https://tethys.pnnl.gov/events/oes-environmentalorjip-workshop-environmental-effects-risk-retirement-mre*	Sydney, Australia	Dec 4, 2019

1.5. REFERENCES

Bigford, T. E. 1991. Sea-level rise, nearshore fisheries, and the fishing industry. *Coastal Management*, 19(4), 417-437. doi:10.1080/08920759109362152 *https://tethys.pnnl.gov/publications/sea-level-rise-nearshore-fisheries-fishing-industry*

Callaway, R., Bertelli, C., Lock, G., Carter, T., Friis-Madsen, E., Unsworth, R., Sorense, H., and Neumann, F. 2017. Wave and Tidal Range Energy Devices Offer Environmental Opportunities as Artificial Reefs. Paper presented at the 12th European Wave and Tidal Energy Conference, Cork, Ireland. *https://tethys.pnnl.gov/publications/wave-tidal-range-energy-devices-offer-environmental-opportunities-artificial-reefs*

Cheung, W. W. L., Watson, R., and Pauly, D. 2013. Signature of ocean warming in global fisheries catch. *Nature*, 497(7449), 365-368. *doi:10.1038/nature12156 https://tethys.pnnl.gov/publications/signature-ocean-warming-global-fisheries-catch*

Copping, A., Hanna, L., Whiting, J., Geerlofs, S., Grear, M., Blake, K., Coffey, A., Massaua, M., Brown-Saracino, J., and Battey, H. 2013. Environmental Effects of Marine Energy Development around the World: Annex IV Final Report. Pacific Northwest National Laboratory, Richland, Washington. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. *https://tethys.pnnl.gov/publications/environmental-effects-marine-energy-development-around-world-annex-iv-final-report*

Copping, A., LiVecchi, A., Spence, H., Gorton, A., Jenne, S., Preus, R., Gill, G., Robichaud, R., and Gore, S. 2018. Maritime Renewable Energy Markets: Power From the Sea. *Marine Technology Society Journal*, 52(5), 99-109. doi:10.4031/MTSJ.52.5.3 *https://tethys.pnnl.gov/publications/maritime-renewable-energy-markets-power-sea*

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewski, G., Staines, G., Gill, A., Hutchison, I., O'Hagan, A., Simas, T., Bald, J., Sparling, C., Wood, J., and Masden, E. 2016. Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. *https://tethys.pnnl.gov/publications/state-of-the-science-2016*

Crain, C. M., Halpern, B. S., Beck, M. W., and Kappel, C. V. 2009. Understanding and Managing Human Threats to the Coastal Marine Environment. *Annals of the New York Academy of Sciences*, 1162(1), 39-62. doi:10.1111/j.1749-6632.2009.04496.x *https://tethys.pnnl.gov/publications/understanding-managing-human-threats-coastal-marine-environment*

Doney, S. C., Fabry, V. J., Feely, R. A., and Kleypas, J. A. 2009. Ocean Acidification: The Other CO2 Problem. *Annual Review of Marine Science*, 1(1), 169-192. doi:10.1146/annurev.marine.010908.163834 *https://tethys.pnnl.gov/publications/ocean-acidification-other-co2-problem*

Elliott, K., Smith, H. C. M., Moore, F., van der Weijde, A. H., and Lazakis, I. 2019. A systematic review of transferable solution options for the environmental impacts of tidal lagoons. *Marine Policy*, 99, 190-200. doi:10.1016/j.marpol.2018.10.021 *https://tethys.pnnl.gov/publications/systematic-review-transferable-solution-options-environmental-impacts-tidal-lagoons*

Fabry, V. J., Seibel, B. A., Feely, R. A., and Orr, J. C. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science*, 65(3), 414-432. doi:10.1093/icesjms/fsn048 *https://tethys.pnnl.gov/publications/impacts-ocean-acidification-marine-fauna-ecosystem-processes*

Harley, C. D. G., Randall Hughes, A., Hultgren, K. M., Miner, B. G., Sorte, C. J. B., Thornber, C. S., Rodriguez, L. F., Tomanek, L., and Williams, S. L. 2006. The impacts of climate change in coastal marine systems. *Ecology Letters*, 9(2), 228-241. doi:10.1111/j.1461-0248.2005.00871.x *https://tethys.pnnl.gov/publications/impacts-climate-change-coastal-marine-systems*

Hooper, T., and Austen, M. 2014. The co-location of offshore windfarms and decapod fisheries in the UK: Constraints and opportunities. *Marine Policy*, 43, 295-300. doi:10.1016/j.marpol.2013.06.011 *https://tethys.pnnl.gov/publications/co-location-offshore-windfarms-decapod-fisheries-uk-constraints-opportunities*

Inger, R., Attrill, M. J., Bearhop, S., Broderick, A. C., James Grecian, W., Hodgson, D. J., Mills, C., Sheehan, E., Votier, S. C., Witt, M. J., and Godley, B. J. 2009. Marine renewable energy: potential benefits to biodiversity? An urgent call for research. *Journal of Applied Ecology*, 46(6), 1145-1153. doi:10.1111/j.1365-2664.2009.01697.x *https://tethys.pnnl.gov/publications/marine-renewable-energy-potential-benefits-biodiversity-urgent-call-research*

International Renewable Energy Agency (IRENA). 2019. Renewable Energy Statistics 2019. Abu Dhabi. *https://tethys-engineering.pnnl.gov/publications/renewable-energy-statistics-2019*

Langhamer, O., and Wilhelmsson, D. 2009. Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes – A field experiment. *Marine Environmental Research*, 68(4), 151-157. doi:10.1016/j.marenvres.2009.06.003 *https://tethys.pnnl.gov/publications/colonisation-fish-crabs-wave-energy-foundations-effects-manufactured-holes-field*

LiVecchi, A., Copping, A., Jenne, D., Gorton, A., Preus, R., Gill, G., Robichaud, R., Green, R., Geerlofs, S., Gore, S., Hume, D., McShane, W., Schmaus, C., and Spence, H. 2019. Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Washington, D.C. *https://tethys.pnnl.gov/publications/powering-blue-economy-exploring-opportunities-marine-renewable-energy-maritime-markets*

Marine Energy Wales. 2020. State of the Sector 2020: Economic Benefits for Wales. *https://tethys.pnnl.gov/publications/state-sector-report-2020-economic-benefits-wales*

Pelc, R., and Fujita, R. M. 2002. Renewable energy from the ocean. *Marine Policy*, 26(6), 471-479. doi:/10.1016/S0308-597X(02)00045-3 *https://tethys.pnnl.gov/publications/renewable-energy-ocean*

Retiere, C. 1994. Tidal power and the aquatic environment of La Rance. *Biological Journal of the Linnean Society*, 51(1-2), 25-36. doi:10.1111/j.1095-8312.1994.tb00941.x *https://tethys.pnnl.gov/publications/tidal-power-aquatic-environment-la-rance*

Smart, G., and Noonan, M. 2018. Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit. Offshore Renewable Energy Catapult, Glasgow UK. *https://tethys-engineering.pnnl.gov/publications/tidal-stream-wave-energy-cost-reduction-industrial-benefit*

Stachowicz, J. J., Terwin, J. R., Whitlatch, R. B., and Osman, R. W. 2002. Linking climate change and biological invasions: Ocean warming facilitates nonindigenous species invasions. *Proceedings of the National Academy of Sciences*, 99(24), 15497. doi:10.1073/pnas.242437499 *https://tethys.pnnl.gov/publications/linking-climate-change-biological-invasions-ocean-warming-facilitates-nonindigenous*

Thresher, R., and Musial, W. 2015. Ocean Renewable Energy's Potential Role In Supplying Future Electrical Energy Needs. *Oceanography*, 23(2), 16-21. doi:10.5670/oceanog.2010.39 *https://tethys.pnnl.gov/publications/ocean-renewable-energys-potential-role-supplying-future-electrical-energy-needs*

United Nations General Assembly. 2012. Report on the work of the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea at its thirteenth meeting (A/67/120). *https://tethys.pnnl.gov/publications/thirteenth-meeting-united-nations-open-ended-informal-consultative-process-oceans-law*

Wernberg, T., Russell, Bayden D., Thomsen, Mads S., Gurgel, C. Frederico D., Bradshaw, Corey J. A., Poloczanska, Elvira S., and Connell, Sean D. 2011. Seaweed Communities in Retreat from Ocean Warming. *Current Biology*, 21(21), 1828-1832. doi:10.1016/j.cub.2011.09.028 *https://tethys.pnnl.gov/publications/seaweed-communities-retreat-ocean-warming*

Yang, Z., Wang, T., Voisin, N., and Copping, A. 2015. Estuarine response to river flow and sea-level rise under future climate change and human development. *Estuarine, Coastal and Shelf Science*, 156, 19-30. doi:10.1016/j.ecss.2014.08.015 *https://tethys.pnnl.gov/publications/estuarine-response-river-flow-sea-level-rise-under-future-climate-change-human*

NOTES

Marine Renewable Energy and Ocean Energy Systems

Copping, A.E. 2020. Marine Renewable Energy and Ocean Energy Systems. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 2-17). doi:10.2172/1632879

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at: *https://tethys.pnnl.gov/publications/state-of-the-science-2020*

CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

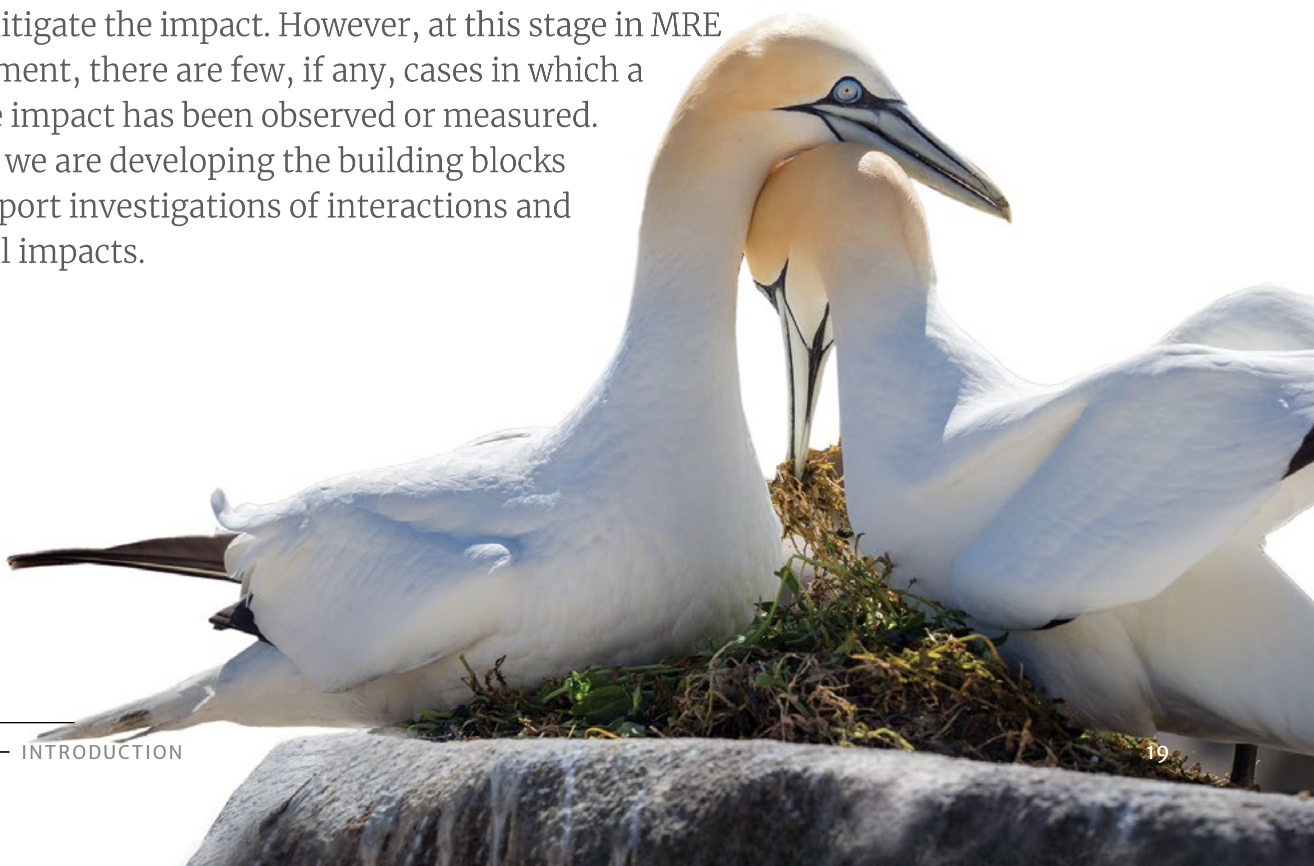
Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

2.0

Chapter author: Andrea E. Copping
Contributor: Deborah J. Rose

Marine Renewable Energy: Environmental Effects and Monitoring Strategies

As we learn more about interactions between marine renewable energy (MRE) devices, the animals and habitats near them, and the oceanographic processes with which they interact, we need to clarify the language used to discuss those interactions. For example, if an MRE device or system negatively affected a number of animals, we could say that the device or the system of foundations, anchors, and mooring lines had an impact on the population, and take steps to avoid the impact or, in some cases, mitigate the impact. However, at this stage in MRE development, there are few, if any, cases in which a negative impact has been observed or measured. Instead, we are developing the building blocks that support investigations of interactions and potential impacts.



2.1.
POTENTIAL EFFECTS OF MARINE RENEWABLE ENERGY

Key investigations to determine effects of MRE devices include determining the presence of animals close enough to devices/cables/lines that are potentially at risk, measuring device and cable outputs such as underwater noise and electromagnetic fields, measuring potential interactions of animals with these emissions or MRE devices, and modeling changes in water flow and sediment transport at large-scale MRE developments.

At this early stage of MRE development, few observations or data collection efforts point to devices or systems that are causing population-level impacts. The emphasis of research and monitoring studies has been on examining changes in or effects on individual organisms, particularly populations under stress or species of special concern. In most cases, it is difficult to determine whether such effects might be sufficiently deleterious to an animal (or a habitat) to have higher level impacts on populations or the marine ecosystem. Throughout this report, we refer to the effects or potential effects of MRE development and make the connection only to the population-level impacts if established methods or regulatory pathways require such examination.

2.2.
STRESSORS AND RECEPTORS

Throughout this report, we examine interactions between MRE systems and the marine environment in terms of stressors and receptors (Boehlert and Gill 2010). Stressors are those parts of an MRE system that may cause harm or stress to a marine animal, a habitat, oceanographic processes, or ecosystem processes. These stressors include the moving blades on turbines, mooring lines, anchors or foundations, power export cables, and the emissions that can result from any of these parts. The receptors include the marine animals living in and traversing the vicinity of an MRE development; the habitats into which the devices are deployed; and oceanographic processes, such as the natural movement of waters, wave heights, sediment transport, and the concentrations of dissolved gases and nutrients that support marine life. It is the intersection of stressors and receptors that define the interactions that can be examined through observations, laboratory and field experiments, and modeling studies. Section 2 of this report (Chapters 3–8) describes the state of scientific understanding of these stressor-receptor interactions (Figure 2.1).

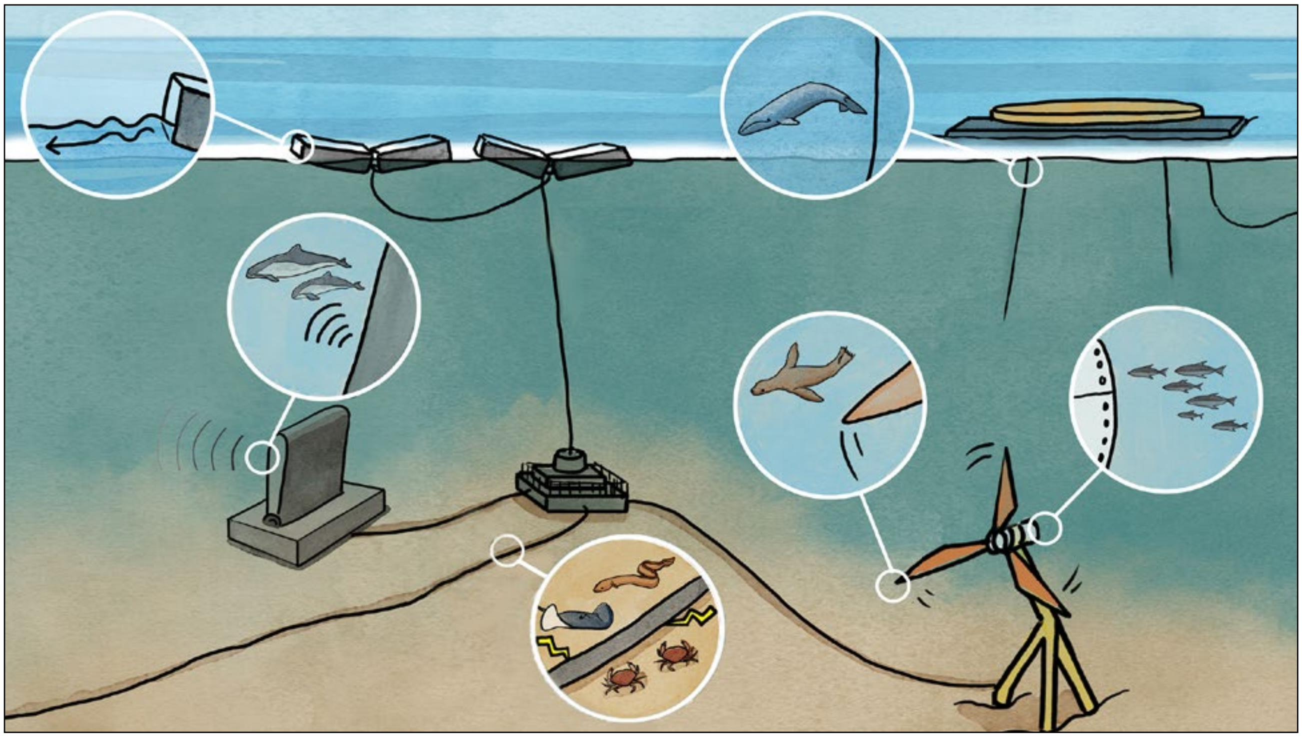


Figure 2.1. Stressor-receptor interactions potentially arising from various marine renewable energy devices. From top left to bottom right: changes in oceanographic systems, underwater noise, electromagnetic fields, mooring entanglement, collision risk, and changes in habitats. (Illustration by Rose Perry)

2.3. DEFINITIONS FOR MEASURING ENVIRONMENTAL EFFECTS

A number of common definitions are used in the measurement, analysis, and reporting of environmental monitoring results around MRE devices (Table 2.1). In addition, there are specific definitions that are used for measurements that describe certain stressor-receptor interactions; these definitions can be found in subsequent chapters.

2.4. MEASURING THE EFFECTS OF MRE DEVICES

Responsible and sustainable development of MRE as a renewable energy source requires that we understand the environments into which turbines or other devices such as kites (for harvesting power from tides, ocean currents, or river flows) and wave energy converters (WECs) will be deployed. Regulations often require that early deployments include extensive monitoring to collect sufficient data to understand the potential interactions of devices and systems with marine animals and habitats. The high-energy locations, and often turbid waters, into which MRE devices are placed add considerable challenges to deploying and operating the oceanographic gear and sensor platforms needed to characterize the stressor-receptor interactions that may be occurring. These challenging locations require that boat-based and human observations be kept to a minimum, in favor of *in situ* remote instrumentation. Collecting and interpreting useful information collected at MRE deployment sites poses significant difficulties, because of the challenges of operating instrumentation underwater, as well as the challenges of processing and transmitting data for analysis. Not all instrumentation and/or data collection efforts related to conducting this type of monitoring over the last decade have succeeded in meeting their monitoring goals. For future monitoring projects at MRE sites to be successful, lessons must be taken from previous efforts to assure that each subsequent effort builds on previous experience, thereby avoiding costly duplication and advancing the industry efficiently.

Details of the methods being used to monitor stressor-receptor interactions can be found in Chapters 3–8; extensive detail about the challenges of and solutions for measuring close interactions of animals and MRE devices can be found in Chapter 10 (Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines).

Table 2.1. Definitions associated with investigations for consenting of marine renewable energy projects and research studies. These definitions are used in multiple chapters in this report; certain chapters, notably Chapter 3 (Collision Risk) and Chapter 4 (Underwater Noise), will define additional terms specific to that interaction.

Term	Definition
Baseline survey/site characterization	• Survey and fieldwork undertaken prior to marine renewable energy (MRE) device installation to gather data to better understand, quantify, and assess potential impacts. • Generally required in support of license/consent applications.
Cumulative effects	• Changes to the environment caused by the combined effects of multiple human activities and natural processes. Cumulative effects may be realized as the effects of repeated actions that may have an effect greater than the sum of their individual effects.
Farfield	• The area of ocean or bay around an MRE device, generally defined as more than five device diameters from the device or array of devices.
Nearfield	• The localized area of sea occupied by and in very close proximity to an MRE device, generally considered to be within one to five device diameters.
Environmental monitoring associated with MRE projects	• Monitoring carried out to gather data before devices are deployed (post-consent monitoring) or monitoring of the environmental effects of deployed MRE devices (post-installation monitoring). • Generally monitoring is required by regulators to validate predictions made in environmental assessments or to provide an evidence base for adaptive management of effects for which there is residual uncertainty.
Project environmental monitoring plan (may go by various names including PEMPs/EMPs/others)	• A document produced as a requirement of licensing/consenting processes for MRE projects setting out the objectives and methodologies of post-installation environmental monitoring.

2.5.
KEY MONITORING QUESTIONS

The most significant stressor-receptor interactions of concern, based on the accumulated knowledge to date (Copping et al. 2016; ICES 2019), and the primary factors that continue to generate interest and concern about these interactions among stakeholders with an interest in MRE development are summarized here.

Gaps in our knowledge and understanding of the potential effects of interactions between MRE stressors and marine receptors span multiple spatial and temporal scales, such that a large range of monitoring efforts would be needed to fully understand and track these effects. The significant increase in our understanding of potential effects across multiple scales over the past decade has come about largely as the result of focusing on two general categories of monitoring questions: direct interactions of stressors and receptors, and the context and environment in which MRE devices are placed.

2.5.1.
DIRECT EFFECTS OF STRESSOR-RECEPTOR INTERACTIONS

Scientific questions that inform our understanding of the direct effects of MRE devices focus on the actions and interactions of organisms as they encounter devices in their natural habitat. Topics that inform those questions include the following:

- rates of encounter and effects (injury/mortality rates) of collision with turbine blades (e.g., Bevelheimer et al. 2019; Copping and Grear 2018; Copping et al. 2017; Joy et al. 2018; Onoufriou et al. 2019; Schmitt et al. 2017)
- avoidance of moving parts or acoustic fields generated by the device (e.g., Grippo et al. 2017; Hastie et al. 2018; Robertson et al. 2018)
- avoidance of or attraction to magnetic and induced electrical fields (e.g., Gill et al. 2014; Westerberg and Lagenfelt 2008)
- attraction to or aggregation around bottom-mounted or floating structures (e.g., Fraser et al. 2018; Kramer et al. 2015; Williamson et al. 2019)
- displacement or permanent alteration of behavior patterns due to novel device presence (e.g., Long 2017; Sparling et al. 2018)
- probability and effects of entrapment or entanglement of large marine animals because of the presence of mooring lines, anchors, and export cables (e.g., Benjamins et al. 2014; Copping et al. 2018).

Studies have been designed to observe specific marine animal behaviors in response to the presence of MRE devices or their acoustic or electrical signatures; these potential effects occur at known or expected locations and/or at times that can be targeted for observation. Many of these interactions can be examined through modeling and other techniques that do not require the in-water study of the physical/biological setting of a specific device. For example, our understanding of the mechanisms for blade strike or collision assume an animal is encountering a device; for electromagnetic field (EMF) effects we assume a receptive organism is located near the cable/component; and when investigating acoustic effects we assume the animal can detect the emitted sound and is within range, etc.

2.5.2.
MONITORING WITHIN THE CONTEXT OR ENVIRONMENT OF MRE DEVICES

The second set of questions on which we focus deals with the context or vicinity of the device(s). While necessarily site-specific, answers to these questions will build our understanding of the biological and physical components of (and their linkages with) the highly energetic environments targeted for wave or tidal power development. It is necessary to understand the background processes at work at a site before designing a monitoring program that will reliably separate effects from the background natural variability as well as from effects of other anthropogenic activities. Topics that inform those questions include the following:

- inventories of organisms that naturally occur in the area and examinations of their normal distribution in space and time, as well as their movement patterns (e.g., Cox et al. 2017; Holdman et al. 2019; Lagerquist et al. 2019; Viehman et al. 2018; Yoshida et al. 2017)
- examinations of the amplitude and other characteristics of the MRE stressors, including underwater noise and EMF (e.g., Dhanak et al. 2015; Nedwell and Brooker 2008; Pine et al. 2019)
- modeling and validation of hydrodynamic and sedimentation patterns, and their associated variability in space and time (e.g., Ashall et al. 2016; Fairley et al. 2017; Haverson et al. 2018; Khaled et al. 2019)

- modeling of potential effects of MRE systems on ecosystems; although relatively little modeling has been carried out to date, agent-based models and ecosystem models will become useful as the industry moves toward large commercial arrays.

This information enables us to predict device effects, with some degree of confidence, and can be used to design effective mitigation measures, if needed. For example, animal distribution and movement patterns at a site will largely determine how likely the animals are to encounter a device or be affected by acoustic or electrical signatures. This contextual information can also indicate patterns of device encounter probability, thereby assisting with the siting of MRE developments to avoid or minimize the most likely adverse environmental effects. Combined with information about what occurs when an animal interacts with a device, such as rates of injury or mortality from blade strike, these results may inform regulatory needs to determine likely population-level impacts. A prime example of this approach can be seen in the outputs from several stages of the SeaGen turbine development and operation in Strangford Lough, Northern Ireland (Savidge et al. 2014) that informed adaptive management programs. These adaptive management programs helped MRE projects like TideGen in Cobscook Bay, Maine, United States (U.S.) develop effective monitoring and mitigation plans (ORPC 2013, 2014, 2017).

2.6. MONITORING STRATEGIES

Answering these wide-ranging questions at the highly energetic sites targeted for power production is a significant challenge. The need to understand environmental consequences has driven innovation in developing environmental monitoring gear. A number of different methods and technologies have been used to describe the close interactions of marine animals with devices at wave and tidal sites around the world, some of which are discussed in Chapter 10 (Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines). As with other stressor-receptor interactions, the myriad and complex questions that need to be answered suggest that no one instrument or method can provide all the answers; rather, a suite of methods, instruments, and study designs must be employed to capture the full picture of how MRE devices interact with their environment.

2.7. REFERENCES

Ashall, L. M., Mulligan, R. P., and Law, B. A. 2016. Variability in suspended sediment concentration in the Minas Basin, Bay of Fundy, and implications for changes due to tidal power extraction. *Coastal Engineering*, 107, 102-115. doi:10.1016/j.coastaleng.2015.10.003 *https://tethys.pnnl.gov/publications/variability-suspended-sediment-concentration-minas-basin-bay-fundy-and-implications*

Benjamins, S., Harnois, V., Smith, H., Johanning, L., Greenhill, L., Carter, C., and Wilson, B. 2014. Understanding the Potential for Marine Megafauna Entanglement Risk from Marine Renewable Energy Developments. Paper presented at the 2nd International Conference on Environmental Interactions of Marine Renewable Energy Technologies, Stornoway, Scotland. *https://tethys.pnnl.gov/publications/understanding-potential-marine-megafauna-entanglement-risk-marine-renewable-energy*

Bevelhimer, M. S., Pracheil, B. M., Fortner, A. M., Saylor, R., and Deck, K. L. 2019. Mortality and injury assessment for three species of fish exposed to simulated turbine blade strike. *Canadian Journal of Fisheries and Aquatic Sciences*, 76(12), 2350-2363. doi:10.1139/cjfas-2018-0386 *https://tethys.pnnl.gov/publications/mortality-and-injury-assessment-three-species-fish-exposed-simulated-turbine-blade*

Boehlert, G. W., and Gill, A. B. 2010. Environmental and Ecological Effects of Ocean Renewable Energy Development: A Current Synthesis. *Oceanography*, 23(2), 68-81. *https://tethys.pnnl.gov/publications/environmental-and-ecological-effects-ocean-renewable-energy-development-current*

Copping, A., and Grear, M. 2018. Applying a simple model for estimating the likelihood of collision of marine mammals with tidal turbines. *International Marine Energy Journal*, 1(1), 27-33. doi:10.36688/imej.1.27-33. *https://tethys.pnnl.gov/publications/applying-simple-model-estimating-likelihood-collision-marine-mammals-tidal-turbines*

Copping, A., Grear, M., Jepsen, R., Chartrand, C., and Gorton, A. 2017. Understanding the potential risk to marine mammals from collision with tidal turbines. *International Journal of Marine Energy*, 19, 110-123. doi:10.1016/j.ijome.2017.07.004 *https://tethys.pnnl.gov/publications/understanding-potential-risk-marine-mammals-collision-tidal-turbines*

Copping, A., Grear, M., and Sanders, G. 2018. Risk of whale encounters with offshore renewable energy mooring lines and electrical cables. Paper presented at the Environmental Interactions of Marine Renewables Conference, Kirkwall, Orkney, Scotland. *https://tethys.pnnl.gov/publications/risk-whale-encounters-offshore-renewable-energy-mooring-lines-and-electrical-cables*

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewski, G., Staines, G., Gill, A., Hutchison, I., O'Hagan, A., Simas, T., Bald, J., Sparling, C., Wood, J., and Masden, E. 2016. Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. *https://tethys.pnnl.gov/publications/state-of-the-science-2016*

Cox, S. L., Witt, M. J., Embling, C. B., Godley, B. J., Hosegood, P. J., Miller, P. I., Votier, S. C., and Ingram, S. N. 2017. Temporal patterns in habitat use by small cetaceans at an oceanographically dynamic marine renewable energy test site in the Celtic Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, 141, 178-190. doi:10.1016/j.dsr2.2016.07.001 *https://tethys.pnnl.gov/publications/temporal-patterns-habitat-use-small-cetaceans-oceanographically-dynamic-marine*

Dhanak, M., Kilfoyle, A., Ravenna, S., Coulson, R., Frankenfield, J., Jermain, R., Valdes, G., and Spieler, R. 2015. Characterization of EMF Emissions from Submarine Cables and Monitoring for Potential Responses of Marine Species. Paper presented at the 11th European Wave and Tidal Energy Conference, Nantes, France. *https://tethys.pnnl.gov/publications/characterization-emf-emissions-submarine-cables-and-monitoring-potential-responses*

Fairley, I., Karunarathna, H., and Chatzirodou, A. 2017. Modelling the Effects of Marine Energy Extraction on Non-Cohesive Sediment Transport and Morphological Change in the Pentland Firth and Orkney Waters. Report by Swansea University for Marine Scotland Science. doi:10.7489/1913-1 *https://tethys.pnnl.gov/publications/modelling-effects-marine-energy-extraction-non-cohesive-sediment-transport*

Fraser, S., Williamson, B. J., Nikora, V., and Scott, B. E. 2018. Fish distributions in a tidal channel indicate the behavioural impact of a marine renewable energy installation. *Energy Reports*, 4, 65-69. doi:10.1016/j.egyr.2018.01.008 *https://tethys.pnnl.gov/publications/fish-distributions-tidal-channel-indicate-behavioural-impact-marine-renewable-energy*

Gill, A. B., Gloyne-Philips, I., Kimber, J., and Sigray, P. 2014. Marine Renewable Energy, Electromagnetic (EM) Fields and EM-Sensitive Animals. In M. A. Shields and A. I. L. Payne (Eds.), *Marine Renewable Energy Technology and Environmental Interactions* (pp. 61-79). Dordrecht: Springer Netherlands. *https://tethys.pnnl.gov/publications/marine-renewable-energy-electromagnetic-em-fields-em-sensitive-animals*

Grippo, M., Shen, H., Zydlewski, G., Rao, S., and Goodwin, A. 2017. Behavioral Responses of Fish to a Current-Based Hydrokinetic Turbine Under Multiple Operational Conditions: Final Report (ANL/EVS-17/6). Report by Argone National Laboratory for U.S. Department of Energy; Argonne, Illinois. *https://tethys.pnnl.gov/publications/behavioral-responses-fish-current-based-hydrokinetic-turbine-under-multiple*

Hastie, G. D., Russell, D. J. F., Lepper, P., Elliott, J., Wilson, B., Benjamins, S., and Thompson, D. 2018. Harbour seals avoid tidal turbine noise: Implications for collision risk. *Journal of Applied Ecology*, 55(2), 684-693. doi:10.1111/1365-2664.12981 *https://tethys.pnnl.gov/publications/harbour-seals-avoid-tidal-turbine-noise-implications-collision-risk*

Haverson, D., Bacon, J., Smith, H. C. M., Venugopal, V., and Xiao, Q. 2018. Modelling the hydrodynamic and morphological impacts of a tidal stream development in Ramsey Sound. *Renewable Energy*, 126, 876-887. doi:10.1016/j.renene.2018.03.084 *https://tethys.pnnl.gov/publications/modelling-hydrodynamic-morphological-impacts-tidal-stream-development-ramsey-sound*

Holdman, A. K., Haxel, J. H., Klinck, H., and Torres, L. G. 2019. Acoustic monitoring reveals the times and tides of harbor porpoise (*Phocoena phocoena*) distribution off central Oregon, U.S.A. *Marine Mammal Science*, 35(1), 164-186. doi:10.1111/mms.12537 *https://tethys.pnnl.gov/publications/acoustic-monitoring-reveals-times-tides-harbor-porpoise-phocoena-phocoena-distribution*

International Council for the Exploration of the Sea (ICES). 2019. Working Group on Marine Benthal Renewable Developments (WGMBRED; Report No. 550297). ICES Scientific Reports, 1:6. doi:10.17895/ices.pub.4914 *https://tethys.pnnl.gov/publications/working-group-marine-benthal-renewable-developments*

Joy, R., Wood, J. D., Sparling, C. E., Tollit, D. J., Copping, A. E., and McConnell, B. J. 2018. Empirical measures of harbor seal behavior and avoidance of an operational tidal turbine. *Marine Pollution Bulletin*, 136, 92-106. doi:10.1016/j.marpolbul.2018.08.052 *https://tethys.pnnl.gov/publications/empirical-measures-harbor-seal-behavior-avoidance-operational-tidal-turbine*

Khaled, F., Guillou, S., Hadri, F., and Méar, Y. 2019. Numerical modelling of the effect of the hydro-kinetic turbines on the transport of sediments - Application to the Rhone site. *MATEC Web Conference*, 261, 05003. doi:10.1051/matecconf /201926105003 *https://tethys.pnnl.gov/publications/numerical-modelling-effect-hydro-kinetic-turbines-transport-sediments-application*

Kramer, S. H., Hamilton, C. D., Spencer, G. C., and Ogston, H. O. 2015. Evaluating the Potential for Marine and Hydrokinetic Devices to Act as Artificial Reefs or Fish Aggregating Devices. Based on Analysis of Surrogates in Tropical, Subtropical, and Temperate U.S. West Coast and Hawaiian Coastal Waters. OCS Study BOEM 2015-021. Report by H. T. Harvey & Associates for U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Golden, Colorado. *https://tethys.pnnl.gov/publications/evaluating-potential-marine-hydrokinetic-devices-act-artificial-reefs-or-fish*

Lagerquist, B. A., Palacios, D. M., Winsor, M. H., Irvine, L. M., Follett, T. M., and Mate, B. R. 2019. Feeding home ranges of Pacific Coast Feeding Group gray whales. *The Journal of Wildlife Management*, 83(4), 925-937. doi:10.1002/jwmg.21642 *https://tethys.pnnl.gov/publications/feeding-home-ranges-pacific-coast-feeding-group-gray-whales*

Long, C. 2017. Analysis of the Possible Displacement of Bird and Marine Mammal Species Related to the Installation and Operation of Marine Energy Conversion Systems. Report No. 947. Report for Scottish Natural Heritage; Redgorton, Scotland. *https://tethys.pnnl.gov/publications/analysis-possible-displacement-bird-marine-mammal-species-related-installation*

Nedwell, J., and Brooker, A. 2008. Measurement and Assessment of Background Underwater Noise and its Comparison with Noise from Pin Pile Drilling Operations During Installation of the SeaGen Tidal Turbine Device, Strangford Lough. Report No. 724R0120. Report by Subacoustech Ltd. for Collaborative Offshore Wind Research into the Environment (COWRIE). *https://tethys.pnnl.gov/publications/measurement-assessment-background-underwater-noise-its-comparison-noise-pin-pile*

Ocean Renewable Power Company (ORPC). 2013. Cobscook Bay Tidal Energy Project: 2012 Environmental Monitoring Report. Report by Ocean Renewable Power Company; Portland, Maine. *https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2012-environmental-monitoring-report*

Ocean Renewable Power Company (ORPC). 2014a. Cobscook Bay Tidal Energy Project: 2013 Environmental Monitoring Report. Report by Ocean Renewable Power Company; Portland, Maine. *https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2013-environmental-monitoring-report*

Ocean Renewable Power Company (ORPC). 2014b. Cobscook Bay Tidal Energy Project: 2013 Environmental Monitoring Report. Report by Ocean Renewable Power Company; Portland, Maine. *https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2016-environmental-monitoring-report*

Onoufriou, J., Brownlow, A., Moss, S., Hastie, G., and Thompson, D. 2019. Empirical determination of severe trauma in seals from collisions with tidal turbine blades. *Journal of Applied Ecology*, 56(7), 1712-1724. doi:10.1111/1365-2664.13388 *https://tethys.pnnl.gov/publications/empirical-determination-severe-trauma-seals-collisions-tidal-turbine-blade*

Pine, M. K., Schmitt, P., Culloch, R. M., Lieber, L., and Kregting, L. T. 2019. Providing ecological context to anthropogenic subsea noise: Assessing listening space reductions of marine mammals from tidal energy devices. *Renewable and Sustainable Energy Reviews*, 103, 49-57. doi:10.1016/j.rser.2018.12.024 *https://tethys.pnnl.gov/publications/providing-ecological-context-anthropogenic-subsea-noise-assessing-listening-space*

Robertson, F., Wood, J., Joslin, J., Joy, R., and Polagye, B. 2018. Marine Mammal Behavioral Response to Tidal Turbine Sound (DOE-UW-06385). Report by University of Washington for U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, Washington D.C. https://tethys.pnnl.gov/publications/marine-mammal-behavioral-response-tidal-turbine-sound

Savidge, G., Ainsworth, D., Bearhop, S., Christen, N., Elsaesser, B., Fortune, F., Inger, R., Kennedy, R., McRobert, A., Plummer, K. E., Pritchard, D. W., Sparling, C. E., and Whittaker, T. J. T. 2014. Strangford Lough and the SeaGen Tidal Turbine. In M. A. Shields and A. I. L. Payne (Eds.), *Marine Renewable Energy Technology and Environmental Interactions* (pp. 153-172). Dordrecht: Springer Netherlands. https://tethys.pnnl.gov/publications/strangford-lough-seagen-tidal-turbine

Schmitt, P., Culloch, R., Lieber, L., Molander, S., Hammar, L., and Kregting, L. 2017. A tool for simulating collision probabilities of animals with marine renewable energy devices. *PLoS ONE*, 12(11), e0188780. doi:10.1371/journal.pone.0188780 https://tethys.pnnl.gov/publications/tool-simulating-collision-probabilities-animals-marine-renewable-energy-devices

Sparling, C., Lonergan, M., and McConnell, B. 2018. Harbour seals (*Phoca vitulina*) around an operational tidal turbine in Strangford Narrows: No barrier effect but small changes in transit behaviour. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 28(1), 194-204. doi:10.1002/aqc.2790 https://tethys.pnnl.gov/publications/harbour-seals-phoca-vitulina-around-operational-tidal-turbine-strangford-narrows-no

Viehman, H., Boucher, T., and Redden, A. 2018. Winter and summer differences in probability of fish encounter (spatial overlap) with MHK devices. *International Marine Energy Journal*, 1(1). doi:10.36688/imej.1.9-18 https://tethys.pnnl.gov/publications/winter-summer-differences-probability-fish-encounter-spatial-overlap-mhk-devices

Westerberg, H., and Lagenfelt, I. 2008. Sub-sea power cables and the migration behaviour of the European eel. *Fisheries Management and Ecology*, 15(5-6), 369-375. doi:10.1111/j.1365-2400.2008.00630.x https://tethys.pnnl.gov/publications/sub-sea-power-cables-migration-behaviour-european-eel

Williamson, B., Fraser, S., Williamson, L., Nikora, V., and Scott, B. 2019. Predictable changes in fish school characteristics due to a tidal turbine support structure. *Renewable Energy*, 141, 1092-1102. doi:10.1016/j.renene.2019.04.065 https://tethys.pnnl.gov/publications/predictable-changes-fish-school-characteristics-due-tidal-turbine-support-structure

Yoshida, T., Kitazawa, D., and Mizukami, Y. 2017. Observing Fish Using Underwater Camera at the Test Site Before Installing Ocean Power Generation. Paper presented at the 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim, Norway. https://tethys.pnnl.gov/publications/observing-fish-using-underwater-camera-test-site-installing-ocean-power-generation

Marine Renewable Energy: Environmental Effects and Monitoring Strategies

Copping, A.E 2020. Marine Renewable Energy: Environmental Effects and Monitoring Strategies. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 18-26). doi:10.2172/1632880

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

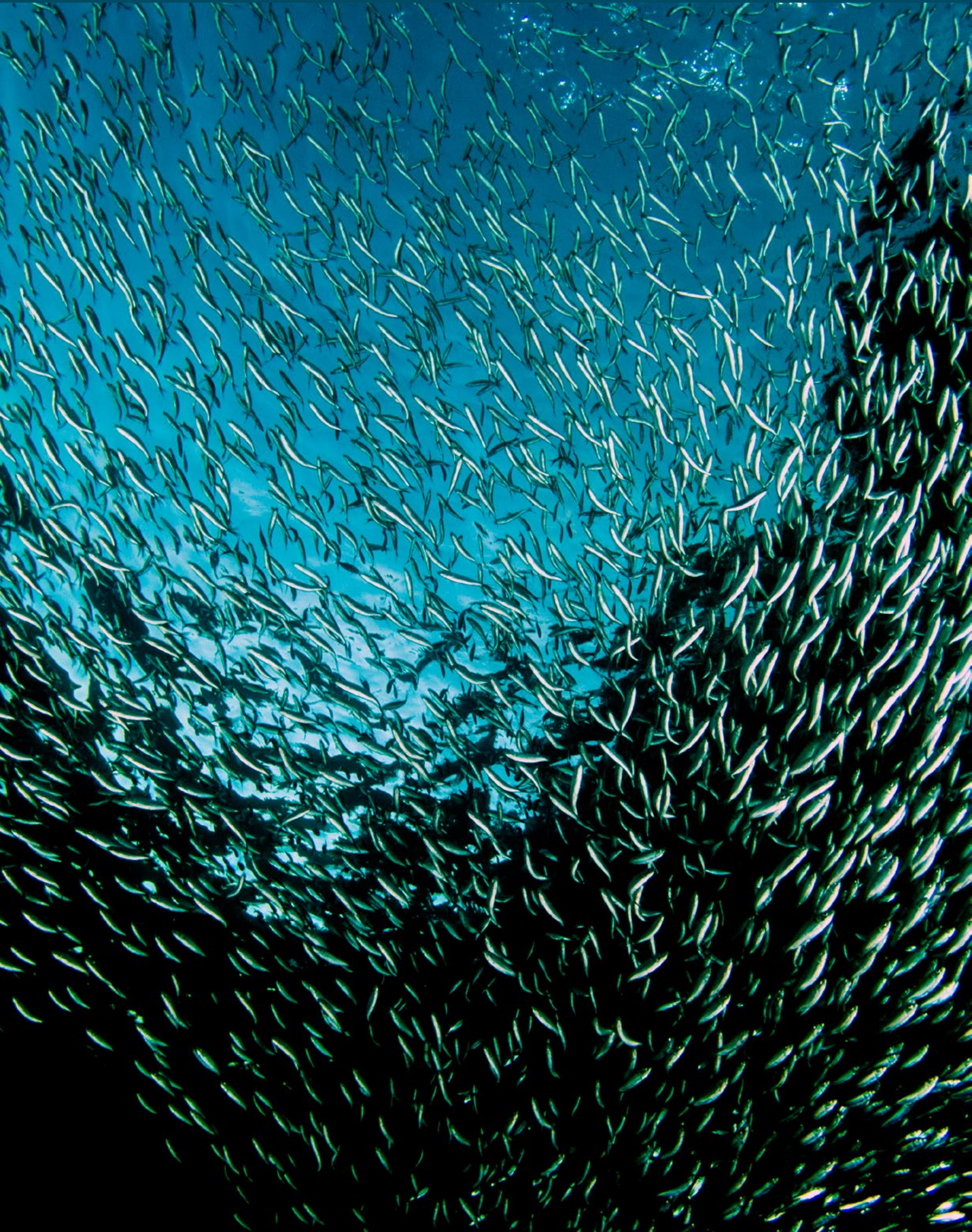
CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

Section B

Current Knowledge of Key Device Interactions with the Marine Environment



3.0

Chapter authors: Carol E. Sparling, Andrew C. Seitz, Elizabeth Masden, Kate Smith
Contributors: Natalie Isaksson, Hayley K. Farr

Collision Risk for Animals around Turbines

The potential for marine animals to encounter and collide with turbines, especially tidal and river turbines, along with the biological, ecological, and regulatory consequences of any such interactions, remain active areas of research and topics of global interest. Uncertainty and knowledge gaps associated with collision risk continue to present challenges within consenting/permitting (hereafter consenting) processes for turbine developments. Consequently, collision risk continues to be the focus of significant research effort, which in recent years has included environmental monitoring of operational devices and arrays. This chapter addresses the overall progress and growth in knowledge across this topic area, and specific progress related to marine mammals, fish, and seabirds.

There are additional risks to marine animals, particularly marine mammals and large fish species, related to collision with the vessels involved in the installation and maintenance of marine renewable energy (MRE) projects. However, this chapter focuses on risks from collision with the moving parts of MRE devices and systems.

3.1. IMPORTANCE OF THE ISSUE

Collision risk is an issue that applies most directly to tidal and river energy conversion technologies (ORJIP Ocean Energy 2017). It relates to the moving components of devices (blades and rotors), as well as dynamic technologies, such as tidal kites or oscillating blades. Wave energy technologies are thought to be more benign with respect to collision risk because there are fewer submerged moving parts that have collision potential (Greaves et al. 2016). The potential risk to marine animals from interactions with the mooring and anchor lines of floating wave or tidal devices is addressed separately in Chapter 8 (Encounters of Marine Animals with Marine Renewable Energy Device Mooring Systems and Subsea Cables). The risk of birds colliding with wind turbines has been extensively studied, offering certain lessons that can be learned and applied to the risk of marine animals colliding with underwater turbines; these lessons are noted where pertinent.

Several factors contribute to the risk associated with the likelihood of animals colliding with turbine blades and the consequences of such collisions to the animal if a collision occurs. The factors that will affect this risk include the characteristics of the devices, animal behavior, and animal densities at the depth of the relevant moving parts of devices; these factors are explored throughout this chapter. The broad overlap between tidal and river resource areas and important habitats for fish, marine mammals, and seabirds (e.g., Benjamins et al. 2017; Macaulay et al. 2015; Staines et al. 2019; Viehman and Zydlewski 2017; Viehman et al. 2018; Waggitt et al. 2016) may increase the potential for encounters (Figure 3.1), including collisions. However, spatial and temporal patchiness in marine animal distribution, influenced by fine-scale hydrodynamics (at the scale of meters to a few hundred meters), could also influence encounter rates and collision risk (Lieber et al. 2018; Waggitt et al. 2017). The ecological significance of any collision events will depend on the physiological, population, and ecosystem consequences of any such interactions (Band et al. 2016).

Despite the potential for encounters and collisions, knowledge of actual risk is limited because the frequency of occurrence of these events (e.g., Copping et al. 2016; Furness et al. 2012) and their consequences are unknown. Detecting encounters or collision events or observing animal movement and behavior in relation to an underwater object (i.e., a turbine) is challenging. In the absence of empirical data, assumptions about how animals might avoid and evade turbines have been made based on lessons learned by the wind energy industry (Scottish Natural Heritage 2016). How an animal might perceive a tidal or river turbine and any associated risk is generally unknown, but information about visual fields and sensory biology may provide some insights into how species may be able to see or hear turbines (Band et al. 2016; Hansen et al. 2017; Hastie et al. 2018a; Martin and Wanless 2015; Martin et al. 2008; Nedelec et al. 2016; Popper and Hawkins 2018).

Many species of mammals, fish, and seabirds are subject to extensive legal protection globally: for example, in the United States (U.S.) they are protected by the Marine Mammal Protection Act (1972), Endangered Species Act (1973), and the Magnuson-Stevens Act (1976); in the European Union by the Habitats Directive (1992) and Birds Directive (2009); in Canada by the Species at Risk Act (2002) and Fisheries Act (1985); and in Australia by the Environment Protection and Biodiversity Act (1999). Further, many species of fish support subsistence, recreational, and commercial fisheries. The nations contributing to this report have invested significant effort in improving the management and movement of species back within safe biological limits (Hilborn 2020); but elsewhere (e.g., in developing economies) practices are reducing an increasing number of commercial stocks to unsustainable levels (FAO 2018). Under either practice, the increased mortality of these stocks is undesirable and undermines the sustainability of the species populations. Many seabird populations are already in decline and experiencing numerous pressures such as climate change, contamination, and fishing bycatch (Paleczny et al. 2015).

In general, where there is uncertainty about impacts, particularly in relation to protected species, regulatory processes in many jurisdictions currently follow the "precautionary principle" regarding the potential impacts and their consequences (Kreibel et al. 2001). In Europe and North America, precautionary regulatory approaches have led to conditions being placed on licenses, permits, and authorizations to reduce collision risk, such as through operational restrictions. Such conditions also commonly require developers to conduct post-installation monitoring that is focused on collision risk (Bennett et al. 2016). The purposes of such monitoring include validating the predictions of collision risk made in environmental impact assessments, and improving the knowledge about nearfield interactions between devices and marine wildlife. Monitoring is also commonly used to inform and enable regulators to adaptively manage tidal and river current projects.

Gaps in knowledge about collision risk and its consequences can therefore lead to conservative approaches in conducting environmental impact assessments and in implementing tidal energy developments (Le Lièvre and O'Hagan 2015; ORJIP Ocean Energy 2019). Although no evidence to date shows that direct interactions with tidal or river current energy technologies will cause measurable harm to individual marine animals or populations, collision risk remains a key issue for the future growth of the tidal and river current energy sector (Copping et al. 2017).

In general, aspects of this chapter that focus on collision risk in relation to marine mammals and seabirds are considered for tidal turbines, while collisions with fish may be applicable for freshwater river turbines or marine tidal turbines. Freshwater turbines may be referred to as river turbines or hydrokinetic turbines.

3.2. SUMMARY OF KNOWLEDGE THROUGH 2016

In 2016, the state of the science for the risk of marine animal collision with MRE devices was in its infancy. Given the few deployed devices and considerable research challenges (e.g., difficulty working in dynamic tidal habitats or fast-flowing rivers, inability to monitor specific strike events, and a lack of a funding mechanisms to undertake strategic research and monitoring that might elucidate the problem), there was limited understanding of the nature of interactions between marine animals and MRE devices, including avoidance and evasion behaviors. Further, the understanding of the likely consequences of any occurrence of collision events, if they occurred, was limited.

No collisions had been observed around single turbines or small arrays prior to 2016, but collision remained a concern and it was one of the most challenging potential occurrences to monitor and observe. The *2016 State of the Science* report (Copping et al. 2016) identified the following key priorities related to collision risk for marine mammals, fish, and seabirds:

- development and refinement of methods to improve the understanding of species' spatial and temporal use of tidal habitat, species' behavior around operating devices and arrays, and the consequences of collision for both individuals and populations; and
- potential advancement of the science by benefiting from continued stakeholder engagement, adoption of an adaptive management approach, and standardization of the language used when describing collision risk, as well as species' avoidance and evasion behaviors.

Figure 3.1. Interactions of (from left to right) a harbor seal, a school of pollack, and a European shag with a non-operating tidal turbine. (Photo courtesy of Nova Innovation)

3.3.
DEFINITIONS

Researchers studying collision risk have created terminology to use in describing interactions, building off definitions provided in the *2016 State of the Science report*. These key definitions for collision risk are provided in Table 3.1.

Table 3. 1. Key terminology of relevance to collision risk between marine animals and MRE devices.

Term	Definition
Avoidance	Animals moving away from the area around an MRE device, at some distance from the object (ABPmer 2010; Wilson et al. 2007).
Collision	• Physical contact between marine animals and moving components of MRE devices, or with dynamically moving technologies. • Does not always imply injury (Amaral et al. 2015). • Includes pressure fields around blades (Wilson et al. 2007).
Collision rate	• Predicted rate of collisions between animals and moving components of MRE devices, or with dynamically moving technologies (Scottish Natural Heritage 2016). • Usually incorporates a correction factor for an "avoidance rate" to account for the assumed proportion of animals taking avoidance or evasive actions (Scottish Natural Heritage 2016), but does not take potential consequences into account.
Density at risk depth	• The density of animals at water depth likely to bring them into contact with relevant moving components of tidal or river turbines, or with dynamically moving technologies (Scottish Natural Heritage 2016). • For seabirds and marine mammals, usually calculated from surface densities from baseline surveys, with a correction factor applied.
Encounter	• To be in close proximity of a turbine. • May lead to a collision but only if the animal does not take appropriate avoidance or evasive action (Wilson et al. 2007).
Encounter rate	Predicted rate of animals and turbines occupying the same point in space and time (Scottish Natural Heritage 2016).
Evasion	Change in behavior to escape impact or contact with an MRE device at close range, analogous to swerving to prevent collision with an obstacle in the road (ABPmer 2010; Wilson et al. 2007).
Farfield	The area of ocean or bay around an MRE device, generally defined as more than five device diameters from the device or array of devices.
Nearfield	The localized area of sea occupied by and in very close proximity to an MRE device, generally considered to be within one to five device diameters.
Passive avoidance	To be swept clear of moving components of MRE devices, or dynamically moving technologies, by hydrodynamic forces (Scottish Natural Heritage 2016).
Post-installation or post-consent monitoring	• Monitoring carried out to gather data before devices are deployed (post-consent monitoring) or monitoring of the environmental effects of deployed MRE devices (post-installation monitoring). • Generally, either required by regulators to validate predictions made in environmental assessments or to provide an evidence base for adaptive management of effects for which there is residual uncertainty.
Sublethal collisions	• Collisions between marine animals and moving parts of devices that result in injury rather than immediate death. • Might include blunt force trauma or concussion and such effects may cause secondary injury or death, or affect an animal's future foraging success and ability to reproduce (Onoufriou et al. 2019). • Sublethal effects are likely to be extremely difficult to predict or measure.

3.4.
COLLISION RISK TO MARINE MAMMALS

Marine mammals are considered in many nations to be most at risk from collision with turbines, particularly as many marine mammal populations are under stress from other anthropogenic activities as well as effects of climate change (Fabry et al. 2008). Knowledge generated prior to and since 2016 about marine mammal collision is addressed, followed by what has been learned since 2016.

3.4.1.
SUMMARY OF KNOWLEDGE THROUGH 2016

As documented in the *2016 State of the Science* report, there was no evidence of direct interactions between marine mammals and tidal devices or that such interactions will cause harm to individuals or populations (Copping et al. 2016). While numerous collision risk models have been developed to predict the likelihood and consequences of collision for marine mammals (e.g., Band 2014; Wilson et al. 2007), the potential for collision will likely vary significantly with site-dependent characteristics such as location, water depth, and tidal velocity. Prior to publication of the *2016 State of the Science* report, the lack of data available from monitoring studies conducted around operational MRE devices significantly hampered our understanding of marine mammals interaction in the vicinity of MRE devices. Several projects were in various stages of development at the time the 2016 report was published (e.g., MeyGen, Inner Sound; Shetland Tidal Array, Bluemull Sound; DeltaStream, Ramsey Sound; Cobscook Bay, Maine). Therefore, at that time, the potential for collisions between marine mammals and tidal turbines remained a significant concern, and uncertainty in this area was causing barriers to the consenting of tidal projects worldwide.

3.4.2.
KNOWLEDGE GENERATED SINCE 2016

Baseline Studies

Studies have maintained a continuing focus on understanding marine mammal use of tidal environments. The results of these studies collectively demonstrate variability between sites and locations, making it difficult to make generalizations about marine mammal use of tidal sites.

Recent investigations into fine-scale harbor porpoise (*Phocoena phocoena*) density and the use of the water column at a variety of tidal sites in Scotland have provided substantial data about harbor porpoise depth distribution and underwater behavior in tidal rapids. These studies found a large degree of variation between sites (Macaulay et al. 2015, 2017). They also showed that the depth distribution of harbor porpoises was typically bimodal; porpoises spent time foraging at the surface or at depth, and spent less time at intermediate depths. This suggests that the depth of turbine placement may strongly influence collision risk. At the only site where measurements were taken at night (Kyle Rhea, Scotland), porpoises were more often located near the sea surface, highlighting the importance of understanding daily variation in species depth distribution to assure accurate prediction of collision risk (Macaulay et al. 2015). Benjamins et al. (2017) demonstrated that the distribution of harbor porpoises can vary in tidal habitats at very small spatial and temporal scales, such that collision risk estimated on the basis of wide-scale average densities may not reflect actual risk at any one specific site.

Seal-tagging studies in the United Kingdom (UK) have increased knowledge about the behavior of harbor and grey seals in tidal environments. In the narrow, tidal channel of Kyle Rhea on the west coast of Scotland, harbor seals (*Phoca vitulina*) are present between April and August, and they haul out during the ebb tide and spend a high proportion of their time during the flood tide actively foraging in the high current areas (Hastie et al. 2016). Another telemetry study (Joy et al. 2018) revealed that in the tidal currents of Strangford Narrows in Northern Ireland, harbor seals predominately swam against the prevailing current during both ebb and flood tides. Similarly, as reported by Band et al. (2016), harbor seals in the Pentland Firth predominately traveled slowly against the current. Similar to the seals at Kyle Rhea, not all seal dives were to the seabed and there was a proportion of mid-water diving. This behavior contrasts with previous studies where most seal diving was thought to be to the seabed. In contrast to the behavior of the Kyle Rhea harbor seals, which were distributed in high current areas on the flood tide, Lieber et al. (2018) reported that harbor seals and grey seals (*Halichoerus grypus*) in the Strangford Narrows were more likely to be distributed on the periphery of high current areas. However, this assertion was based on a limited sample of observations from a vessel conducting repeat line transect surveys over two days (one on a spring tide and one on a neap tide). Similar to the case presented above for harbor porpoises, these studies indicate a high degree of between-site variability in seal occurrence and behavior, making it difficult to generalize collision risk between sites. Studies of prey abundance might provide additional information about the presence of marine mammals around turbines, but no such studies have been undertaken to date.

Project- and Site-based Monitoring

MeyGen, Inner Sound, Pentland Firth, Scotland

The first turbines at the MeyGen tidal energy site were deployed in 2016 in the Inner Sound of Pentland Firth in Scotland (Figure 3.2). Four 1.5 MW turbines were installed during the 2016–2017 timeframe and, to date, the array has generated more than 15 GWh of energy for the grid. The project environmental monitoring plan (PEMP; Rollings et al. [2016]) associated with the turbine array was developed to understand collision risk; one of the main elements that required monitoring as a condition of consent was "collision/encounter interactions with the tidal turbines for diving birds, marine mammals and fish of conservation concern." The PEMP included two primary objectives:

- Detect and quantify potential avoidance and collision rates for harbor seals, and verify and improve the accuracy of collision/encounter rate models.
- Provide sufficient monitoring data for impact assessment to allow each subsequent stage of the development to proceed.

Although the principal objective of the PEMP was to monitor the presence of harbor seals, the technology deployed (video cameras, active and passive acoustic monitoring [PAM]) was capable of monitoring for other marine mammal species, including grey seals and harbor porpoises, as well as fish (e.g., Atlantic salmon [*Salmo salar*]) and diving seabirds (e.g., black guillemots [*Cepphus grylle*] and shags [*Phalacrocorax aristotelis*]).). The exact details of the sensor technologies are covered in Chapter 10 (Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines).

Figure 3.2. A MeyGen tidal turbine ready for deployment in the Inner Sound of Pentland Firth in Scotland. (Photo courtesy of SIMEC Atlantis Energy)

During the initial 322 days of data collection (October 2017 to September 2018), more than 740 million transient sounds were recorded on the PAM system. After post-processing and verification, 724 porpoise and 26 dolphin events had 10 or more clicks. The numbers of porpoise clicks per event varied considerably with a mean of 220 (95 percent confidence interval [CI] 31–979). Similarly, the durations of the events varied from 0.5 to more than 2700 seconds (95 percent CI 21–1200). It is likely that some of these events involved more than one animal. Monthly reports of cetacean detections and system operations were provided to MeyGen and the Scottish Government between October 2017 and January 2019. A key output of the PAM data analyses will be the temporal occurrence of porpoise and dolphins around the turbine and the three-dimensional (3D) locations of echolocation clicks in relation to the position and operational status of the turbine; these data are not yet available although ongoing analysis suggests evidence of avoidance at both a medium (tens of meters) and a fine-scale (meters) from the rotors.

In addition to activities associated with the MeyGen PEMP and as part of the Marine Mammal Scientific Support program at the Sea Mammal Research Unit (SMRU) (University of St Andrews, Scotland), a series of seal telemetry studies have been undertaken close to the area in which the MeyGen array is located. Prior to the deployment of the turbines, 24 harbor seals were tagged in the Inner Sound to quantify the movements of seals in a wider spatial context. The results from these tag deployments are presented by Hastie et al. (2018b). An additional 16 harbor seals were tagged between April 16 and 18, 2018, to provide data during the turbine operation phase. Of these tagged seals, 12 transmitted both location data and high-resolution dive data. From the tags deployed in 2018, 504 days of data were collected, which included 53,484 global positioning system (GPS) locations (i.e., a GPS fix obtained from the tag during a surfacing event). During this deployment, tagged seals spent approximately 12 percent of their time within the Inner Sound and approximately 0.001 percent within the whole MeyGen lease area. A total of four GPS locations were recorded within 100 m of a turbine and the closest GPS location was 35 m from a turbine. To assess the effects of the turbine installation on harbor seal distribution, the species' use of space before and after installation was quantified. In general, seal use of the area showed a pattern of reduced usage within the Inner Sound post-deployment compared to pre-deployment. Furthermore, seal usage within the Inner Sound was reduced during turbine operation relative to non-operation in the post-deployment phase (Onoufriou 2020; Palmer et al. 2019).

The MeyGen project team is currently collaborating with SMRU to deploy an integrated monitoring platform during the next phase of turbine installation at the MeyGen site (Project Stroma, previously known as MeyGen Phase 1b, comprises an additional two turbines) to add key data about seal behavior and encounter rates. For technical details about this monitoring platform, see Section 10.4.4. of this report.

Nova Innovation, Bluemull Sound, Shetland, Scotland
In 2014, Nova Innovation installed a 30 kW demonstration turbine in Bluemull Sound. This turbine was decommissioned in 2016 and was followed in the same year by the installation and commissioning of the world's first offshore tidal array, comprising two Nova M100 (100 kW) turbines. A third turbine was added in early 2017 and Tesla battery storage was added in 2018 (Figure 3.3).

Current plans, under the Enabling Future Arrays in Tidal (EnFAIT)[1] project, are to extend the array from three to six turbines during 2020 to 2021 to achieve a total rated capacity of 600 kW. Nova's Shetland Tidal Array is approximately 25 km from the Yell Sound Coast Special Area of Conservation (SAC) designated for harbor seal. The average foraging distance of harbor seals is

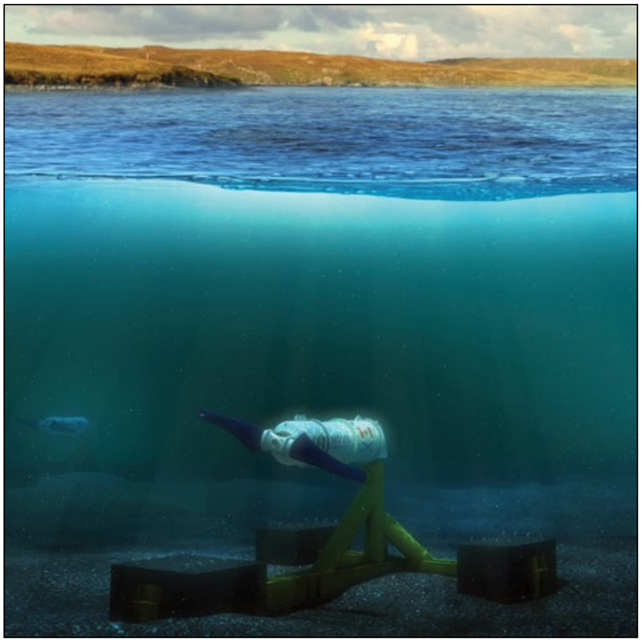


Figure 3.3. Nova Innovation's three-turbine tidal array in Bluemull Sound, Shetland, Scotland. (Photo courtesy of Nova Innovation)

1. *https://www.enfait.eu/*

30 to 50 km (Sharples et al. 2012), so animals associated with the SAC may forage within Bluemull Sound. The environmental assessment report for the six-turbine array[2] predicts that up to four harbor seal collisions per year may occur, assuming a 98 percent avoidance rate, based on the Encounter Risk Model detailed by the Scottish Natural Heritage (2016). Because this number was less than the potential biological removal (Wade 1998) for the relevant seal management unit (calculated to be 20 seals), regulatory and advisory bodies considered it to be acceptable, provided that appropriate monitoring was in place to validate these numbers.

The conditions of project licenses issued by Shetland Island Council and Marine Scotland require the environmental effects of the array to be monitored, as set forth in an environmental monitoring plan.[3] Land-based visual surveys of the site are carried out to gather information about the spatiotemporal distribution of marine mammals and birds in Bluemull Sound, and subsea video is used to monitor for potential collisions and nearfield interactions of marine animals with turbines. Land-based surveys that began in 2010 prior to the deployment of any turbines at the site, are still ongoing, and methodologies have recently been modified to focus on the turbine array area, rather than the wider Sound to gather information more specific to understanding collision risk. The approach is based on understanding site-use at different scales, to understand the likelihood of nearfield encounters between marine animals and turbines, as a descriptor of collision risk. Nearfield encounters are only possible if an animal uses the site. The likelihood increases if an animal uses the area immediately around the turbines and increases again if the animal actively swims or dives around the turbines during turbine operation.

Video monitoring uses three cameras per turbine, each attached to the nacelle (two directed toward the turbine rotor and one directed toward the seabed). The turbine is not illuminated, so video monitoring is only effective during daylight hours; water clarity at the site is generally very good and can be exceptional. The cameras record continuously but use a motion-detection system to automatically retain footage of potential wildlife-turbine interactions. A sub-sample of over 4000 hours of Nova's full 20,000+ hours of video footage have been examined and analyzed to date, representing approximately 20% of all footage recorded between October 2015 and March 2020. A combination of random and stratified sampling approaches was used to extract footage for analysis, to ensure coverage across the full tidal cycle, and times of presumed increased collision risk.

Eight mammal species (including Eurasian otter, *Lutra lutra*) have been recorded in land-based surveys, with grey seal, harbor seal and harbor porpoise the most frequently recorded (Nova Innovation 2020). Harbor porpoise were recorded in the area immediately around the turbines in 0.71% of scans, grey seal in 0.06% of scans and harbor seal in 0.32% of scans. For the nine years of survey data, the modeled probability of occurring within the area immediately around the turbines is < 0.02 for harbor porpoise and < 0.001 for both grey and harbor seals, indicating a very low turbine encounter risk for even the most commonly occurring marine mammals. Harbor seal is the only mammal species that has been observed in the subsea video footage analyzed to date. Thirteen instances of harbor seal have been observed, all during periods of slow tidal flow below the turbine cut-in speed, when the turbines were not operating. On one occasion, a harbor seal was observed actively pursuing fish around the base of the turbine. No physical contact between marine mammals and the turbine blades has been observed in any of the video footage to date (Nova Innovation 2020).

SeaGen Strangford Lough, Northern Ireland

There has been no new monitoring work at the SeaGen site since 2016 because the turbine (Figure 3.4) ceased to be operational in 2015 and was decommissioned in 2019. However, two scientific papers were published based on the outcomes of the monitoring program, which added to the knowledge base about collision risk. Sparling et al. (2018) presented the results of a seal telemetry study, which indicated that tagged seals transited less often and swam farther away from the turbine when it was operational than when it was not, and demonstrated that seals continued to use the narrows to transit through Strangford Lough with no overall change in their transit rates. This indicates that the turbine did not create a barrier effect, but that there was some degree of mid-range avoidance (of ~200 m). Joy et al. (2018) quantified the degree of local avoidance as a 68 percent reduction in seal use of the area within 200 m of the turbine. Building upon these results, Joy et al. (2018) demonstrated that taking this avoidance action indicates that a 90 percent

2. *https://www2.gov.scot/Topics/marine/Licensing/marine/scoping/NOVA-AdditionalTurbine/MLApp-022018/Ext-EA-Report*

3. *https://www2.gov.scot/Topics/marine/Licensing/marine/scoping/nova*

Figure 3.4. The SeaGen tidal turbine when installed in Strangford Lough, Northern Ireland. (Photo courtesy of SIMEC Atlantis Energy)

reduction in collision risk is likely, compared to estimates derived from standard collision risk models.

DeltaStream, Ramsey Sound, Wales

At the time the *2016 State of the Science* report was published, the DeltaStream tidal energy device had been recently deployed in Ramsey Sound, Pembrokeshire, in Wales. The approach to monitoring was described but no data were presented. The turbine was deployed in December 2015 and remained operational until March 2016. The 12-channel hydrophone PAM system provided data (Malinka et al. 2018), while the Remote Acoustic Monitoring Platform, which had a multibeam sonar, produced no usable data. The PAM results indicated that the monitoring system successfully detected and localized porpoise and dolphin vocalizations over the three-month deployment period (Malinka et al. 2018). Porpoises and dolphins were detected, respectively, on 91.3 percent and 13.2 percent of the days during the monitoring period, and patterns of porpoise occurrence at the site could be linked to a range of covariates, such as tidal cycle, diurnal cycle, and season, which may be important when characterizing the risk of collision for devices at this location. Most of the encounters (71 percent of dolphin encounters and 91 percent of porpoise encounters) occurred during hours of darkness. Porpoises were detected across a wide range of flow rates, but detections were higher during ebb tide than during flood tide, higher during neap tides than spring tides, and lower at the highest rates of flow. The short period over which the monitoring was carried out limited analysis of porpoise behavior or their presence near the turbine. Analysis of tracks suggested that porpoises and dolphins were capable of detecting the structure and responding to it.

FORCE, Bay of Fundy, Nova Scotia, Canada

The Fundy Ocean Research Centre for Energy (FORCE) environmental effects monitoring program monitors effects at the FORCE test site outside the immediate vicinity of the devices with the initial understanding that developers with berth sites are responsible for monitoring close range effects around their own turbines. Monitoring using PAM to detect harbor porpoises within 200 to 1700 m of the site did not indicate any evidence of porpoise exclusion during the deployment or operation of Cape Sharp Tidal Venture's 16 m diameter 2 MW Open Hydro tidal turbine at Berth D (presence detected on 98.5 percent of the days monitored). However, click activity was significantly reduced at the C-PODs (i.e., PAM devices) closest to the turbine (200 to 230 m) and increased at the site 1700 m away, suggesting short-range acoustic effects on activity and spatial use by porpoises (Tollit et al. 2019). This suggests a reduction in potential collision risk relative to that assumed from baseline assessments.

Work is also under way at FORCE to establish an integrated, performance-tested sensor package that is accepted by regulators, for use by developers deploying equipment to monitor close range interactions, under a program named "The Pathway Program," in collaboration with the Offshore Energy Research Association and Nova Scotia Department of Energy and Mines. This program aims to provide a proven platform alongside automated data processing algorithms and software for analysis of passive and active acoustic data (see Chapter 10, Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines), which will provide important data for resolving uncertainties related to collision risk.

Sustainable Marine Energy, Grand Passage, Nova Scotia, Bay of Fundy, Canada

In late 2018, Sustainable Marine Energy (Canada) Ltd. (SME) deployed a floating tidal energy converter (PLAT-I), in Grand Passage, Canada. The project environmental effects monitoring plan is designed to provide information about underwater noise added to the marine environment by PLAT-I, and assess how marine animals respond to PLAT-I. Mitigation measures implemented during the deployment included daylight-only operation of turbines and halting turbine operation if species at risk were observed near the device. In addition, direct monitoring of the platform was required during all periods of turbine operation. This monitoring included video camera recording of each of the four operating turbines, recording of acoustic data over the full range of marine mammal vocalizations, and conducting marine animal observations at 30-minute intervals.

To meet these requirements, four video cameras were positioned facing downstream, each camera approximately centered on its associated rotor. The method provided an effective means of monitoring turbine rotors and assessing potential interactions with marine life, because visibility was generally good, light was sufficient, and suspended particles were few. An experienced third-party contractor conducted video analysis, which included screening representative samples for potential animal sightings and verifying or refuting potential sightings. Video quality was mainly rated as fair to good; inanimate materials such as seaweed and other debris were noted frequently. Aside from several observations of jellyfish, only one positive identification of marine life was made (a fish – smelt) (C. Chandler, personal communication).

Passive acoustic data collection was accomplished using a stationary icListen high-frequency hydrophone suspended beneath the PLAT-I hull. Ambient noise data indicated that turbine noise is below noise levels typically emitted by fishing and recreational vessels, so no hearing injury to fish or harbor porpoise would be expected.

Intermittent marine animal observations made either from onboard PLAT-I or from the control shore station resulted in no observations of marine animals within 500 m of the platform during the initial testing period (C. Chandler, personal communication).

Subsequent testing phases will incorporate learnings and expand research and development activities aimed at developing cost-effective environmental monitoring systems that will function effectively and reliably during future deployments.

Minesto: Strangford Lough, Northern Ireland and Holyhead Deep, Anglesey, Wales

Minesto UK has carried out a number of studies of the collision risk posed by their unique kite-design tidal energy generator. The collaborative, European Union (EU)-funded Powerkite[4] project collected environmental data (Kregting et al. 2018), and collision risk models were developed (Schmitt et al. 2017) and recently translated to an open-source game engine called Blender (*blender.org*). Simulations loosely based on the quarter-scale Minesto device indicated that there is a variable collision probability ranging from an inevitable collision if an animal passes at the position of the mooring point to the probability of collision decreasing with distance from the central mooring point (Schmitt et al. 2017). At the mean flight depth of the kite, the probability of collision is approximately 80 percent in the center of the kite trajectory, and more collisions are predicted to occur with the tether than with the kite itself.

Multibeam sonars were deployed around the Minesto quarter-scale device installed in Strangford Lough in Northern Ireland to (1) understand the spatiotemporal variability in seal and fish presence around the device and how it corresponds to fine-scale changes in hydrodynamics, and (2) collect evidence of nearfield subsurface behavior, including data about animal movement, depth, trajectories, and possible evasive behaviors (Lieber et al. 2017).

In addition to the Powerkite project, Minesto has also conducted simulation-based assessments of collision risk for consenting applications for their Strangford Lough and Holyhead Deep (Anglesey, Wales) projects. Booth et al. (2015) assessed collision probabilities for harbor seals in relation to the Strangford Lough deployment, based on their reported depth distributions. This work reported that the probability of a simulated animal coming into direct contact with the device varied depending on the anchor point of the device (surface or bottom-mounted) and the animal's swimming speed and behavior. Overall, collision probabilities varied between 0.05 percent and 8 percent depending on the conditions simulated. Booth et al. (2015) also assessed the consequences relative to population levels of a range of collision rates to provide context for the results of the collision probability modeling exercise. This allowed for an exploration of the level of collision risk that might be

4. *https://www.powerkite-project.eu/*

considered acceptable (i.e., not resulting in a significant impact on each population in the long term). For grey seals and harbor porpoises, very high encounter rates would be required to achieve collision rates that would be of concern at the population level (higher still if assuming some form of evasion). These encounter rates were considered to be beyond what one would reasonably expect to see at any site at the scale of this project. However, for bottlenose dolphins, based on the collision probabilities and population consequence assessment (assuming no evasion), even a single collision would be detrimental and therefore, effort was required to understand empirical encounter rates in the presence of the turbine for this species.

Minesto recently installed a Deep Green device (their 0.5 MW kite) at Holyhead Deep, Anglesey, in Wales (Figure 3.5). In 2019, a PAM system was developed in conjunction with the commissioning of the kite; further details of the system are provided in Chapter 10 (Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines). The objective was to monitor cetacean movement and investigate response around the operational kite. The species of interest were harbor porpoise and several dolphin species, in particular bottlenose dolphin (*Tursiops truncatus*) for which a single collision is estimated to cause population-level effects (G. Veneruso, personal communication).

Figure 3.5. Minesto's Deep Green 0.5 MW tidal kite being deployed at Holyhead Deep, in Anglesey, Wales. (Photo courtesy of Minesto)

Oosterschekering, Netherlands

The Oosterschekering, a storm surge barrier in the Netherlands, houses five integrated tidal turbines in an area where harbor porpoise, grey seals, and harbor seals are known to occur (Leopold and Scholl 2019). The surge barrier has been in place since 1986 and the turbines were installed in December 2015. Before the tidal turbines were installed, a small number of seals were tagged and shown to pass through the storm surge barrier, suggesting that it did not act as a physical barrier to their movement. It is not clear how the seals are traversing the storm surge barrier, however; their depth of passage and favored phase of the tides are not known. This lack of information makes it difficult to estimate the risk of collision.

Field Trials

Progress has been made in understanding the potential consequences of collision risk. Researchers at SMRU in Scotland have carried out a series of collision trials, using a vessel-mounted turbine blade and seal and porpoise carcasses to mimic blade strikes. Magnetic resonance imaging scans of carcasses after the trials demonstrated that significant skeletal damage occurs at speeds above 6 m/s (Onoufriou et al. 2019). Although tidal-stream velocities will seldom reach this speed, the speed of the blade tip may. Below these speeds, there was no evidence of skeletal trauma or obvious indicators of extensive soft-tissue damage, but because of the difficulties in assessing soft-tissue damage such as bruising and tissue edema in previously frozen carcasses, the soft-tissue assessments were not considered reliable indicators. Grear et al. (2018) tested two mechanical properties of harbor seal tissues to understand the ability of the skin and blubber to resist blunt force trauma. There were significant differences in responses between the test speeds and age of the animal, but not in the orientation of the tissue relative to the strike. Tissues were either frozen or fresh. In the case of the frozen tissue, an increase in stiffness and strength of the skin was found, but there was no conclusive trend in blubber material properties. They concluded that frozen tissue, especially skin, cannot serve as an accurate replacement for testing fresh material. It is also important to note that there has been no reliable assessment of the likelihood or consequence of concussion as a result of strike, which has the potential to be fatal (i.e., the animal loses consciousness and drowns).

The potential for marine mammals to hear tidal energy devices is an important concept related to understanding collision risk (Hastie et al. 2018a). The interactions are complex and depend on turbine source levels, ambient sound, propagation in moving water, sensory abilities, swim speeds, and diving behaviors. Empirical measurement of the noise emitted by turbines and the understanding of how noise propagates is one area in which progress has been made, as reviewed in detail in Chapter 4 (Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices). All indications from sites monitored to date are that marine mammals should detect tidal turbines acoustically and may use avoidance behaviors if they perceive the turbines to be a threat. Field playback studies using recordings of tidal turbines indicate responses at the scale of a few hundred meters, although the responses depend on the acoustic characteristics of the signal and the hearing sensitivity of the species (Hastie et al. 2018a; Robertson et al. 2018). Turbines that emit mostly low-frequency noise may not be audible at long ranges to high-frequency specialists such as harbor porpoises. Similarly, devices that emit more higher-frequency sound may not be audible to low-frequency hearing species. This highlights the need to take into account the turbine-specific acoustic footprint and the hearing capabilities of the species likely to be present. Predictive modeling of the acoustic energy output of new turbines prior to their deployment should inform the range at which marine animals may be able to hear devices and provide insight into the ability of animals to respond appropriately and avoid collision (Marmo 2017). However, the degree to which the audibility and "warning distance" actually influence behavior, and ultimately the risk of collision, is uncertain.

Modeling and Data Inputs

Since the publication of the *2016 State of the Science* report, considerable progress has been made in the area of collision risk modeling, including the development of modified models to quantify predictions of collision risk for non-horizontal-axis turbine designs (see the discussion by Booth et al. [2015] and Schmitt et al. [2017] above in relation to the Minesto device). Other examples include simulations that provide a framework to allow behavioral influences such as food availability and responses to noise to be incorporated, as was created for Ramsey Sound (Lake et al. 2017). A spatially explicit Individual-Based Modeling (IBM) approach is being developed at SMRU to explore the potential consequences of the impacts of MRE projects, including collision. However, this outcome is still at least a year away from completion (B. McConnell, personal communication). Given the complexity of behavioral responses and the need to understand collision risk at the array scale, the future of collision risk modeling is uncertain. As collision risk models are improved, field monitoring data will still be needed to validate predictive models.

Several studies have investigated the sensitivity of collision models to various input parameters. For example, Copping and Grear (2018) presented an analysis that incorporated a number of different parameters into a simple collision risk model, including variation in site-specific geography, tidal current, depth distribution of animals, and a prediction of the likely severity of collision. This analysis suggested that collisions leading to "serious injury" were likely to be relatively rare events but that the risk of serious injury varied between species and site and, in particular, in the degree of channel "blockage" created by turbines. Similarly, Band et al. (2016) demonstrated a reduction in predicted collision risk with sequential parameter refinements, which incorporated detailed information about seal behavior, depth distribution, turbine characteristics, severity of collision, etc. However, analyses such as these also indicate that predictions of risk are extremely sensitive to assumptions about behavioral parameters that can only be measured around operating turbines, parameters such as avoidance or fine-scale evasive responses. For instance, Joy et al. (2018), by incorporating empirical data collected around SeaGen (Sparling et al. 2018), recently demonstrated the effect of incorporating observed levels of avoidance of the turbine. As summarized in Section 3.4.2, collision risk estimates using empirical seal density estimates in the presence of the turbine were 90 percent lower than those estimated using data from before turbine installation, indicating an avoidance value of approximately 60 percent.

3.4.3. RESEARCH AND MONITORING NEEDS TO RETIRE THE ISSUE

There are still a number of knowledge gaps and uncertainties in relation to the probability and consequences of collisions between marine mammals and tidal energy devices, including better understanding of the likelihood of collision with and avoidance of turbines, better understanding of the consequences of a collision with a turbine blade, translating individual collision risk to population-level risk, better understanding of the sublethal effects that may cause secondary injury or death, scaling of collision risk from a single turbine to arrays, and the need for collaboration among sectors to retire the risk of collision, as described in the following paragraphs.

Likelihood of collision with and avoidance of turbines by marine mammals – There are indications that some degree of "mid-range" avoidance exists at the scale of a few hundred meters around devices, and in response to playbacks (Hastie et al. 2018a; Joy et al. 2018; Sparling et al. 2018). However, information describing the occurrence and behavior of marine mammals at close range to devices (1–10s of meters) does not exist. The tools and technologies to allow this research to be conducted are being developed (Cotter et al. 2018; Gillespie et al. 2020; Hastie et al. 2019; Malinka et al. 2018; Sparling et al. 2016). Information about the equipment and techniques that contribute to determining collision risk and close encounters with animals and turbines can be found in Chapter 10 (Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines).

Consequences of collision with a turbine blade – Further work is needed to determine the consequence of a collision and how likely it is that a marine mammal will die as a result of the encounter. Indications are that this likelihood will vary with species, device type, speed of encounter, the body part struck, and the part of the device with which the animal collides (Copping and Grear 2018; Onoufriou et al. 2019).

Translating individual collision risk to population-level risk – There is a need to understand the potential population-level consequences of collision. If mortality rates can be determined from predicted collision rates, then it is straightforward to incorporate the latter as an additional source of mortality into traditional matrix population models to predict the future population trajectory of affected populations. These models must be dynamic to enable incorporation of a changing collision risk as the population size changes. Alternative approaches include comparison of predicted mortality rates to a calculated potential biological removal value (Wade 1998).

Sublethal effects – Effects that do not result in serious injury or death are difficult to predict or measure but could have serious consequences; for example, blunt force trauma or concussion could affect an animal's future foraging success and ability to reproduce. Techniques exist for incorporating sublethal effects into the prediction of future population consequences, but the necessary knowledge to carry out these analyses does not currently exist for collision risk and marine mammals. More information about (1) the occurrence and nature of the injuries, and (2) the links between injury and an individual's ability to survive and reproduce is needed for these analyses.

Scaling collision risk from a single turbine to arrays – With few devices in the water, insight into the potential risk to marine mammals from turbine blades cannot be well predicted as the industry moves toward larger commercial arrays. Among the challenges for scaling up the knowledge of collision risk from a single device would be whether animal responses to individual turbines might influence collision risk with other turbines in an array. Predictive models validated with collision risk data collected around single devices and small arrays may be useful to understanding the range of potential outcomes, identifying particular sensitivities, and directing future avenues of research. It may also be possible to directly incorporate array-scale predictive modeling into array design optimization, combining collision risk constraints with other optimization parameters.

Collaboration among sectors to retire the risk of collision – Collaborative approaches involving academia, industry, and government have been shown to be good models for determining the level of risk associated with collision and for enabling the development of a common understanding that can lead to risk retirement for collision. A number of academic/government/industry collaborations have been successful, including those associated with Ocean Energy Systems (OES)-Environmental for other stressors (as detailed in Chapter 13, Risk Retirement and Data Transferability for Marine Renewable Energy). However, retiring collision risk involves additional challenges beyond the technical challenges already noted. Issues of commercial confidentiality, project timelines, and budgetary constraints sometimes conflict with academic requirements, including open-source requirements, data sharing, and attitudes toward publishing. To address these challenges, funding sources need to have a degree of flexibility to respond to changing project timelines, and research institutions need to retain key expertise. There also needs to be a degree of external governance of monitoring and research programs to assure that maximum benefit is drawn for all stakeholders, and that objective and trusted science is delivered.

3.5. COLLISION RISK TO FISH

Many species of fish have been considered to be at risk from collision with turbines in tidal and river environments. However, few empirical data were available before the *2016 State of the Science* report was written to assess the risk. A summary of what was known at that time is followed here by more recent findings.

3.5.1. SUMMARY OF KNOWLEDGE THROUGH 2016

At the time the *2016 State of the Science* report was published, fish species were considered to be potentially at risk of collision with MRE devices. Results from several fish-turbine interaction tests in laboratory settings suggested high survival rates (>95 percent; Amaral et al. 2015; Castro-Santos and Haro 2015). Similarly, field studies were used to elucidate fish presence, avoidance, and evasion around MRE devices, but fish strikes had not been observed (Broadhurst et al. 2014; Hammar et al. 2013; Viehman and Zydlewski 2015). Substantial progress was made in the development of models that estimate the possibility of fish encountering MRE devices (Shen et al. 2015; Tomechik et al. 2015), the consequences of blade strike (Romero-Gomez and Richmond 2014), and the population-level ecological risks (Amaral et al. 2015; Hammar et al. 2015).

3.5.2. KNOWLEDGE GENERATED SINCE 2016

Flume/Laboratory Studies

Three flume studies conducted since publication of the *2016 State of the Science* report were aimed at understanding certain aspects of the risk hydrokinetic turbines may pose to fishes, as well as understanding fishes' avoidance behavior around an operating turbine (Yoshida et al. 2020; Zhang et al. 2017) and the results of blade strike on fishes (Bevelhimer et al. 2019). To understand avoidance behavior, the ratios of turbine tip speed to fish size and swimming velocity were estimated for a proposed turbine in coastal Japan and were replicated in a scaled-down laboratory setting (Zhang et al. 2017). The passing rates, positions, and reactions of Japanese rice fish (*Oryzias latipes*) were recorded after upstream and downstream releases near an axial flow turbine in a rectangular swim flume, during which the flow velocity was held constant and the rotation frequency was varied. Based on the study results, Zhang et al. (2017) concluded that, similar to other flume and field studies, turbine operation significantly affected the avoidance behavior of fish, which increased as rotational frequency and tip speed increased. These behavioral alterations likely decrease collision risk for fishes in the wild and provide information for parameter estimation of numerical models aimed at further understanding fish behavior around turbines. The study results led the authors to recommend that hydrokinetic turbines with relatively high rotational frequencies be placed at the downstream end of a channel to minimize the collision risk to fishes. Currently, the feasibility of transferring these results to other fish taxa and turbine designs is unknown. Yoshida et al. (2020) similarly carried out a laboratory-scale water tank test to examine the behaviors of the ray-finned Tamoroko (*Gnathopogon elongatus*) around turbine blades rotated by a motor. A water current was applied to the flume as well. Although most fish passed outside the turbine blades throughout the duration of the experiment, when the current was added to the flume the behavior of the fish changed, resulting in approximately a one percent chance of collision with a blade. However, of two fish collisions observed, neither resulted in injury to the fish and both were thought to have occurred because the fish was affected by the current. Comparing with the results for Japanese rice fish (Zhang et al. 2017), the authors suggested that the ray-finned Tamoroko has a higher risk of collision despite its faster swimming speed (Yoshida et al. 2020). In addition, it appears that fishes capable of avoiding turbine blades without a current may be less capable of doing so when a current is running (Yoshida et al. 2020).

To understand the effects of blade strikes on fishes, three fish species (gizzard shad [*Dorosoma cepedianum*], rainbow trout [*Oncorhynchus mykiss*], and hybrid striped bass [*Morone saxatilus* x *M. chrysops*]) were exposed to simulated blade strikes in a laboratory setting (Bevelhimer et al. 2019). The relationships among blade thickness, impact velocity, and body orientation were examined to understand the relationships between turbine characteristics and the probability of injury and mortality of different fish species. Mid-body strikes resulted in the highest mortality, followed by head strikes, while tail strikes produced the lowest mortality. Lateral strikes caused greater mortality than dorsal and ventral strikes, and higher strike velocities and thinner blades contributed to increased mortality. Results such as these ultimately could be used to inform injury and mortality estimates of fish interacting with turbines and by turbine designers to modify designs to minimize the probability and impact of blade strike. Currently, there are no reports of such studies informing the design of turbines, but this is an important area to inform the evolution of future device designs.

Baseline Field Studies

Two baseline studies conducted since 2016 had a primary focus on understanding the presence/absence of fishes at two different sites—one in the Bay of Fundy, in Cobscook Bay, Maine (Viehman and Zydlewski 2017) and the other in Minas Passage, Nova Scotia (Viehman et al. 2018), while a third baseline study quantified how the distribution of fish schools overlaps with the operational depth and tidal current speeds used by tidal kites in the Irish Sea (Whitton et al. 2020). Investigators used different acoustic methods to examine fish presence/absence and vertical distribution, including single-beam and split-beam echosounders in Cobscook Bay, and an Acoustic Zooplankton and Fish Profiler (AZFP) in Minas Passage, while in the Irish Sea, both methods were used. In Cobscook Bay, data were continuously collected for two years at the proposed depth of an MRE turbine using a bottom-mounted, side-looking echosounder. From these data, fish counts were determined and temporal patterns in abundance were examined. In Minas Passage, data were collected during one month each in winter and summer by an upward-facing AZFP deployed at the FORCE test site. In the Irish Sea at the West Anglesey Demonstration Zone for tidal energy, AZFP data were collected for three months in late fall to winter, while split-beam echosounder data were collected and trawls were conducting for groundtruthing at the beginning and end of the AZFP data collection period. From these data, fish density, distribution, and overlap with a proposed hydrokinetic device were calculated in relation to one or more of the following: season, tide stage, diel stage, tidal current speeds, or suspended particulate matter.

In study locations in the Bay of Fundy and the Gulf of Maine where tidal turbines are proposed for deployment, fish abundance (quantified as counts and density) and vertical distribution varied with the season, diel stage, and tidal stage (Viehman and Zydlewski 2017; Viehman et al. 2018). In the Irish Sea, fish school diel vertical migrations were driven by depth of light penetration into the water column, which in turn is controlled by the supply of solar radiation and cross-sectional area of suspended particulate matter (Whitton et al. 2020). As a result, fish schools were found shallower in the morning and evening, and deeper in the middle of the day, with the fish at the deepest depths during lower current speeds corresponding with neap tides. When fish schools were present, they only overlapped with predicted kite operation depths 5% of the time, representing a mean of 6% of the potential kite operating time.

These baseline observations aid in understanding the potential collision risk of fishes and turbines. Because fish counts may be proportional to the encounter rate of fish with a turbine at the same depth, variable fish abundance and distribution in both studies indicate that the risk to fish is similarly variable (Viehman and Zydlewski 2017). Furthermore, the linkage between fish presence and environmental cycles may not be restricted to the locations mentioned in these studies, which could help refine the predictions of potential fish interactions at other tidal energy sites by using modeling exercises.

Deployed Support Structures and Turbines

Group Behavior

By extending the same methodologies and approaches used in pre-deployment baseline studies, installation and post-installation assessment of the impacts of support structures and turbines on fishes, such as avoidance behavior and encounter probability, can be inferred at a group level by observing multiple fish, such as shoals or even local populations. Specifically, comparisons of fish presence/absence, counts, or densities in locations where a turbine is deployed and in nearby reference locations (where a turbine is not deployed) can be made. Similar comparisons can be made before and after a support structure or turbine is deployed to infer the effects of turbines as part of post-consent monitoring programs.

One study examined the relative impacts of device installation vs. normal operation by using a Before-After-Control-Impact study design to compare an index of fish density close to and farther away from an MRE tidal energy device deployed in Cobscook Bay, Maine (Staines et al. 2019). The index consisted of mean volume backscattering strength obtained from 24-hour stationary, down-looking hydroacoustic surveys. These data were collected several times per year at an "impact" site close to an MRE device and at a control site farther away from the MRE device, both before and after turbine installation. One of the main findings was that the operational status of the installed turbine and on-water activity disturbances (e.g., industry vessel and diving activities) varied at the impact site and possibly influenced results. Specifically, lower fish densities were observed during installation and maintenance periods than during normal device operation. The authors emphasized the importance of timing device installation, maintenance and decommissioning to avoid major fish migrations or presence of endangered and threatened species (Staines et al. 2019).

One study was conducted to understand the aggregation characteristics of fishes around a turbine support structure in a high-energy tidal site near the Orkney Islands in Scotland (Fraser et al. 2018; Williamson et al. 2019). Using multifrequency echosounder data, the initial analysis found a large increase in fish-school numbers at the turbine site relative to a control site, which was inferred to be an attraction effect of the static support structure (Fraser et al. 2018). The second analysis used a predictive approach that relied on Generalized Additive Models, and found that the fish-school area and occupied depth around the static turbine support structure were significantly related to the time of day, current velocity, and tide stage (ebb/flood; Williamson et al. 2019). Both analyses found that there were more fish schools present at water velocities less than 1.0 m/s than at higher velocities, and there were more fish schools present near the turbine site than at the control site. From the results, it was inferred that the aggregation of prey fishes near turbine structures may increase prey availability and predator foraging efficiency, which may increase predator collision risk (Williamson et al. 2019). It was further inferred that the biggest change in the behavior of predatory fish would occur at night when they were predicted to occupy deeper waters, which may be manifested in energetics and collision risk, both of which may ultimately have effects at the population level. The investigators concluded that information about changes in fishes around turbine structures can be used to estimate the cumulative effects on predators at a population level, by incorporating observational results into ecosystem and population models. Lieber et al. (2019) also reported the presence of a predictable foraging hotspot for several tern species in the surface wake of the SeaGen device. Although no observations of marine mammals were reported, it is possible that predators could be attracted to such a hotspot, thereby increasing the potential for collision.

During the EnFAIT project in Bluemull Sound, Scotland, fish of the genus *Pollachius* (identified as saithe, *Pollachius virens*) were regularly observed in the subsea video footage (around 20-30% of footage analyzed to date— Nova Innovation 2020). The only other fish species observed in the footage was an individual long-spined scorpion fish (*Taurulus bubalis)* attached to one of the cameras lenses and an unidentified large species thought to be a dogfish, around the base of the turbine. The saithe usually occurred in groups of five or more individuals, often much larger. Individuals were generally seen around the nacelle and blades of the turbines at slack tide and the start of the flood and ebb, moving closer to the seabed or to the shelter created by the nacelle as tidal flow increased. Some exceptions were observed, with individual fish persisting in the vicinity of the nacelle and blades once the turbines started rotating. However, most fish observations corresponded to periods of slower flow speeds and no physical contact between fish and the turbine blades was ever observed in any of the footage.

To understand the aggregation characteristics of fishes near rotating turbines, hydroacoustic surveys were conducted in the East River, New York (Bevelhimer et al. 2017) and in Cobscook Bay, Maine (Grippo et al. 2017) to examine fish densities and distributions in relation to turbines. In both studies, the results suggest that rotating turbines elicit an avoidance response in fishes, even as far as 140 m from the device (Grippo et al. 2017). Collectively, these studies demonstrate that groups of fish show avoidance behavior relative to turbines on different time scales, indicating a reduced probability that fish will physically interact with a rotating device.

Individual Behavior of Fishes

To monitor the individual behavior of fishes near turbines, relatively fine-scale (centimeter to meter scale) information must be collected using cameras or acoustic imaging systems. In cases when individual behavior is being monitored, individual fish are identified and their reactions (or lack thereof) near a turbine are classified into different types, such as attraction or avoidance. Optical cameras provide relatively high-resolution information, but their use is limited by darkness or lack of water clarity. In contrast, acoustic imaging systems (i.e., BlueView, Dual-Frequency Identification Sonar [DIDSON], ARIS) can be used in darkness and low-clarity water, but they provide lower-resolution information than that of optical cameras, and species identification is not always possible.

In the relatively turbid East River of New York, DIDSON data collected in the vicinity of a bottom-mounted horizontal-axis turbine were analyzed to identify and understand individual fish swim tracks around a rotating horizontal-axis turbine (Bevelhimer et al. 2017). In contrast, in the Kvichak River in Alaska, which is relatively clear, optical cameras were used to document and understand fish behavior around a horizontal-axis helical turbine (Matzner et al. 2017). In general, individual fishes appeared to adjust their behavior around turbines. In the East River, some fish responded to the turbine by adjusting their swimming behavior, for example by making small adjustments in their swimming direction and velocity as they passed near the turbine, which can be termed evasion (Bevelhimer et al. 2017). Specifically, individual fishes that were headed toward rotating blades usually avoided the blades by reducing their swimming velocity, adjusting their horizontal swimming direction slightly, and angling away. In the Kvichak River, all adult fish demonstrated some type of avoidance reaction, as did the majority of juveniles; approximately one-third of juveniles passed through the turbine (Matzner et al. 2017).

This information about the behavior of individual fishes around rotating turbines can be scaled up to the group level by incorporating it into collective behavior models or individual-based models to improve the understanding of the impacts of turbines on populations (Shen et al. 2016). However, current field-based efforts to include such information are infrequent (Hammar et al. 2015; Staines et al. 2020) and, as such, real-world data to parameterize these behaviors in models are limited (Bevelhimer et al. 2017). Consequently, these two studies represent an important step toward understanding the behavior of individual fishes near rotating turbines.

Collisions between Turbines and Fishes

While most field-based research focuses on group-level and individual-level behavior around turbines, relatively little focuses on the frequency of actual collisions between turbines and fishes. This line of research is in its infancy, as demonstrated by the fact that no fish collision research was reviewed in the *2016 State of the Science* report. Since 2016, two projects have examined fish collisions with turbines (Bevelhimer et al. 2017; Matzner et al. 2017). Both research projects that examined the frequency of fish collisions relied on manual review of data, because automated detections and descriptions of collision events are currently not possible. In the East River, New York, potential collision events documented in DIDSON data collected in the vicinity of a bottom-mounted horizontal-axis turbine were identified through automated analyses (Bevelhimer et al. 2017). Subsequently, potential collision events were manually evaluated by examining the characteristics of those fish tracks to infer blade strikes. In the Kvichak River, Alaska, optical camera footage was visually examined for collision events (Matzner et al. 2017).

In both studies, collisions ranged from infrequent to nonexistent. In the East River, 36 individual tracks were identified as having the possibility of having had a close encounter with the turbine based on each fish's proximity to the turbine, but there were no observations of fish being struck by rotating blades in the video images that were obtained (Bevelhimer et al. 2017). In more than 42 hours of camera footage reviewed from the Kvichak River, there were only 20 potential contact interactions, of which only 3 were classified as "maybe" collisions after close visual examination (Matzner et al. 2017). On only one occasion was an actual contact confirmed, and it involved an adult fish that contacted the camera, not the turbine itself. More interactions with the turbine were detected at night, which the investigators hypothesized resulted from probable bias introduced by nighttime use of artificial light. The bias was speculated to exist because lights were thought to possibly attract fish and increase their detection probability as a result of the light being reflected from the fish itself (Matzner et al. 2017).

Modeling Studies

As a valuable complement to field-based studies, modeling studies have been conducted to understand several facets of potential impacts of hydrokinetic devices on fishes, including encounter risk, behavior, and collision risk. These models can fill information gaps when field studies are not feasible or lack the spatial or temporal resolution to answer important questions. In the past, many models did not incorporate empirical data (i.e., data collected in the field), but this is changing as research on turbines effects matures.

Encounter Risk

In the context of MRE devices, encounter risk is considered to be the probability that a fish spatially overlaps with different components of a hydrokinetic device (Viehman et al. 2018). These components can vary among studies and are typically predefined by investigators to address regulatory questions. To understand encounter risk, probabilistic models are used to determine the probability that a fish will occur in a predefined volume of water that corresponds to some component(s) of a turbine. Generally, these models rely on understanding horizontal and vertical fish distribution, the physical characteristics of the turbine site including water depth and bathymetric characteristics, and turbine characteristics including their placement in the environment and their dimensions. Encounter risk was modeled in two studies, one in Cobscook Bay, Maine (Shen et al. 2016) and one in Minas Passage, Nova Scotia (Viehman et al. 2018). In Cobscook Bay, a model used empirically collected echosounder data from stationary and mobile hydroacoustic surveys to examine the probability that fish would be at the depth of the turbine and could therefore encounter it as close as 10 m upstream (Shen et al. 2016). In Minas Passage, empirical fish density and vertical distribution data collected by an echosounder were used to estimate the probability of spatial overlap with the device under three fish distribution scenarios: (1) uniform vertical distribution; (2) winter vertical distribution; and (3) summer vertical distribution (Viehman et al. 2018).

In general, the probability of encounter is low and varies with the season, fish community, and turbine design. In Cobscook Bay, the maximum probability of a given fish encountering the whole device during a year was 0.432 (95 percent CI: [0.305, 0.553]), and the probability of a given fish encountering only device blades during a year was 0.058 (95 percent% CI: [0.043, 0.073]; Shen et al. 2016). In Minas Passage, the probability that fish would encounter the marine hydrokinetic device based on spatial overlap alone was 0.00175 with uniform vertical distribution (Viehman et al. 2018). The probability of encounter was 0.00064 for the winter vertical distribution of fish (median proportion of fish at turbine depth = 0.365), and 0.00099 for the summer vertical distribution (median proportion of fish at turbine depth = 0.566). These are likely conservative estimates of encounter probability because neither model incorporated the avoidance or evasion behaviors of fishes. If avoidance and evasion behaviors are considered, the encounter probability would likely be considerably lower.

Behavior of Fishes when Encountering a Turbine

The behavior of fishes when encountering a turbine has been explored in one study in an IBM framework

(Grippo et al. 2017). The goal of the study was to use empirical data to characterize the magnitude, ecological significance, and potential drivers of behavioral responses. To accomplish this, data from field surveys, hydrodynamic modeling, and behavioral simulations that described fish responses hundreds of meters upstream and downstream of the turbine were correlated to stimuli generated by the turbine, as well as currents in the environment. Fish behavior near the turbine was simulated in a relatively simple individual-based model (Eulerian-Lagrangian-Agent Method [ELAM]) and related to three potential stimuli generated by the turbine, including flow patterns, noise, and visual stimuli. Initial results indicated low impacts to fish (Grippo et al. 2017).

Collision Risk Modeling

Collision risk modeling is used to understand, predict, and assess potential rates of a fish either running into static components of a turbine or being struck by moving parts of the turbine (Xodus Group 2016). In general, collision risk models use a physical description of the turbine and characteristics of fishes such as body size, abundance, and swimming activity to estimate potential collision rates. To accomplish this, the models quantify how often the turbine parts will be in the same place at the same time as a fish. The occurrence of turbine parts will depend on the turbine size, architecture, and movement characteristics.

To understand collision risk for Atlantic salmon passing near the turbine site, four scenarios based on two project stages and two different types of turbines were considered (Xodus Group 2016). Turbine characteristics were taken from device-specific engineering information, whereas the sources of hydrodynamic and bathymetric characteristics were not described. Using a 95 percent avoidance rate for Atlantic salmon, which is based on previous research and is assumed to be precautionary (Scottish Natural Heritage 2016), and the worst-case scenario of an array consisting of 200 individual 10-bladed turbines, the collision risk for any given individual fish of a certain life stage that passes through the turbine site during its oceanic migratory circuit is expected to be 0.007 percent for grilse and adults, and 0.003 percent for smolts. Scenarios with fewer turbines and turbines with fewer blades produced lower collision risk estimates.

3.5.3. RESEARCH AND MONITORING NEEDS TO RETIRE THE ISSUE

Additional research and monitoring, including field studies, modeling, and flume studies, can advance our understanding of the risks of fish collision with MRE and hydrokinetic devices. In addition, in many cases, the results from one approach can inform other approaches, such as field study results providing information for model validation and improvement. These studies should focus on all stages of MRE development, including the collection of baseline information and post-installation impacts on fishes. Because monitoring of and research on the potential impacts of turbines on fishes is a relatively new field, most of the recommendations are basic compared to other mature fields related to understanding anthropogenic impacts on organisms. Some of the priority needs for understanding collision risk for fishes with MRE devices are listed below.

Placement of MRE devices – The generalized recommendation, based upon flume research (Zhang et al. 2017), for placing MREs at the downstream end of a channel should be re-examined, because it is likely that placement recommendations will vary with location and fish species.

Groundtruthing acoustic targets – To determine which fish species are in the vicinity of MRE devices, acoustic targets should be groundtruthed for both baseline and post-installation research and monitoring that use acoustic methods (echosounders), which will lead to better understanding of fish distribution and behavior.

Individual fish behavior – Detailed information about the behavior of individual fishes should be collected to complement information gained from group-level observations to understand the ramifications of altered behavior (Bevelhimer et al. 2017) and to inform encounter probability and collision risk models. Once methodologies are refined, they can be used to answer behavioral questions that have eluded researchers. Because echosounders (e.g., split-beam sonar) have not been particularly effective in sampling nearfield areas, once a fish gets close to a turbine, this method is less helpful than cameras for determining the extent and outcomes of interactions. Even with cameras, identifying collision versus avoidance at close distances remains problematic (Matzner et al. 2017). The use of newly (or yet to be) developed echosounder and camera data processing algorithms should provide valuable information. Actual collisions between turbines and fishes are thought to be rare, but determining the effect of a collision on a fish will help understand actual impacts that can be used to model the population-level impacts of turbines.

Effects of underwater lights on fish behavior – The effects of lights used for monitoring fish behavior during periods of darkness should be examined to understand the potential influences of light on fish behavior and subsequent biases that may be introduced during nighttime monitoring of fish/turbine interactions (Matzner et al. 2017). Lights can either attract or repel fishes, and without knowing the exact effects of light on fish behavior on a species-specific basis, it is not possible to understand the sampling bias. Literature from research around hydroelectric dams may provide some insight.

Automated detection of fish collisions – Many monitoring methods still rely heavily on manual and visual processing. Although this approach likely leads to accurate results, it is time-consuming and, in some cases, prevents comprehensive monitoring (Matzner et al. 2017) or reporting. Efforts should be devoted to developing automated detection to better understand the frequency of the collision of fishes with turbines in the field and to avoid the need for manual processing of echosounder data. Further development of automated algorithms for both echosounder and camera data are also needed to reduce the burden of the storage and post-processing of collected data.

Correlation of fish behavior with stimuli – High-resolution information about fish behavior should be quantitatively correlated to stimulus fields around turbines, including noise, pressure, velocity, acceleration, and water particle characteristics, to advance understanding of fish behavior in response to these stimuli (Figure 3.6). Grippo et al. (2017) qualitatively examined these questions, but rigorous quantitative analyses are needed. To do this, fields around the operating/rotating turbine, including water velocity, pressure, acceleration, and water particle characteristics (Nedelec et al. 2016; Popper and Hawkins 2018) should be measured. Next, fine-scale fish behavior

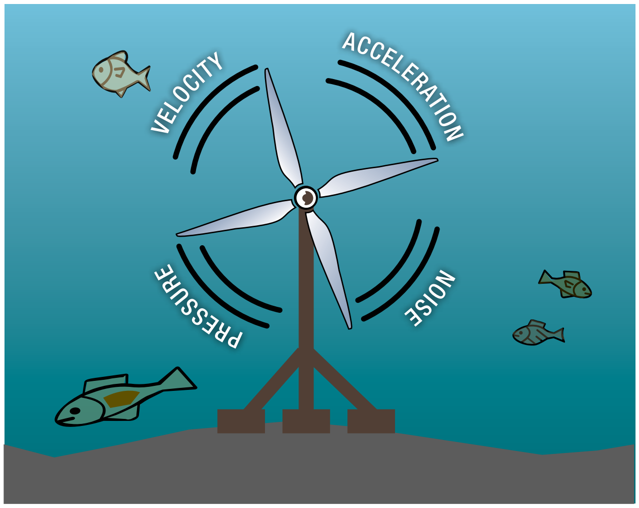


Figure 3.6. Schematic of stimulus fields produced by a turbine that could affect fish behavior. (Illustration by Robyn Ricks)

elucidated through tagging or other methods should be overlaid on the fields around the turbine, and correlations among environmental fields, physical covariates, and fish behavior should be determined. Conducting such an exercise would enable more accurate prediction of fish behavior in the absence of other means, such as field monitoring. In addition, there is a need to understand fish behavior in close proximity with turbines. In many cases, particularly when using echosounders to monitor fishes, the turbine blades and fishes are indistinguishable, or the turbine blades cause feedback and mask fish detections at close range (Shen et al. 2016).

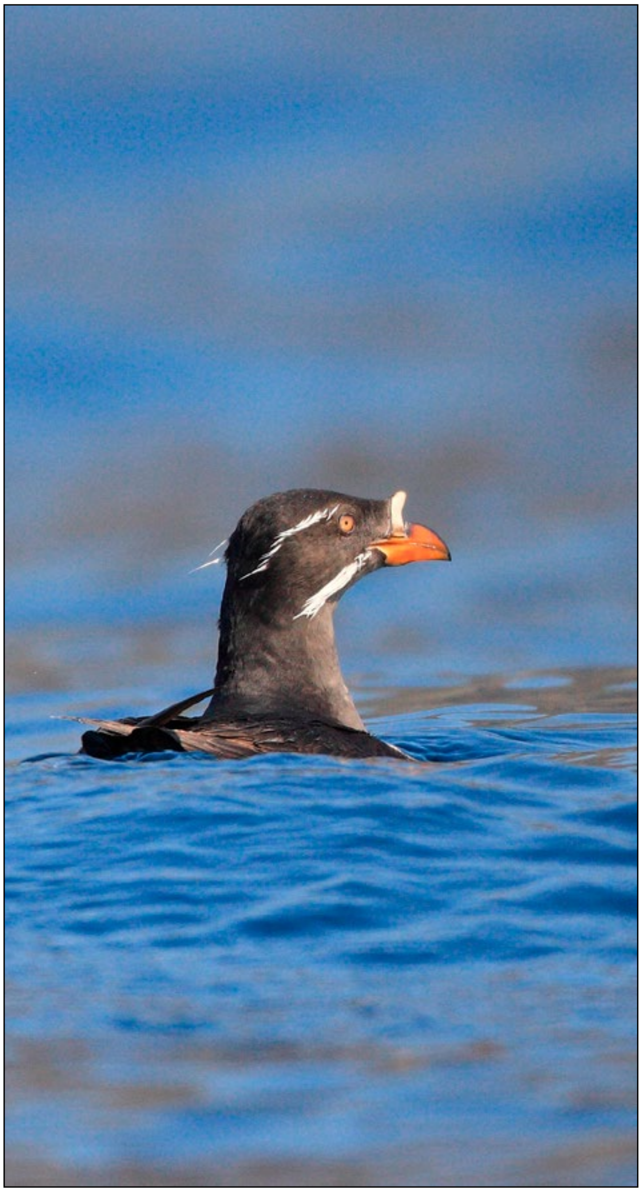
Consequences of the collision of fish with turbines – The outcomes of actual collisions of fishes and MREs are relatively unknown and should be examined. Even if a fish is not actually struck by a turbine, it may experience other sublethal behavioral and physiological effects. Investigating sublethal and non-contact effects will also be important for understanding the effects of turbines on fishes.

Optimizing turbine operation for fish safety – While also considering electricity production, research to identify optimum blade velocity should examine the trade-off between avoidance behavior and severity of injuries, because increased blade velocity results in increased avoidance behavior, while decreased blade velocity results in decreased severity of injuries and mortality (Zhang et al. 2017).

Realism and groundtruthing of collision and encounter models – Encounter probability models need to incorporate realistic representations of fish behavior, including avoidance and evasion behavior observed during field studies (Viehman and Zydlewski 2017). These models need to be rigorously groundtruthed to determine the realism of their outputs.

Effects of MRE arrays on fish – Future studies should examine the impacts of MRE arrays, which may have implications that differ substantially from those of single devices (Shen et al. 2016). The effects of turbines on fishes beyond the individual-turbine and individual-fish levels should be pursued as the MRE industry scales up. For example, how a device (or devices) affects the migration of groups of animals, such as schooling salmon or herring, over prolonged periods should be investigated, and expanded to include consideration of turbine arrays. It is likely that a turbine array will alter the biota in an ecosystem by repelling some species and attracting others (Fraser et al. 2018).

Implications of fish collision on populations – The population-level impacts of MRE devices on fishes should be determined using a variety of approaches, including using population dynamics modeling and examining long-term data about the abundance of fishes, to provide a more holistic understanding of fish collision risks. As the industry develops, regulators will have to consider the potential effects on fish populations, using data gathered from single devices and small arrays, and applying tools used in consideration of other development processes. Also of consideration are the community-level effects that might be caused by MRE development. By altering the fish community, ecosystem effects such as changes in the food web structure, as well as the overall and relative abundance of fishes, will likely be realized. Furthermore, an attractant effect, particularly of predatory fishes, may disproportionately affect other fish species, particularly low-abundance species like Atlantic salmon and some populations of Pacific salmon.



3.6. COLLISION RISK TO SEABIRDS

Seabirds are considered to be at risk from tidal turbine development if they dive at the locations and depths of operational turbines. Understanding this risk involves understanding the geographic distribution, seasonal habitat use, diving depth and timing, and other behavioral movements of the seabirds of concern, as they may overlap with operational turbines.

3.6.1. SUMMARY OF KNOWLEDGE THROUGH 2016

As of 2016, knowledge about the risk of seabird collision with MRE devices was limited, in part because of a lack of operational devices. Consequently, most studies focused on the potential vulnerability of seabirds' habitat relative to the presence of MRE devices rather than collision risk. While no empirical data were available about the collision impacts of seabirds with MRE devices, several studies assessed the relative sensitivities of different seabird species or species groups to the potential adverse effects of MRE devices (e.g., Furness et al. 2012; Wilson et al. 2007). Cormorants and auk species including European shag (*Phalacrocorax aristotelis*) and black guillemot (*Cepphus grylle*) were highlighted as the species most at risk because of their diving behavior and depth and the resulting potential for overlap with operating or moving turbine parts (Furness et al. 2012; Langton et al. 2011). Several studies used land- and boat-based visual observations to investigate seabird presence and use of tidal areas. Their findings suggested that although highly energetic tidal channels may provide predictable foraging sites for a range of seabird species, the specific details of habitat use and therefore risk will be site-specific and may also vary within a site (Wade 2015; Waggitt and Scott 2014).

Technology and remote observation methods were also used to investigate the potential impacts of MRE devices on seabirds. Williamson et al. (2017) used the Flow, Water Column and Benthic Ecology (FLOWBEC) platform equipped with a variety of sensors to assess the underwater interactions of seabirds (as well as fish and marine mammals) with tidal turbines. A similar integrated instrumentation system was also developed by Polagye et al. (2014). In addition, Jackson (2014) used above-water cameras on the Pelamis wave energy device at the European Marine Energy Centre (EMEC) in the Orkney Islands, Scotland, to assess the use of the wave structure and surrounding water by seabirds, and they found use by eight species, most frequently by Arctic terns (*Sterna paradisaea*). Floating tidal turbines operate near the surface; therefore, for these types of devices, the results from Jackson (2014) suggest the implications for collision risk should be investigated further. Bird-borne technology (particularly time-depth recorders) were also used to collect data about the potential risk from MRE devices, but it was not possible to couple the diving profiles of seabirds with GPS location data to gain dive profiles for seabirds at MRE sites. In the absence of empirical seabird collision data, collision risk models were under development to estimate likely collision rates (Grant et al. 2014; Scottish Natural Heritage 2016), but the data to parameterize the models were limited.

3.6.2. KNOWLEDGE GENERATED SINCE 2016

Since the publication of the *2016 State of the Science* report, studies have continued to investigate habitat use and fine-scale interactions with turbines as well as the development of monitoring techniques, as a proxy for collision risk for seabirds and tidal turbines.

Site-wide Scale and Habitat Use

An understanding of seabird habitat use across a potential tidal-stream development site can provide information about the likelihood of a diving seabird and a tidal turbine co-occurring in two-dimensional space (i.e., latitude and longitude). Waggitt et al. (2016) used a combination of vessel-based seabird surveys, hydrodynamic modeling, and acoustic surveys to test for associations between diving seabirds and physical features in a tidal-stream environment—the Fall of Warness in the Orkney Islands, Scotland. Their results showed that for the species of interest (Atlantic puffins [*Fratercula arctica*], black guillemots, common guillemots [*Uria aalge*], and European shags), individuals were associated with fast and slow horizontal currents, high turbulence, upward and downward vertical currents, and hard-rough seabeds. However, the strength of the associations was species-specific. In particular, the study demonstrated a strong association of Atlantic puffins with fast horizontal flow, highlighting the potential for this species to be at risk of collision with tidal turbines. Following on from this, Waggitt et al. (2017) used data from shore-based seabird surveys across six sites in Scotland to identify trends in the use of habitats by black guillemots and European shags. However, their results did not provide any clear generalizations, suggesting that species habitat use of tidal-stream environments and the associated risk of collision with turbines may vary greatly between development sites.

GPS tracking of black guillemot breeding on the island of Stroma in the Pentland Firth, UK, found little overlap between birds and the MeyGen lease area; 73.2 percent of the GPS points fell outside the area (Johnston 2019). Foraging occurred at shallower depths (at mean depths of 24 m) and at slower tidal velocities than in the lease area. This may be due to the energetic cost of benthic diving in strong currents. The study found a large amount of individual variability in habitat use, suggesting that in addition to species- and site-specificity, individual specialization may modulate collision risk.

Cole et al. (2018) used a modified ornithodolite (a pair of binoculars with a built-in laser rangefinder, digital compass, and inclinometer) to quantify animal space use and the fine-scale space use in a highly dynamic tidal area (Ramsey Sound, Wales) by diving seabirds, to locate the birds. Their results showed that the standard deviation of distance measurements was 1–2 m within a 2 km range. However, systematic error in the laser rangefinder distance measurement, as well as the influence of the target bird size and color, could lead to an increase in the actual 3-D positional error (Cole et al. 2018). Despite these limitations, the ornithodolite is a useful tool for assigning individuals to locations in space and therefore for understanding how they might be at risk of collision. In relation to bird behavior and habitat use, they found that individuals avoided the main channel where mean current speeds were fastest, preferring instead the relatively slack waters. They also noted that diving birds oriented into the flow and could therefore potentially drift backward if their swim speed was less than the current speed, potentially drifting into a turbine if they occupied the same stretch of water (Cole et al. 2018). Similar behavior of "conveyor belt foraging" was documented by Robbins (2017) for black guillemots in Bluemull Sound, Scotland, where the density of black guillemots also showed a significant negative relationship with current speed.

Thirty-three bird species have been recorded in land-based surveys during the EnFAIT project in Bluemull Sound (Nova Innovation 2020). Fifteen species are known to dive to the turbine depth (≥ 15m below sea level), and therefore capable of encountering and interacting with the turbines. Black guillemot and European shag accounted for over 90% of all sightings, with other diving bird species, such as Atlantic puffin, northern gannet (*Morus bassanus*), common guillemot and red-throated diver (*Gavia stellata*) recorded infrequently. Black guillemot were recorded diving in the area immediately around the turbines in 2.75% of scans, European shag in 1.04% of scans and puffin in 1.08% of scans. For the 9 years of survey data, the modeled probability of a bird diving in the area immediately around the turbines is <0.05 for both black guillemot and Atlantic puffin, <0.03 for European shag and <0.01 for all other species. In general, the probability of birds diving around the turbines was greater on flood tides than the ebb and lower at faster tidal flows, indicating a very low turbine encounter risk for even the most commonly occurring diving birds. Black guillemot and European shag were the only bird species observed in the subsea video footage. Eleven occurrences of shag and seven of guillemot were observed, all during slack tide or periods of tidal flow below the cut-in speed, when the turbines were not operating. On three occasions, European shag were observed actively pursuing fish around turbines. No physical contact between birds and the turbine blades was ever observed in any of the footage.

Unmanned aerial vehicles (UAVs) have recently been used to understand how seabirds use tidal flow areas in high-flow tidal areas of the Pentland Firth (Williamson et al. 2018). Limited research has been conducted on the effect of UAVs on birds and specifically non-breeding, resting, or feeding birds (Vas et al. 2015) rather than breeding birds (Brisson-Curadeau et al. 2017; Weimerskirch et al. 2017). It is thought that the effect on behavior is minimal when UAVs are operated at appropriate heights, though this will be species-specific. UAVs provide a cost-effective method for measuring seabird distributions and hydrodynamic features concurrently. Vessel-based observers were used to confirm UAV observations of seabirds while their UAV hydrodynamic measurements were groundtruthed against vessel-based hydroacoustics (Williamson et al. 2018). This research aims to develop algorithms for the automated detection of animals and hydrodynamic features from UAV data. A UAV was used with vantage point surveys to observe top predators around a manmade structure (SeaGen) in Strangford Lough, Northern Ireland, demonstrating the presence of a predictable foraging hotspot for several tern species in the surface wake of the device (Lieber et al. 2019). During the study, SeaGen was being decommissioned and the rotors were removed, although the monopile was still in place, thereby creating a surface wake effect. It has been hypothesized that foraging hotspots generated around operational devices could potentially lead to an ecological trap, i.e., a situation in which birds are attracted to an operating turbine because of the increased foraging opportunities and consequently experiencing an increased collision risk (Lieber et al. 2019). An ecological trap occurs when "organisms make poor habitat choices based on cues that correlated formerly with habitat quality" (Schlaepfer et al. 2002). This behavior could increase the risk of collision, thereby outweighing the benefit gained from foraging (Battin 2004; Kristan 2003). The degree to which the surface wave effects observed at SeaGen might be replicated at depth by wakes created by fully submerged devices and any corresponding implications for the creation of feeding hotspots at depth is unclear.

Fine-scale Interactions

To better understand the risk of collision of seabirds with underwater turbines, it is vital to understand how individuals will interact with the devices. To date, there has been limited information about the underwater movements and behaviors of seabirds around tidal turbines, in part because of the low number of operational devices. A proxy for empirical data about interactions information has been collated about seabird diving behavior in an attempt to parameterize collision risk models. Robbins (2017) produced a synthesis of data about seabird diving behavior (18 different parameters) for 22 species found in UK waters. This study found that existing knowledge of foraging and diving behavior is highly variable across species and parameters and that for some of the most vulnerable species, such as loons and black guillemots (Furness et al. 2012), data uncertainty is high. For such species, targeted research will be required.

Guidance on Collision Risk and Monitoring

Since the publication of the *2016 State of the Science* report, Scottish Natural Heritage has published guidance on how to assess collision risk between underwater turbines and marine wildlife, including diving seabirds (Scottish Natural Heritage 2016). The guidance presents three separate models: (1) the Encounter Rate Model, (2) the Collision Risk Model, and (3) the Exposure Time Population Model. The approaches of the Encounter Rate and Collision Risk Models are similar to those used for wind turbines (Band 2012); they use a model for the turbine and the animal to estimate the likely risk of collision. The Exposure Time Population Model takes a different approach; it uses population modeling to determine "the critical additional mortality due to underwater collisions with a turbine which would cause an adverse effect to an animal population" (Scottish Natural Heritage 2016). All three models require data to parameterize, and recommended values for some of these standard parameters, such as biometrics (body length and wingspan) and diving behavior (dive depths, swim speeds, etc.), are provided in the guidance. The guidance can be used to determine which model is best suited to the specific circumstance of an MRE development and for the data available.

3.6.3. RESEARCH AND MONITORING NEEDS TO RETIRE THE ISSUE

Significant data gaps remain because only a limited number of studies have been conducted, so there is no evidence to show that direct interactions with tidal turbines will occur or cause harm to individual seabirds or populations.

Seabird Movement and Behavior – There is a lack of data about and observations of nearfield animal movements and behaviors around tidal turbines, which would be required for a variety of designs and across a range of tidal locations. This means that we do not currently understand how seabirds interact with operational turbines and we are unable to predict how devices might affect individuals at new development sites, which limits the evidence base for environmental impact assessments. This is also evident when using collision risk models, which currently make assumptions about avoidance or evasion responses of seabirds, based on learning from offshore wind turbines (Scottish Natural Heritage 2016), because there are no empirical data from tidal turbines.

Detecting Collisions – Even if more data about the close-range behavior of seabirds relative to turbines become available, it will still be necessary to detect and record actual collision events, and doing so may not be possible because of poor underwater visibility and turbidity (RPS Group 2010). Having empirical evidence of collisions (or the lack thereof) not only allows for a better understanding of risk but will aid in the validation of collision risk models. In addition, there is a lack of information about the consequences of collisions for seabirds, if they occur; i.e., whether a collision event would lead to mortality. Research has started to address this issue for marine mammals but it has yet to be explored for seabirds (Onoufriou et al. 2019).

Seabird Species Behavior – Gaps in our knowledge of seabird diving behavior remain. Although some seabirds are well-studied, studies often focus on a limited number of species at only a few locations. The synthesis of marine bird diving behavior conducted by Robbins (2017) to inform our understanding of the risk of underwater collision with tidal-stream turbines found that data gaps remain, particularly for some vulnerable species such as black guillemots and loons. Data need to be collected from more than one location over several seasons including the breeding season. Improved data should be used to parameterize underwater collision risk models.

Seabird Use of Tidal Races – Wade et al. (2016) incorporated uncertainty into an assessment of seabird vulnerability relative to MRE developments and found high levels of uncertainty associated with seabird use of tidal races. This affects confidence in our estimates of the likely risk of collisions between diving seabirds and tidal turbines, so wherever possible uncertainty should be presented transparently. However, careful consideration should be given to who is communicating the uncertainty, in what form, and to whom, as well as importantly, for what reason (van der Bles et al. 2019).

Research Priorities – Many of the priorities for reducing the risk of seabird collisions with tidal turbines overlap with those proposed for marine mammals and fish, and many remain from those recommended in the *2016 State of the Science* report. The priorities that could be addressed by research, monitoring, and methods and tools, are listed below.

Priorities for research include the following:

- Improve the knowledge of seabird diving behavior where knowledge gaps remain for vulnerable species to increase the evidence base for use in estimation of collision rates in models.
- Develop collision risk methods that incorporate the movement of seabirds around turbine arrays rather than around single turbines.
- Test the assumption of collision risk models that all mortality is associated with collision events.
- Include variability and uncertainty in collision risk modeling.
- Improve the understanding of the displacement of seabirds from operating tidal energy sites to understand the true size of the population at risk.

The priorities for monitoring at future tidal energy development sites are as follows:

- Monitor nearfield underwater interactions with and behaviors of seabirds in response to deployed devices.
- Target observations (rather than generic monitoring) of seabird habitat use in relation to hydrodynamic features to improve the understanding of how seabirds use high-flow environments.
- Target observations to determine the extent of displacement effects.

The priorities for the development of technology, methodologies, and tools include the following:

- Develop methods to improve the understanding of the behavior of seabirds around operating devices, particularly avoidance and evasion behaviors.
- Develop sensors and cameras to assure that any collisions can be detected with confidence and that collisions can be classified by species, and to determine the effects/consequences of collision (i.e., mortality rate).
- Develop automated methods for processing the large quantities of data, such as underwater video/camera images, that are often recorded at sites.

3.7.
CONCLUSIONS AND RECOMMENDATIONS

Key progress has been made to better understand collision risk, and evidence is steadily growing across a range of disciplines, informed by research and post-installation monitoring of operational devices. No collisions have been observed in nearfield monitoring carried out to date around operational turbines. However, because deployments have been limited and monitoring challenges are significant, gaps in knowledge remain. It is also important to acknowledge that the absence of observations of collisions does not provide definitive evidence that collisions will not occur. Uncertainty about collision risk, including the potential for collision events to occur, continues to be a significant influential factor in consenting processes and their outcomes for tidal and river energy developments. The increase in turbine device and array deployments, coupled with increased reporting about the findings derived from monitoring at existing operational projects over the next few years, will be critical in addressing some of the key gaps and uncertainties. Crucial to this effort will be improving the dissemination, sharing, and use of the data gathered around operational devices, and the information generated from these data, in a way that does not compromise any commercial confidentiality or intellectual property for device developers, suppliers, or researchers.

3.7.1.
INTEGRATION OF INFORMATION, TECHNOLOGY, AND ENGINEERING EXPERTS IN MONITORING PROGRAMS

Improvements in the methodologies used to collect, store, share, and analyze data pertaining to collision risk are required. Key to achieving these improvements will be better integration, from the design stage, of the efforts of experts in engineering and information technology to improve the technologies used in monitoring (including improved reliability, survivability, and cost), as well as managing, analyzing, and disseminating the data. The development of automated data processing algorithms and software for analyzing data gathered around operational devices will be key to resolving uncertainties about collision risk.

In addition, it is vital to examine the overlap and potential interaction that may occur among predator and prey species, through the integration of data collected about marine mammals, fish, and diving seabirds around turbines (Scott et al. 2014). By collecting data about the three major groups of marine animals at risk through coordinated monitoring programs (adding sea turtles in appropriate waters), the understanding of the potential interactions around MRE devices will be improved for each group and the potential interactions between the groups, such as the availability of forage fish around turbines forming prey for marine mammals or seabirds, will be better elucidated.

3.7.2.
EVIDENCE OF FACTORS AFFECTING COLLISION RISK

The broad-scale use of tidal energy areas by mobile marine predators for feeding and foraging is well-established (e.g., Benjamins et al. 2015). However, recent research presented in this chapter indicates that collision risk is more nuanced than the straightforward spatial overlap of animals with tidal and river energy areas. Predator occupancy patterns appear to be strongly associated with tidal phases, current strengths, and flow structures, most likely in response to forced prey distribution and behaviors (Lieber et al. 2018, 2019), which will affect the likelihood of spatial overlap at times of risk (i.e., when turbine blades are rotating). There appears to be some heterogeneity in these associations across different tidal sites (e.g., Waggitt et al. 2017) but also some differences (e.g., Hastie et al. 2016). As evidence of the influence of fine-scale hydrodynamics on marine animal distribution and behavior in tidal energy habitats grows, it will improve our understanding of the probability of encounters with operating tidal devices, and the corresponding implications for collision risk.

Where there is spatial overlap between operating tidal devices and marine animals, the animals' behavioral responses to the physical and acoustic presence of devices will be the primary factors influencing collision risk. Such responses include attraction, avoidance, and evasion. These factors can be better understood by measuring the response of marine animals to the actual presence of installed devices and arrays.

3.7.3. ASSESSING COLLISION RISK AND ITS CONSEQUENCES

Assessments of collision risk for tidal energy projects often include the use of predictive models to quantify potential collisions (e.g., Scottish Natural Heritage 2016) and the likely consequences of such predictions for species' populations (e.g., King et al. 2015). In general, collision models are relatively simple, based on the broad spatial overlap of marine animals with tidal energy development areas, and on the measured or estimated animal density, often across a much wider area. Outputs should therefore be treated with caution to avoid inflating their scientific basis. Outputs provide a useful indication of the potential magnitude of collision risk, but contextualization and interpretation also are crucial.

Equally uncertain are the consequences to an individual animal if a collision with a moving part of a turbine were to occur. For some species, the research is moving beyond the assumption that all collisions will result in the death of the animal, but the potential consequences for marine mammals across the size range from small pinnipeds and cetaceans to large whales, as well as fish and diving seabirds, are not well known. More investigations are needed to assure that an overly conservative approach to predicting the outcomes of collisions can be avoided.

A key driver of the global concern about collision risk is the potential for such effects to lead to losses of individuals, which may affect ecosystem dynamics and the long-term status of populations. For many species, particularly those with spatially restricted, declining, or small populations, even a very low collision risk could result in concern about its effects on long-term population viability. For many species, limited evidence of life history or population demographics presents a challenge to understanding the potential for such effects. In the case of some species of "charismatic megafauna," the loss of individual animals might be deemed unacceptable from a societal or legal, rather than biological, perspective.

3.7.4. POST-INSTALLATION MONITORING OF COLLISION RISK

Globally, uncertainty and knowledge gaps about collision risk have been key drivers of the requirement for and design of post-installation monitoring programs for tidal and river energy projects (see Chapter 12, Adaptive Management with Respect to Marine Renewable Energy). This is an area in which there has been significant activity in recent years, and there is a growing body of evidence about the interactions between animals and tidal devices. Significant progress has also been made in the development of monitoring techniques and instruments to address the challenges of gathering robust information of relevance to collision risk in tidal energy environments and around operating devices (see Chapter 10, Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines).

The increase in tidal device and array deployments, as well as reporting on the findings of existing operational projects over the next few years, are expected to further address some of the collision risk critical gaps and uncertainties. These efforts include opportunities for meta-analyses across multiple sites and projects. Key to the success of this work will be the MRE industry, regulators, researchers, and funding agencies working collaboratively to understand how to best fund, share, and disseminate the results of research and monitoring programs to collectively move toward a better understanding of collision risk. This will require the exploration and development of mechanisms for sharing data and information without compromising commercial interests or intellectual property rights, as well as consideration of the needs of the consenting processes, including independent review and scrutiny of outputs.

3.8.
REFERENCES

ABP Marine Environmental Research Ltd. (ABPmer) 2010. Collision Risk of Fish with Wave and Tidal Devices (R.1516). Report by ABP Marine Environmental Research Ltd for Welsh Assembly Government, Southhampton, Hampshire. *https://tethys.pnnl.gov/publications/collision-risk-fish-wave-and-tidal-devices*

Amaral, S. V., Bevelhimer, M. S., Čada, G. F., Giza, D. J., Jacobson, P. T., McMahon, B. J., and Pracheil, B. M. 2015. Evaluation of Behavior and Survival of Fish Exposed to an Axial-Flow Hydrokinetic Turbine. *North American Journal of Fisheries Management*, 35(1), 97-113. doi:10.1080/02755947.2014.982333 *https://tethys.pnnl.gov/publications/evaluation-behavior-survival-fish-exposed-axial-flow-hydrokinetic-turbine*

Band, B. 2012. Using a collision risk model to assess bird collision risks for offshore windfarms. Report by British Trust for Ornithology for The Crown Estate. *https://tethys.pnnl.gov/publications/using-collision-risk-model-assess-bird-collision-risks-offshore-wind-farms*

Band, B. 2014. Annex 3. Detailed Collision Risk Assessment: Marine Mammals, Basking Shark, and Diving Birds (Report No. REP 443-04-01 20141120). European Marine Energy Centre, Stromness, Orkney. *https://tethys.pnnl.gov/publications/emec-fall-warness-test-site-environmental-appraisal*

Band, B., Sparling, C. E., Thompson, D., Onoufriou, J., San Martin, E., and West, N. 2016. Refining Estimates of Collision Risk for Harbour Seals and Tidal Turbines. Scottish Marine and Freshwater Science Vol 7 No 17. Marine Scotland Science, Aberdeen, Scotland. *https://tethys.pnnl.gov/publications/refining-estimates-collision-risk-harbour-seals-tidal-turbines*

Battin, J. 2004. When Good Animals Love Bad Habitats: Ecological Traps and the Conservation of Animal Populations. *Conservation Biology*, 18(6), 1482-1491. doi:10.1111/j.1523-1739.2004.00417.x *https://tethys.pnnl.gov/publications/when-good-animals-love-bad-habitats-ecological-traps-conservation-animal-populations*

Benjamins, S., Dale, A. C., Hastie, G., Waggitt, J. J., Lea, M.-A., Scott, B., and Wilson, B. 2015. Confusion Reigns? A Review of Marine Megafauna Interactions with Tidal-Stream Environments. In R. N. Hughes, D. J. Hughes, I. P. Smith, and A. C. Dale (Eds.), *Oceanography and Marine Biology* (Vol. 53, pp. 54). Boca Raton, FL: CRC Press. *https://tethys.pnnl.gov/publications/confusion-reigns-review-marine-megafauna-interactions-tidal-stream-environments*

Benjamins, S., van Geel, N., Hastie, G., Elliott, J., and Wilson, B. 2017. Harbour porpoise distribution can vary at small spatiotemporal scales in energetic habitats. *Deep Sea Research Part II: Topical Studies in Oceanography*, 141, 191-202. doi:10.1016/j.dsr2.2016.07.002 *https://tethys.pnnl.gov/publications/harbour-porpoise-distribution-can-vary-small-spatiotemporal-scales-energetic-habitats*

Bennet, F., Culloch, R., and Tait, A. 2016. Guidance on effective adaptive management and post-consent monitoring strategies (RiCORE Project Report No. RICORE-D5-2D5-4). Report by Robert Gordon University for European Commission; Project, Aberdeen, Scotland. *https://tethys.pnnl.gov/publications/guidance-effective-adaptive-management-post-consent-monitoring-strategies*

Bevelhimer, M. S., Pracheil, B. M., Fortner, A. M., Saylor, R., and Deck, K. L. 2019. Mortality and injury assessment for three species of fish exposed to simulated turbine blade strike. *Canadian Journal of Fisheries and Aquatic Sciences*, 76(12), 2350-2363. doi:10.1139/cjfas-2018-0386 *https://tethys.pnnl.gov/publications/mortality-injury-assessment-three-species-fish-exposed-simulated-turbine-blade-strike*

Bevelhimer, M., Scherelis, C., Colby, J., and Adonizio, M. A. 2017. Hydroacoustic Assessment of Behavioral Responses by Fish Passing Near an Operating Tidal Turbine in the East River, New York. *Transactions of the American Fisheries Society*, 146(5), 1028-1042. doi:10.1080/00028487.2017.1339637 *https://tethys.pnnl.gov/publications/hydroacoustic-assessment-behavioral-responses-fish-passing-near-operating-tidal*

Birds Directive (Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds). OJ L 20, 26.1.2010, p. 7-25. [European Union]

Booth, C., Sparling, C., Wood, J., Tollitt, D., Scott-Hey-ward, L., Rexstad, E., Hultgren, Y., Johnsson, M., and Knutzen, E. 2015. Advancing a Key Consenting Risk for Tidal Energy: The Risk of Marine Mammal Collision for In-Stream Tidal Energy Devices. Paper presented at the 3rd Marine Energy Technology Symposium, Washington, D.C. *https://tethys.pnnl.gov/publications/advancing-key-consenting-risk-tidal-energy-risk-marine-mammal-collision-stream-tidal*

Brisson-Curadeau, É., Bird, D., Burke, C., Fifield, D. A., Pace, P., Sherley, R. B., and Elliott, K. H. 2017. Seabird species vary in behavioural response to drone census. *Scientific Reports*, 7(1), 17884. doi:10.1038/s41598-017-18202-3 *https://tethys.pnnl.gov/publications/seabird-species-vary-behavioural-response-drone-census*

Broadhurst, M., Barr, S., and Orme, C. D. L. 2014. In-situ ecological interactions with a deployed tidal energy device; an observational pilot study. *Ocean & Coastal Management*, 99, 31-38. doi:10.1016/j.ocecoaman.2014.06.008 *https://tethys.pnnl.gov/publications/situ-ecological-interactions-deployed-tidal-energy-device-observational-pilot-study*

Castro-Santos, T., and Haro, A. 2015. Survival and Behavioral Effects of Exposure to a Hydrokinetic Turbine on Juvenile Atlantic Salmon and Adult American Shad. *Estuaries and Coasts*, 38(1), 203-214. doi:10.1007/s12237-013-9680-6 *https://tethys.pnnl.gov/publications/survival-behavioral-effects-exposure-hydrokinetic-turbine-juvenile-atlantic-salmon*

Cole, E.-L., Waggitt, J. J., Hedenstrom, A., Piano, M., Holton, M. D., Börger, L., and Shepard, E. L. C. 2018. The Ornithodolite as a tool to quantify animal space use and habitat selection: a case study with birds diving in tidal waters. *Integrative Zoology*, 14(1), 4-16. doi:10.1111/1749-4877.12327 *https://tethys.pnnl.gov/publications/ornithodolite-tool-quantify-animal-space-use-habitat-selection-case-study-birds-diving*

Copping, A., and Grear, M. 2018. Applying a simple model for estimating the likelihood of collision of marine mammals with tidal turbines. *International Marine Energy Journal*, 1, 27-33. doi:10.36688/imej.1.27-33 *https://tethys.pnnl.gov/publications/applying-simple-model-estimating-likelihood-collision-marine-mammals-tidal-turbines*

Copping, A., Grear, M., Jepsen, R., Chartrand, C., and Gorton, A. 2017. Understanding the potential risk to marine mammals from collision with tidal turbines. *International Journal of Marine Energy*, 19, 110-123. doi:10.1016/j.ijome.2017.07.004 *https://tethys.pnnl.gov/publications/understanding-potential-risk-marine-mammals-collision-tidal-turbines*

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewski, G., Staines, G., Gill, A., Hutchison, I., O'Hagan, A., Simas, T., Bald, J., Sparling, C., Wood, J., and Masden, E. 2016. Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. *https://tethys.pnnl.gov/publications/state-of-the-science-2016*

Cotter, E. D., Joslin, J., and Polagye, B. 2018. Tracking and classification of targets detected by a moving multibeam sonar. *The Journal of the Acoustical Society of America*, 143(3), 1957. doi:10.1121/1.5036430 *https://tethys-engineering.pnnl.gov/publications/tracking-classification-targets-detected-moving-multibeam-sonar*

Endangered Species Act of 1973, as amended. 16 U.S.C. ch. 35 § 1531 et seq. [U.S.]

Environment Protection and Biodiversity Conservation Act 1999 (Cth). [Australia]

Fabry, V. J., Seibel, B. A., Feely, R. A., and Orr, J. C. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science*, 65(3), 414-432. doi:10.1093/icesjms/fsn048 *https://tethys.pnnl.gov/publications/impacts-ocean-acidification-marine-fauna-ecosystem-processes*

Fisheries Act, S.C. 1985, c. F-14, s. 1. [Canada]

Food and Agriculture Organization of the United Nations (FAO) 2018. The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals (ISBN 978-92-5-130562-1). Report by United Nations; Rome, Italy. *https://tethys.pnnl.gov/publications/state-world-fisheries-aquaculture-2018-meeting-sustainable-development-goals*

Fraser, S., Williamson, B. J., Nikora, V., and Scott, B. E. 2018. Fish distributions in a tidal channel indicate the behavioural impact of a marine renewable energy installation. *Energy Reports*, 4, 65–69. doi:10.1016/j.egyr.2018.01.008 *https://tethys.pnnl.gov/publications/fish-distributions-tidal-channel-indicate-behavioural-impact-marine-renewable-energy*

Furness, R. W., Wade, H. M., Robbins, A. M. C., and Masden, E. A. 2012. Assessing the sensitivity of seabird populations to adverse effects from tidal stream turbines and wave energy devices. *ICES Journal of Marine Science*, 69(8), 1466–1479. doi:10.1093/icesjms/fss131 *https://tethys.pnnl.gov/publications/assessing-sensitivity-seabird-populations-adverse-effects-tidal-stream-turbines-wave*

Gillespie, D., Palmer, L., Macaulay, J., Sparling, C., Hastie, G. 2020. Passive acoustic methods for tracking the 3D movements of small cetaceans around marine structures. PLoS ONE 15(5), e0229058. doi:10.1371/journal.pone.0229058 *https://tethys.pnnl.gov/publications/passive-acoustic-methods-tracking-3d-movements-small-cetaceans-around-marine*

Grant, M., Trinder, M., and Harding, N. 2014. A diving bird collision risk assessment framework for tidal turbines (Report No. 773). Report by RPS group for Scottish Natural Heritage; Inverness, Scotland. *https://tethys.pnnl.gov/publications/diving-bird-collision-risk-assessment-framework-tidal-turbines*

Grear, M. E., Motley, M. R., Crofts, S. B., Witt, A. E., Summers, A. P., and Ditsche, P. 2018. Mechanical properties of harbor seal skin and blubber – a test of anisotropy. *Zoology*, 126, 137–144. doi:10.1016/j.zool.2017.11.002 *https://tethys.pnnl.gov/publications/mechanical-properties-harbor-seal-skin-blubber-test-anisotropy*

Greaves, D., Conley, D., Magagna, D., Aires, E., Chambel Leitão, J., Witt, M., Embling, C. B., Godley, B. J., Bicknell, A. W. J., Saulnier, J.-B., Simas, T., O'Hagan, A. M., O'Callaghan, J., Holmes, B., Sundberg, J., Torre-Enciso, Y., and Marina, D. 2016. Environmental Impact Assessment: Gathering experiences from wave energy test centres in Europe. *International Journal of Marine Energy*, 14, 68–79. doi:10.1016/j.ijome.2016.02.003 *https://tethys.pnnl.gov/publications/environmental-impact-assessment-gathering-experiences-wave-energy-test-centres-europe*

Grippo, M., Shen, H., Zydlewski, G., Rao, S., and Goodwin, A. 2017. Behavioral Responses of Fish to a Current-Based Hydrokinetic Turbine Under Multiple Operational Conditions: Final Report (ANL/EVS-17/6). Report by Argone National Laboratory for U.S. Department of Energy; Argonne, Illinois. *https://tethys.pnnl.gov/publications/behavioral-responses-fish-current-based-hydrokinetic-turbine-under-multiple*

Habitats Directive (Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora). OJ L 206, 22.7.1992, p. 7–50. [European Union]

Hammar, L., Andersson, S., Eggertsen, L., Haglund, J., Gullström, M., Ehnberg, J., and Molander, S. 2013. Hydrokinetic turbine effects on fish swimming behaviour. *PLoS ONE*, 8(12), e84141. doi:10.1371/journal.pone.0084141 *https://tethys.pnnl.gov/publications/hydrokinetic-turbine-effects-fish-swimming-behaviour*

Hammar, L., Eggertsen, L., Andersson, S., Ehnberg, J., Arvidsson, R., Gullström, M., and Molander, S. 2015. A Probabilistic Model for Hydrokinetic Turbine Collision Risks: Exploring Impacts on Fish. *PLoS ONE*, 10(3), e0117756. doi:10.1371/journal.pone.0117756 *https://tethys.pnnl.gov/publications/probabilistic-model-hydrokinetic-turbine-collision-risks-exploring-impacts-fish*

Hansen, K. A., Maxwell, A., Siebert, U., Larsen, O. N., and Wahlberg, M. 2017. Great cormorants (*Phalacrocorax carbo*) can detect auditory cues while diving. *The Science of Nature*, 104(5), 45. doi:10.1007/s00114-017-1467-3 *https://tethys.pnnl.gov/publications/great-cormorants-phalacrocorax-carbo-can-detect-auditory-cues-while-diving*

Hastie, G. D., Bivins, M., Coram, A., Gordon, J., Jepp, P., MacAulay, J., Sparling, C., and Gillespie, D. 2019. Three-dimensional movements of harbour seals in a tidally energetic channel: Application of a novel sonar tracking system. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 29(4), 564–575. doi:10.1002/aqc.3017 *https://tethys.pnnl.gov/publications/three-dimensional-movements-harbour-seals-tidally-energetic-channel-application-novel*

Hastie, G. D., Evers, C., Gillespie, D., Irving, P., Onoufriou, J., Sparling, C. E., and Thompson, D. 2018b. Marine Mammals and Tidal Energy: Report to Scottish Government – MRE Theme. Report by Sea Mammal Research Unit for Scottish Government; St Andrews, Scotland. *https://tethys.pnnl.gov/publications/marine-mammals-tidal-energy-report-scottish-government*

Hastie, G. D., Russell, D. J. F., Benjamins, S., Moss, S., Wilson, B., and Thompson, D. 2016. Dynamic habitat corridors for marine predators; intensive use of a coastal channel by harbour seals is modulated by tidal currents. *Behavioral Ecology and Sociobiology*, 70(12), 2161-2174. doi:10.1007/s00265-016-2219-7 https://tethys.pnnl.gov/publications/dynamic-habitat-corridors-marine-predators-intensive-use-coastal-channel-harbour-seals

Hastie, G. D., Russell, D. J. F., Lepper, P., Elliott, J., Wilson, B., Benjamins, S., and Thompson, D. 2018a. Harbour seals avoid tidal turbine noise: Implications for collision risk. *Journal of Applied Ecology*, 55(2), 684-693. doi:10.1111/1365-2664.12981 https://tethys.pnnl.gov/publications/harbour-seals-avoid-tidal-turbine-noise-implications-collision-risk

Hilborn, R., Amoroso, R. O., Anderson, C. M., Baum, J. K., Branch, T. A., Costello, C., de Moor, C. L., Faraj, A., Hively, D., Jensen, O. P., Kurota, H., Little, L. R., Mace, P., McClanahan, T., Melnychuk, M. C., Minto, C., Osio, G. C., Parma, A. M., Pons, M., Segurado, S., Szuwalski, C. S., Wilson, J. R., and Ye, Y. 2020. Effective fisheries management instrumental in improving fish stock status. *Proceedings of the National Academy of Sciences*, 117(4), 2218. doi:10.1073/pnas.1909726116 https://tethys.pnnl.gov/publications/effective-fisheries-management-instrumental-improving-fish-stock-status

Kristan, W. B.. 2003. The role of habitat selection behavior in population dynamics: source–sink systems and ecological traps. *Oikos*, 103(3), 457-468. doi:10.1034/j.1600-0706.2003.12192.x https://tethys.pnnl.gov/publications/role-habitat-selection-behavior-population-dynamics-source-sink-systems-ecological

Jackson, A. C. 2014. Riding the waves: use of the Pelamis device by seabirds. Paper presented at the 2nd International Conference on Environmental Interactions of Marine Renewable Energy Technologies, Stornoway, Scotland. https://tethys.pnnl.gov/publications/riding-waves-use-pelamis-device-seabirds

Johnston, D. T. 2019. Investigating the Foraging Ecology of Black Guillemots *Cepphus grylle* in Relation to Tidal Stream Turbines and Marine Protected Areas. Doctoral Dissertation, University of the Highlands and Islands, Inverness, Scotland. https://tethys.pnnl.gov/publications/investigating-foraging-ecology-black-guillemots-cepphus-grylle-relation-tidal-stream

Joy, R., Wood, J. D., Sparling, C. E., Tollit, D. J., Copping, A. E., and McConnell, B. J. 2018. Empirical measures of harbor seal behavior and avoidance of an operational tidal turbine. *Marine Pollution Bulletin*, 136, 92-106. doi:10.1016/j.marpolbul.2018.08.052 https://tethys.pnnl.gov/publications/empirical-measures-harbor-seal-behavior-avoidance-operational-tidal-turbine

King, S. L., Schick, R. S., Donovan, C., Booth, C. G., Burgman, M., Thomas, L., and Harwood, J. 2015. An interim framework for assessing the population consequences of disturbance. *Methods in Ecology and Evolution*, 6(10), 1150-1158. doi:10.1111/2041-210X.12411 https://tethys.pnnl.gov/publications/interim-framework-assessing-population-consequences-disturbance

Kregting, L., Schmitt, P., Lieber, L., Culloch, R., Horne, N., and Smyth, D. 2018. D6.2 Environmental Impact Report of the H2020 project PowerKite. Report by Queen's University Belfast for European Commission; Northern Ireland, UK. https://tethys.pnnl.gov/publications/d62-environmental-impact-report-h2020-project-powerkite

Kreibel, D., Tickner, J., Epstein, P., Lemons, J., Levins, R., Loechler, E. L., and Stoto, M. 2001. The precautionary principle in environmental science. *Environmental Health Perspectives*, 109(9), 871-876. https://tethys.pnnl.gov/publications/precautionary-principle-environmental-science

Kristan, W. B. I. 2003. The role of habitat selection behavior in population dynamics: source-sink systems and ecological traps. *Oikos*, 103(3), 457–468. doi: 10.1034/j.1600-0706.2003. 12192.x https://tethys.pnnl.gov/publications/role-habitat-selection-behavior-population-dynamics-source-sink-systems-ecological

Lake, T., Masters, I., and Croft, N. 2017. Algorithms for Marine Mammal Modelling and an Application in Ramsey Sound. Paper presented at the 12th European Wave and Tidal Energy Conference, Cork, Ireland. https://tethys.pnnl.gov/publications/algorithms-marine-mammal-modelling-application-ramsey-sound

Langton, R., Davies, I. M., and Scott, B. E. 2011. Seabird conservation and tidal stream and wave power generation: Information needs for predicting and managing potential impacts. *Marine Policy*, 35(5), 623-630. doi:10.1016/j.marpol.2011.02.002 https://tethys.pnnl.gov/publications/seabird-conservation-tidal-stream-wave-power-generation-information-needs-predicting

Le Lièvre, C., and O'Hagan, A. M. 2015. Legal and institutional review of national consenting processes (RiCORE Project, Deliverable 2.2). Report by University College Cork for European Commission; Aberdeen, Scotland. *https://tethys.pnnl.gov/publications/legal-institutional-review-national-consenting-processes*

Leopold, M., and Scholl, M. 2019. Monitoring getijdenturbines Oosterscheldekering: Jaarrapportage 2018 (Report C010/19). Wageningen Marine Research, Wageningen UR (University & Research centre), Netherlands. *https://tethys.pnnl.gov/publications/monitoring-getijdenturbines-oosterscheldekering-oosterscheldekering-tidal-turbines*

Lieber, L., Nilse, T., Zambrano, C., and Kregting, L. 2017. Optimising multiple multibeam sonars to assess marine life interactions with an underwater kite. Paper presented at the 12th European Wave and Tidal Energy Conference, Cork, Ireland. *https://tethys.pnnl.gov/publications/optimising-multiple-multibeam-sonars-assess-marine-life-interactions-underwater-kite*

Lieber, L., Nimmo-Smith, W. A. M., Waggitt, J. J., and Kregting, L. 2018. Fine-scale hydrodynamic metrics underlying predator occupancy patterns in tidal stream environments. *Ecological Indicators*, 94, 397-408. doi:10.1016/j.ecolind.2018.06.071 *https://tethys.pnnl.gov/publications/fine-scale-hydrodynamic-metrics-underlying-predator-occupancy-patterns-tidal-stream*

Lieber, L., Nimmo-Smith, W. A. M., Waggitt, J. J., and Kregting, L. 2019. Localised anthropogenic wake generates a predictable foraging hotspot for top predators. *Communications Biology*, 2(1), 123. doi:10.1038/s42003-019-0364-z *https://tethys.pnnl.gov/publications/localised-anthropogenic-wake-generates-predictable-foraging-hotspot-top-predators*

Macaulay, J., Gordon, J., Gillespie, D., Malinka, C., and Northridge, S. 2017. Passive acoustic methods for fine-scale tracking of harbour porpoises in tidal rapids. *The Journal of the Acoustical Society of America*, 141(2), 1120-1132. doi:10.1121/1.4976077 *https://tethys.pnnl.gov/publications/passive-acoustic-methods-fine-scale-tracking-harbour-porpoises-tidal-rapids*

Macaulay, J., Malinka, C., Coram, A., Gordon, J., and Northridge, S. 2015. The density and behaviour of marine mammals in tidal rapids (Report No. MR 7.1.2). Report by Sea Mammal Research Unit for Scottish Government; St. Andrews, Scotland. *https://tethys.pnnl.gov/publications/mr712-density-behaviour-marine-mammals-tidal-rapids*

Magnuson-Stevens Fisheries Conservation and Management Act of 1976. 16 U.S.C. ch 38 § 1801 et seq. [U.S.]

Malinka, C. E., Gillespie, D. M., Macaulay, J. D. J., Joy, R., and Sparling, C. E. 2018. First in situ passive acoustic monitoring for marine mammals during operation of a tidal turbine in Ramsey Sound, Wales. *Marine Ecology Progress Series*, 590, 247-266. doi:10.3354/meps12467 *https://tethys.pnnl.gov/publications/first-situ-passive-acoustic-monitoring-marine-mammals-during-operation-tidal-turbine*

Marine Mammal Protection Act of 1972. 16 U.S.C. ch 31 § 1361 et seq. [U.S.]

Marmo, B. 2017. Operational noise from tidal turbine arrays and the accessment of collision risk with marine mammals. *The Journal of the Acoustical Society of America*, 141(5), 3921-3921. doi:10.1121/1.4988862 *https://tethys.pnnl.gov/publications/operational-noise-tidal-turbine-arrays-assessment-collision-risk-marine-mammals*

Martin, G. R., and Wanless, S. 2015. The visual fields of Common Guillemots *Uria aalge* and Atlantic Puffins *Fratercula arctica*: foraging, vigilance and collision vulnerability. *Ibis*, 157(4), 798-807. doi:10.1111/ibi.12297 *https://tethys.pnnl.gov/publications/visual-fields-common-guillemots-uria-aalge-atlantic-puffins-fratercula-arctica*

Martin, G. R., White, C. R., and Butler, P. J. 2008. Vision and the foraging technique of Great Cormorants Phalacrocorax carbo: pursuit or close-quarter foraging? *Ibis*, 150(3), 485-494. doi:10.1111/j.1474-919X.2008.00808.x *https://tethys.pnnl.gov/publications/vision-foraging-technique-great-cormorants-phalacrocorax-carbo-pursuit-or-close*

Matzner, S., Trostle, C., Staines, G., Hull, R., Avila, A., and Harker-Klimes, G. 2017. Triton: Igiugig Fish Video Analysis (PNNL-26576). Pacific Northwest National Laboratory, Richland, Washington. *https://tethys.pnnl.gov/publications/triton-igiugig-fish-video-analysis*

Nedelec, S. L., Campbell, J., Radford, A. N., Simpson, S. D., and Merchant, N. D. 2016. Particle motion: the missing link in underwater acoustic ecology. *Methods in Ecology and Evolution*, 7(7), 836-842. doi:10.1111/2041-210X.12544 https://tethys.pnnl.gov/publications/particle-motion-missing-link-underwater-acoustic-ecology

Nova Innovation Ltd. 2020. EnFAIT - Enabling Future Arrays in Tidal Year 3 Environmental Monitoring Report. Available at: https://www.enfait.eu/publications/

Onoufriou, J. 2020. Harbour seals in a tidal stream environment: movement ecology and the effects of a renewable energy installation. Doctoral Dissertation. University of St Andrews, St Andrews, Scotland.

Onoufriou, J., Brownlow, A., Moss, S., Hastie, G., and Thompson, D. 2019. Empirical determination of severe trauma in seals from collisions with tidal turbine blades. *Journal of Applied Ecology*, 56(7), 1712-1724. doi:10.1111/1365-2664.13388 https://tethys.pnnl.gov/publications/empirical-determination-severe-trauma-seals-collisions-tidal-turbine-blade

Offshore Renewables Joint Industry Programme (ORJIP). 2017. ORJIP Ocean Energy: The Forward Look; an Ocean Energy Environmental Research Strategy for the UK. Report by Aquatera Ltd for The Crown Estate, Marine Scotland Science, Welsh Assembly Government, Scottish Natural Heritage, Natural Resources Wales; Stromness, Orkney. https://tethys.pnnl.gov/publications/orjip-ocean-energy-forward-look-ocean-energy-environmental-research-strategy-uk-0

Offshore Renewables Joint Industry Programme (ORJIP). 2019. Supporting good practice in consenting for tidal steam and wave technologies in Wales. Report by Aquatera Ltd for The Crown Estate, Marine Scotland Science, Welsh Assembly Government, Scottish Natural Heritage, Natural Resources Wales; Stromness, Orkney. http://www.orjip.org.uk/documents

Paleczny, M., Hammill, E., Karpouzi, V., and Pauly, D. 2015. Population Trend of the World's Monitored Seabirds, 1950-2010. *PLoS ONE*, 10(6), e0129342. doi:10.1371/journal.pone.0129342 https://tethys.pnnl.gov/publications/population-trend-worlds-monitored-seabirds-1950-2010

Palmer, L., Gillespie, D., Macaulay, J., Onoufriou, J., Sparling, C. E., Thompson, D., and Hastie, G. D. 2019. Marine Mammals and Tidal Energy: Annual Report to Scottish Government -MRE Theme. Report by Sea Mammal Research Unit for Scottish Government; St. Andrews, Scotland. https://tethys.pnnl.gov/publications/marine-mammals-tidal-energy-annual-report-scottish-government

Polagye, B., Copping, A., Suryan, R., Kramer, S., Brown-Saracino, J., and Smith, C. 2014. Instrumentation for Monitoring around Marine Renewable Energy Converters: Workshop Final Report (PNNL-23100). Pacific Northwest National Laboratory, Richland, Washington. https://tethys.pnnl.gov/publications/instrumentation-monitoring-around-marine-renewable-energy-converters-workshop-final

Popper, A. N., and Hawkins, A. D. 2018. The importance of particle motion to fishes and invertebrates. *The Journal of the Acoustical Society of America*, 143(1), 470-488. doi:10.1121/1.5021594 https://tethys.pnnl.gov/publications/importance-particle-motion-fishes-invertebrates

Robbins, A. 2017. Seabird Ecology in High-Energy Environments: Approaches to Assessing Impacts of Marine Renewables. Doctoral Dissertation, University of Glasgow, Glasgow, Scotland. https://tethys.pnnl.gov/publications/seabird-ecology-high-energy-environments-approaches-assessing-impacts-marine

Robertson, F., Wood, J., Joslin, J., Joy, R., and Polagye, B. 2018. Marine Mammal Behavioral Response to Tidal Turbine Sound (DOE-UW-06385). Report by University of Washington for U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, Washington D.C. https://tethys.pnnl.gov/publications/marine-mammal-behavioral-response-tidal-turbine-sound

Rollings, E., Donovan, C., Eastham, C. 2016. MeyGen Tidal Energy Project Phase 1 Project Environmental Monitoring Programme (Report No. MEY-1A-70-HSE-018-I-PEMP). Report by MeyGen. https://tethys.pnnl.gov/publications/meygen-tidal-energy-project-phase-1-project-environmental-monitoring-programme

Romero-Gomez, P., and Richmond, M. C. 2014. Simulating blade-strike on fish passing through marine hydrokinetic turbines. *Renewable Energy*, 71, 401-413. doi:10.1016/j.renene.2014.05.051 https://tethys.pnnl.gov/publications/simulating-blade-strike-fish-passing-through-marine-hydrokinetic-turbines

RPS Group. 2010. A review of the potential use of sonar to observe the underwater behaviour of diving birds near tidal energy devices. Scottish Natural Heritage Archive Report No. 051. https://tethys.pnnl.gov/publications/review-potential-use-sonar-observe-underwater-behaviour-diving-birds-near-tidal-energy

Schlaepfer, M. A., Runge, M. C., and Sherman, P. W. 2002. Ecological and evolutionary traps. *Trends in Ecology & Evolution*, 17(10), 474-480. doi:10.1016/S0169-5347(02)02580-6 https://tethys.pnnl.gov/publications/ecological-evolutionary-traps

Schmitt, P., Culloch, R., Lieber, L., Molander, S., Hammar, L., and Kregting, L. 2017. A tool for simulating collision probabilities of animals with marine renewable energy devices. *PLoS ONE*, 12(11), e0188780. doi:10.1371/journal.pone.0188780 https://tethys.pnnl.gov/publications/tool-simulating-collision-probabilities-animals-marine-renewable-energy-devices

Scott, B., Langton, R., Philpott, E., and Waggitt, J. 2014. Seabirds and Marine Renewables: Are we Asking the Right Questions? In S. M. and P. A. (Eds.), *Marine Renewable Energy Technology and Environmental Interactions. Humanity and the Sea* (pp. 81-92). Dordrecht, Netherlands: Springer https://tethys.pnnl.gov/publications/seabirds-marine-renewables-are-we-asking-right-questions

Scottish Natural Heritage. 2016. Assessing collision risk between underwater turbines and marine wildlife. Scottish Natural Heritage Guidance Note. https://tethys.pnnl.gov/publications/assessing-collision-risk-between-underwater-turbines-marine-wildlife

Sharples, R. J., Moss, S. E., Patterson, T. A., and Hammond, P. S. 2012. Spatial variation in foraging behaviour of a marine top predator (*Phoca vitulina*) determined by a large-scale satellite tagging program. *PLoS ONE*, 7(5), e37216. doi:10.1371/journal.pone.0037216 https://tethys.pnnl.gov/publications/spatial-variation-foraging-behaviour-marine-top-predator-phoca-vitulina-determined

Shen, H., Zydlewski, G., Viehman, H., and Staines, G. 2015. Estimating the Probability of Fish Encountering a Marine Hydrokinetic Device. Paper presented at the 3rd Marine Energy Technology Symposium (METS), Washington, D.C. https://tethys.pnnl.gov/publications/estimating-probability-fish-encountering-marine-hydrokinetic-device-conference-paper

Shen, H., Zydlewski, G. B., Viehman, H. A., and Staines, G. 2016. Estimating the probability of fish encountering a marine hydrokinetic device. *Renewable Energy*, 97, 746-756. doi:10.1016/j.renene.2016.06.026 https://tethys.pnnl.gov/publications/estimating-probability-fish-encountering-marine-hydrokinetic-device

Sparling, C., Gillespie, D., Hastie, G., Gordon, J., Macaulay, J., Malinka, C., Wu, M., and McConnell, B. 2016. Scottish Government Demonstration Strategy: Trialling Methods for Tracking the Fine Scale Underwater Movements of Marine Mammals in Areas of Marine Renewable Energy Development. Scottish Marine and Freshwater Science Vol 7 No 14. Marine Scotland Science, Aberdeen, Scotland. https://tethys.pnnl.gov/publications/scottish-government-demonstration-strategy-trialling-methods-tracking-fine-scale

Sparling, C., Lonergan, M., and McConnell, B. 2018. Harbour seals (*Phoca vitulina*) around an operational tidal turbine in Strangford Narrows: No barrier effect but small changes in transit behaviour. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 28(1), 194-204. doi:10.1002/aqc.2790 https://tethys.pnnl.gov/publications/harbour-seals-phoca-vitulina-around-operational-tidal-turbine-strangford-narrows-no

Species at Risk Act, S.C. 2002. c. 29. [Canada]

Staines, G., Deng, Z. D., Li, X., Martinez, J., Kohn, N., and Harker-Klimes, G. 2020. Using acoustic telemetry for high-resolution sablefish movement informing potential interactions with a tidal turbine. Paper presented at OCEANS 2019 MTS/IEEE SEATTLE, Seattle, WA. doi:10.23919/OCEANS40490.2019.8962600 https://tethys.pnnl.gov/publications/using-acoustic-telemetry-high-resolution-sablefish-movement-informing-potential

Staines, G., Zydlewski, G., and Viehman, H. 2019. Changes in Relative Fish Density Around a Deployed Tidal Turbine during on-Water Activities. *Sustainability*, 11(2). doi:10.3390/su11226262 *https://tethys.pnnl.gov/publications/changes-relative-fish-density-around-deployed-tidal-turbine-during-water-activities*

Tollit, D., Joy, R., Wood, J., Redden, A., Booth, C., Boucher, T., Porskamp, P., and Oldreive, M. 2019. Baseline Presence of and Effects of Tidal Turbine Installation and Operations on Harbour Porpoise in Minas Passage, Bay of Fundy, Canada. Paper presented at Marine Renewables Canada 2018, Halifax, Nova Scotia. *https://tethys.pnnl.gov/publications/baseline-presence-effects-tidal-turbine-installation-operations-harbour-porpoise-minas*

Tomichek, C., Colby, J., and Adonizio, M. 2015. Improvements to Probabilistic Tidal Turbine-Fish Interaction Model Parameters. Paper presented at the 3rd Marine Energy Technology Symposium (METS), Washington, D.C. *https://tethys.pnnl.gov/publications/improvements-probabilistic-tidal-turbine-fish-interaction-model-parameters*

van der Bles, A. M., van der Linden, S., Freeman, A. L. J., Mitchell, J., Galvao, A. B., Zaval, L., and Spiegelhalter, D. J. 2019. Communicating uncertainty about facts, numbers and science. *Royal Society Open Science*, 6(5), 181870. doi:10.1098/rsos.181870 *https://tethys.pnnl.gov/publications/communicating-uncertainty-about-facts-numbers-science*

Vas, E., Lescroël, A., Duriez, O., Boguszewski, G., and Grémillet, D. 2015. Approaching birds with drones: first experiments and ethical guidelines. *Biology Letters*, 11(2), 20140754. doi:10.1098/rsbl.2014.0754 *https://tethys.pnnl.gov/publications/approaching-birds-drones-first-experiments-ethical-guidelines*

Viehman, H., Boucher, T., and Redden, A. 2018. Winter and summer differences in probability of fish encounter (spatial overlap) with MHK devices. *International Marine Energy Journal*, 1(1). doi:10.36688/imej.1.9-18 *https://tethys.pnnl.gov/publications/winter-summer-differences-probability-fish-encounter-spatial-overlap-mhk-devices*

Viehman, H. A., and Zydlewski, G. B. 2015. Fish Interactions with a Commercial-Scale Tidal Energy Device in the Natural Environment. *Estuaries and Coasts*, 38(1), 241-252. doi:10.1007/s12237-014-9767-8 *https://tethys.pnnl.gov/publications/fish-interactions-commercial-scale-tidal-energy-device-natural-environment*

Viehman, H. A., and Zydlewski, G. B. 2017. Multi-scale temporal patterns in fish presence in a high-velocity tidal channel. *PLoS ONE*, 12(5), e0176405. doi:*10.1371/journal.pone.0176405* *https://tethys.pnnl.gov/publications/multi-scale-temporal-patterns-fish-presence-high-velocity-tidal-channel*

Wade, H. M. 2015. Investigating the Potential Effects of Marine Renewable Energy Developments on Seabirds. Doctoral Dissertation, University of Aberdeen, Aberdeen, Scotland. *https://tethys.pnnl.gov/publications/investigating-potential-effects-marine-renewable-energy-developments-seabirds*

Wade, H. M., Masden, E. A., Jackson, A. C., and Furness, R. W. 2016. Incorporating data uncertainty when estimating potential vulnerability of Scottish seabirds to marine renewable energy developments. *Marine Policy*, 70, 108-113. doi:10.1016/j.marpol.2016.04.045 *https://tethys.pnnl.gov/publications/incorporating-data-uncertainty-when-estimating-potential-vulnerability-scottish*

Wade, P. R. 1998. Calculating Limits to the Allowable Human-Caused Mortality of Cetaceans and Pinnipeds. *Marine Mammal Science*, 14(1), 1-37. doi:10.1111/j.1748-7692.1998.tb00688.x *https://tethys.pnnl.gov/publications/calculating-limits-allowable-human-caused-mortality-cetaceans-pinnipeds*

Waggitt, J. J., Cazenave, P. W., Torres, R., Williamson, B. J., and Scott, B. E. 2016. Quantifying pursuit-diving seabirds' associations with fine-scale physical features in tidal stream environments. *Journal of Applied Ecology*, 53(6), 1653-1666. doi:10.1111/1365-2664.12646 *https://tethys.pnnl.gov/publications/quantifying-pursuit-diving-seabirds-associations-fine-scale-physical-features-tidal*

Waggitt, J. J., Robbins, A. M. C., Wade, H. M., Masden, E. A., Furness, R. W., Jackson, A. C., and Scott, B. E. 2017. Comparative studies reveal variability in the use of tidal stream environments by seabirds. *Marine Policy*, 81, 143-152. doi:10.1016/j.marpol.2017.03.023 https://tethys.pnnl.gov/publications/comparative-studies-reveal-variability-use-tidal-stream-environments-seabirds

Waggitt, J. J., and Scott, B. E. 2014. Using a spatial overlap approach to estimate the risk of collisions between deep diving seabirds and tidal stream turbines: A review of potential methods and approaches. *Marine Policy*, 44, 90-97. doi:10.1016/j.marpol.2013.07.007 https://tethys.pnnl.gov/publications/using-spatial-overlap-approach-estimate-risk-collisions-between-deep-diving-seabirds

Weimerskirch, H., Prudor, A., and Schull, Q. 2017. Flights of drones over sub-Antarctic seabirds show species- and status-specific behavioural and physiological responses. *Polar Biology*, 41(2), 259-266. doi:10.1007/s00300-017-2187-z https://tethys.pnnl.gov/publications/flights-drones-over-sub-antarctic-seabirds-show-species-status-specific-behavioural

Whitton, T. A., Jackson, S. E., Hiddink, J. G., Scoulding, B., Bowers, D., Powell, B., D'Urban Jackson, T., Gimenez, L., and Davies, A. G. 2020. Vertical migrations of fish schools determine overlap with a mobile tidal stream marine renewable energy device. *Journal of Applied Ecology*, 57(4), 729-741. doi:10.1111/1365-2664.13582 https://tethys.pnnl.gov/publications/vertical-migrations-fish-schools-determine-overlap-mobile-tidal-stream-marine

Williamson, B., Fraser, S., Blondel, P., Bell, P. S., Waggitt, J. J., and Scott, B. E. 2017. Multisensor Acoustic Tracking of Fish and Seabird Behavior Around Tidal Turbine Structures in Scotland. *IEEE Journal of Oceanic Engineering*, 42(4), 948-965. doi:10.1109/JOE.2016.2637179 https://tethys.pnnl.gov/publications/multisensor-acoustic-tracking-fish-seabird-behavior-around-tidal-turbine-structures

Williamson, B., Fraser, S., McIlvenny, J., Couto, A., Chapman, J., Wade, H., Martin, J., Wilson, J., Evans, T., Hunter, D., Fenn, S., Culloch, R., Tait, A., Chimienti, M., Edwards, E., Williamson, L., Davies, I., and Scott, B. 2018. Multi-platform studies of the MeyGen tidal energy site – using UAVs to measure animal distributions and hydrodynamic features. Paper presented at the MASTS: Annual Science Meeting, Glasgow, UK. https://tethys.pnnl.gov/publications/multi-platform-studies-meygen-tidal-energy-site-using-uavs-measure-animal

Williamson, B., Fraser, S., Williamson, L., Nikora, V., and Scott, B. 2019. Predictable changes in fish school characteristics due to a tidal turbine support structure. *Renewable Energy*, 141, 1092-1102. doi:10.1016/j.renene.2019.04.065 https://tethys.pnnl.gov/publications/predictable-changes-fish-school-characteristics-due-tidal-turbine-support-structure

Wilson, B., Batty, R., Daunt, F., and Carter, C. 2007. Collision Risks Between Marine Renewable Energy Devices and Mammals, Fish and Diving Birds. Report by Scottish Association for Marine Science for Scottish Government; Oban, Scotland. https://tethys.pnnl.gov/publications/collision-risks-between-marine-renewable-energy-devices-mammals-fish-diving-birds

Xodus Group. 2016. Brims Tidal Array Collision Risk Modelling - Atlantic Salmon. Report by Xodus Group for Brims Tidal Array Ltd; London, UK. https://tethys.pnnl.gov/publications/brims-tidal-array-collision-risk-modelling-atlantic-salmon

Yoshida, T., Zhou, J., Park, S., Muto, H., and Kitazawa, D. 2020. Use of a model turbine to investigate the high striking risk of fish with tidal and oceanic current turbine blades under slow rotational speed. *Sustainable Energy Technologies and Assessments*, 37, 100634. doi:10.1016/j.seta.2020.100634 https://tethys.pnnl.gov/publications/use-model-turbine-investigate-high-striking-risk-fish-tidal-oceanic-current-turbine

Zhang, J., Kitazawa, D., Taya, S., and Mizukami, Y. 2017. Impact assessment of marine current turbines on fish behavior using an experimental approach based on the similarity law. *Journal of Marine Science and Technology*, 22(2), 219-230. doi:10.1007/s00773-016-0405-y https://tethys.pnnl.gov/publications/impact-assessment-marine-current-turbines-fish-behavior-using-experimental-approach

NOTES

Collision Risk for Animals Around Turbines

Sparling, C.E., A.C. Seitz, E. Masden, and K. Smith. 2020. Collision Risk for Animals around Turbines. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 28-65). doi:10.2172/1632881

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

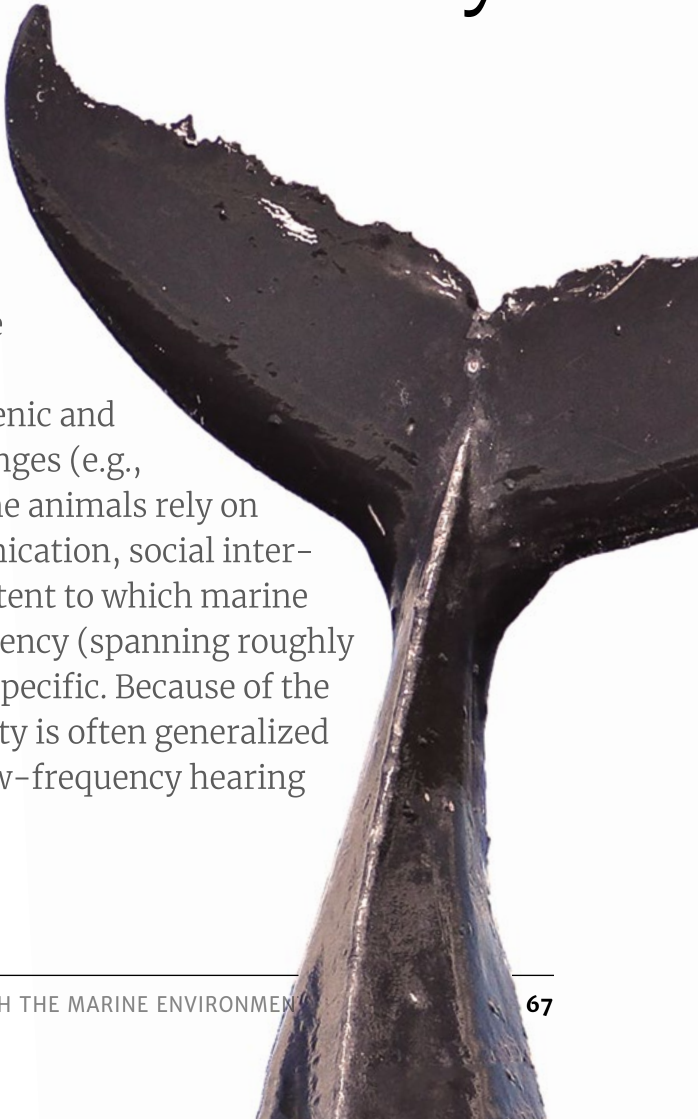
Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

4.0

Chapter authors: Brian Polagye and Christopher Bassett
Contributor: Dorian M. Overhus

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



In all ocean environments, desirable locations for wave and tidal energy development have multiple natural sources of sound (e.g., waves, wind, and sediment transport), varying levels of anthropogenic and biological noise, and measurement quality challenges (e.g., flow-noise, self-noise) (Wenz 1962). Many marine animals rely on sound for biological functions, including communication, social interaction, orientation, foraging, and evasion. The extent to which marine animals detect and produce sound varies by frequency (spanning roughly four decades from 10 Hz to 100 kHz) and is taxa-specific. Because of the relatively limited data available, hearing sensitivity is often generalized to taxonomic groups (e.g., cetaceans that have low-frequency hearing specialization) (NMFS 2018).

When considering the risks to marine animals that result from any anthropogenic activity, one must consider the amplitude, frequency, and directionality of the noise source, as well as propagation losses, prevailing ambient noise, hearing thresholds, and possible behavioral responses (Figure 4.1). Measurements that support any of these individual topics can be difficult to obtain, but it is not feasible to quantify risks without first adequately constraining these factors.

As with other marine industries, there is a general interest in understanding the noise radiated by marine renewable energy (MRE) devices and whether this noise has implications for marine animals that inhabit areas in which MRE development could occur. This chapter focuses on new knowledge related to noise produced by MRE devices that has been published since 2016. While the acoustic footprint of construction and maintenance activities (e.g., vessel traffic) can be considered in a comprehensive analysis of acoustic effects, the activities that potentially cause risk are not unique to MRE devices, are better characterized, and their effects on marine animal behaviors are better understood (e.g., Holt et al. 2009; Jensen et al. 2009; Lesage et al. 1999). In addition, construction and maintenance activities are of relatively short duration in comparison to MRE device operation. Consequently, we emphasize noise produced by MRE device operation. Further, while the importance of acoustic particle velocity to fishes is widely recognized (Popper and Hawkins 2018), we only discuss radiated noise in terms of acoustic pressure. This is because in the acoustic farfield, particle velocity can be directly related to acoustic pressure (i.e., for our area of interest, these are not independent quantities).

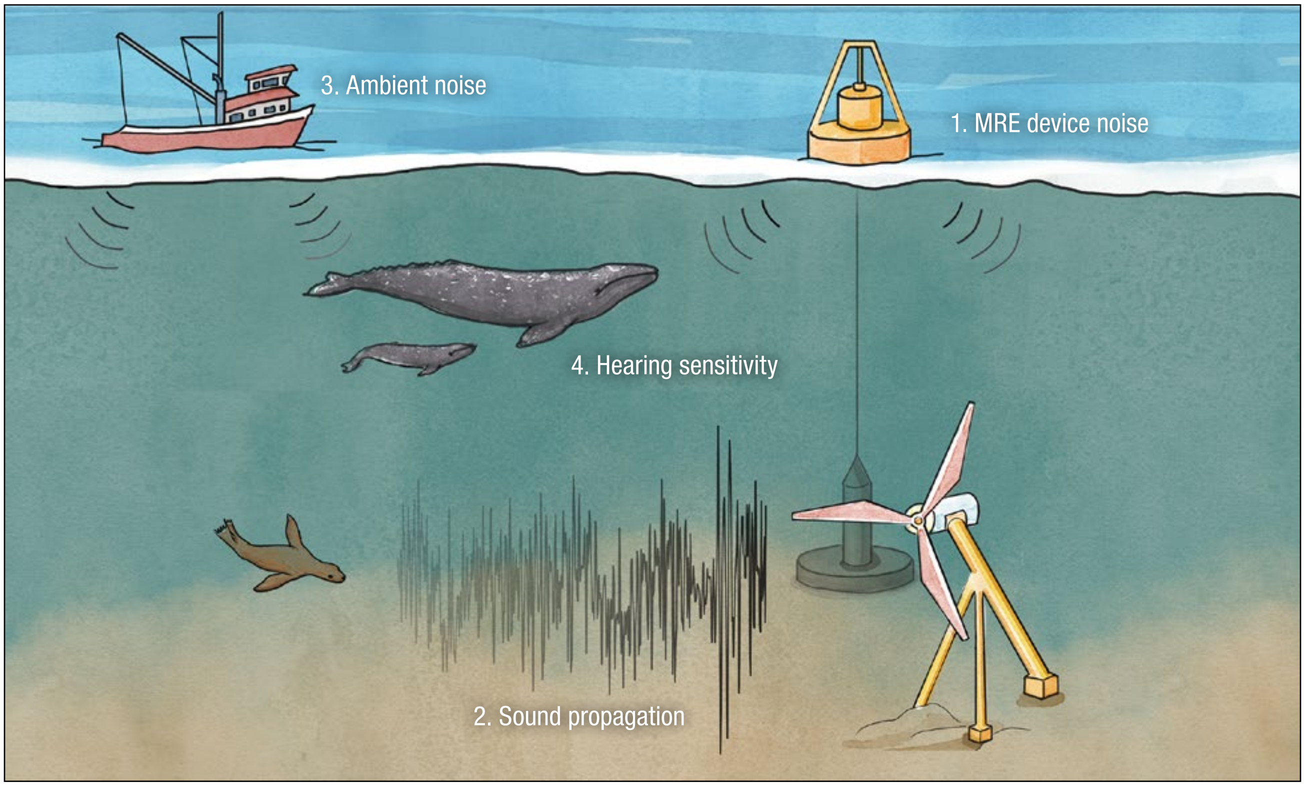


Figure 4.1. Determining the impact of radiated noise from marine energy converters is difficult and requires physical and biological inputs. (1) The sound produced by a marine renewable energy (MRE) device is affected by its design and is expected to vary with operating state. (2) As for other sources, sound radiated from MRE devices decreases in intensity as it propagates outward. The total decrease in sound intensity between a source and any location in space is affected by the frequency of the sound, water properties, bathymetry, and composition of the seabed. (3) An animal at some distance from the MRE device will receive both that sound and other ambient noise from natural, biological, and anthropogenic sources. If radiated MRE device noise is below ambient noise levels, then it cannot be detected by any marine animal and any biological response cannot be attributed to MRE device noise. (4) In addition, different marine animals have hearing sensitivities that vary both in frequency and intensity, making their abilities to detect or respond to a sound dependent on its characteristics. Consequently, even if MRE device noise exceeds ambient noise, it would still not be detectable if it is below a marine animal's hearing threshold. (Illustration by Rose Perry)

4.1.
IMPORTANCE OF THE ISSUE

Because sound is central to the way that many marine animals interact with their surroundings, and each other, the potential impacts of anthropogenic noise have received considerable attention. These impacts include auditory masking, stress, behavioral changes, and acoustic responses or injuries (Southall et al. 2007). Acoustic injuries resulting from noise exposure include temporary threshold shifts and, in extreme cases, barotrauma or death. Much of regulatory and research interest has been concerned about noise sources that are more pervasive (e.g., vessel traffic) and/or of higher amplitudes (e.g., seismic surveys), and these concerns have been extended to MRE devices (wave energy converters [WECs] and tidal, river, and ocean current turbines). Consequently, MRE device noise or its potential impacts have been the focus of multiple studies (e.g., Robinson and Lepper 2013).

Globally, the regulatory protections afforded to marine animals, particularly marine mammals (e.g., the Marine Mammal Protection Act [1972] in the United States [U.S.], the Marine Strategy Framework Directive [2008] and the Habitats Directive [1992] in the European Union [E.U.]) mandate that measures be taken to minimize any ecological impacts arising from emissions of anthropogenic underwater noise. As such, consideration of the potential impacts of MRE device noise is often required as part of the environmental assessments carried out in support of licensing processes related to MRE deployments. However, the outcomes of these requirements vary by region. In the U.S., this has included requirements for pre- and post-installation acoustic measurements around the majority of MRE deployments. In the E.U., acoustic measurements have also often been carried out but are optional, because the existing knowledge base has been sufficient to assess ecological impacts. Although significant uncertainties remain about the risks posed to marine animals by sounds generated by MRE devices, observations to date, which are summarized by Copping et al. (2016) and in the ensuing sections of this chapter, suggest that acoustic injury to marine animals from operational MRE device noise is unlikely. Further, acoustic injuries attributed to sound produced during installation are also unlikely, particularly if pile driving is not employed. While pile driving is a construction technique commonly used for offshore wind farms,[1] it is rarely used in the MRE sector and, unless device designs change considerably, this practice of rare use is unlikely to change.[2] However, radiated noise from operational MRE devices may be audible to some marine animals and could induce behavioral responses.

Because sound is one of several factors that affect animal behavior, it can be challenging to establish an *in situ* link between underwater noise and animal behavior. For example, establishing such a link has been difficult even for offshore wind (e.g., Bailey et al. 2010; Russell et al. 2016), which has been deployed at a much greater scale than MRE devices; for the acoustic effects of vessel traffic (e.g., Rolland et al. 2012), which occurs at a larger scale than any renewable energy generation in the ocean; and for seismic surveys (e.g., Przeslawski et al. 2018), which produce much higher-amplitude sound than any MRE devices. Consequently, most studies investigating the underwater noise effects of MRE deployments assess received sound levels at various distances from operating devices and compare these levels to ambient noise and/or animal hearing sensitivity as a proxy for potential behavioral responses. Because MRE device noise is radiated over a range of frequencies, knowledge of marine animal hearing sensitivity is important for establishing the context for radiated noise (Figure 4.2). As discussed in the following sections, a number of studies have found that MRE device noise only exceeds ambient noise at short distances from the source (e.g., <50 m). Under these conditions, it is unlikely that any observed *in situ* behavioral change could be attributed solely to radiated noise.

1. Pile driving involves applying impact or vibratory forces to large diameter metal piles to drive them into soft sediments. The forces applied to the pile cause sound to radiate directly from the pile, as well as secondary radiation through the sediment (Dahl et al. 2015). The pressure waves have high peak-to-peak amplitudes, which can cause acoustic injury to marine animals.

2. A number of tidal turbines use pile foundations, but they are embedded in gravity anchors or installed by drilling, which produces lower-amplitude sound than piling driving (Aquatera 2011).

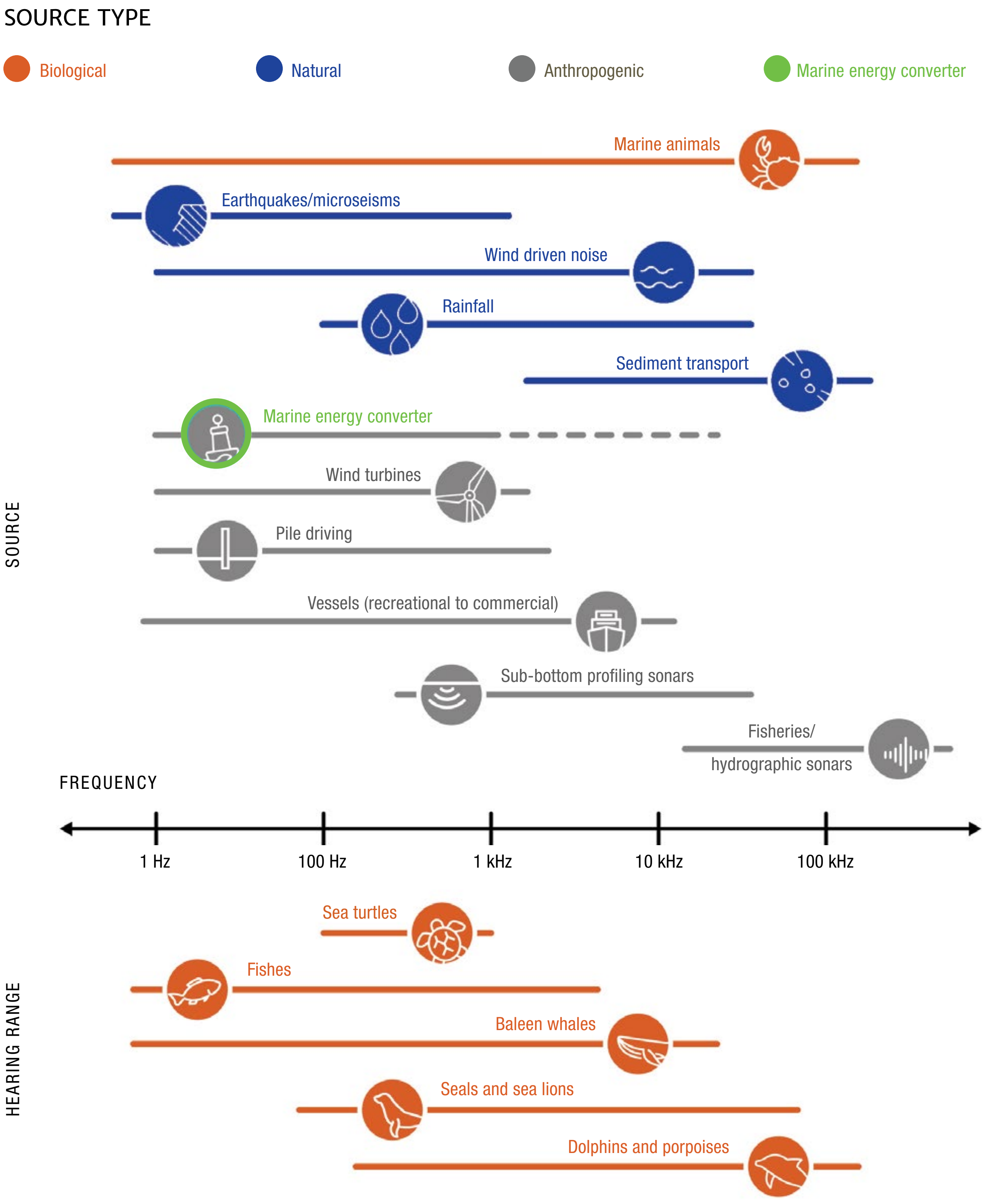


Figure 4.2. An overview of biological, natural physical, and anthropogenic noises in marine environments and the hearing ranges of marine animals. For sources, the horizontal bars denote the frequencies associated with the most energetic sound they generate. Many of these sources produce less energetic sound outside of the indicated range. In the case of marine energy converters, the dashed line at higher frequencies conveys scientific uncertainties about the upper frequency limit of their radiated noise. For hearing ranges, the horizontal bars correspond to the full range of frequencies likely audible to the groups of animals. Information used in this figure is drawn from resources including Discovery of Sound in the Sea (DOSITS) and similar figures, such as presented in Scholik-Schlomer (2015). (Illustration by Rose Perry)

4.2. SUMMARY OF KNOWLEDGE THROUGH 2016

By 2016, few studies or modeling efforts had been published that extended the knowledge of MRE device noise or its effects on marine animals. The *2016 State of the Science* report (Copping et al. 2016) addressed the effects of MRE device noise on marine wildlife described in systematic reviews, field studies, and modeling studies. The conclusions of each study varied slightly based upon its environment, marine animal presence, and proximity to coastal areas that had significant sources of other anthropogenic noise. However, all studies shared similar findings.

The first systematic review (Robinson and Lepper 2013) reported uncertainties (e.g., uncertainty in MRE device noise characteristics, marine animal response to this noise) similar to those of a contemporary report about the environmental effects of MRE (Copping et al. 2013). Even given these uncertainties, Robinson and Lepper (2013) concluded that MRE devices were unlikely to cause acoustic injury to marine animals (even during construction) and unlikely to cause behavioral effects at long distances. A second systematic review (Thomsen et al. 2015) concluded that operational MRE device noise was not of concern. Further, the authors concluded that acoustic injury as a result of underwater noise generated by MRE developments was unlikely, with the possible exception of cases where pile driving was used during construction.

In addition to these reviews, measurements of sound from individual MRE devices were conducted in several locations. Tougaard (2015), based on field measurements from the Danish coast of the North Sea, suggested that harbor seals (*Phoca vitulina*) were likely to be able to discern the noise from hydraulic pumps used during startup and shutdown for a WEC, but were unlikely to detect noise during normal operation. Similarly, Cruz et al. (2015) determined that the noise emitted by an oscillating surge WEC was minor compared to noise generated from other marine activities (e.g., sonars, ships, pile driving), but that such noise levels from WECs could elicit behavioral responses by certain cetaceans. Observations of a cross-flow tidal turbine suggested that some marine animals might detect the emitted sound, but behavioral modifications and acoustic injury were unlikely (ORPC 2014). Other studies measured radiated noise from WECs but did not draw conclusions about their potential environmental effects (Beharie and Side 2012; Lepper et al. 2012).

Modeling of radiated noise prior to 2016 was more limited. One modeling study indicated that a tidal turbine's peak noise level at 1 m would exceed hearing thresholds for some fish and marine mammals species, but that the noise levels would be unlikely to result in acoustic effects including hearing threshold shifts (Lloyd et al. 2014). Another modeling study reported that noise from a WEC could be audible to harbor seals at frequencies below 1 kHz and distances beyond 50 m (Ikpekha et al. 2014). Although this result appears to conflict with Tougaard (2015), different treatments of ambient noise account for this apparent inconsistency. Specifically, the simulations by Ikpekha et al. (2014) do not account for audibility with respect to ambient noise. When accounting for the ambient noise conditions reported by Tougaard (2015), these results are consistent and suggest the modeled WEC noise would not be audible to harbor seals, even at short ranges.

In aggregate, these studies support the assertion that underwater noise emitted by operational MRE devices is unlikely to cause acoustic injury to marine animals (Copping et al. 2013; Cruz et al. 2015; Haikonen et al. 2013; Lloyd et al. 2014; Robinson and Lepper 2013; Tougaard 2015). However, some studies suggest a possibility of behavioral responses (Cruz et al. 2015; Haikonen et al. 2013). Based on the available information at the time, Copping et al. (2016) identified the following challenges and targets for future work:

- Distinguishing an MRE device's noise from that of the ambient environment
- Establishing an international standard for measuring noise emitted by MRE devices
- Accurately modeling noise from an array of MRE devices using measurements from a single device
- Quantifying the direct and indirect effects of noise from MRE devices on animals
- Closing knowledge gaps related to hearing thresholds and threshold shifts in marine animals.

All of these challenges share features common to a variety of anthropogenic noise sources. Further, the last two items above are broad-ranging and not possible for the MRE community to address in isolation.

4.3.
KNOWLEDGE GENERATED SINCE 2016

Since 2016, limited progress has been made in some of the five challenging areas targeted above. First, robustly distinguishing MRE device sound from ambient noise remains a challenge. Second, no significant attempts have been made to model arrays with high fidelity, but few arrays exist against which models can be benchmarked. Such modeling efforts require reliable acoustic source and environmental parameters (e.g., sound velocity variations in water and sediments), which are often not available when taking measurements around MRE devices or at potential deployment sites for arrays. Third, as discussed below, quantification of direct and indirect effects on marine animals has been challenging because of the limited number of MRE device deployments, large device-to-device variations in radiated noise, and the inherent difficulty of quantifying behavioral responses.

On a more progressive note, several advances have been made in understanding marine animal hearing thresholds and shifts, including updated regulatory guidance for the U.S. about appropriate weighting functions for different marine mammal hearing groups (NMFS 2018). In addition, under the auspices of the International Electrotechnical Commission (IEC) Technical Committee 114 (TC 114), an international consensus Technical Specification has been published, which lays out a standardized approach to characterizing radiated noise around MRE devices (IEC 2019). More significantly, several MRE devices have been characterized in the field and a few studies have made progress toward establishing links between radiated noise and behavioral responses. As for studies published prior to 2016, none of them suggest that radiated noise from MRE device operation is likely to cause acoustic injury.

The following subsections summarize advances in MRE device measurements, biological consequences, and measurement standards. These discussions include brief notes about methodology and key findings, but do not fully review the work; hence, readers are encouraged to consult the primary sources. The acoustic terminology used in the papers cited in this chapter is summarized in Box 4.1.

BOX 4.1.

ACOUSTIC TERMINOLOGY

In this chapter “received levels” correspond to radiated noise from an acoustic source that would be detected by a receiver (hydrophone or marine animal) at some distance away. A particular case of received levels is the “source level,” which corresponds to received levels at a reference distance of 1 m from the sound source. Source levels are used in combination with propagation modeling to estimate received levels at greater distances. Other terms are described in the table below and in the online supplementary material (accessible at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-underwater-noise*), and additional mathematical detail is included in the International Organization for Standardization (2016) terminology list and the IEC (2019) Technical Specification. For readers unfamiliar with the subject matter and standard nomenclature, many high-quality resources provide introductory material. Two recommended sources are the *Discovery of Sound in the Sea* website (*www.dosits.org*) and United Kingdom National Physical Laboratory’s Good Practice Guide No. 133 (Robinson et al. 2014). For two reasons, it is important not to conflate received levels of radiated noise in water with those in air. First, the decibel scales in water and air use different reference values, so they are not directly comparable (Dahl et al. 2007). Second, because marine animal hearing is significantly different than human hearing, marine animal perception of underwater sound is considerably different than human perception of in-air sound.

Terminology	Description	Units
Sound pressure spectral density level	Sound pressure associated with a particular frequency presented with a bandwidth of 1 Hz.	dB re 1 $\mu Pa^2/Hz$
Decidecade sound pressure level (decidecade SPL)	The sound pressure level (SPL) in a decidecade (one-third octave) band.	dB re 1 μPa
Broadband sound pressure level (broadband SPL)	SPL across a range of frequencies. The associated frequencies must be specified. If calculated over all measured frequencies, this is equal to the root mean square (RMS) SPL.	dB re 1 μPa
Source level	A measure of sound radiated by a source defined as the sound pressure level at a reference distance of 1 m. The associated frequencies must be specified.	dB re 1 μPa at 1 m

4.3.1. TIDAL, OCEAN, AND RIVER CURRENT TURBINES

Lossent et al. (2018) measured radiated noise from a tidal turbine and estimated its audibility for marine mammals. The authors used a drifting hydrophone (see Chapter 10, Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines) to measure radiated noise from an OpenHydro tidal turbine (axial-flow, high solidity) deployed in the English Channel (Brittany, France) at distances between 100 and 2400 m. Turbine source levels were estimated from regressions of spatially binned averages of decidecade sound pressure level (SPL). These source levels were then used with ray tracing and parabolic equation modeling to estimate the distance at which received levels would exceed relatively low levels of ambient noise typical of the open ocean, and would exceed audibility thresholds for different species. The maximum source level estimated by Lossent et al. (2018) was 152 dB re 1 µPa at 1 m in the 128 Hz decidecade band, and all other decidecade source levels fell below 137 dB re 1 µPa at 1 m. The authors noted broadband components of radiated noise at frequencies from approximately 40 to 8000 Hz, with amplitude modulations related to the turbine rotation rate. Multiple tonal components of noise were also noted between 20 and 1300 Hz. Measurements suggested the source is omnidirectional. On the basis of acoustic modeling, the authors estimated that radiated noise would exceed ambient noise at distances up to 1.5 km. When combined with hearing thresholds, maximum estimated marine mammal detection ranges were approximately 1 km.

The results presented by Lossent et al. (2018) highlight some of the challenges of separating ambient noise from radiated MRE device noise, particularly as a function of distance from the assumed source. Clear MRE device signatures attributed to the turbine were present at relatively close ranges but had low signal-to-noise ratios relative to ambient noise farther from the device. At some frequencies, regressions for propagation losses appeared to have coefficients that were inconsistent with expected range-dependent spreading and attenuation losses (e.g., cylindrical or spherical spreading), suggesting that some of this noise should not be attributed to the turbine. Consequently, for some frequencies, source levels may be biased high because of a conflation of ambient noise and radiated noise from the turbine. Direct comparisons to site-specific ambient noise, rather than literature values for relatively quiet, open ocean conditions, would better support conclusions regarding audibility ranges. While a number of statements were made regarding behavioral changes and avoidance, no direct measurements of animal behavior were made in the study.

Schmitt et al. (2018) measured radiated noise from a tidal turbine and correlated noise with operating conditions. Measurements of a ¼-scale Minesto AB subsea kite equipped with an axial-flow turbine were presented in the study. In this work, a drifting hydrophone was used to measure sound from the MRE device operating in Strangford Narrows (Northern Ireland, United Kingdom [UK]) during a period when currents were constant at approximately 1 m/s. Measured decidecade SPLs were reported for three operating conditions involving different turbine shaft speeds, kite velocities, and tether twists. Decidecade SPLs for all cases were based on average levels from 15 seconds before and 15 seconds after the hydrophone passed directly above the center of the kite's flight path (i.e., within 15 m of the kite). Given the uncertainty of the specific location of the kite, results are presented as the mean received levels over the sampling period, and multiple samples were averaged for each operational condition. Maximum decidecade SPLs reported by Schmitt et al. (2018) were less than 110 dB re 1 µPa at a frequency of approximately 300 Hz. Over much of the reported bandwidth (20 Hz to 100 kHz), observed decidecade SPLs were less than 95 dB re 1 µPa. For some operational conditions, clear modulation of the signal was observed and related to the kite's flight-path period. Results from the three measured operational conditions demonstrated that the largest differences in radiated noise were attributable to changes in the turbine speed (i.e., higher rotor speeds were correlated with increased noise levels). In comparison, changes in radiated noise due to tether twists or through-water kite speed were limited. Schmitt et al. (2018) made no attempt to address the potential biological consequences or audibility ranges of the device. Although source levels were not estimated, the distances from the hydrophone to the source in this study were on the order of tens of meters and may be considered a coarse proxy for source levels. Ambient noise levels from the site were used to contextualize radiated noise. This suggests that radiated noise from the kite exceeds ambient noise across most of the reported bandwidth at locations close to the source. However, ambient noise data were collected in 2014, while turbine measurements were obtained in 2016. Because of this temporal gap, there is some inherent uncertainty in the portions of the acoustic spectrum that were ascribed to radiated noise from the MRE device.

Risch et al. (2020) measured radiated noise from an Atlantis AR1500 tidal turbine (18 m diameter; 1.5 MW rated capacity) in Pentland Firth, Scotland (UK). The radiated noise measurements were obtained using drifting hydrophones at ranges up to approximately 2300 m, during which mean tidal currents ranged from 2.2 to 3.1 m/s. Measurements revealed that, when operating, the noise attributable to the turbine occurred primarily in the 50 to 1000 Hz range, although lower intensity device noise was observed above ambient conditions at higher and lower frequencies. Decidecade sound pressure levels showed increases of at least 30 to 40 dB relative to ambient noise for close range measurements (range less than 20 m). Turbine noise intensity increased with rotation rate, with 10 to 20 dB differences observed between the lowest and fastest rotation rates, but the frequency content was similar for all rotation rates. Broadband noise was observed at relatively short ranges (approximately 300 m or less), while, at greater ranges, observed noise was dominated by a series of oscillating tones from 100 to 2000 Hz. A high-frequency (20 kHz) narrowband tone was also identified, which was present when the turbine was in an operating mode, but did not vary with rotation rate. This noise was attributed by the authors to the generator, although no further details are provided to support this conclusion and it might be attributable to other, non-rotating system components (e.g., switching converters in power electronics). Noise increases of 5 dB or less were attributed to the turbine at ranges up to 2300 m during periods with relatively calm conditions. However, measurements suggest that beyond ranges of approximately 100 m, turbine noise is only observed above ambient noise for frequencies below 2 kHz. The biological implications for the observed variations in sound with rotational rate are briefly noted, but there is no formal analysis of detection ranges by marine animals.

Pine et al. (2019) estimated source spectral density levels from two turbines and evaluated the reduction in "listening space", a proxy for behavioral change, for harbor seals and harbor porpoises (*Phocoena phocoena*) in varying conditions of ambient noise. This study built on Schmitt et al.'s (2018) by combining source spectra for two MRE devices with seasonal ambient noise measurements and species audiograms to investigate the "listening space reduction" for harbor seals and harbor porpoises. Listening space is defined by the volume over which an animal can detect biologically relevant sound. Therefore, listening space reductions contextualize the regions of potential biological responses for the two marine mammal species. The two MRE devices considered were a tidal kite (Schmitt et al. 2018) and an axial-flow turbine (Schottel, characterized by Schmitt et al. 2015). In the case of the tidal kite, radiated noise measurements were converted to source levels using spherical spreading with the distances between the devices and the hydrophone at the closest point of approach (approximately 6 m). The ranges of ambient noise for summer and winter conditions were constrained by the 5th and 95th percentiles. Parabolic equation and ray tracing models were used to model propagation losses between the hypothetical turbines and receiver locations.

The results presented by Pine et al. (2019) demonstrate the importance of well-constrained source spectra, ambient noise levels, and species audiograms. Different patterns were present in the listening space reductions across species, seasons, and turbine types. These patterns were attributed to the relative distributions of noise as a function of frequency in the source spectra and the audiograms of the species. As a proxy for behavioral effects, listening space is conservative in that relatively large reductions still occur when received levels from an MRE device are close to ambient levels. For example, when MRE device noise exceeds ambient levels by 1, 3, and 6 dB, the respective decreases in listening space are 26%, 60%, and 84% if a representative propagation loss coefficient of 15 is applied. In the context of the measured variability in ambient noise (30 dB within individual frequency bands), these are small changes and contribute to large, implicit uncertainties in estimates for listening space reduction. Further, the conservative nature of this approach is apparent when comparing it to Hastie et al.'s (2018) approach (discussed further later in this section), in which received levels that could be correlated with observed behavioral responses exceed the source level used by Pine et al.'s (2019) analysis. In other words, while the methodology underpinning the listening space reduction accounts for key variables, because a reduction in listening space will not necessarily lead to a behavioral response, this is likely an extremely conservative proxy for behavioral change. Nonetheless, this metric may be helpful for constraining the focus areas for studies attempting to observe behavioral changes as a consequence of exposure to radiated noise from MRE devices.

Bevelhimer et al. (2016) compared measured ambient noise in a river to characteristics of turbine noise to estimate detection ranges for five fish species. Relatively few studies have considered ambient noise in rivers or the potential acoustic effects of MRE devices in riverine environments. Bevelhimer et al. (2016) compared measurements of ambient noise sources in the Mississippi River to measurements of the Ocean Renewable Power Company (ORPC) TidGen tidal turbine in Cobscook Bay, Maine. Other sources of anthropogenic ambient noise, namely different types of vessels, were noted to be of higher amplitude than the TidGen turbine. Finally, Bevelhimer et al. (2016) compared the TidGen spectrum to audiograms for five fish species, noting that the turbine noise should fall below all of their reported hearing thresholds at a distance of 21 m from the source.

4.3.2. WAVE ENERGY CONVERTERS

A limited number of new studies of noise generated by WECs have been published since 2016, but they include a study of one WEC, the Fred Olsen Lifesaver, a point absorber, which was characterized at two locations using different methodologies.

Walsh et al. (2017) measured radiated noise from the Lifesaver, during a 2-year test at the FabTest test site in Falmouth Bay, UK. The objective of the study was to evaluate the feasibility of using hydrophones at a relatively large stand-off distance from a WEC (200 m) to monitor its physical condition. No attempt was made to study the potential effects of radiated noise on marine animal behavior. Measurements were conducted using moored hydrophones at a distance of 10 m above the seabed in water depths of 25 to 45 m. Results are presented for frequencies from 10 Hz to 32 kHz. Consistent with prior studies (e.g., Robinson and Lepper 2013), because of vessel traffic, received levels were higher during installation than during operation. On average, at a 200 m distance, the WEC was undetectable in a statistical sense (i.e., deviations of, at most, 1 dB between times of WEC operation and non-operation). However, the results of a focused examination of WEC-attributed sound during periods of low ambient noise suggest a primary contribution from tonal sound at 30 Hz, 60 Hz, 80 Hz, and 100 Hz with received spectral density levels exceeding 100 dB re 1 μPa^2/Hz when the power take-off units were active, as well as periodic, intermittent sound at frequencies from 100 to 1000 Hz that were hypothesized to be a consequence of the power take-offs reaching their end stops. Because of the difficulty of definitively attributing sound to the WEC, the authors recommended that, in the future, multiple hydrophone recording systems be simultaneously deployed to localize WEC sound. A minor weakness of the Walsh et al. (2017) study was that underwater noise measurements were treated in a relatively qualitative manner, and it is not clear whether the presented information is received levels at the 200 m stand-off distance from the WEC or nominal acoustic source levels calculated using a simple propagation model.

Polagye et al. (2017) measured radiated noise from the same point-absorber WEC at a different location. After testing in Falmouth Bay, the Lifesaver was redeployed at the U.S. Navy's Wave Energy Test Site (WETS) in Kaneohe, Hawaii, U.S. Two deployments were conducted between 2016 and 2019, one at the 60 m berth and one at the 30 m berth. Polagye et al. (2017) described outcomes from fixed platform measurements on the seabed at a distance of approximately 100 m and drifting measurements, primarily at closer range, for the deployment at the 60 m berth. Drifting measurements resolved frequencies from 10 Hz to 200 kHz and were used to attribute radiated noise to the WEC and its moorings based on co-temporal comparisons between measurements in close proximity to the WEC and a "reference" site at a distance of 1200 m from the WEC. In addition to sound consistent with the power take-off reported by Walsh et al. (2017) (i.e., periodic tonal elevation from 30 Hz to 1 kHz), multiple intermittent sounds associated with the WEC or its mooring were detected at frequencies up to 200 kHz, and the highest frequencies were associated with impact noise from a failing mooring chain. At a distance of 35 m from the

WEC, the sound attributed to the power take-off had a pressure spectral density level that was approximately flat from 50 Hz to 300 Hz at ~85 dB re 1 μPa²/Hz, and declined to 70 dB re 1 μPa²/Hz at 1 kHz. All WEC and mooring sounds were detected in the fixed observations, albeit at lower amplitudes because of the greater distance between the source and the receiver. Variations in broadband (0 to 40 kHz) received SPLs as a function of wave height and period showed some dependence on sea state, but frequency-domain analysis demonstrated that this was primarily a consequence of flow-noise from wave orbital velocities close to the seabed in the 0 to 10 Hz band, which exceeded radiated noise from the WEC (Polagye 2017). Broadband received SPLs at a range of 100 m were centered around 115 dB re 1μPa, and ranged from 105 to 125 dB re 1 μPa.

Similar methods were applied to the subsequent deployment of the Lifesaver at the 30 m berth (Polagye, pers. comm.). Drifting measurements again identified elevated sound attributed to the power take-off, but at a stand-off distance of 25 m with the power take-off disabled, received spectral levels of approximately 75 dB re 1 μPa²/Hz were still present around 60 Hz, and declined to approximately 65 dB re 1 μPa²/Hz at 1000 Hz. No WEC-attributable sound was identifiable above 1000 Hz.

The measurements at WETS are also indicative of the challenge of attributing sound to a particular component of the WEC using short-duration, single-hydrophone measurements. Specifically, Polagye et al. (2017) attributed a tonal "warble" with a fundamental frequency around 790 Hz to a failing bearing on one of the power take-off units. This diagnosis was consistent with the periodicity of the sound in this frequency band having a moderate correlation with wave period and mechanical wear observed on the power take-off during an engineering inspection. Between recovery from the 60 m berth and redeployment at the 30 m berth, the Lifesaver underwent minor maintenance and, therefore the absence of this sound in measurements at the 30 m berth was considered unremarkable. However, subsequent analysis of fixed observations (Polagye, pers. comm.) during recovery of the WEC from the 60 m berth found that the warble persisted even with the power take-offs being inactive, that this sound vanished when the WEC was removed from its moorings, and that the sound then returned after the moorings were re-tensioned without the WEC present. Consequently, this sound was actually attributable to the permanent moorings at the site, not the WEC. This forensic analysis also highlights the benefits of conducting relatively long-term acoustic measurements around a WEC, including during pre-installation, installation, operation, removal, and post-removal. Another tangential benefit of such long-term monitoring, as discussed by Walsh et al. (2017), is the potential for monitoring the mechanical health of MRE devices.

4.3.3. BIOLOGICAL CONSEQUENCES OF RADIATED NOISE

As previously discussed, all of the research published prior to 2016, as well as the studies of MRE device noise reviewed in this chapter, used sound detection as a proxy for biological consequence. Since 2016, several attempts, with varying success, have been made to directly observe the behavioral responses of various species to MRE device noise. These efforts have relied on "playbacks" of MRE device noise, which isolates underwater noise effects from other, potentially confounding, effects of device presence (e.g., accumulations of prey around an artificial reef).

Schram et al. (2017) used a mesocosm experiment to investigate the behavioral responses of four fish species to simulated tidal turbine noise. The authors exposed four species of freshwater fish to turbine sound in a mesocosm setting to evaluate changes in fish location as a consequence of sound amplitude and duration of exposure. One species (redhorse suckers [*Moxostoma carinatum*]) showed some response by increasing their distance from the sound source, while the three other species displayed either a mixed or limited response. The turbine sound was based on recordings of the ORPC TidGen tidal turbine (Bevelhimer et al. 2016). The authors noted several challenges associated with interpreting and generalizing their results. First, because of the limitations of the underwater speaker system, the frequency content of the playback departed from the original measurement. Specifically, the measured sound from the turbine had its highest amplitude at frequencies less than 0.3 kHz, but the playback had a relatively flat spectrum that peaked around 10 kHz. Consequently, fish behavioral changes were interpreted relative to the broadband SPLs that were not entirely consistent with the actual structure of turbine sound. Second, the acoustic localization system used to track the fish was primarily effective in the along-pen direction, while received levels varied in the across-pen direction, particularly close to the sound source. Overall, the authors concluded that a significant behavioral response would not likely be anticipated for either short-term or long-term exposures to turbine sound.

Hastie et al. (2018) used shore observers and tagging to demonstrate the behavioral response (localized avoidance) of harbor seals to simulated tidal turbine noise in a tidal channel. To assess behavioral changes and avoidance exhibited by harbor seals exposed to tidal turbine noise, the authors tagged and remotely observed harbor seals during exposures to simulated tidal turbine noise in Kyle Rhea, an energetic tidal channel on the west coast of Scotland, UK. They evaluated the behavioral response by comparing patterns in spatially resolved abundance between periods with simulated turbine sound (playback) and periods with only ambient noise (control). The playbacks were based on interpreted measurements from the SeaGen turbine (Strangford Lough, Northern Ireland, UK) and had a broadband (115 to 3750 Hz) source level of 175 dB re 1 µPa at 1 m. Hastie et al. (2018) reported no changes in total numbers of seals in the water in the study area (defined as the distance at which harbor seals could be observed in the 450 m wide channel) between the control and playback periods. However, usage decreased between 11 to 41 percent at distances of less than 500 m from the acoustic source. Given that no differences in overall abundance were noted, these results suggested localized avoidance without a broader-scale impact. The authors extensively discussed a number of issues related to their results. First, in comparison to other measured tidal turbines, the playback source levels were of relatively high amplitude. Second, the playback sound consisted of a series of seven frequency-modulated narrowband tones from 115 to 3750 Hz. These playbacks would be a novel stimulus for the seals and may have contributed to the observed avoidance behavior. Whether or not similar behavior would be observed with any combination of lower source levels, differences in frequency content, or greater levels of habituation are unknown. The tracking tags on the seals also only reported their positions, not the received sound level, so a quantitative dose-response analysis was not possible.

Robertson et al. (2018) used shore observers to quantify the behavioral response of harbor seals and harbor porpoises to simulated tidal turbine noise in a tidal channel (Admiralty Inlet, Washington, U.S., using a method similar to that of Hastie et al. (2018). Here, an amplified recording from the ORPC RivGen turbine (unpublished data) was used as a sound source and, as for the Hastie et al. (2018) effort, the study was partitioned into control and playback periods. Broadband (30 Hz to 10 kHz) source levels were 158 dB re 1 µPa at 1 m, which was lower than the source level used by Hastie et al. (2018) (175 dB re 1 µPa at 1 m), but substantially higher than the actual RivGen turbine. Unlike the Hastie et al. (2018) effort, harbor seals showed no measurable response to the simulated turbine sound. However, because of the lower source level, harbor seals would have needed to be within 10 m of the source to experience received levels similar to those correlated with localized avoidance by Hastie et al. (2018). The difference in geographic location and turbine sound signature may also have contributed to the apparent divergence in outcomes. Over the three seasonal playback trials (each two weeks in duration, divided between control and playback periods), harbor porpoises were found to initially avoid the playback source by 300 m, but this distance declined to 100 m during the second trial, and no avoidance was apparent during the third trial. This could be an indication of habituation or increased tolerance. However, because the vessel used to deploy the sound source was only present during the playback periods (for reasons of cost), it is uncertain whether the avoidance and potential habituation were in response to simulated turbine sound, survey vessel presence, or seasonal variations in harbor porpoise behavior.

4.3.4. PROGRESS ON MODELING

The availability of numerical modeling tools should be exploited, when helpful, to support the assessment of the underwater noise impacts of MRE devices. Farcas et al. (2016) summarized considerations related to their application and parameterization for environmental impact assessment. A recent modeling result of relevance for planning the installation and subsequent monitoring of MRE devices was published by Lin et al. (2019) and focused on the use of parabolic equation modeling for propagation losses at an offshore wind site. A key finding was that seasonal differences in the water properties (well-mixed vs. stratified) resulted in considerable differences in propagation losses because of a downward refracting sound speed profile. Such findings could be used to inform construction plans to mitigate potential impacts by exploiting time periods when depth-averaged propagation losses are expected to be at a maximum. Conversely, these findings could inform monitoring plans intended to observe biological responses when depth-integrated propagation losses are expected to be at a minimum, and therefore, the signal-to-noise ratio at a given distance could be maximized.

Since 2016, relatively little progress has been made with regard to the modeling of sound produced by MRE devices. Halfa et al. (2018) focused on the development of a temporal-domain, three-dimensional finite-element sound propagation model. This model, Paracousti, has been compared to multiple analytical and modeling approaches with favorable results and facilitates the integration of multiple acoustic sources. No other efforts have developed new models for MRE device noise or focused on the development of advanced tools for propagation modeling. It is, however, noteworthy that many of the studies highlighted here used models common in other underwater acoustics applications (e.g., parabolic equation modeling, ray tracing).

4.3.5. INTERNATIONAL STANDARDS

The IEC TC 114, which develops international consensus standards for marine energy conversion technologies, has published its first Technical Specification for characterizing radiated noise from MRE devices: IEC 62600-40 (IEC 2019). The specification, developed over a 4-year period with input from multiple National Committees (Canada, France, Germany, Ireland, Netherlands, Spain, UK, U.S.), describes methods for characterizing received levels in the vicinity of WECs, current turbines (tidal and river), and ocean thermal energy conversion (OTEC) plants. The specification incorporates many of the unique considerations for observations in MRE environments summarized by Lepper and Robinson (2016).

The specification establishes two levels of characterizations. Both use the same methods for measurement, analysis, and reporting, such that the types of characterization are differentiated only by the number of required measurements and the conclusions that can be supported. The "Level A" characterization is more extensive and evaluates temporal trends (e.g., correlation between received levels and wave height and period for WECs) and spatial variability (i.e., degree of directional variations in received levels). The "Level B" characterization provides a snapshot of received levels at a single temporal condition and spatial location. These two levels of characterization recognize that radiated noise from some MRE devices may not warrant a comprehensive characterization, but that more limited characterizations should be conducted in a consistent manner for comparability across projects. Effectively, a Level A characterization is a series of Level B characterizations conducted at several temporal conditions and spatial positions.

The Technical Specification includes end-to-end requirements for acoustic measurements, including the following:

- The capabilities of the acoustic measurement system and calibration requirements
- Contextual measurements (e.g., wave height and period around WECs, current speed around tidal turbines)
- Temporal conditions and spatial locations for measurements to meet Level A or Level B characterization for each category of MRE device (i.e., WEC, current turbine, or OTEC plant)
- Data review to exclude measurements with obvious contamination from other acoustic sources (e.g., vessel traffic)
- Analysis methods to reduce acoustic measurements to sound pressure density levels, decidecade SPLs, and broadband SPLs
- Requirements for reporting temporal and spatial variations in received levels.

Crucially, IEC 62600-40 implicitly attributes all sound in measurement sequences that satisfy data acceptance criteria to the MRE device. This approach was taken because no international consensus yet exists for objectively attributing radiated noise to an MRE device. As discussed later in this chapter, this is a critical research need and, as methods are matured, they should be incorporated into subsequent editions of IEC 62600-40.

By default, measurements are required to resolve frequencies from 10 Hz to 100 kHz, though there are allowances for expanding or contracting this frequency range as warranted by specific conditions and regulatory requirements. At the lower end of this range, flow-noise, which is non-propagating sound caused by water motion relative to a hydrophone, is a concern because it has the potential to artificially inflate decidecade and broadband SPLs. Flow-noise can arise from turbulence advected over the hydrophone element and vortices shed by the hydrophone element. Consequently, the specification includes recommendations to identify the probability of flow-noise in measurements and potential mechanisms to minimize flow-noise. While flow-noise is a well-documented issue for fixed platforms in tidal energy environments (e.g., Bassett et al. 2014), experience suggests that this can also be a concern for fixed platforms in wave energy environments when wave orbital velocities extend to hydrophone depths. For example, at WETS, flow-noise periodically masked propagating ambient noise at frequencies up to 50 Hz for a fixed hydrophone at the 30 m depth (Polagye et al. 2017). In general, accurate measurement of propagating sound at low frequencies (<50 Hz) is complicated by flow-noise masking and typical roll-offs in hydrophone sensitivity when higher frequencies (>10 kHz) are also of interest.

4.4. RESEARCH AND MONITORING NEEDS TO RESOLVE THE ISSUE

Of all the outstanding research and monitoring needs, the most critical undeveloped capability is differentiating between MRE device noise and ambient noise. Such differentiation is needed to establish the true acoustic characteristics of MRE devices and estimate received levels as a function of depth and range. Although source localization is widely used in ocean environments to localize radiated noise, it has not yet been used to discriminate between ambient noise and radiated MRE device noise (i.e., frequency-dependent localization of noise sources compared to known MRE device position). In the absence of localization capabilities, there is a risk that ambient noise or, worse, flow-noise, can be conflated with MRE device noise. In such cases, estimated source levels for sound propagation studies would be biased high and potentially overstate the acoustic footprint of operating MRE devices. This difficulty is compounded if ambient noise at some frequencies is driven by the same physical processes as MRE power generation. For example, as the current speed rises, the power output and rotation rate for most turbines increase, but depending on the site, the radiated noise from sediment transport (e.g., Bassett et al. 2013) also increases and can be mistaken for MRE device noise. Despite these challenges, attempting to distinguish radiated noise from ambient contributions, even when uncertainties remain, is an important step in the process of understanding the potential consequences of radiated noise from MRE devices.

The second research need is to connect radiated noise to behavioral changes in marine animals. If the radiated noise of an MRE device only marginally exceeds ambient noise at close range (e.g., <50 m), it is not practically possible to solely ascribe a behavioral response to radiated noise. For higher received levels, the link between radiated noise and animal behavior is a complicated one to establish and is best addressed by bioacoustic specialists. However, the broader acoustic research community can support such efforts in two important ways. The first is to present acoustic data in a frequency-resolved manner that allows species-specific audibility to be taken into account. While broadband SPLs can be helpful for comparisons across MRE devices, they are insufficient for biological interpretation. Second, as discussed above, when possible, differentiating between MRE device noise and ambient noise will facilitate biological interpretation. Overall, given the potential uncertainty related to acoustic sources, ambient noise, and species-specific audiograms, behavioral response studies are only likely to provide useful information if MRE device noise and ambient noise are well characterized.

4.5. GUIDANCE ON MEASURING UNDERWATER NOISE FROM MRE DEVICES

IEC 62600-40 provides guidance for the measurement of underwater noise around MRE devices, including instrument calibration, methods for acoustic and contextual measurements, methods for data processing, and uniform presentation of results. However, in areas where international consensus does not yet exist, several considerations are not prescriptively addressed. First, as previously discussed, no method is given to differentiate between MRE device noise and ambient noise. Second, while flow-noise is described as being problematic at low frequencies (frequencies audible only to fish and low-frequency cetaceans), no prescriptive guidance is given about its identification or mitigation. We note that it has been established that free-drifting measurements reduce flow-noise, but do not guarantee that it will be negligible, because any velocity differential between the hydrophone and surrounding water at the scale of the hydrophone element will generate flow-noise. Progress in these areas will be tracked by IEC TC 114 through an *ad hoc* group and, as international consensus emerges, improved methods will be incorporated into the next edition (nominally expected in 2024) of the Technical Specification by a Maintenance Team. Consequently, experience using the first edition of the Technical Specification should be communicated to the relevant IEC National Committees or the Convener of the *ad hoc* group. Contributors of feedback are encouraged to contact their IEC TC 114 National Committee Lead if they are from a participating country. Individuals from other countries can contact the TC 114 Chair to discuss mechanisms for involvement.

In interpreting measurements of underwater noise around MRE devices, it is important to remember that variations in received levels can be a consequence of factors other than variations in the acoustic source (e.g., seasonal changes in propagation). As explanatory factors for ambient noise are identified, they can be controlled for in experimental design and reduce the risk of ambient noise being conflated with MRE device noise. IEC 62600-40 takes steps in this direction by recommending that measurements be undertaken only in a restricted set of metocean conditions for each category of MRE device.

4.6. RECOMMENDATIONS

We recommend two categories of activity going forward. Successful execution of these activities will not answer all the remaining research questions identified by Copping et al. (2016; e.g., effects of arrays), but will establish a strong foundation for future study.

- Expand the evidence base of rigorous, comparable acoustic measurements across a broader range of MRE devices and settings. These should be included in a publicly-accessible library of MRE device noise signatures. Direct comparisons are enabled by the measurement guidance discussed in Section 4.5, particularly Level A characterization under IEC 62600-40. Use of standardized methods will allow outcomes from individual studies to be generalized in a way that contributes to global risk identification. An improved understanding of the characteristics of the radiated noise from MRE devices and the factors that control them will facilitate effective study designs to understand behavioral responses to this noise. To achieve this, it will be necessary to establish robust methods for differentiating MRE device noise from ambient noise and, at the lowest frequencies, minimize contamination from flow-noise. Finally, challenges and recommended refinements to the methodology should be communicated to the IEC *ad hoc* group monitoring the implementation of IEC 62600-40.
- Establish a framework for studying the behavioral consequences of radiated noise from MRE devices. To fully understand the risks, it will be necessary to move beyond using audibility as a proxy for behavioral response. However, as discussed here, establishing the link between radiated noise and behavioral responses in mesocosm or field studies is challenging for a variety of reasons, including the confounding variables that affect animal behavior and the generally low amplitude of observed MRE device noise relative to ambient noise. Such links will be particularly difficult to establish for threatened or endangered species because of the low sample sizes in the field and uncertainty in their audiograms. Research community agreement on a framework for evaluating behavioral consequences could begin to answer this important question.

4.7. REFERENCES

Aquatera. 2011. Environmental Monitoring Report - 2011 Installation of monopile at Voith Hydro test berth, Fall of Warness, Orkney. Report by Aquatera Ltd. for Voith Hydro, Orkney, Scotland. *https://tethys.pnnl.gov/publications/environmental-monitoring-report-2011-installation-monopile-voith-hydro-test-berth-fall*

Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G., and Thompson, P. M. 2010. Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. *Marine Pollution Bulletin*, 60(6), 888-897. doi:10.1016/j.marpolbul.2010.01.003 *https://tethys.pnnl.gov/publications/assessing-underwater-noise-levels-during-pile-driving-offshore-windfarm-its-potential*

Bassett, C., Thomson, J., Dahl, P. H., and Polagye, B. 2014. Flow-noise and turbulence in two tidal channels. *Journal of the Acoustical Society of America*, 135(4), 1764-1774. doi:10.1121/1.4867360 *https://tethys.pnnl.gov/publications/flow-noise-turbulence-two-tidal-channels*

Bassett, C., Thomson, J., and Polagye, B. 2013. Sediment-generated noise and bed stress in a tidal channel. *Journal of Geophysical Research*, 118(4), 2249-2265. doi:*10.1002/jgrc.20169* *https://tethys.pnnl.gov/publications/sediment-generated-noise-bed-stress-tidal-channel*

Beharie, R., Side, J. 2012. Acoustic Environmental Monitoring - Wello Penguin Cooling System Noise Study (2012/01/AQ). Report by International Centre for Island Technology for Aquatera Ltd., Orkney, Scotland. *https://tethys.pnnl.gov/publications/acoustic-environmental-monitoring-wello-penguin-cooling-system-noise-study*

Bevelhimer, M. S., Deng, Z. D., and Scherelis, C. 2016. Characterizing large river sounds: Providing context for understanding the environmental effects of noise produced by hydrokinetic turbines. *Journal of the Acoustical Society of America*, 139(1), 85-92. doi:10.1121/1.4939120 *https://tethys.pnnl.gov/publications/characterizing-large-river-sounds-providing-context-understanding-environmental*

Copping, A., Hanna, L., Whiting, J., Geerlofs, S., Grear, M., Blake, K., Coffey, A., Massaua, M., Brown-Saracino, J., Battey, H. 2013. Environmental effects of marine energy development around the world. Annex IV Final Report (PNNL-22176). Pacific Northwest National Laboratory, Richland, Washington. Report by Pacific Northwest National Laboratory for Ocean Energy Systems *https://tethys.pnnl.gov/publications/environmental-effects-marine-energy-development-around-world-annex-iv-final-report*

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewski, G., Staines, G., Gill, A., Hutchison, I., O'Hagan, A., Simas, T., Bald, J., Sparling, C., Wood, J., Masden, E. 2016. Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. *https://tethys.pnnl.gov/publications/state-of-the-science-2016*

Cruz, E., Simas, T., Kasanen, E. 2015. Discussion of the effects of the underwater noise radiated by a wave energy device - Portugal. Paper presented at the 11th European Wave and Tidal Energy Conference, Nantes, France. *https://tethys.pnnl.gov/publications/discussion-effects-underwater-noise-radiated-wave-energy-device-portugal*

Dahl, P., de Jong, C. Popper, A. 2015. The Underwater Sound Field from Impact Pile Driving and Its Potential Effects on Marine Life. *Acoustics Today*, *11*, 18-25. *https://tethys.pnnl.gov/publications/underwater-sound-field-impact-pile-driving-its-potential-effects-marine-life*

Dahl, P., Miller, J., Cato, D., Andrew, R. 2007. Underwater Ambient Noise. *Acoustics Today*, *3*, 23-33. *https://tethys.pnnl.gov/publications/underwater-ambient-noise*

Farcas, A., Thompson, P. M., and Merchant, N. D. 2016. Underwater noise modelling for environmental impact assessment. *Environmental Impact Assessment Review*, 57, 114-122. doi:10.1016/j.eiar.2015.11.012 *https://tethys.pnnl.gov/publications/underwater-noise-modelling-environmental-impact-assessment*

Habitats Directive (Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora). OJ L 206, 22.7.1992, p. 7-50. [European Union]

Hafla, E., Johnson, E., Johnson, C. N., Preston, L., Aldridge, D., and Roberts, J. D. 2018. Modeling underwater noise propagation from marine hydrokinetic power devices through a time-domain, velocity-pressure solution. *Journal of the Acoustical Society of America*, 143(6), 3242-3253. doi:10.1121/1.5039839 *https://tethys.pnnl.gov/publications/modeling-underwater-noise-propagation-marine-hydrokinetic-power-devices-through-time*

Haikonen, K., Sundberg, J., and Leijon, M. 2013. Characteristics of the Operational Noise from Full Scale Wave Energy Converters in the Lysekil Project: Estimation of Potential Environmental Impacts. *Energies*, 6(5), 2562-2582. doi:10.3390/En6052562 *https://tethys.pnnl.gov/publications/characteristics-operational-noise-full-scale-wave-energy-converters-lysekil-project*

Hastie, G. D., Russell, D. J. F., Lepper, P., Elliott, J., Wilson, B., Benjamins, S., and Thompson, D. 2018. Harbour seals avoid tidal turbine noise: Implications for collision risk. *Journal of Applied Ecology*, 55(2), 684-693. doi:10.1111/1365-2664.12981 *https://tethys.pnnl.gov/publications/harbour-seals-avoid-tidal-turbine-noise-implications-collision-risk*

Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K., and Veirs, S. 2009. Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. *The Journal of the Acoustical Society of America*, 125(1), EL27-EL32. doi:10.1121/1.3040028 *https://tethys.pnnl.gov/publications/speaking-killer-whales-orcinus-orca-increase-their-call-amplitude-response-vessel*

Ikpekha, O.W., Soberon, F., and Daniels, S. 2014. Modelling the Propagation of Underwater Acoustic Signals of a Marine Energy Device Using Finite Element Method. Paper presented at the International Conference on Renewable Energies and Power Quality (ICREPQ'14), Cordoba, Spain. *https://tethys.pnnl.gov/publications/modelling-propagation-underwater-acoustic-signals-marine-energy-device-using-finite*

International Electrotechnical Commission (IEC). 2019. Marine energy - Wave, tidal and other water current converters - Part 40: Acoustic characterization of marine energy converters (IEC TS 62600-40:2019). *https://tethys.pnnl.gov/publications/acoustic-characterization-marine-energy-converters-iec-ts-62600-402019*

International Organization for Standardization (ISO). 2016. ISO/DIS 18405.2:2016(E): Underwater Acoustics - Terminology. *https://tethys.pnnl.gov/publications/iso-184052017-underwater-acoustics-terminology*

Jensen, F. H., Bejder, L., Wahlberg, M., Aguilar Soto, N., Johnson, M., and Madsen, P. T. 2009. Vessel noise effects on delphinid communication. *Marine Ecology Progress Series*, 395, 161-175. doi:10.3354/meps08204 *https://tethys.pnnl.gov/publications/vessel-noise-effects-delphinid-communication*

Lepper, P., Harland, E., Robinson, S., Theobald, P., Hastie, G., and Quick, N. 2012. Acoustic noise measurement methodology for the Billia Croo wave energy test site: Annex A: Summary of operational underwater noise from a Pelamis WEC system at the EMEC wave energy test site May 2011: Comparison of Pelamis system operational and baseline noise measurements (Report No. 374-01-02). Report by European Marine Energy Centre (EMEC), Orkney, Scotland. *https://tethys.pnnl.gov/publications/acoustic-noise-measurement-methodology-billia-croo-wave-energy-test-site*

Lepper, P., and Robinson, S. 2016. Measurement of Underwater Operational Noise Emitted by Wave and Tidal Stream Energy Devices. In A. N. Popper and A. Hawkins (Eds.), *The Effects of Noise on Aquatic Life II* (pp. 615-622), Springer: New York, NY. *https://tethys.pnnl.gov/publications/measurement-underwater-operational-noise-emitted-wave-tidal-stream-energy-devices*

Lesage, V., Barrette, C., Kingsley, M. C. S., and Sjare, B. 1999. The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence River estuary, Canada. *Marine Mammal Science*, 15(1), 65-84. doi:10.1111/j.1748-7692.1999.tb00782.x *https://tethys.pnnl.gov/publications/effect-vessel-noise-vocal-behavior-belugas-st-lawrence-river-estuary-canada*

Lin, Y.-T., Newhall, A. E., Miller, J. H., Potty, G. R., and Vigness-Raposa, K. J. 2019. A three-dimensional underwater sound propagation model for offshore wind farm noise prediction. *Journal of the Acoustical Society of America*, 145(5), EL335-EL340. doi:10.1121/1.5099560 *https://tethys.pnnl.gov/publications/three-dimensional-underwater-sound-propagation-model-offshore-wind-farm-noise*

Lloyd, T. P., Turnock, S. R., and Humphrey, V. F. 2014. Assessing the influence of inflow turbulence on noise and performance of a tidal turbine using large eddy simulations. *Renewable Energy*, 71, 742–754. doi:10.1016/j.renene.2014.06.011 https://tethys.pnnl.gov/publications/assessing-influence-inflow-turbulence-noise-performance-tidal-turbine-using-large-eddy

Lossent, J., Lejart, M., Folegot, T., Clorennec, D., Di Iorio, L., and Gervaise, C. 2018. Underwater operational noise level emitted by a tidal current turbine and its potential impact on marine fauna. *Marine Pollution Bulletin*, 131, 323–334. doi:10.1016/j.marpolbul.2018.03.024 https://tethys.pnnl.gov/publications/underwater-operational-noise-level-emitted-tidal-current-turbine-its-potential-impact

Marine Mammal Protection Act of 1972. 16 U.S.C. ch 31 § 1361 et seq. [United States]

Marine Strategy Framework Directive (Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy). OJ L 164, 25.6.2008, p. 19–40. [European Union]

National Marine Fisheries Service (NMFS). 2018. 2018 Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts. NOAA Technical Memorandum NMFS-OPR-59. Report by National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Silver Spring, MD. https://tethys.pnnl.gov/publications/2018-revisions-technical-guidance-assessing-effects-anthropogenic-sound-marine-mammal

Ocean Renewable Power Company (ORPC). 2014. Cobscook Bay Tidal Energy Project: 2013 Environmental Monitoring Report. Report by Ocean Renewable Power Company, Portland, ME. https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2013-environmental-monitoring-report

Pine, M. K., Schmitt, P., Culloch, R. M., Lieber, L., and Kregting, L. T. 2019. Providing ecological context to anthropogenic subsea noise: Assessing listening space reductions of marine mammals from tidal energy devices. *Renewable and Sustainable Energy Reviews*, 103, 49–57. doi:10.1016/j.rser.2018.12.024 https://tethys.pnnl.gov/publications/providing-ecological-context-anthropogenic-subsea-noise-assessing-listening-space

Polagye, B. 2017. Challenges to characterization of sound produced by marine energy converters. In *Marine Renewable Energy*. Springer, Cham. https://tethys.pnnl.gov/publications/challenges-characterization-sound-produced-marine-energy-converters

Polagye, B., Murphy, P., Cross, P., and Vega, L. 2017. Acoustic characteristics of the Lifesaver wave energy converter. Paper presented at the 12th European Wave and Tidal Energy Conference (EWTEC), Cork, Ireland. https://tethys.pnnl.gov/publications/acoustic-characteristics-lifesaver-wave-energy-converter

Popper, A., and Hawkins, A. 2018. The importance of particle motion to fishes and invertebrates. *Journal of the Acoustical Society of America*, 143(1), 470–488. doi:10.1121/1.5021594 https://tethys.pnnl.gov/publications/importance-particle-motion-fishes-invertebrates

Przeslawski, R., Brooke, B., Carroll, A. G., and Fellows, M. 2018. An integrated approach to assessing marine seismic impacts: Lessons learnt from the Gippsland Marine Environmental Monitoring project. *Ocean & Coastal Management*, 160, 117–123. doi:10.1016/j.ocecoaman.2018.04.011 https://tethys.pnnl.gov/publications/integrated-approach-assessing-marine-seismic-impacts-lessons-learnt-gippsland-marine

Risch, D, van Geel, N., Gillespie, D. and Wilson, B. 2020. Characterisation of underwater operational sound of a tidal stream turbine. *Journal of the Acoustical Society of America*, 147(4), 2547–2555. doi:10.1121/10.0001124 https://tethys.pnnl.gov/publications/characterisation-underwater-operational-sound-tidal-stream-turbine

Robertson, F., Wood, J., Joslin, J., Joy, R., and Polagye, B. 2018. Marine Mammal Behavioral Response to Tidal Turbine Sound (Report No. DOE-UW-06385). Report by University of Washington for U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, Washington D.C. https://tethys.pnnl.gov/publications/marine-mammal-behavioral-response-tidal-turbine-sound

Robinson, S., and Lepper, P. 2013. Scoping Study: Review of Current Knowledge of Underwater Noise Emissions from Wave and Tidal Stream Energy Devices. The Crown Estate, London, UK. https://tethys.pnnl.gov/publications/scoping-study-review-current-knowledge-underwater-noise-emissions-wave-tidal-stream

Robinson, S., Lepper, P., and Hazelwood, R. 2014. Good Practice Guide for Underwater Noise Measurement. National Physical Laboratory Good Practice Guide No. 133. The Crown Estate, London, UK. *https://tethys.pnnl.gov/publications/good-practice-guide-underwater-noise-measurement*

Rolland, R. M., Parks, S. E., Hunt, K. E., Castellote, M., Corkeron, P. J., Nowacek, D. P., Wasser, S. K., and Kraus, S. D. 2012. Evidence that ship noise increases stress in right whales. *Proceedings of the Royal Society B: Biological Sciences*, 279(1737), 2363-2368. doi:10.1098/rspb.2011.2429 *https://tethys.pnnl.gov/publications/evidence-ship-noise-increases-stress-right-whales*

Russell, D. J. F., Hastie, G. D., Thompson, D., Janik, V. M., Hammond, P. S., Scott-Hayward, L. A. S., Matthiopoulos, J., Jones, E. L., and McConnell, B. J. 2016. Avoidance of wind farms by harbour seals is limited to pile driving activities. *Journal of Applied Ecology*, 53(6), 1642-1652. doi:10.1111/1365-2664.12678 *https://tethys.pnnl.gov/publications/avoidance-wind-farms-harbour-seals-limited-pile-driving-activities*

Schmitt, P., Elsäßer, B., Coffin, Hood, and Starzmann, R. 2015. Field Testing a Full-Scale Tidal Turbine Part 3: Acoustic Characteristics. Paper presented at the 11th European Wave and Tidal Energy Conference, Nantes, France. *https://tethys.pnnl.gov/publications/field-testing-full-scale-tidal-turbine-part-3-acoustic-characteristics*

Schmitt, P., Pine, M. K., Culloch, R. M., Lieber, L., and Kregting, L. T. 2018. Noise characterization of a subsea tidal kite. *Journal of the Acoustical Society of America*, 144(5), EL441-EL446. doi:10.1121/1.5080268 *https://tethys.pnnl.gov/publications/noise-characterization-subsea-tidal-kite*

Scholik-Schlomer, A. 2015. Where the Decibels Hit the Water: Perspectives on the Application of Science to Real-World Underwater Noise and Marine Protected Species Issues. *Acoustics Today*, 11(3), 36-44. *https://tethys.pnnl.gov/publications/where-decibels-hit-water-perspectives-application-science-real-world-underwater-noise*

Schramm, M. P., Bevelhimer, M., and Scherelis, C. 2017. Effects of hydrokinetic turbine sound on the behavior of four species of fish within an experimental mesocosm. *Fisheries Research*, 190, 1-14. doi:10.1016/j.fishres.2017.01.012 *https://tethys.pnnl.gov/publications/effects-hydrokinetic-turbine-sound-behavior-four-species-fish-within-experimental*

Southall, B., Bowles, A., Ellison, W., Finneran, J., Gentry, R., Greene, C. J., Kastak, D., Ketten, D., Miller, J., Nachtigall, P., Richardson, W., Thomas, J., and Tyack, P. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. *Aquatic Mammals*, 33(4), 411-521. doi:10.1080/09524622.2008.9753846 *https://tethys.pnnl.gov/publications/marine-mammal-noise-exposure-criteria-initial-scientific-recommendations*

Thomsen, F., Gill, A. B., Kosecka, M., Andersson, M., André, M., Degraer, S., Folegot, T., Gabriel, J., Judd, A., Neumann, T., Norro, A., Risch, D., Sigray, P., Wood, D., and Wilson, B. 2016. MaRVEN – Environmental Impacts of Noise, Vibrations and Electromagnetic Emissions from Marine Renewable Energy (RTD-KI-NA-27738-EN-N). Report for European Commission, Brussels. doi:10.2777/272281 *https://tethys.pnnl.gov/publications/marven-environmental-impacts-noise-vibrations-electromagnetic-emissions-marine*

Tougaard, J. 2015. Underwater Noise from a Wave Energy Converter Is Unlikely to Affect Marine Mammals. *PLoS ONE*, 10(7), 1-7. doi:10.1371/journal.pone.0132391 *https://tethys.pnnl.gov/publications/underwater-noise-wave-energy-converter-unlikely-affect-marine-mammals*

Walsh, J., Bashir, I., Garrett, J. K., Thies, P. R., Blondel, P., and Johanning, L. 2017. Monitoring the condition of Marine Renewable Energy Devices through underwater Acoustic Emissions: Case study of a Wave Energy Converter in Falmouth Bay, UK. *Renewable Energy*, 102(Part A), 205-213. doi:10.1016/j.renene.2016.10.049 *https://tethys.pnnl.gov/publications/monitoring-condition-marine-renewable-energy-devices-through-underwater-acoustic*

Wenz, G. M. 1962. Acoustic Ambient Noise in the Ocean: Spectra and Sources. *Journal of the Acoustical Society of America*, 34(12), 1936-1956. doi:10.1121/1.1909155 *https://tethys.pnnl.gov/publications/acoustic-ambient-noise-ocean-spectra-sources*

NOTES

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

Polagye, B. and C. Bassett. 2020. Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 66-85). doi:10.2172/1633082

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

5.0

Chapter authors: Andrew B. Gill, Marieke Desender
Contributor: Levy G. Tugade

Risk to Animals from Electromagnetic Fields Emitted by Electric Cables and Marine Renewable Energy Devices

Interest in the potential effects of anthropogenic electromagnetic fields (EMFs) within the marine environment has increased in recent years, in part as a result of advanced knowledge gained from conducting dedicated research studies. To understand and interpret the potential environmental interactions of marine renewable energy (MRE)-related EMF emissions, it is necessary to consider the source of the EMFs and address the source within the context of the knowledge about the electro- and magneto-sensitivity of marine species.

5.1. IMPORTANCE OF THE ISSUE

Any anthropogenic activity that uses electrical cables in the marine environment is a primary source of EMFs. The cables emit EMFs along their entire lengths, whether transmitting high-voltage direct current (DC) or alternating current (AC). Currently, high-voltage AC (HVAC) electrical cables are used to connect all types of offshore and MRE devices both among units in an array and to marine substations; and HVAC or high-voltage DC (HVDC) can be used to export power to shore. The interactions between EMFs emitted by MRE power generation with the naturally occurring geomagnetic field (GMF) can potentially alter the behavior of marine animals that are receptive to these fields (Figure 5.1), including potentially altering avoidance or attraction behaviors. It is important to know the intensity of the emitted EMF, which depends on the type of current (DC or AC), the cable characteristics, the power transmitted, the local GMF, and surrounding environmental factors (Figure 5.1). The EMF scales with the energy produced by multiple and/or larger MRE devices and higher power-rated cables. The response of receptor animals fundamentally depends on the sensitivity of the animals, which is determined by the sensory systems they possess (Snyder et al. 2019). The movement and distribution of the animals also plays a role in the probability of an encounter with an EMF and may depend on the species life stage, as well as the spatial and temporal use of the environment where the EMF occurs (Figure 5.1).

An EMF has two components: electric fields (E-fields) and magnetic fields (B-fields[1]). The Earth creates its own GMF and has E- and B-fields associated with natural phenomena (e.g., lightning), while also being permeated by EMFs from outside the Earth's atmosphere (Gill et al. 2014). In seawater, natural E-fields are produced by the interaction between the conductivity of the water, the Earth's rotation of the B-field, and the motion of tides/currents (Stanford 1971), which creates localized motion-induced fields.

The primary source of anthropogenic EMF emissions associated with MRE systems is the cables used to transmit the electricity produced, and their emissions depend on the cable configurations in relation to the ambient environment. EMF emissions may also be associated with offshore substations receiving multiple cables and, in some cases, transforming voltages between AC and DC. Current interest is focused on EMFs generated within the cable and existing along its length, propagating perpendicular to the cable axis into the surrounding environment, and decaying with distance from the source. In DC cables, the EMF emitted is a static field, whereas in AC cables, the EMF is normally a low-frequency sinusoidal field. E-fields are contained within the cable by shielding and grounding that allow the field to dissipate quickly, but a B-field is still emitted in the outside environment. When an animal or water current causes motion through a B-field, secondary induced electric fields (iE-fields) are generated (Figure 5.1). AC current passing through a standard, three-core cable will also create iE-fields (Figure 5.1).

In Figure 5.1, the separate E-field and B-field components of the EMFs emitted by a buried subsea cable (red) are shown, as well as the ambient geomagnetic field (black) and bioelectric fields from living organisms (orange). Figure 5.1a shows the EMF associated with a DC cable; Figure 5.1b shows the EMF associated with a standard three-phase AC subsea cable with the current following a typical sine wave back and forth through each core. For both cables the direct E-field is shielded by cable material (black outer cable), but B-fields (blue) are not shielded and propagate to the surrounding environment. An iE-field is created in the fish (yellow) as it moves through the B-field emitted by the cable. Localized iE-fields will also be induced by seawater moving through the B-field and the GMF. In addition, for the AC cable, the out-of-phase B-field emitted by each core of the cable causes a rotation in the magnetic emission, which induces an iE-field in the surrounding conductive seawater (red), that is emitted into the environment above the seabed.

1. B-field is the accepted nomenclature for the magnetic field. It is technically termed the magnetic flux density. The B-field is easily measured (in the International System of Units unit of Tesla) and takes account of the permeability of the medium.

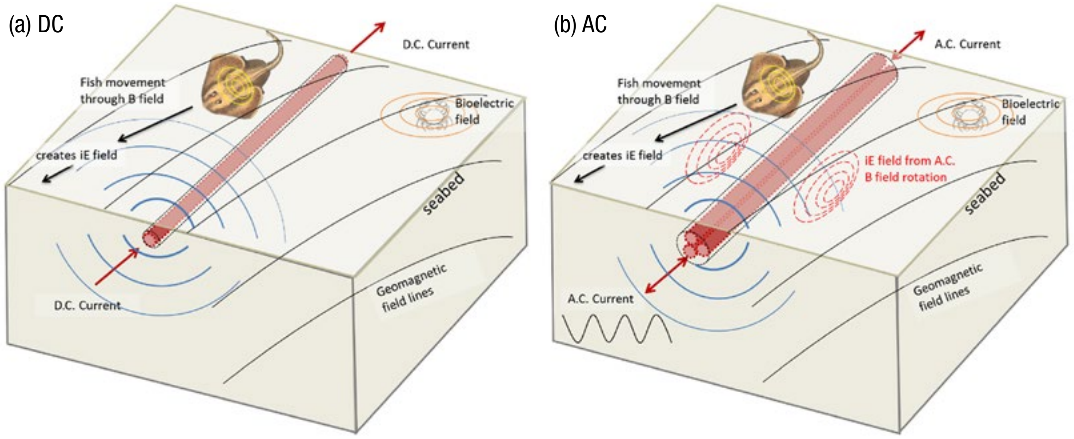


Figure 5.1. Diagrams summarizing the natural and anthropogenic electric fields (E-fields), induced electric fields (iE-fields) and magnetic fields (B-fields) encountered by an electromagnetic-sensitive fish moving across the seabed. (Adapted from Newton et al. 2019)

5.2. SUMMARY OF KNOWLEDGE THROUGH 2016

Some marine animals are capable of sensing EMFs to aid in their orientation, migration, and prey location (Kirschvink 1997; Tricas and New 1998; Walker et al. 1992). As of 2016, studies have focused on a diversity of organisms such as elasmobranchs (sharks, skates, and rays), agnatha (lampreys), crustacea (lobsters and prawns), mollusks (bivalves, snails, and cephalopods), cetaceans (whales and dolphins), bony fish (teleosts and chondrosteans), and sea turtles (Copping et al. 2016). Anthropogenic EMFs may interfere with the ambient EMF, and anomalies in the behavioral patterns of animals have been observed (Gill et al. 2014). Some studies have shown that sensitive animals may respond to anthropogenic B-fields at or below the geomagnetic intensity or ambient conditions (in the range of 30 to 60 microtesla [μT] approximately). However, EMFs are currently considered unlikely to generate any ecologically significant impacts on receptive species at these low field intensities (Gill et al. 2014).

The strength of anthropogenic E-fields associated with MRE-type cables, that have been measured, are in the 1 to 100 μV/cm range, which is similar to the bioelectric fields emitted by prey species; such E-fields act as attractants for electroreceptive ocean predators (Kalmijn 1982; Peters et al. 2007; Tricas and New 1998). Cables associated with larger MRE arrays will produce greater B- and E-fields, potentially interfering with migratory movements due to a perceived barrier effect (Tesch and Lalek 1973; Westerberg and Begout-Anras 2000; Westerberg and Lagenfelt 2008) and possibly reaching the limit between animal attraction to and repulsion from EMFs (Huveneers et al. 2013). However, the state of the knowledge until 2016 was limited, which prevented further interpretation (Gill et al. 2014).

While most of the field and semi-natural studies conducted before 2016 focused on behavioral effects, none have shown any demonstrable significant impacts of EMF on sensitive species (e.g., Gill et al. 2014). However, a controlled laboratory experiment showed some adverse effects of prolonged exposure to high-intensity EMFs (in the millitesla [mT] range) on the physiology, development, and growth of several species of demersal fish and crustaceans (Woodruff et al. 2012). It is important to note that, to date, EMF levels similar to these experimental conditions have not been observed around deployed MRE devices. These effects would be more likely observed for sessile species that stay near undersea cables than motile species, but knowledge of the effects of EMF on these sessile species had not been established by 2016.

B-field patterns produced by different cable configurations can be detected and mapped using magnetometers (Normandeau et al. 2011), but it is more difficult to measure E-field emissions. As of 2016, only a few groups had developed or were developing the instrumentation to detect E-fields at the low-intensity levels expected to occur around MRE devices (e.g., Oregon State University, Swedish Defense Research Agency). Mathematical modeling has been used to complement field and laboratory measurements, because it is more cost-effective for predicting conditions over larger areas than measurements recorded under difficult field conditions. However, the measurement data needed to validate EMF models are lacking.

Based on the knowledge acquired up to 2016, there was insufficient reason to consider establishing definitive mitigation efforts. However, if mitigation was deemed necessary, technical design standards could be proposed, such as the use of helically twisted three-conductor cables to reduce EMF emissions (Petterson and Schönborg 1997). Burial of cables is not an effective mitigation measure for EMFs because the cables emit EMFs into the environment directly as B-fields and create iE-fields in the seawater and, therefore, have the potential to affect sea life. Cable burial does, however, separate most demersal and benthic animals from the maximum EMF emissions at the cable surface, owing to the physical distance between the seabed surface and the cable.

To fill significant knowledge gaps about EMFs, the *2016 State of the Science* report (Copping et al. 2016) recommended further efforts toward

- characterizing EMFs in AC vs. DC transmission systems, in single vs. multiple cables configurations, and in the electrical topology of various MRE devices
- measuring actual EMF levels linked to the location and depth of devices, as well as the spatial and temporal variability of EMFs to which animals would potentially be subjected
- carrying out dose-response studies to establish species-specific ranges of detections, and thresholds for and types of responses
- developing modeling tools that combine EMF models and dose-response studies with ecological models
- implementing long-term research and monitoring to assess cumulative impacts, especially impacts on vulnerable life-history stages.

5.3. KNOWLEDGE GENERATED SINCE 2016

In the *2016 State of the Science* report (Copping et al. 2016), the importance of differentiating the potential environmental effects of EMFs when assessing the interactions between MRE devices and receptors was highlighted (e.g., by Boehlert and Gill 2010). The present update focuses on whether an effect or response recorded in a study can be considered an impact.

In the four years since the publication of the *2016 State of the Science* report, interest in the topic of EMFs has grown, and some notable research projects have provided an improved understanding of the interactions between EMFs and aquatic life, with a focus on fish and invertebrate receptor species. The research has either involved laboratory-based controlled studies of B- or E-fields or field-based experiments or surveys of EMF-emitting subsea cables. Within the academic literature, some key reviews have been published, specifically about magnetoreception in fish (Formicki et al. 2019), electroreception in marine fish (Newton et al. 2019), the perception of anthropogenic electric and magnetic emissions by marine animals (Nyqvist et al. 2020), and the environmental impacts of subsea cables (Taormina et al. 2018).

These reviews demonstrate that when considering the potential response of an organism to EMFs, the topic should be divided into two categories: organisms that have the sensory capability to detect and respond to B-fields, and organisms that have the sensory capability to detect and respond to E-fields (although recent evidence suggests that some organisms may be able to detect both types of fields directly) (see Newton et al. 2019). The primary consideration for EMFs emitted by subsea cables is the B-field, which should be considered in relation to the ambient GMF and the iE-fields that occur. For organisms that detect E-fields, direct E-fields will only occur in the environment if a cable (AC or DC) is not properly grounded or if the design of the electrical system leads to electrical leaks; however, iE-fields will be associated with the B-field. Therefore, while understanding both elements of EMFs is important, the B-field is regarded as the primary focus for understanding organism response to MRE EMFs.

The predominant taxonomic groups discussed in the *2016 State of the Science* report were fish and invertebrates. The current review of recent literature includes consideration of new knowledge about the responses of electro- and magnetoreceptive organisms to changes in the magnetic and/or electric environment. An overview of knowledge generated since 2016 and a set of recommendations are covered in the remainder of this chapter.

5.3.1. RESPONSES TO EMF – FISH (ADULT)

Field Studies of EMFs

Studies of magnetosensitive species migration have continued to be a focus of field investigations. The migration success of Chinook salmon (*Oncorhynchus tshawytscha*) in San Francisco Bay, California (United States [U.S.]) was found to be largely unchanged after installation of a 200 kV HVDC subsea cable (Wyman et al. 2018). However, the proportion of salmon crossing the cable location was larger than the proportion not crossing it. Furthermore, fish were more likely to be detected on one side of their normal migration route. Fish migration paths moved closer to the cable at some locations, but farther away at others, which was attributed to other higher-intensity B-field sources, such as metal bridges. Together with other environmental factors, transit times through some parts of the bay were slightly reduced (Wyman et al. 2018).

The results of a field experiment conducted in Long Island Sound, Connecticut (U.S.) showed that little skates (*Leucoraja erinacea*) crossed over a 300 kV HVDC transmission cable. However, the skates showed a strong distributional response associated with the higher EMF zone, moved significantly greater distances along the cable route, and displayed increased turning activity (Hutchison et al. 2018).

Magnetic Fields

A number of species have the ability to detect and respond to B-fields, likely via a magnetite-based sensory process (Diebel et al. 2000; Kirschvink and Gould 1981; Kirschvink and Walker 1985), but other hypotheses remain to be demonstrated (Binhi and Prato 2017). Research on elasmobranch response to EMFs in the environment has considered that when an individual approaches an EMF, it experiences an iE- field, which stimulates its electroreceptive sensory apparatus. This hypothesized mechanism of indirect magnetic stimulus detection has been offered as a plausible explanation of the responses of yellow stingray (*Urobatus jamaicensis*), which learned to associate magnetic anomalies with food rewards up to six months after first exposure (Newton and Kajiura 2017). Other recent studies suggest that elasmobranchs can detect magnetic fields directly rather than via induction of E-fields (Anderson et al. 2017). To date, elasmobranchs have no known direct B-field receptors, but putative magnetoreceptive structures may reside within the naso-olfactory capsules of sandbar sharks (Anderson et al. 2017). Strong permanent magnets, used in shark-repellent studies, have been shown to induce avoidance behaviors in a number of elasmobranch species (Richards et al. 2018; Siegenthaler et al. 2016). However, it is unclear whether the avoidance effects were a result of the fish responding directly to magnetic stimuli or to iE-fields. Newton (2017) showed that the yellow stingray uses GMF polarity to solve spatial tasks and detect changes in GMF strength and inclination angle. These two magnetic cues may be used for orientation and to derive a location.

Electric Fields

The anatomy, physiology, and behavior of electroreceptive species have been the subjects of a number of studies over the past few decades. Most studies since 2016 have focused on determining whether electroreceptive species detect B-fields directly or indirectly by induction (see above). Bellono et al. (2018) indicated that the electroreceptive sensitivity of some species of benthic shark appears to be adapted to a narrow range of electrical stimuli, such as those emitted by prey, whereas in some species of skate the EMF receptors are more broadly tuned, which may enable them to detect both prey stimuli and the electric organ discharges of other individuals.

A number of fish can be affected adversely by high-intensity E-fields, such as those used in electric fishing (de Haan et al. 2016), but these E-fields are several orders of magnitude greater (30 to 100 V/m approximately 20 cm from electrodes) than those associated with subsea cables (Table 5.1) and are not regarded as relevant to MRE EMFs.

5.3.2. RESPONSE TO EMF – FISH (EMBRYONIC AND LARVAL)

The strongest effects of EMFs on an individual organism will most likely occur during either the embryonic or larval stages of species settling on the bottom, particularly for those species that have a long incubation period (see Nyqvist et al. 2020 and references therein). Most early life-history studies have been conducted on freshwater fish species and have focused on the B-field. The application of B-field studies will not differ between fresh and ocean water, but for E-fields, direct or iE-fields only propagate in seawater because of the conductivity of the medium.

In a study of rainbow trout (*Oncorhynchus mykiss*), demersal eggs and larvae were exposed under experimental conditions to static B-fields (10 mT, DC) and a low-frequency EMF (1 mT, AC) for 36 days (Fey et al. 2019a). No effect on embryonic or larval mortality, hatching time, larval growth, or swim-up from the bottom was found. However, both low-frequency and static exposures enhanced the yolk-sac absorption rate. Larvae with absorbed yolk-sacs were less efficient at first feeding, resulting in smaller weights at age. A smaller yolk sac and faster absorption rate were also observed in exposed (static magnetic, 10 mT, DC) freshwater Northern pike (*Esox lucius*) (Fey et al. 2019b). In addition, hatching was one day earlier, but no differences in hatching success and larval mortality or size of larvae were noted. The appearance of embryonic melanophores, a key developmental marker, in common whitefish (*Coregonus lavaretus*) and vendace (*Coregonus albula*) was delayed, while increased static field intensities caused a concentration of melanin in their cells (Brysiewicz et al. 2017). A low-intensity (hypo)magnetic field (i.e., weaker than the GMF) has been found to cause a decrease in the activity of intestinal enzymes, proteinases, and glycosidases in crucian carp (*Carasius carasius*) (Kuz'mina et al. 2015). Furthermore, the activity of intracellular calcium (Ca^{2+})-dependent proteinase (calpains) decreased, and this could have potential consequences for calcium signaling pathways leading to changes in the morphology and activity of cell organelles. These calpains were also inactivated in crucian carp, roach (*Rutilus rutilus*), and common carp (*Cyprinus carpio*) (Kantserova et al. 2017). A newer study investigating the genotoxicity and cytotoxicity responses during the early development of rainbow trout exposed to a low-frequency (50 Hz 1 mT) EMF for 40 days, showed nuclear abnormalities and alterations in the number of cell nuclei (Stankevičiūtė et al. 2019).

Even though these studies were conducted under controlled laboratory conditions, they highlight how exposure to B-fields in the millitesla range have implications for developmental, genetic, and physiological outcomes for early life stages. The laboratory-induced B-field intensities are high compared to microtesla or nanotesla fields measured around subsea cables (Table 5.1). However, with increased cable power transmission and subsequent B-field strength, the effects on the development of early life stages may become a consideration in the future.

No studies concerning E-fields in the predictive range associated with MRE devices have been conducted to date, largely because the industry is still emerging and power generation levels are relatively low and isolated, and EMF studies have seldom been required in the marine environment for established industries.

5.3.3. RESPONSE TO EMF – INVERTEBRATES

Relatively little is known about the effects of EMFs on marine benthic invertebrates, but some decapod crustaceans are known to be magnetosensitive. Research since 2016 concerning invertebrates generally supports previous studies that demonstrated no or minor effects of encounters with EMFs, but some findings are equivocal (Albert et al. 2020).

Field Studies

During a field experiment in southern California and the Puget Sound, Washington State (U.S.), no evidence was found that the catchability of two commercially important crab species (*Metacarcinus magister* and *Cancer productus*) was influenced by their having to traverse an energized low-frequency submarine AC power cable (35 kV and 69 kV, respectively) to enter a baited trap (Love et al. 2017a). Greater turning activity and altered distribution of American lobster (*Homarus americanus*) in the presence of static HVDC EMFs (Cross Sound Cable: 300 kV; Table 5.1) were highlighted recently in a field study using large enclosures above a domestic electrical power cable in Long Island Sound, Connecticut (U.S.) (Hutchison et al. 2018, 2020).

Magnetic Fields

In a laboratory study, Scott et al. (2018) observed a clear attraction of European edible crabs (*Cancer pagurus*) to shelters that had a relatively high B-field (2.8 mT, compared to nT- or µT-level EMFs measured in the field) associated with them, and the crabs spent less time roaming. The daily behavioral and physiological rhythmic processes (i.e., circadian rhythm) of the haemolymph L-Lactate and D-Glucose levels were disrupted. However, the EMF (2.8 mT and 40 mT) had no effect on stress-related parameters, such as haemocyanin concentrations, respiration rate, activity level, or the antennular flicking rate.

An experimental study by Taormina et al. (2020) exposed juvenile European lobsters (*Homarus gammarus*) to a DC or AC B-field (maximum up to 200 µT) and found no statistically significant effect on their exploratory and sheltering behaviors. They suggested that a behavioral response to B-fields, up to 200 μT, does not appear to be a factor influencing the European lobster's juvenile life stage, although there was a confounding influence of light affecting their sheltering behavior. The authors commented that higher magnetic values (which could be encountered while seeking shelter close to a cable) may need to be considered when studying the potential B-field effects on the behavior of this species.

A laboratory study assessing the effects of environmentally realistic, low-frequency B-field (1 mT) exposure on the behavior and physiology of the common ragworm (*Hediste diversicolor*) did not find any evidence of avoidance or attraction behaviors (Jakubowska et al. 2019). The polychaetes did, however, exhibit enhanced burrowing activity when exposed to the B-field. In addition, food consumption and respiration rates were not affected, but ammonia excretion was reduced in exposed animals, with plausible consequences for their metabolism; however, knowledge about the biological relevance of this response is currently absent (Jakubowska et al. 2019).

Stankevičiūtė et al. (2019) investigated potential genetic damage (i.e., genotoxicity) and damage or destruction of cells (i.e., cytotoxicity) in the common ragworm and Baltic clam (*Limecola balthica*) after a relatively long-term (12 days) exposure to a 50 Hz 1 mT EMF. The exposure affected both species, but the strongest response was elicited in the Baltic clam, for which six out of the eight measured parameters were significantly elevated in the gill cells. No cytotoxic effect was induced in common ragworm immune system cells, but the development of micronuclei and nuclear buds on filaments demonstrated a potential effect on the integrity of genetic material that may cause diseases.

Electric Fields

Relative to species navigation and prey detection, a limited number of previous studies indicated that some freshwater invertebrate species may be able to detect low-intensity E-fields comparable to those induced by subsea cables (Patullo and MacMillan 2010). However, no similar studies of marine invertebrate response to E-fields are found in the literature for the period from 2016 to 2019. Invertebrates have been shown to respond to high-intensity fields such as those used in electric fishing at sea (Polet et al. 2005; Soetaert et al. 2014). Although these fields have been shown to cause neuromuscular disruption, they are several orders of magnitude greater than those associated with subsea cables and so are not considered further in this report.

5.3.4. RESPONSE TO THE PRESENCE OF SUBSEA CABLES – FAUNAL COMMUNITIES

To assess the effects on the community of species inhabiting the environment on or adjacent to subsea cables, a small number of studies have conducted field surveys along cable routes.

Love et al. (2017b) used submersible surveys of energized cables (35 kV) to compare the invertebrate colonizing community and the fish assemblages present in southern California (U.S.). Magnetic fields of energized cables reached background levels within 1 m and no statistical differences in the faunal communities were found. Factors such as substrate or depth were more relevant than proximity to the cable in explaining the variation of fish community and density in association with a 245 kV HVAC transmission cable in Lake Ontario, Ontario (Canada) (Dunlop et al. 2016). Dunham et al. (2015) found that the abundance of decapods (principally the prawn and shrimp species) associated with the glass sponge reefs colonizing three 230 kV HVAC cables off Vancouver Island, British Columbia (Canada) differed from their abundance at control survey sites; they were less abundant around the cables. Diver and remotely operated vehicle surveys across Bass Strait in Tasmania (Australia) found a third of a cable route visually undetectable within two years; after three and a-half years, the colonizing benthic species were similar to the nearby hard-bottom species (Sherwood et al. 2016).

These studies collectively suggest that benthic communities growing along cables routes are generally similar to those in nearby areas, although some locations perhaps show a difference in the abundance of a few species. However, it is important to note that any observed changes could be the result of the physical presence of the cable or other features in the environment, rather than an EMF effect (see Chapter 6, Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices).

5.4. GUIDANCE ON MEASURING EMF FROM MRE DEVICES AND CABLES

Advancing our knowledge of the characteristics of EMFs emitted by cables or MRE devices is essential for understanding the possible consequences of exposure of the aquatic environment and for developing accurate predictive models of EMFs. Since the MaRVEN (Marine Renewable Energy, Vibration, Electromagnetic fields and Noise) project deployed the SEMLA (Swedish Electromagnetic Low-Noise Apparatus) device to measure *in situ* E-fields and B-fields emitted by subsea MRE cables (Thomsen et al. 2015), a few studies have continued to focus on quantifying the extent of anthropogenic EMFs using field measurements and modeling (Table 5.1). Field strengths and the depth and angle of buried HVDC power cables are parameters that determine the extent of the EMF above the seabed and can be modeled, but these models need to be validated in the field.

Dhanak et al. (2016) used an autonomous underwater vehicle equipped with a commercial magnetometer and custom-built, three-axis E-field sensor that simultaneously measured E-fields and B-fields by following a lawnmower-type survey path above AC and DC power cables on the east coast of Florida (U.S.). The values of the emitted fields were within the expected EMF intensity of these cables. The modeled B-fields for the Trans Bay Cable in San Francisco, California (U.S.) were very similar to field measurements and consistent with expectations (Kavet et al. 2016), as was the case for measurements of the B-field emitted by the Basslink HVDC across Bass Strait in Tasmania (Australia) (Sherwood et al. 2016). Nonetheless, the emissions from other B-field sources, such as metal bridge structures or geological deposits, might be up to a hundred times greater than the B-field emission from the cable and might distort the B-field, making it impossible to model and discern B-fields emitted by and measured around the cable in some locations (Kavet et al. 2016). Hence, in some cases the actual EMF emitted into the environment will not match the modeled outputs.

Table 5.1. Measurements from high-voltage alternative current (AC) and direct current (DC) subsea cables since 2016. The distances above the seafloor were extracted from studies when provided. The electromagnetic field (EMF) extent refers to the distance that EMF is measurable in relation to the ambient fields perpendicular to the cable axis.

Cable	Current	Location	Magnetic field (B-field)	Electric field (E-field)	Extent EMF	Reference
2 - 2.4 amps 0.98 - 1.59 amps, 60 Hz	DC AC	South Florida (U.S.)	Max: 150 μT Mean: 30 nT 2.2 m above seafloor	Max: 60 μV/m 4 m above cable	10s m (estimated) AC > DC	Dhanak et al. (2016)
Trans Bay Cable (200 kV, 400 MW, 85 km)	DC	San Francisco Bay, California (U.S.)	1.15 - 1.2 μT 3 m above seafloor	n/a	<40 m	Kavet et al. (2016)
Basslink (500 kV, 237 MW, 290 km)	DC	Bass Strait, Tasmania (Australia)	58.3 μT	5.8 μV/m	15 - 20 m	Sherwood et al. (2016)
Cross Sound (300 kV, 330 MW, 40 km)	DC	Connecticut (U.S.)	DC: 0.4 - 18.7 μT AC: max 0.15 μT	AC: max: 0.7 mV/m	AC-DC B-fields: 5 - 10 m	Hutchison et al. (2018)
Neptune (500 kV, 660 MW, 105 km)	DC	New Jersey (U.S.)	DC: 1.3 - 20.7 μT AC: max 0.04 μT	DC: 0.4 mV/m	AC: max: E-fields up to 100 m	Hutchison et al. (2018)
Sea2shore (502 amps, 30 MW, 32 km)	AC	Rhode Island (U.S.)	0.05 - 0.3 μT	1-25 μV/m	AC: B-field up to 10 m AC: E-field up to 50 m (estimated)	Hutchison et al. (2018)

Hutchison et al. (2018, 2020) discovered AC fields associated with two HVDC power cables (Cross Sound and Neptune Cables, Table 5.1) that extended tens of meters farther than the DC fields. This unexpected finding is most likely explained by harmonic currents created during AC-DC conversion at the converter station on each end of the cables. In the same study, an AC cable at a small wind farm emitted B-fields that were ten times lower than those modeled, suggesting self-cancellation inside the three-conductor cable owing to the twisted design of the cable.

Remote-sensing satellites have the potential to become a new tool for studying EMFs in the ocean. The European Space Agency (ESA) launched satellites in 2013 (as part of the SWARM mission) to study various aspects of the Earth's B-field. One of the goals of SWARM was to study ocean circulation based on its EMF signature. In 2018, electric currents generated in the world's oceans due to seawater movement through the Earth's B-field were detected by the ESA satellites. These large-scale datasets will provide further context for the electromagnetic environment relevant to marine life.

5.5. RESEARCH AND MONITORING NEEDS TO RESOLVE THE ISSUE

The *2016 State of the Science* report highlighted significant gaps in the current knowledge of the impacts of EMF from MRE on receptive species. In the intervening years, the conduct of more specific research has increased the knowledge base, allowing for further consideration of whether the interaction between receptive species and EMFs has any biological significance that could translate to ecological impacts. New research has shown evident effects and responses of individual species at behavioral, physiological, developmental, and genetic levels. However, based on the evidence to date, the ecological impacts associated with MRE subsea power cables may be weak or moderate at the scale that is currently considered or planned. Nonetheless, it is important to recognize that this assessment comes from studies of a small number of cables, and several researchers have acknowledged that data about impacts are scarce and many uncertainties concerning electromagnetic effects remain (Taormina et al. 2018). Furthermore, knowledge about how sensitive species will respond and adapt to an aquatic environment that is being increasingly altered by anthropogenic E- and B-fields, not just from MRE but other human activities, is lacking (Newton et al. 2019).

In general, the research concerning EMF effects requires an understanding of both the EMF environment in which the sensitive organisms will encounter EMFs and the context of their responses. With a growing number of cables being deployed, and increases in the power being transmitted, the extent of EMFs emitted into the environment will increase with additional MRE deployments and associated cables. Therefore, the likelihood of animals encountering EMFs in the aquatic environment will increase, as will the intensities experienced.

MRE installations currently are of relatively small scale and they are not the only sources of EMFs in the environment. Questions about the environmental effects of EMFs remaining to date can be addressed and management decisions can be supported by considering some key elements (Figure 5.2).

To date, although some of the study results suggest effects of EMFs on certain species (see Section 5.4), the lack of specific information has led to the general conclusion that EMFs associated with subsea cables are not harmful and do not pose a risk to biota. This would appear to be an appropriate conclusion for MRE devices and cables because their EMF signatures are low. However, the lack of evidence does not necessarily equate to a lack of impacts. Future increases in EMFs in the marine environment, due to the development of MRE arrays, may increase the potential risk to sensitive receptors and require additional investigation to enhance our knowledge and understanding of the emerging spectrum of effects.

If studies provide evidence that a given receptor organism responds to EMFs, then the next step toward the determination of any impact would be to investigate the likelihood of a receptor to encounter the EMF emission extent (Figure 5.2). For non-mobile receptors, the emission-response relationship will depend on the duration of the exposure, the intensity and frequency of the EMF, and the threshold levels at which a response will occur. Knowledge about thresholds is currently very poor and, therefore, requires more specific attention.

For mobile species, the most likely response is expected to be attraction to the EMF or avoidance of higher-level EMFs. However, physiological effects could occur within the receptor animal. With multiple cables (or sources of EMFs), the likelihood of encounter will be greater (Figure 5.2); hence, cumulative effects of an encounter with EMFs are plausible. To date, studies have been conducted in controlled settings (either in laboratories or field-deployed enclosures) or have involved visual observations around single cables. No EMF receptor interaction studies have been conducted in relation to multiple subsea cables, even around existing offshore wind farms, so there is no evidence to enable cumulative effects assessments to be undertaken, and no other data about this topic exist from other industries.

Additional research is needed to determine the specific environmental impacts of EMFs on the aquatic life highlighted in Figure 5.2. This knowledge will be required because the more extensive EMFs associated with future MRE and subsea cable deployments will require a greater degree of confidence than currently exists. The targeted priorities for future research include the following:

- The sources and intensity of EMFs emitted by subsea cables are directly determined by the cable characteristics and the power being transmitted. Quantifying these parameters in the aquatic environment is crucial for characterizing emissions and for accurate modeling. Deployment of small-scale devices is required to gather data to quantify the EMFs related to power transmission.
- Cables and MRE devices are part of a whole power system of electrical generation and transmission infrastructure. Each of the different parts will have a role in the variability of the EMFs emitted. Understanding the whole power system and how its different parts influence EMF variability is important for determining the EMF environment encountered by receptor species. In addition, evidence that wide AC fields are associated with DC cables (Hutchison et al. 2018) makes the interpretation of the biological effects of EMFs from DC cables more complex.

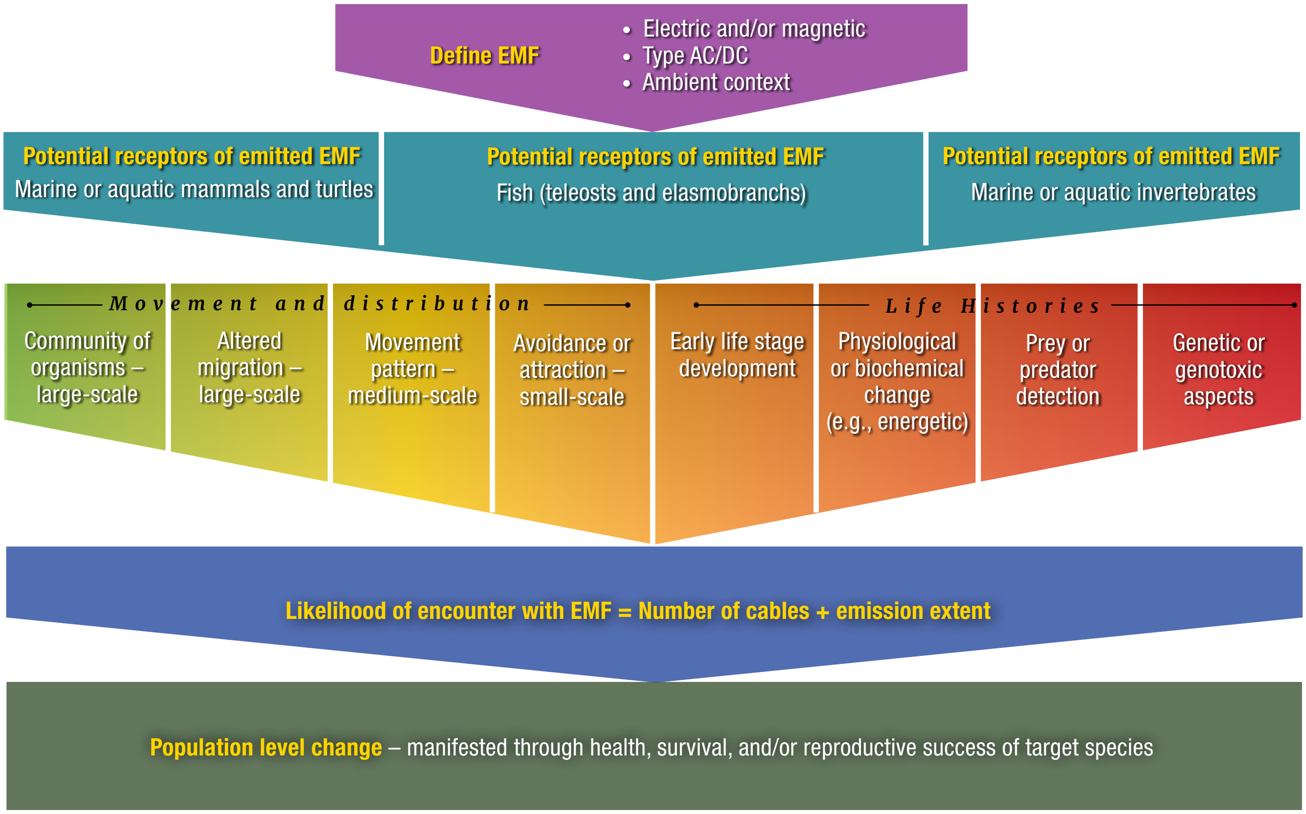


Figure 5.2. The key elements that need to be considered when assessing the environmental impact of electromagnetic fields (EMFs) on sensitive receptors. If a population-level change is demonstrated, there is the potential for cumulative or cascading effects at the ecological community level. (Graphic by Robyn Ricks)

- Field measurements of EMF intensity and its variability within the environment are required to better predict the actual EMF emitted. To date, some electromagnetic models predict EMFs similar to those of the small number of cables actually measured; however, where cables are not perfectly grounded or have leakage currents, further EMFs can also propagate, and models are not set up to predict these situations. These other EMFs may be relevant to the response of sensitive receptors and may require ambient measurements of EMFs at MRE development sites. Measuring the environmental EMF requires equipment that has the necessary sensitivity and accuracy to simultaneously measure the E- and B-fields. To date, only a handful of devices have been built to achieve these measurements, which are vital for validating EMF models. Therefore, affordable methods and equipment for measuring EMFs should be developed so that measurements taken with these instruments at MRE project sites can be compared to the power output of the devices.
- Understanding the relationship between EMFs and sensitive receptor species requires dose-response studies. If the effects are determined to be significant and negative, then appropriate mitigation measures may need to be developed. Given the current lack of sufficient evidence, additional studies of the most sensitive life stages of receptor animals to exposure to different EMFs (sources, intensities) are required and should be focused on the early embryonic and juvenile life stages of elasmobranchs, crustacea, mollusks, and sea turtles.
- Laboratory studies of species response to EMFs at different intensities and durations will be required to determine the thresholds for species-specific and life stage-specific dose responses. The threshold indicators could be developmental, physiological, genetic, and/or behavioral.
- Field studies using modern tagging and tracking systems will provide insight into behavioral and, in some cases, physiological evidence for determining the potential effects on mobile receptors of encountering multiple cables. These types of studies may be required when considering the installation of cable networks and large arrays of MRE devices. The findings should be collected with regard to their use in modeling the exposure likelihood for determining dose-response scenarios and applying population-based approaches (e.g., ecological modeling).
- Data gaps exist between the interaction of pelagic species (like pelagic sharks, marine mammals or fishes) and dynamic cables (i.e., cables in the water column). These gaps remain in part because of difficulties in evaluating impacts at population scales around these deployments (Taormina et al. 2018). Field-tagging studies can be used to improve the knowledge base.
- Long-term and *in situ* studies are needed to address the question of the effects of chronic EMF exposure on egg development, hatching success, and larval fitness. Furthermore, because cables may be protected and stabilized with rock armor or artificial structures, the potential role of any habitat/refuge associated with subsea cables needs to be considered. Because some of these artificial structures are now being designed to attract species of interest (e.g., commercial species), an important question has arisen about determining whether their role as suitable habitat may be counteracted by potentially "negative" impacts of EMFs emitted by the electrical cable.
- To determine whether an effect is negative, demonstration of the effect at the biologically relevant unit of the species population is required (Figure 5.2). Impacts can only be determined through replicated studies that show consistent evidence of a response.
- Because EMFs are associated with any subsea transmission cable, regardless of the MRE device, the collection and sharing of EMF characteristics should be encouraged and facilitated. If local conditions are also taken into consideration, their consideration will assist with assessments of similar cables in different environments.
- To date, there are no environmental standards or guidelines for subsea cable deployment or the measurement of EMFs. Synthesizing current knowledge requires a number of assumptions and, because the nature of the knowledge is patchy, there are no apparent significant environmental impacts that require regulation. This interpretation and the associated assumptions will likely need to be reviewed in the future as the knowledge and understanding of subsea conditions expands, particularly when considering the planned larger power-rated cables, greater networks of MREs, and the subsea infrastructure.

5.6. CONCLUSION

Since the publication of the *2016 State of the Science* report, which highlighted significant gaps in the knowledge of the impacts of EMFs from MRE on receptive species, more targeted research has increased the knowledge base. This has increased our understanding of whether the interactions between receptive species and EMFs have any biological significance that could translate into ecological impacts. New research, both field and laboratory studies, has shown measurable effects and responses to E- and/or B-fields on a small number of individual species (behavioral, physiological, developmental and genetic levels), but not at the EMF intensities associated with MRE. However, an effect or response to MRE EMFs does not necessarily mean there are impacts. Currently, conclusive evidence is insufficient and additional knowledge about receptor species (at different life stages), exposure to different EMFs (sources, intensities), and the determination of the EMF environment is needed. Based on the knowledge to date, biological or ecological impacts associated with MRE subsea power cables may be weak or moderate at the scale that is currently being considered or planned. It is important, however, to acknowledge that this assessment comes from a handful of studies and that data about impacts are scarce, so significant uncertainties concerning electromagnetic effects remain. Because EMFs are associated with any subsea transmission cable, the collection and sharing of EMF characteristics should be encouraged and facilitated, for example, by making these practices a condition of permissions being granted for MRE deployments. Taking local conditions into consideration will help with future assessments of similar cables in different environments to assist the MRE industry.

5.7. REFERENCES

Albert, L., Deschamps, F., Jolivet, A., Olivier, F., Chauvaud, L., and Chauvaud, S. 2020. A current synthesis on the effects of electric and magnetic fields emitted by submarine power cables on invertebrates. *Marine Environmental Research*, 159, 104958. doi:10.1016/j.marenvres.2020.104958 *https://tethys.pnnl.gov/publications/current-synthesis-effects-electric-magnetic-fields-emitted-submarine-power-cables*

Anderson, J. M., Clegg, T. M., Véras, L. V. M. V. Q., and Holland, K. N. 2017. Insight into shark magnetic field perception from empirical observations. *Scientific Reports*, 7(1), 11042. doi:10.1038/s41598-017-11459-8 *https://tethys.pnnl.gov/publications/insight-shark-magnetic-field-perception-empirical-observations*

Bellono, N.W., Leitch, D., and Julius, D. 2018. Molecular tuning of electroreception in sharks and skates. *Nature*, 558, 122-126. doi:10.1038/s41586-018-0160-9 *https://tethys.pnnl.gov/publications/molecular-tuning-electroreception-sharks-skates*

Binhi, V. N., and Prato, F. S. 2017. Biological effects of the hypomagnetic field: An analytical review of experiments and theories. *PLoS ONE*, 12(6), e0179340. doi:10.1371/journal.pone.0179340 *https://tethys.pnnl.gov/publications/biological-effects-hypomagnetic-field-analytical-review-experiments-theories*

Boehlert, G., and Gill, A. 2010. Environmental and Ecological Effects of Ocean Renewable Energy Development: A Current Synthesis. *Oceanography*, 23(2), 68-81. *https://tethys.pnnl.gov/publications/environmental-ecological-effects-ocean-renewable-energy-development-current-synthesis*

Brysiewicz, A., Formicki, K., Tański, A., and Wesołowski, P. 2017. Magnetic field effect on melanophores of the European whitefish *Coregonus lavaretus* (Linnaeus, 1758) and vendace *Coregonus albula* (Linnaeus, 1758) (Salmonidae) during early embryogenesis. *The European Zoological Journal*, 84(1), 49-60. doi:10.1080/11250003.2016.1272644 *https://tethys.pnnl.gov/publications/magnetic-field-effect-melanophores-european-whitefish-coregonus-lavaretus-linnaeus*

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewski, G., Staines, G., Gill, A., Hutchison, I., O'Hagan, A., Simas, T., Bald, J., Sparling, C., Wood, J., and Masden, E. 2016. Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. *https://tethys.pnnl.gov/publications/state-of-the-science-2016*

de Haan, D., Fosseidengen, J. E., Fjelldal, P. G., Burggraaf, D., and Rijnsdorp, A. D. 2016. Pulse trawl fishing: characteristics of the electrical stimulation and the effect on behaviour and injuries of Atlantic cod (*Gadus morhua*). *ICES Journal of Marine Science,* 73(6), 1557-1569. doi:10.1093/icesjms/fsw018 *https://tethys.pnnl.gov/publications/pulse-trawl-fishing-characteristics-electrical-stimulation-effect-behaviour-injuries*

Dhanak, M., Coulson, R., Dibiasio, C., Frankenfield, J., Henderson, E., Pugsley, D., and Valdes, G. 2016. Assessment of Electromagnetic Field Emissions from Subsea Cables. Paper presented at the 4th Marine Energy Technology Symposium, Washington, D.C. *https://tethys.pnnl.gov/publications/assessment-electromagnetic-field-emissions-subsea-cables*

Diebel, C. E., Proksch, R., Green, C. R., Neilson, P., and Walker, M. M. 2000. Magnetite defines a vertebrate magnetoreceptor. *Nature,* 406(6793), 299-302. doi:10.1038/35018561 *https://tethys.pnnl.gov/publications/magnetite-defines-vertebrate-magnetoreceptor*

Dunham, A., Pegg, J. R., Carolsfeld, W., Davies, S., Murfitt, I., and Boutillier, J. 2015. Effects of submarine power transmission cables on a glass sponge reef and associated megafaunal community. *Marine Environmental Research,* 107, 50-60. doi:10.1016/j.marenvres.2015.04.003 *https://tethys.pnnl.gov/publications/effects-submarine-power-transmission-cables-glass-sponge-reef-associated-megafaunal*

Dunlop, E. S., Reid, S. M., and Murrant, M. 2016. Limited influence of a wind power project submarine cable on a Laurentian Great Lakes fish community. *Journal of Applied Ichthyology,* 32(1), 18-31. doi:10.1111/jai.12940 *https://tethys.pnnl.gov/publications/limited-influence-wind-power-project-submarine-cable-laurentian-great-lakes-fish*

Fey, D. P., Jakubowska, M., Greszkiewicz, M., Andrulewicz, E., Otremba, Z., and Urban-Malinga, B. 2019a. Are magnetic and electromagnetic fields of anthropogenic origin potential threats to early life stages of fish? *Aquatic Toxicology,* 209, 150-158. doi:10.1016/j.aquatox.2019.01.023 *https://tethys.pnnl.gov/publications/are-magnetic-electromagnetic-fields-anthropogenic-origin-potential-threats-early-life*

Fey, D. P., Greszkiewicz, M., Otremba, Z., and Andrulewicz, E. 2019b. Effect of static magnetic field on the hatching success, growth, mortality, and yolk-sac absorption of larval Northern pike *Esox lucius. Science of the Total Environment,* 647, 1239-1244. doi:10.1016/j.scitotenv.2018.07.427 *https://tethys.pnnl.gov/publications/effect-static-magnetic-field-hatching-success-growth-mortality-yolk-sac-absorption*

Formicki, K., Korzelecka-Orkisz, A., and Tański, A. 2019. Magnetoreception in fish. *Journal of Fish Biology,* 95(1), 73-91. doi:10.1111/jfb.13998 *https://tethys.pnnl.gov/publications/magnetoreception-fish*

Gill, A. B., Gloyne-Philips, I., Kimber, J., and Sigray, P. 2014. Marine Renewable Energy, Electromagnetic (EM) Fields and EM-Sensitive Animals. In M. A. Shields and A. I. L. Payne (Eds.), *Marine Renewable Energy Technology and Environmental Interactions* (pp. 61-79). Dordrecht: Springer Netherlands. *https://tethys.pnnl.gov/publications/marine-renewable-energy-electromagnetic-em-fields-em-sensitive-animals*

Hutchison, Z., Sigray, P., He, H., Gill, A., King, J., and Gibson, C. 2018. Electromagnetic Field (EMF) Impacts on Elasmobranch (shark, rays, and skates) and American Lobster Movement and Migration from Direct Current Cables (OCS Study BOEM 2018-003). Report by University of Rhode Island for Bureau of Ocean Energy Management, U.S. Department of Interior, Sterling, VA. *https://tethys.pnnl.gov/publications/electromagnetic-field-emf-impacts-elasmobranch-shark-rays-skates-american-lobster*

Hutchison, Z. L., Gill, A. B., Sigray, P., He, H., and King, J. W. 2020. Anthropogenic electromagnetic fields (EMF) influence the behaviour of bottom-dwelling marine species. *Scientific Reports,* 10(1), 4219. doi:10.1038/s41598-020-60793-x *https://tethys.pnnl.gov/publications/anthropogenic-electromagnetic-fields-emf-influence-behaviour-bottom-dwelling-marine*

Huveneers, C., Rogers, P. J., Semmens, J. M., Beckmann, C., Kock, A. A., Page, B., and Goldsworthy, S. D. 2013. Effects of an Electric Field on White Sharks: In Situ Testing of an Electric Deterrent. *PLoS ONE*, 8(5), e62730. doi:10.1371/journal.pone.0062730 *https://tethys.pnnl.gov/publications/effects-electric-field-white-sharks-situ-testing-electric-deterrent*

Jakubowska, M., Urban-Malinga, B., Otremba, Z., and Andrulewicz, E. 2019. Effect of low frequency electromagnetic field on the behavior and bioenergetics of the polychaete *Hediste diversicolor. Marine Environmental Research*, 150, 104766. doi:10.1016/j.marenvres.2019.104766 *https://tethys.pnnl.gov/publications/effect-low-frequency-electromagnetic-field-behavior-bioenergetics-polychaete-hediste*

Kalmijn, A. J. 1982. Electric and magnetic field detection in elasmobranch fishes. *Science*, 218(4575), 916-918. doi:10.1126/science.7134985 *https://tethys.pnnl.gov/publications/electric-magnetic-field-detection-elasmobranch-fishes*

Kantserova, N. P., Krylov, V. V., Lysenko, L. A., Ushakova, N. V., and Nemova, N. N. 2017. Effects of Hypomagnetic Conditions and Reversed Geomagnetic Field on Calcium-Dependent Proteases of Invertebrates and Fish. *Izvestiya, Atmospheric and Oceanic Physics*, 53(7), 719-723. doi:10.1134/S0001433817070040 *https://tethys.pnnl.gov/publications/effects-hypomagnetic-conditions-reversed-geomagnetic-field-calcium-dependent-proteases*

Kavet, R., Wyman, M. T., and Klimley, A. P. 2016. Modeling Magnetic Fields from a DC Power Cable Buried Beneath San Francisco Bay Based on Empirical Measurements. *PLoS ONE*, 11(2), e0148543. doi:10.1371/journal.pone.0148543 *https://tethys.pnnl.gov/publications/modeling-magnetic-fields-dc-power-cable-buried-beneath-san-francisco-bay-based*

Kirschvink, J. L. 1997. Homing in on vertebrates. *Nature*, 390(6658), 339-340. doi:10.1038/36986 *https://tethys.pnnl.gov/publications/magnetoreception-homing-vertebrates*

Kirschvink, J. L., and Gould, J. L. 1981. Biogenic magnetite as a basis for magnetic field detection in animals. *Biosystems*, 13(3), 181-201. doi:10.1016/0303-2647(81)90060-5 *https://tethys.pnnl.gov/publications/biogenic-magnetite-basis-magnetic-field-detection-animals*

Kirschvink, J. and Walker, M. 1985. Particle-Size Considerations for Magnetite-Based Magnetoreceptors. In Kirschvink, J., Jones, D., and MacFadden, B. (Eds.), *Magnetite Biomineralization and Magnetoreception in Organisms* (pp. 243-254). New York, NY: Plenum Press. *https://tethys.pnnl.gov/publications/particle-size-considerations-magnetite-based-magnetoreceptors*

Kuz'mina, V. V., Ushakova, N. V., and Krylov, V. V. 2015. The effect of magnetic fields on the activity of proteinases and glycosidases in the intestine of the crucian carp *Carassius carassius. Biology Bulletin*, 42(1), 61-66. doi:10.1134/S1062359015010070 *https://tethys.pnnl.gov/publications/effect-magnetic-fields-activity-proteinases-glycosidases-intestine-crucian-carp*

Love, M. S., Nishimoto, M. M., Clark, S., McCrea, M., and Bull, A. S. 2017a. Assessing potential impacts of energized submarine power cables on crab harvests. *Continental Shelf Research*, 151, 23-29. doi:10.1016/j.csr.2017.10.002 *https://tethys.pnnl.gov/publications/assessing-potential-impacts-energized-submarine-power-cables-crab-harvests*

Love, M. S., Nishimoto, M. M., Snook, L., Schroeder, D. M., and Scarborough Bull, A. 2017b. A Comparison of Fishes and Invertebrates Living in the Vicinity of Energized and Unenergized Submarine Power Cables and Natural Sea Floor off Southern California, USA. *Journal of Renewable Energy*, 13. doi:10.1155/2017/8727164 *https://tethys.pnnl.gov/publications/comparison-fishes-invertebrates-living-vicinity-energized-unenergized-submarine-power*

Newton, K. C. 2017. Cognitive and Magnetosensory Ecology of the Yellow Stingray, *Urobatis jamaicensis.* Doctoral Dissertation, Florida Atlantic University, Boca Raton, FL. *https://tethys.pnnl.gov/publications/cognitive-magnetosensory-ecology-yellow-stingray-urobatis-jamaicensis*

Newton, K. C., Gill, A. B., and Kajiura, S. M. 2019. Electroreception in marine fishes: chondrichthyans. *Journal of Fish Biology*, 95(1), 135-154. doi:10.1111/jfb.14068 *https://tethys.pnnl.gov/publications/electroreception-marine-fishes-chondrichthyans*

Newton, K. C., and Kajiura, S. M. 2017. Magnetic field discrimination, learning, and memory in the yellow stingray (*Urobatis jamaicensis*). *Animal Cognition*, 20; 603-614. doi:10.1007/s10071-017-1084-8 *https://tethys.pnnl.gov/publications/magnetic-field-discrimination-learning-memory-yellow-stingray-urobatis-jamaicensis*

Normandeau Associates Inc., Exponent Inc., Tricas, T., and Gill, A. 2011. Effects of EMFs from Undersea Power Cables on Elasmobranchs and other Marine Species (OCS Study BOEMRE 2011-09). Report by Normandeau Associates Inc. for Bureau of Ocean Energy Management Pacific OCS Region, U.S. Department of the Interior, Camarillo, CA. *https://tethys.pnnl.gov/publications/effects-emfs-undersea-power-cables-elasmobranchs-other-marine-species*

Nyqvist, D., Durif, C., Johnsen, M. G., De Jong, K., Forland, T. N., and Sivle, L. D. 2020. Electric and magnetic senses in marine animals, and potential behavioral effects of electromagnetic surveys. *Marine Environmental Research,* 155, 104888. doi:10.1016/j.marenvres.2020.104888 *https://tethys.pnnl.gov/publications/electric-magnetic-senses-marine-animals-potential-behavioral-effects-electromagnetic*

Patullo, B. W., and Macmillan, D. L. 2010. Making sense of electrical sense in crayfish. *The Journal of Experimental Biology,* 213(4), 651. doi:10.1242/jeb.039073 *https://tethys.pnnl.gov/publications/making-sense-electrical-sense-crayfish*

Peters, R. C., Eeuwes, L. B. M., and Bretschneider, F. 2007. On the electrodetection threshold of aquatic vertebrates with ampullary or mucous gland electroreceptor organs. *Biological Reviews,* 82(3), 361-373. doi:10.1111/j.1469-185X.2007.00015.x *https://tethys.pnnl.gov/publications/electrodetection-threshold-aquatic-vertebrates-ampullary-or-mucous-gland*

Pettersson, P., and Schonborg, N. 1997. Reduction of power system magnetic field by configuration twist. *IEEE Transactions on Power Delivery,* 12(4), 1678-1683. doi:10.1109/61.634190 *https://tethys.pnnl.gov/publications/reduction-power-system-magnetic-field-configuration-twist*

Polet, H., Delanghe, F., and Verschoore, R. 2005. On electrical fishing for brown shrimp (*Crangon crangon*): I. Laboratory experiments. *Fisheries Research,* 72(1), 1-12. doi:10.1016/j.fishres.2004.10.016 *https://tethys.pnnl.gov/publications/electrical-fishing-brown-shrimp-crangon-crangon-i-laboratory-experiments*

Richards, R. J., Raoult, V., Powter, D. M., and Gaston, T. F. 2018. Permanent magnets reduce bycatch of benthic sharks in an ocean trap fishery. *Fisheries Research,* 208, 16-21. doi:10.1016/j.fishres.2018.07.006 *https://tethys.pnnl.gov/publications/permanent-magnets-reduce-bycatch-benthic-sharks-ocean-trap-fishery*

Scott, K., Harsanyi, P., and Lyndon, A. R. 2018. Understanding the effects of electromagnetic field emissions from Marine Renewable Energy Devices (MREDs) on the commercially important edible crab, *Cancer pagurus* (L.). *Marine Pollution Bulletin,* 131, 580-588. doi:10.1016/j.marpolbul.2018.04.062 *https://tethys.pnnl.gov/publications/understanding-effects-electromagnetic-field-emissions-marine-renewable-energy-devices*

Sherwood, J., Chidgey, S., Crockett, P., Gwyther, D., Ho, P., Stewart, S., Strong, D., Whitely, B., and Williams, A. 2016. Installation and operational effects of a HVDC submarine cable in a continental shelf setting: Bass Strait, Australia. *Journal of Ocean Engineering and Science,* 1(4), 337-353. doi:10.1016/j.joes.2016.10.001 *https://tethys.pnnl.gov/publications/installation-operational-effects-hvdc-submarine-cable-continental-shelf-setting-bass*

Siegenthaler, A., Niemantsverdriet, P. R. W., Laterveer, M., and Heitkönig, I. M. A. 2016. Aversive responses of captive sandbar sharks *Carcharhinus plumbeus* to strong magnetic fields. *Journal of Fish Biology,* 89(3), 1603-1611. doi:10.1111/jfb.13064 *https://tethys.pnnl.gov/publications/aversive-responses-captive-sandbar-sharks-carcharhinus-plumbeus-strong-magnetic-fields*

Snyder, D., Bailey, W., Palmquist, K., Cotts, B., and Olsen, K. 2019. Evaluation of Potential EMF Effects on Fish Species of Commercial or Recreational Fishing Importance in Southern New England (OCS Study BOEM 2019-049). Report by CSA Ocean Sciences Inc. and Exponent for Bureau of Ocean Energy Management, U.S. Department of the Interior, Sterling, VA. *https://tethys.pnnl.gov/publications/evaluation-potential-emf-effects-fish-species-commercial-or-recreational-fishing*

Soetaert, M., Chiers, K., Duchateau, L., Polet, H., Verschueren, B., and Decostere, A. 2014. Determining the safety range of electrical pulses for two benthic invertebrates: brown shrimp (*Crangon crangon L.*) and ragworm (*Alitta virens S.*). *ICES Journal of Marine Science,* 72(3), 973-980. doi:10.1093/icesjms/fsu176 *https://tethys.pnnl.gov/publications/determining-safety-range-electrical-pulses-two-benthic-invertebrates-brown-shrimp*

Stanford, T. 1971. Motionally Induced Electric and Magnetic Fields in the Sea. *Journal of Geophysical Research,* 76(15), 3476-3492. doi:10.1029/JC076i015p03476 *https://tethys.pnnl.gov/publications/motionally-induced-electric-magnetic-fields-sea*

Stankevičiūtė, M., Jakubowska, M., Pažusienė, J., Makaras, T., Otremba, Z., Urban-Malinga, B., Fey, D. P., Greszkiewicz, M., Sauliutė, G., Baršienė, J., and Andrulewicz, E. 2019. Genotoxic and cytotoxic effects of 50 Hz 1 mT electromagnetic field on larval rainbow trout *(Oncorhynchus mykiss)*, Baltic clam *(Limecola balthica)* and common ragworm *(Hediste diversicolor). Aquatic Toxicology,* 208, 109-117. doi:10.1016/j.aquatox.2018.12.023 *https://tethys.pnnl.gov/publications/genotoxic-cytotoxic-effects-50-hz-1-mt-electromagnetic-field-larval-rainbow-trout*

Taormina, B., Bald, J., Want, A., Thouzeau, G., Lejart, M., Desroy, N., and Carlier, A. 2018. A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions. *Renewable and Sustainable Energy Reviews,* 96, 380-391. doi:10.1016/j.rser.2018.07.026 *https://tethys.pnnl.gov/publications/review-potential-impacts-submarine-power-cables-marine-environment-knowledge-gaps*

Taormina, B., Di Poi, C., Agnalt, A.-L., Carlier, A., Desroy, N., Escobar-Lux, R. H., D'eu, J.-F., Freytet, F., and Durif, C. M. F. 2020. Impact of magnetic fields generated by AC/DC submarine power cables on the behavior of juvenile European lobster *(Homarus gammarus). Aquatic Toxicology,* 220, 105401. doi:10.1016/j.aquatox.2019.105401 *https://tethys.pnnl.gov/publications/impact-magnetic-fields-generated-acdc-submarine-power-cables-behavior-juvenile*

Tesch, F. W., and Lelek, A. 1973. Directional behaviour of transplanted stationary and migratory forms of the eel, *Anguilla Anguilla,* in a circular tank. *Netherlands Journal of Sea Research,* 7, 46-52. doi:10.1016/0077-7579(73)90031-8 *https://tethys.pnnl.gov/publications/directional-behaviour-transplanted-stationary-migratory-forms-eel-anguilla-anguilla*

Thomsen, F., Gill, A., Kosecka, M., Andersson, M., André, M., Degraer, S., Folegot, T. G., J., Judd, A., Neumann, T., Norro, A., Risch, D., Sigray, P., Wood, D., and Wilson, B. 2015. MaRVEN - Environmental Impacts of Noise, Vibrations and Electromagnetic Emissions from Marine Renewable Energy. Report No. RTD-K3-2012-MRE. Report by Danish Hydraulic Institute for European Union, Brussels. *https://tethys.pnnl.gov/publications/marven-environmental-impacts-noise-vibrations-electromagnetic-emissions-marine*

Tricas, T. C., and New, J. G. 1997. Sensitivity and response dynamics of elasmobranch electrosensory primary afferent neurons to near threshold fields. *Journal of Comparative Physiology A,* 182(1), 89-101. doi:10.1007/s003590050161 *https://tethys.pnnl.gov/publications/sensitivity-response-dynamics-elasmobranch-electrosensory-primary-afferent-neurons*

Walker, M. M., Kirschvink, J. L., Ahmed, G., and Dizon, A. E. 1992. Evidence that fin whales respond to the geomagnetic field during migration. *Journal of Experimental Biology, 171(1), 67. https://tethys.pnnl.gov/publications/evidence-fin-whales-respond-geomagnetic-field-during-migration*

Westerberg, H., and Begout-Anras, M-L. 2000. Orientation of silver eel (*Anguilla anguilla*) in a disturbed geomagnetic field. In Advances in telemetry, Proceedings of the third conference on fish telemetry in Europe. Norwich, England, June 1999. Moore, A., andI Russel, I. (eds.), CEFAS, Lowestoft.

Westerberg, H., and Lagenfelt, I. 2008. Sub-sea power cables and the migration behaviour of the European eel. *Fisheries Management and Ecology,* 15(5-6), 369-375. doi:10.1111/j.1365-2400.2008.00630.x *https://tethys.pnnl.gov/publications/sub-sea-power-cables-migration-behaviour-european-eel*

Woodruff, D., Schultz, I., Marshall, K., Ward, J., and Cullinan, V. 2012. Effects of Electromagnetic Fields on Fish and Invertebrates Task 2.1.3: Effects on Aquatic Organisms Fiscal Year 2011 Progress Report. Report No. PNNL-20813. Report by Pacific Northwest National Laboratory for U.S. Department of Energy, Washington DC. *https://tethys.pnnl.gov/publications/effects-electromagnetic-fields-fish-invertebrates-task-213-effects-aquatic-organisms*

Wyman, M. T., Peter Klimley, A., Battleson, R. D., Agosta, T. V., Chapman, E. D., Haverkamp, P. J., Pagel, M. D., and Kavet, R. 2018. Behavioral responses by migrating juvenile salmonids to a subsea high-voltage DC power cable. *Marine Biology,* 165(8), 134. doi:10.1007/s00227-018-3385-0 *https://tethys.pnnl.gov/publications/behavioral-responses-migrating-juvenile-salmonids-subsea-high-voltage-dc-power-cable*

NOTES

Risk to Animals from Electromagnetic Fields Emitted by Electric Cables and Marine Renewable Energy Devices

Gill, A.B. and M. Desender. 2020. Risk to Animals from Electromagnetic Fields Emitted by Electric Cables and Marine Renewable Energy Devices. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 86-103). doi:10.2172/1633088

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

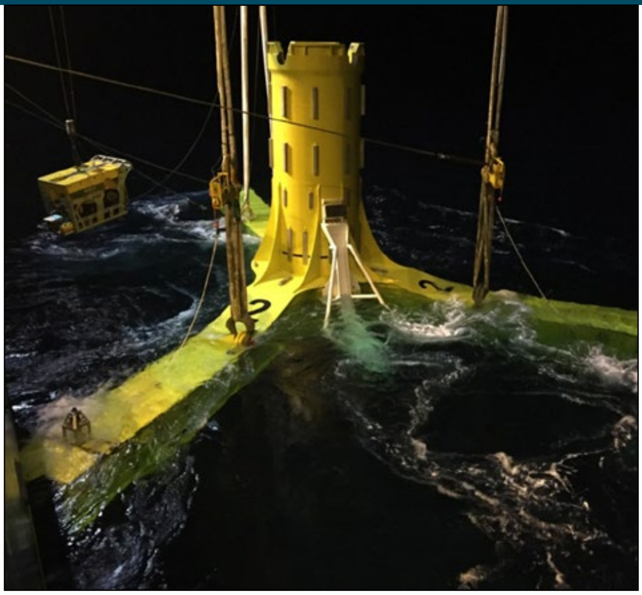
Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

OES OCEAN ENERGY SYSTEMS An IEA Technology Initiative

OES ENVIRONMENTAL

Pacific Northwest NATIONAL LABORATORY



Chapter author: Lenaïg G. Hemery
Contributor: Deborah J. Rose

Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices

Most marine renewable energy (MRE) devices must be attached to the seafloor in some way, either through gravity foundations, pilings, or anchors, and with mooring lines, transmission cables, and devices themselves in the water column. Physical changes in benthic and pelagic habitats have the potential to alter species occurrence or abundance at a localized scale, lead to some level of habitat loss, provide opportunities for colonization by non-native species, alter patterns of ecological succession, modify ecosystem functioning, and affect behavioral responses of marine organisms. The transformation of the seafloor and/or water column habitat to new hard substratum because of the presence of the MRE devices may also lead to artificial reef effects or changes in animal behavior.

While there is no indication that MRE devices affect marine habitats differently than other structures currently and historically placed in the ocean, regulators and stakeholders may continue to have concerns.

6.1. IMPORTANCE OF THE ISSUE

The potential changes in marine habitats induced by MRE may be similar to those of other industries that interact with the seabed and/or have water column or surface expression, like offshore wind farms (OWFs), oil and gas platforms (OGPs), navigation buoys, or communication cables. Regulators and stakeholders have raised concerns about several effects on marine habitats caused by these other industries (e.g., modification of benthic and pelagic habitats, artificial reef effect, biofouling by non-native species). As Want and Porter (2018) wrote, "with a general trend towards stricter statutory environmental controls, the onus will be on the MRE industry to demonstrate minimal disturbance." Deploying single MRE devices and/or arrays of devices in a sustainable way means assuring that environmental risks related to a change in habitat (especially habitats for threatened or endangered species) are identified at each site, avoided, managed, and/or mitigated. Experience at OWFs provides evidence that local biodiversity may drastically change in the vicinity of an MRE device over time, thereby modifying the resilience of the ecosystem (Causon and Gill 2018). However, because marine ecosystems are exposed to natural environmental fluctuations at various temporal and spatial scales, the ability to detect changes due to anthropogenic pressures will depend on the robustness of the survey design (Bicknell et al. 2019; Sheehan et al. 2018). In addition, the cumulative effects of activities across diverse sectors may be substantial at the scale of an MRE deployment site and will need to be taken into account to understand and manage changes in the marine environment (Causon and Gill 2018; Wilding et al. 2017).

The distribution of benthic communities is strongly influenced by the depth and characteristics of the seafloor as well as the current speed, and few studies have described the natural variability of assemblages in high-energy-flow environments (Kregting et al. 2016). The exploitation of tidal energy requires high tidal velocities that are usually associated with a seafloor dominated by coarse sediments, boulders, or rocky outcrops. Benthic communities associated with these habitats are typically stress-tolerant, opportunistic organisms that are highly influenced by physical processes and natural variability, such as current velocity and sediment dynamics (Kregting et al. 2016; O'Carroll et al. 2017a). These environments are often rich in biodiversity and there are concerns that the turbulent wake of a tidal turbine might alter the local benthic communities (Kregting et al. 2016; O'Carroll et al. 2017a). The wake may also alter the phytoplankton and primary production in the water column, especially near large-scale arrays that may have the potential to change the hydrodynamics of the ambient flow (Schuchert et al. 2018). Laying cable may prove challenging in such environments, compared to those that feature a soft-sediment seafloor, and pose risks of damaging benthic habitats (Taormina et al. 2018).

Any structure left long enough in the marine environment has the potential to be colonized by fouling organisms and then act as an artificial reef by attracting fish and other mobile animals; MRE devices are no different, especially because of their seabed moorings and associated infrastructures (Alexander et al. 2016). While a single tidal turbine or wave energy converter (WEC) has a relatively limited ecological footprint, an array of devices may act as a network of interconnected artificial reef, in a way similar to that of OWFs (Causon and Gill 2018). This reef effect may spread at the ecosystem scale, with yet-to-be-identified effects on the structure and functioning of local and regional food webs (Raoux et al. 2017).

As the worldwide economy keeps growing and maritime shipping lanes expand, dispersion and propagation of non-native species is becoming a more prominent issue for the marine environment, especially in nearshore habitats. MRE devices may act as "stepping stones" for many of these non-native species to colonize new places and cross biogeographical barriers (Adams et al. 2014; Wilding et al. 2017). The connectedness of deployment sites with harbors and marinas, more particularly those where non-native species have been documented to occur, is an important consideration to keep in mind during the initial planning of a project (Bray et al. 2017).

6.2. SUMMARY OF KNOWLEDGE THROUGH 2016

Before 2016, there were only a few deployed wave and tidal devices, notably the SeaGen tidal turbine in Northern Ireland, the OpenHydro tidal generator in the Orkney Islands of Scotland, European Marine Energy Centre tidal devices in the Orkney Islands, and the Lysekil WEC in Sweden. OWFs have been found to be reasonably comparable to MRE devices in terms of their effects on artificial reef and benthic habitats (Kramer et al. 2015), and they were used as a surrogate for many of the analyzed effects of wave and tidal devices in 2016. Additional structures in the ocean, such as fish aggregating devices, offshore oil platforms, sunken vessels, artificial reefs, and navigation buoys, were also used as surrogate devices for predicting the effects of MRE devices on benthic habitats (Arena et al. 2007; Clynick et al. 2008; Kramer et al. 2015; Page et al. 1999; Vaselli et al. 2008; Wehkamp and Fischer 2013).

By 2016, several studies showed no impacts of MRE devices or OWF locations on benthic communities or species abundance (De Backer et al. 2014; Lindeboom et al. 2011, 2015; Wilhelmsson et al. 2006). Other studies examining benthic communities at the deployed OpenHydro tidal device in the Orkney Islands, Scotland, found increased abundance and diversity of fish and predators over time compared to a control site (Broadhurst et al. 2014; Broadhurst and Orme 2014). Benthic organisms and fish at the Lysekil WEC project site in Sweden were found to have higher biomass, density, species richness, and species diversity than the reference location because of the increased structural complexity of the seabed at the foundations, although the results were not statistically significant (Langhamer 2010; Langhamer and Wilhelmsson 2009).

At the SeaGen tidal turbine, organisms including mussels, barnacles, brittle stars, crabs, and more, have been found to colonize structures on the seafloor and in the water column (Keenan et al. 2011). Colonization of the vertical structure of offshore wind pilings by species such as blue mussels (*Mytilus edulis*) led to the creation of new habitats and thus colonization by other benthic organisms and reef fish (Krone et al. 2013; Maar et al. 2009). Keenan et al. (2011) also reported that benthic communities were different during each subsequent survey at the SeaGen tidal turbine. Changes detected in benthic communities over time were attributed to temporal variability and natural processes including species competition and succession. Overall, changes in community composition were similar across all sampling stations and the reference station. Under natural ocean conditions, benthic communities undergo succession with changes in the dominant species as the communities reach a dynamic mature state. This pattern of succession and the time needed to reach the mature state must be considered when monitoring benthic communities around MRE devices to determine whether changes are natural or caused by the presence of an MRE device or array.

Concerns have been expressed about MRE devices potentially providing opportunities for non-native species to colonize new areas and spread across habitats, especially with the additional connectivity provided by MRE arrays (Adams et al. 2014; Mineur et al. 2012). Although there have been reports of non-native species colonizing underwater structures associated with offshore wind devices (Langhamer 2012), few studies have examined the mechanisms for dissemination of non-native species or suggested that MRE devices pose a higher risk for invasions than other existing marine installations (Mineur et al. 2012).

The *2016 State of the Science* report (Copping et al. 2016) identified the following data gaps and priorities for future research regarding changes in habitats:

- Determine the effects of MRE devices (wave and tidal) in the field on benthic habitats, as opposed to relying on surrogate structures.
- Address the potential benthic and artificial reef effects from arrays or co-located wave and tidal sites to determine their cumulative impacts.
- Develop a framework of ecosystem changes that incorporates the potential for cascading effects as well as natural patterns of succession.
- Validate models of community change and artificial reef effects with field data.
- Determine whether MRE devices create novel stepping stones for non-native species.
- Monitor impacts on benthic communities at existing wave and tidal locations to evaluate and determine the extent of the response to installation and operation of MRE devices.

6.3. KNOWLEDGE GENERATED SINCE 2016

Several different types of WECs and tidal turbines have been tested in real conditions over the last decade at various locations. However, few have stayed in the water long enough (i.e., several years) to monitor and observe persistent or long-term environmental changes caused by the presence and functioning of the device. Most of the knowledge related to changes in habitats caused by MRE devices still comes from surrogate industries like OWFs, OGPs, or power and communication cables (Dannheim et al. 2019), as well as from a few modeling studies. However, the hard and sturdy structures of most OWFs and OGPs span the entire water column from the seafloor to the surface, while most MRE devices are either bottom-mounted without surface expression or floating and attached to the seafloor by mooring structures (e.g., Figure 6.1). Knowledge transfer from surrogate industries thus depends on the context.

Two main types of changes for the benthic and pelagic habitats are generated by MRE devices (Figure 6.1): damaging effects (e.g., trenching, footprint effect) and creation of habitats (e.g., biofouling, artificial reef, reserve effect). These habitat changes may also lead to indirect effects, for example facilitating the propagation of non-native invasive species.

6.3.1. ALTERATION OF EXISTING HABITATS AND RECOVERY TIMEFRAMES

The installation and operation of MRE devices may lead to alteration and/or loss of existing benthic habitats, for example during cable installation or due to turbulence and scouring around device and mooring foundations.

Trenching and Digging for Installation of Devices and Cables

There is currently a great diversity of tidal turbine and WEC technology designs, most of them floating or bottom-mounted. The loss of benthic habitat due to the footprint of anchors and foundations is widely acknowledged by decision-makers, particularly when vulnerable marine ecosystems or other fragile habitats have been identified during the siting process and avoidance and mitigation measures are taken (Greaves and Iglesias 2018). Cable laying to link MRE devices to an offshore substation and/or the onshore grid may lead

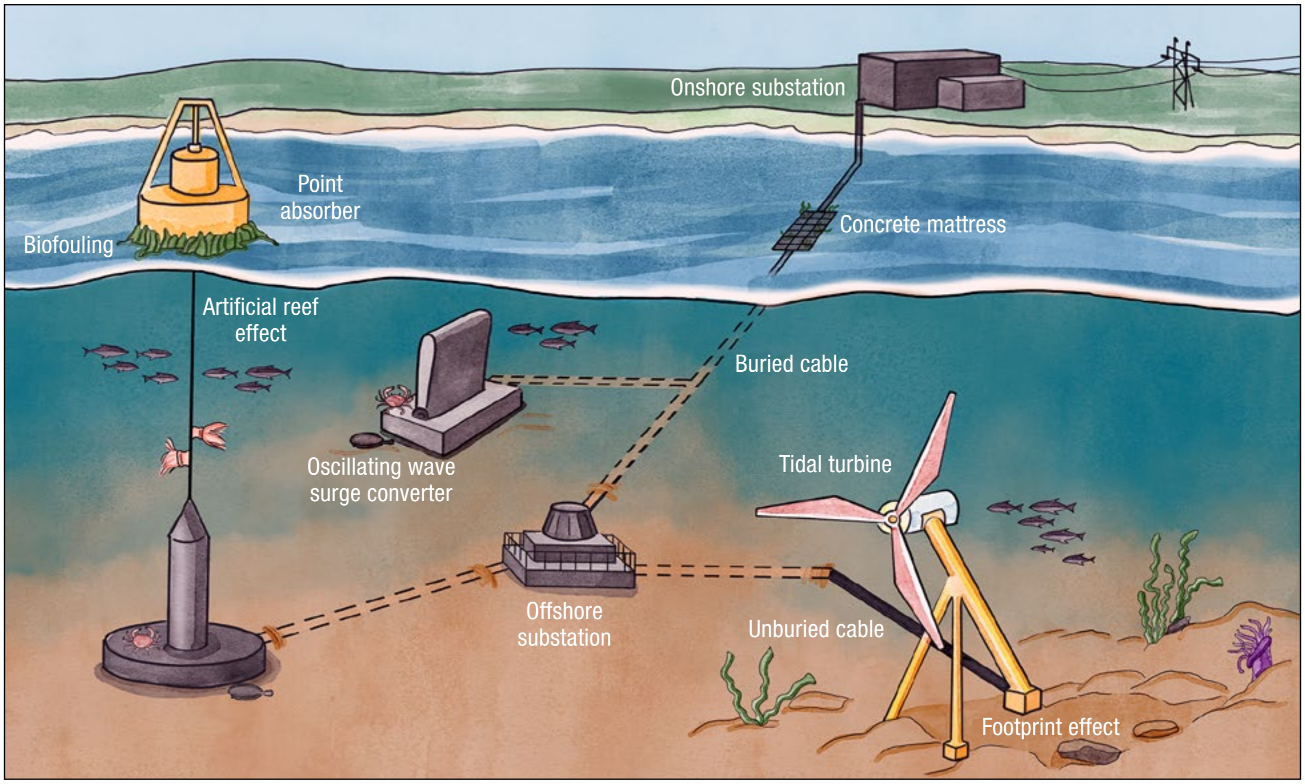


Figure 6.1. Schematic of various wave and tidal energy devices, and associated equipment, and their potential effects on the benthic and pelagic habitats. (Illustration by Rose Perry)

to direct disturbance or alteration of a much larger area of benthic habitats (i.e., following a path on the seafloor hundreds to thousands meters long), even though the physical disturbance of the seabed is very limited compared to other human activities, such as bottom fishing or deep-sea mining (Taormina et al. 2018). The cable-laying method used depends on the nature of the seafloor, and each method may result in different spatial and temporal scales of damage (Kraus and Carter 2018; Taormina et al. 2018).

Jetting and ploughing are among the favored methods for burying cables in soft sediments, the former resulting in a much wider disturbance strip than the latter (100 to 2000 m and 2 to 8 m respectively; Kraus and Carter 2018; Taormina et al. 2018). Depending on the wave and current dynamics, turbidity resulting from cable laying can persist for several days, thereby limiting the available light for primary producers, reducing prey detectability for fish and filtration efficiency for suspension-feeders. However, these effects are short-term, and resuspended sediment tends to settle in a matter of days (Taormina et al. 2018). Habitat recovery is site-specific, but seafloors where jetting or ploughing have been used to lay cables have shown rates of full recovery to pre-trenching benthic communities from two weeks to six years, similar to recovery rates for the sediment itself (Kraus and Carter 2018 and examples therein; Sheehan et al. 2018; Taormina et al. 2018). A subsequent effect of cables buried in the sediment is the localized increase in temperature at the cable-sediment interface, which has unknown consequences for benthic organisms (Taormina et al. 2018 and references therein).

Where the seafloor is dominated by unconsolidated or consolidated hard substrate, cables are usually laid on top of the sediment, sometimes encased in protective iron pipes or covered with concrete mattresses (Figure 6.2) or natural rocks (Kraus and Carter 2018; Sheehan et al. 2018; Taormina et al. 2018). In this case, disturbance is limited to the footprint of the cable itself and its protection material, unless unstabilized portions of the cable drag the surrounding seafloor if caught up in local hydrodynamic disturbances (Dunham et al. 2015; Taormina et al. 2018). Direct impacts of such methods of cable laying are the crushing, damaging, or displacement of organisms (Dunham et al. 2015; Taormina et al. 2018). However, unless cables are laid on slow-growing taxa like glass sponge reefs (Dunham et al. 2015), colonization of the iron, concrete, or rocky cable protections by encrusting organisms may lead to full recovery of the disturbed seafloor to the pre-cable state. Recovery has happened within one to eight years (Kraus and Carter 2018 and examples therein; Sheehan et al. 2018; Taormina et al. 2018), in some cases showing evidence of successful ecological successions (Sheehan et al. 2018).

The recovery timeframe for benthic communities after buried or unburied cable laying may be difficult to distinguish from natural variability (Dunham et al. 2015; Kraus and Carter 2018; Sheehan et al. 2018), and post-installation monitoring might be needed over the span of a few years to assess whether mitigation measures are necessary along the cable route. Monitoring may be required over longer periods of time in areas where fragile and/or slow-growing engineer species (e.g., seagrass meadows) cannot technically be avoided by a cable route.

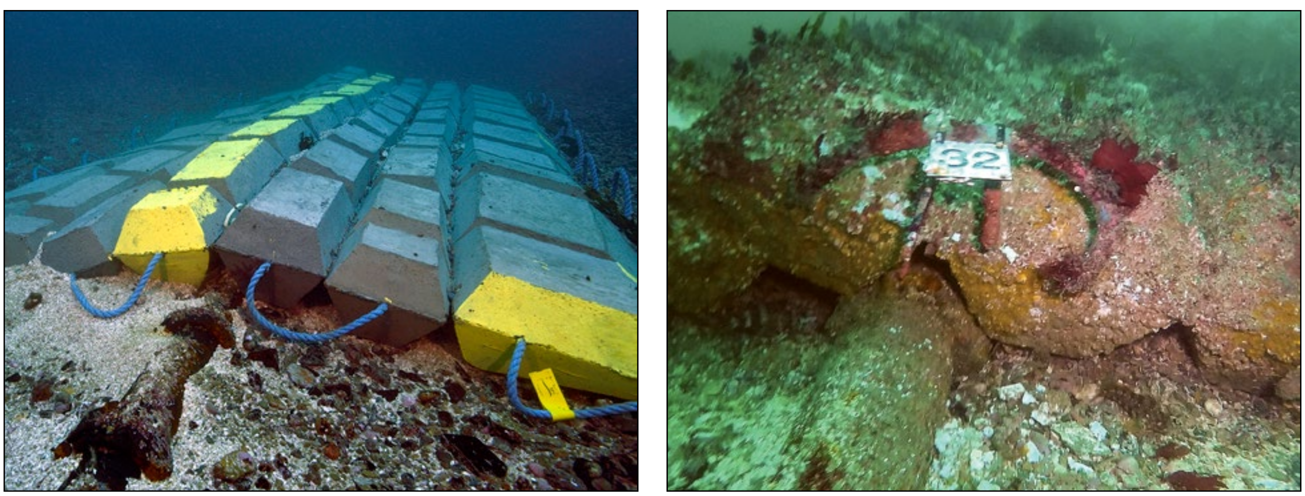


Figure 6.2. Pictures of iron shells and concrete mattresses used to protect an unburied cable at the Paimpol-Bréhat tidal turbine test site in France. The picture on the left was taken one month after the installation of the concrete mattress in 2013 (photo courtesy of Olivier Dugornay, Ifremer), and the picture on the right was taken six years later during a video survey (photo courtesy of Ifremer).

Scouring by Local Turbulences during Operation: The Footprint Effect

While the loss of seafloor habitat directly under the anchors or foundations of MRE devices is inevitable and should be mitigated during the siting process, further loss of benthic habitats during operation due to scouring by local turbulence in the immediate vicinity of the anchors and/or foundations (i.e., the footprint effect) is also a concern. This concern has been assessed and measured in real conditions involving tidal turbines (Kregting et al. 2016; O'Carroll et al. 2017a; O'Carroll et al. 2017b), concrete anchors on soft sediments (Henkel 2016), and artificial structures in an estuary (Mendoza and Henkel 2017). The last two studies particularly looked at infauna and the authors did not find any statistically significant differences in species richness, diversity, or assemblage composition compared to reference sites (Henkel 2016; Mendoza and Henkel 2017). However, the sediment mean grain size significantly varied and the abundance of organisms was slightly higher in sediments closer to the structures in the estuary setting (Mendoza and Henkel 2017).

The three former studies focused on epifaunal communities on rocky habitats around the SeaGen tidal turbine in Strangford Lough, Northern Ireland (Kregting et al. 2016; O'Carroll et al. 2017a; O'Carroll et al. 2017b). Benthic communities were highly variable within the study area, and covered a large spectrum of successional stages (Kregting et al. 2016; O'Carroll et al. 2017a). Although the epifauna in the area directly under the blades and legs of the turbine was significantly more variable than farther away from the turbine (O'Carroll et al. 2017a), seasonal variability significantly affected epifaunal communities regardless of the station (O'Carroll et al. 2017b). It is thought that at this particular site, as well as in other high-velocity-flow environments favorable to tidal energy developments, epifaunal communities are highly resilient and mainly composed of mosaics of opportunistic species adapted to great physical disturbance (Kregting et al. 2016; O'Carroll et al. 2017a, 2017b). While the authors noticed a negative effect of SeaGen on epifaunal organisms in the immediate vicinity of the turbine, probably due to the increased local turbulences that kept benthic communities at an early successional stage, the effect quickly dissipated with distance from the turbine (i.e., one rotor diameter away; O'Carroll et al. 2017a). The footprint effect of a tidal turbine on benthic communities is thus likely to be limited to the seafloor area directly adjacent to the device (Kregting et al. 2016; O'Carroll et al. 2017a).

6.3.2. CREATION OF NEW HABITATS

MRE devices can also provide new habitats to biofouling species, have effects similar to artificial reefs and fish aggregating devices, and even act as marine reserves.

Biofouling

Biofouling is a design and engineering concern for devices because it might affect performance and maintenance schedules. No antifouling paint or coating has proven fully efficient in preventing biofouling in the long run, and placing MRE devices, foundations, and cables in the water may create new hard-bottom habitats in areas where none previously existed (Figure 6.3). Few MRE devices have been in the water long enough (i.e., several years) to characterize biofouling communities and successional rates (Want and Porter 2018), but experience at OWFs and OGPs can provide some related insight. However, the structures used by the wind energy and oil and gas industries usually provide habitats for fouling organisms from the seafloor to the surface, whereas MRE devices typically do not span the whole water column (except for their mooring structures and dynamic cables). Fouling assemblages will inevitably vary between deployment sites (geography, habitats), devices, and components (Macleod et al. 2016; Want et al. 2017), but all start with a biofilm of marine bacteria and fungi followed over time by successions of initial (e.g., barnacles, hydroids and tubeworms) then secondary (e.g., anemones, ascidians and mussels) colonizers (Causon and Gill 2018; Dannheim et al. 2019). These communities are specific to hard substrates and often follow a vertical zonation (Dannheim et al. 2019). Various successional stages may be observed within an array of MRE devices in the same way different stages of development are observed in OWFs (Causon and Gill 2018).

Some of the most common biofoulers on OWFs are mussels; they compose 90 percent of epistructural biomass in the upper zone of wind turbine foundations in some locations (Slavik et al. 2018). Prolific biofouling organisms (e.g., barnacles, serpulid worms, ascidians) often have short pelagic larval durations and may be transported to artificial structures by construction

Figure 6.3. Heavily colonized tripod of a decommissioned tidal turbine in the Orkney Islands, Scotland (left), and 25 x 25 cm quadrat showing a close-up of the biofouling organisms, mainly barnacles, sponges, and brittle stars (right). (Photos courtesy of Andrew Want, Heriot-Watt University)

and maintenance vessels (Bray et al. 2017; Wilding et al. 2017). Successful colonization by biofoulers will be influenced by natural ocean variability, the seasonal availability of larvae, and the survival rates of recruits (Langhamer 2016). Biofouling can occur relatively rapidly; bare space can be colonized to almost 90 percent within two months in some cases (Viola et al. 2018). Relatively high densities of opportunistic species were found on some WECs at the Lysekil test site in Sweden (Langhamer 2016). The overall species compositions found in the intertidal habitats provided by wind turbine foundations and oil platform pilings often resemble those of nearby natural intertidal habitats and/or local harbors (Coolen et al. 2018; Viola et al. 2018). Similarly, species composition on the deeper sections of such structures as well as on the concrete foundations of MRE devices more resemble those of local subtidal natural reefs (Coolen et al. 2018; Langhamer 2016). Maximum biodiversity has been found at intermediate depths (i.e., halfway up the water column) on the foundations of wind turbines, where disturbance is also intermediate (Coolen et al. 2018). In high-energy environments, the floating parts of WECs may not provide much of a suitable intertidal habitat for biofoulers because of the constant motion and wave impacts (Causon and Gill 2018). Ultimately, biofouling is a natural process that is nearly impossible to avoid on artificial structures deployed in marine environments.

Artificial Reef Effect

In addition to providing artificial substrate for sessile (fouling) species, MRE devices may potentially attract mobile organisms like decapods, demersal and pelagic fish, and apex predators, and in that sense have effects similar to artificial reefs or fish aggregating devices (Dannheim et al. 2019; Langhamer 2016). This effect has been measured and described within several OWFs in European waters (Methratta and Dardick 2019). Several fish species have been shown to aggregate around offshore wind turbine foundations and other artificial hard structures, benefiting from foraging on the benthic communities on the foundations and adjacent habitats (Causon and Gill 2018; Dannheim et al. 2019). By increasing the complexity of the seafloor and surrounding water, OWFs and MRE devices also provide shelter and food (e.g., fouling organisms) for aggregating species, thereby potentially leading to changes in the diversity, abundance, and size of taxa making up the local communities (Causon and Gill 2018; Dannheim et al. 2019; Langhamer et al. 2018). However, the type of device and foundation, their spacing (in the case of an array), local arrangement, and portion of water occupied are important factors controlling the impact of the artificial reef effect (Adams et al. 2014; Causon and Gill 2018; Krone et al. 2017; Langhamer 2016). At the scale of an array of MRE devices, the artificial reef effect could lead to regional changes, including a shift from soft-sediment to hard-substrate communities and, potentially, intertidal communities (Causon and Gill 2018).

The artificial reef effect may not apply to every species, as demonstrated by the case of viviparous eelpouts (*Zoarces viviparous*) at the foundations and scour protection of an OWF in Sweden, where no clear attraction or avoidance was observed or could be distinguished from natural variability (Langhamer et al. 2018). However, scour protection structures on the seabed at OWFs in the southern North Sea, as well as foundations without scour protection, have been shown to attract high numbers of benthic and demersal mobile taxa such as cod (*Gadus morhua*), wrasse (*Ctenolabrus rupestris*), and edible crab (*Cancer pagurus*), and even serve as nursery grounds for some of these species (e.g., Krone et al. 2017; van Hal et al. 2017). Tidal turbines and the foundations of wind turbines also tend to attract pelagic fish; significantly increased observations and sizes of fish schools in the wake flow and changes in the vertical distribution of fish schools in the vicinity of a turbine have been noted, although there was some variability in the depths, days, and tidal cycles (Fraser et al. 2018; van Hal et al. 2017; Williamson et al. 2019). In addition to providing food, artificial structures may also provide flow refuges for pelagic fish (Fraser et al. 2018).

Recent studies have also demonstrated that power cables and associated armoring structures between MRE devices and substations may act as smaller artificial reefs as they are colonized and create new habitats (Bicknell et al. 2019; Taormina 2019; Taormina et al. 2018). Once past the first stages of biofouling, cable structures and their new epifaunal communities attract mobile macro- and megafauna (Taormina et al. 2018). This effect was observed on cables laid at a wave test site in Cornwall, England, where the abundance of pollack and saithe (*Pollachius* spp.) was higher around the cables than in the surrounding natural habitats (Bicknell et al. 2019). The reef effect is expected to be stronger on soft sediments (if cables are not buried) than where cables are laid on top of or among natural rocky reefs (Taormina et al. 2018), thereby creating small local reefs and hubs of biodiversity. However, if the cable protections are of a different structure than the surrounding natural reef (e.g., concrete mattresses vs. boulders), different species assemblages and reef effects may result (Sheehan et al. 2018).

The reef effect of artificial structures can be considered to be ecologically positive because the artificial reef increases habitat complexity and functions as an additional food source, refuge for endangered species, and nursery ground (Krone et al. 2017; Langhamer et al. 2018; Loxton et al. 2017; Raoux et al. 2017; Taormina et al. 2018). Conversely, these structures can also lead to negative effects by facilitating the introduction of non-native species or causing important shifts in local communities (Dannheim et al. 2019; Loxton et al. 2017). The nature and importance of the effects may vary according to the location of the deployment, the existing ecosystem, and natural habitats (Loxton et al. 2017).

Reserve Effect

The reserve effect is defined as the condition in which habitats and marine communities in the vicinity of a device or array of devices are *de facto* protected from fishing when exclusion zones are in place (Alexander et al. 2016). This effect can be beneficial; it promotes the potential recovery of local populations of some vulnerable species and benefits local fisheries if spillover is observed in the wider surrounding (non-protected) area around the devices (Coates et al. 2016). This reserve effect has already been confirmed, with various degrees of success, around some OWFs such as those in the North Sea (Coates et al. 2016; Krone et al. 2017; van Hal et al. 2017). For example, three years after the exclusion of bottom fisheries, fragile benthic communities within an OWF showed subtle changes toward recovery, and the authors suspected illegal trawling in the no-fishery area prevented far more significant changes from being observed (Coates et al. 2016). Nonetheless, significant increases in edible crab, wrasse, and cod populations were observed within the exclusion zone of other OWFs compared to open areas nearby (Krone et al. 2017; van Hal et al. 2017), suggesting that exclusion zones around MRE devices may act as large-scale refugia for vulnerable organisms, potentially those that are of commercial value.

While it might take several years to observe a significant reserve effect during recovery within an exclusion zone around MRE devices (Causon and Gill 2018; Coates et al. 2016), models can help understand the extent of this effect. Alexander et al. (2016) used an Ecopath with Ecosim (EwE) and Ecospace modeling approach to investigate the implications of artificial reef and exclusion zone effects in relation to MRE devices. The model showed a substantial increase in the biomass of several taxa within the exclusion zone, but not much over-spilling outside of the MRE area (Alexander et al. 2016). However, the authors highlighted some noticeable caveats of their study (e.g., fixed rectangular spatial map, coarse spatial scale, binary habitat type assignment to species) that would need to be addressed before generalizing similar approaches (Alexander et al. 2016). Similarly, Raoux et al. (2019) used an EwE model to simulate the potential reef effect by an OWF, its reserve effect, and the combined reef and reserve effect. The results showed an overall limited reserve effect at the ecosystem level, because of the relatively small size of the fishery closure area.

6.3.3. ADDITIONAL INDIRECT EFFECTS

The environmental effects discussed above are direct changes to marine habitats associated with MRE devices. These changes can become ecologically significant beyond the physical boundaries of the area of deployment (Krone et al. 2017; Slavik et al. 2018) or trigger a diversity of indirect effects and cascading processes locally, such as increases in biomass or recruitment of non-native invasive species (Causon and Gill 2018; Dannheim et al. 2019). However, these indirect effects have not been documented for MRE developments at this time and are presented here as a summary of discussions within the MRE and OWF communities.

Facilitation of Non-Native Species Dispersion

While biofouling of an exposed surface in the water is a natural process, it can also facilitate the installation of non-native species. Most non-native invasive species are organisms that have been moved around maritime traffic lines by ballast water and have established themselves on harbor structures (piers, pilings, docks) and nearby shallow-water reefs. This phenomenon has already been described for OWFs in Europe and OGPs in California (e.g., Coolen et al. 2016, 2018; van Hal et al. 2017; Viola et al. 2018) and is a potential concern regarding MRE devices (Dannheim et al. 2019; Loxton et al. 2017; Want et al. 2017), even if non-native species have yet to be reported to occur on MRE devices already deployed offshore (Want et al. 2017; Want and Porter 2018).

Studies of OWFs and OGPs have shown that non-native species are mainly found on structures occupying the upper water column, similar to intertidal habitats (Coolen et al. 2018; Viola et al. 2018), and that some of these organisms exhibit habitat preferences different from related native species, which allows them to occupy different ecological niches and avoid direct competition (Coolen et al. 2016). However, the development of native communities seemed to inhibit the recruitment of non-native species on OGP pilings in southern California (Viola et al. 2018) and marine cables in the English Channel (Taormina 2019). In the OGP piling case, the authors also demonstrated that anthropogenic disturbance (e.g., maintenance by scraping) enhanced the colonization by non-native species for at least 15 months, unless maintenance was timed to occur after the peak of the reproductive season (Viola et al. 2018). Non-native invasive species will be more likely to colonize parts of MRE devices that stay on the surface (e.g., surface attenuators) or occupy the top section of the water column (e.g., point-absorber buoys, oscillating water columns, overtopping devices, tidal lagoons), thereby providing environmental conditions similar to intertidal habitats (Causon and Gill 2018). For example, while underwater cables and their armoring structures on the seafloor can act as artificial reefs, there is very little evidence of colonization by non-native species (Taormina et al. 2018). In fact, only three occurrences of non-indigenous sea squirts were recorded during five years of monitoring along the cable route at Wave Hub, Cornwall, in the United Kingdom (UK) (Sheehan et al. 2018), and the densities of two non-native species along the cable at Paimpol-Bréhat in Brittany, France, became similar to those measured on the natural surrounding seafloor six years after the installation of the cable (Taormina 2019).

New MRE sites, especially large arrays of devices, are believed to provide new habitats for biofouling and artificial reef non-native species and could potentially act as stepping stones between already colonized areas and new natural habitats (Adams et al. 2014; Bray et al. 2017; Loxton et al. 2017). Like other biofouling organisms, non-native species might be transported to the energy extraction sites via construction and maintenance vessels (Bray et al. 2017; Wilding et al. 2017); however, a more likely means of introduction may be the towing of MRE devices to local harbors for maintenance, where non-native species are present and are likely to colonize (Loxton et al. 2017; Want et al. 2017). The use of biophysical models along with pelagic larval durations of known non-native species may help predict the connectedness of sites with local habitats and harbors (Adams et al. 2014; Bray et al. 2017; Vodopivec et al. 2017). Such models have shown that potential MRE and OWF sites in Scotland and the Adriatic Sea could provide suitable habitats for pelagic larvae produced in local harbors or nearshore habitats that would otherwise have perished offshore, *de facto* improving their survival rate (Adams et al. 2014; Bray et al. 2017; Vodopivec et al. 2017). These sites could, in turn, act as source populations and allow species to disperse further, potentially across natural biogeographical barriers (Adams et al. 2014). Siting and device maintenance need to be thought through carefully to prevent such connectedness between harbors and MRE sites for non-native species.

Local and Regional Increase in Biomass and Organic Matter

So far, the increases in local and regional biomass and changes in food webs due to the biofouling and artificial reef effects of MRE devices are mostly hypotheses and a matter of modeling approaches, because such effects may take years, if not decades, to be observed through environmental monitoring. Benthic food webs are predicted to benefit from MRE devices and OWFs through litter falls, i.e., the deposition of feces and dead organisms from fouling and aggregating organisms that enrich sediments (Causon and Gill 2018; Langhamer 2016; Slavik et al. 2018). Local enrichment of organic matter is more likely to occur near WECs and wind turbines, especially because of associated mussel growth (Langhamer 2016), rather than near tidal turbines where hydrodynamic forces may be too strong to favor local accumulations of organic matter. An increase in benthic biomass would in turn benefit higher trophic levels, up to apex predators, thereby potentially intensifying the reef effect (Raoux et al. 2017).

Two recent studies have used an EwE modeling approach (Alexander et al. 2016; Raoux et al. 2017), respectively conducted for periods of 25 years at an MRE site and 30 years at an OWF while increasing the biomass of targeted benthic and fish compartments (Figure 6.4). Both studies showed that the biomass and local food webs changed significantly within the model areas, especially with an increase in mussel biomass leading to a rise in detritivory in the food web (Raoux et al. 2017). In the case of the OWF, the total system biomass increased by 40 percent after 30 years (Raoux et al. 2017). In addition, the approach by Alexander et al. (2016) added an Ecospace component to predict changes beyond the MRE area, showing that the biomass changes were mainly occurring inside the area, rather than outside of it.

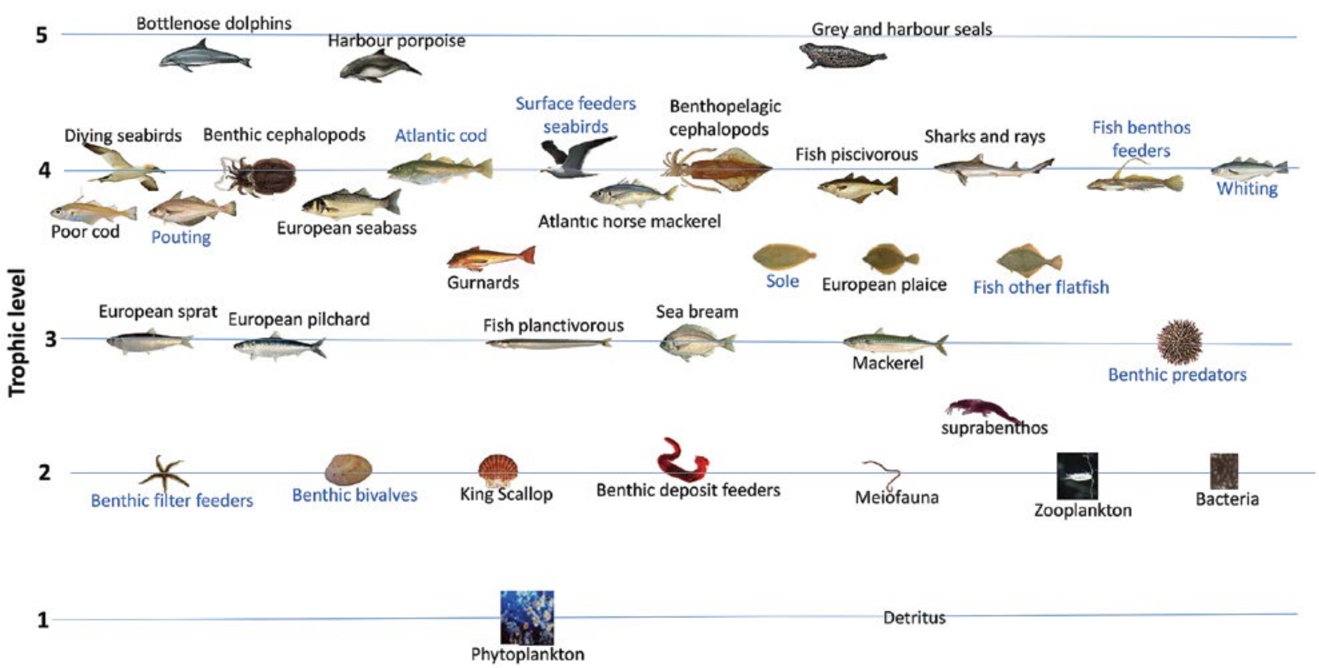


Figure 6.4. Functional groups used in an Ecopath with Ecosim model, arranged by trophic levels on the y-axis and benthic/pelagic coupling across all trophic levels on the x-axis. Functional groups in blue had their biomasses set to their accumulated maximum during the modeling approach. (From Raoux et al. 2017)

Effects of Oceanographic Changes

Other indirect effects of WECs and tidal turbines on marine habitats are the local and regional effects that changes in flow created by MRE devices (see Chapter 7, Changes in Oceanographic Systems Associated with Marine Renewable Energy Devices), especially arrays, could have on benthic and pelagic organisms. A habitat suitability modeling approach demonstrated that barnacles would largely respond negatively to the reduction in bed-shear stress generated by tidal turbine farms, whereas edible crabs would respond positively (du Feu et al. 2019). However, these effects are thought to be mainly restricted to the direct vicinity of tidal arrays, similar to the footprint effect, and farfield effects on benthic communities are unlikely (du Feu et al. 2019; Kregting et al. 2016).

Changes in flow and hydrographic conditions due to MRE devices (see Chapter 7, Changes in Oceanographic Systems Associated with Marine Renewable Energy Devices) may add a level of variability in local and farfield phytoplankton dynamics and processes (Dannheim et al. 2019). The idea is that local disturbances in the wake of devices would modify the stratification, thereby increasing vertical mixing and turbidity, which in turn would either increase the phytoplankton primary production because of higher nutrient availability, or lower it because of lack of light (Dannheim et al. 2019; Floeter et al. 2017). The question was recently addressed using biogeochemical models in the context of large-scale tidal turbine arrays: 66 MW, 800 MW, and 8 GW (Schuchert et al. 2018; van der Molen et al. 2016). Model results suggested the loss of up to 25 percent of local phytoplankton concentrations, although well below the natural seasonal variations (Schuchert et al. 2018), as well as negligible farfield effects in the case of an 800 MW tidal array, or increase in farfield phytoplankton primary production with a less-realistic 8 GW tidal array (van der Molen et al. 2016).

Extreme biofouling by filter-feeding organisms on device components is also thought to modify local hydrodynamics and phytoplankton processes. Slavik et al. (2018) used a biogeochemical model to investigate the question in relation to OWFs. Model results suggested losses of up to 8 percent of regional annual primary productivity due to increased filtration by epifauna, with the maximum loss occurring within the OWFs (Slavik et al. 2018). However, biofouling on MRE devices is not expected to reach levels observed on wind turbine foundations, because they do not provide as much habitat throughout the water column as their wind counterparts (Causon and Gill 2018).

6.4. RESEARCH AND MONITORING NEEDS TO RESOLVE THE ISSUE

This literature review has highlighted several gaps in our knowledge that need to be addressed to advance our understanding of the risks associated with changes in benthic and pelagic habitats. Often, monitoring and research programs are disconnected from one another, so the results from one program do not necessarily contribute to answering questions asked by another (Dannheim et al. 2019; Loxton et al. 2017). Benthic and pelagic communities change over time (e.g., seasonal variability, succession stages, post-disturbance resilience), and long-term studies are required to understand their ecological processes (Langhamer 2016; Taormina et al. 2018; Wilding et al. 2017). However, there is little understanding of appropriate spatial and temporal scales for environmental impact assessment (EIA) and monitoring in relation to MRE, or of the suitable thresholds of undesirable consequences (Wilding et al. 2017).

Stakeholders need justified guidelines for the levels of biodiversity, as well as the assemblages and scales to be considered (Wilding et al. 2017). This holds true for native communities as well as for potentially invasive organisms that may constitute part of the biofouling and artificial reef taxa (Loxton et al. 2017). There are gaps to fill concerning the composition of biofouling assemblages on MRE devices and aggregating species found around devices, their geographic distribution, connectivity, and dispersion abilities (Adams et al. 2014; Bray et al. 2017; Want and Porter 2018), so that regulators can knowingly assess risk and develop biosecurity measures to prevent the spread of non-native invasive species (Loxton et al. 2017).

Underwater visual surveys are very useful approaches for observing changes in species and habitat composition and distribution on and around MRE devices, either through scuba diver surveys, unmanned video transects, or cameras mounted on static structures (Bender et al. 2017). However, the high-energy environments and presence of structures and cables in the water often make for challenging conditions, and methods may need to be refined (e.g., Sheehan et al. 2020). Even greater challenges associated with image-based surveys are the amount of footage that needs to be processed to extract ecologically relevant information and the need for optimized protocols (e.g., Taormina et al. 2020).

The potential impact of localized temperature increase caused by electric cables on infauna communities is an aspect of environmental effects on benthic organisms that has not been addressed much yet (Taormina et al. 2018). Infauna communities constitute important food sources for benthic and demersal organisms like flatfish. However, considering the narrow footprint of the cables and the expected low levels of thermal radiation, this impact may turn out to be insignificant. Nonetheless, it needs to be tested, at least through modeling studies, especially in the case of larger arrays of devices.

Different types of modeling approaches (e.g., biogeochemical, food web, habitat suitability) were recently used to address several questions related to changes in benthic and/or pelagic habitats due to MRE devices and/or OWFs (Adams et al. 2014; Alexander et al. 2016; Bray et al. 2017; du Feu et al. 2019; Raoux et al. 2017; Schuchert et al. 2018; Slavik et al. 2018; van der Molen et al. 2016). Such modeling efforts need to be pursued, because models help answer questions that are difficult to address with monitoring and field observations and on a reasonable time scale. Multispecies and trophic interaction models are particularly valuable, but trickier to implement, because they may require physiological and ecological data that are not yet available (Schuchert et al. 2018).

The effects of partial and complete decommissioning of MRE devices are still unclear. As highlighted earlier, devices left long enough in the water will create habitat colonized by biofoulers and act as artificial reefs, thereby enhancing local biodiversity, so partial decommissioning could be favored. However, devices may also facilitate the establishment of invasive species and total decommissioning may be recommended (Coolen et al. 2018; Sheehan et al. 2018). Both options have benefits and drawbacks that will most likely be weighed on a case-by-case basis, but regulators will need guidelines for preferable options given certain circumstances (Fowler et al. 2018; Sheehan et al. 2018).

6.5. GUIDANCE ON MEASURING CHANGES IN BENTHIC AND PELAGIC HABITATS CAUSED BY MRE

Before-after-control-impact (BACI) analyses are among the best-suited survey designs for measuring changes over spatial and temporal anthropogenic impacts like the deployment of MRE devices (Smokorowski and Randall 2017; Wilding et al. 2017). Such analyses are particularly effective when impacts are important and/or long-lasting, and less effective when changes are variable or gradual (Wilding et al. 2017). Some authors, especially in the case of tidal turbine arrays, recommend an asymmetrical BACI survey design, in which there are more control stations than impact stations (O'Carroll et al. 2017a). Other survey designs, like a before-after-gradient design, are equally suitable for MRE development sites (Bailey et al. 2014; Ellis and Schneider 1997). In any case, it is important that good quality baseline data be collected to provide information about the natural variability within the survey area (Bicknell et al. 2019).

Some authors have highlighted the difficulty involved in characterizing the temporal natural variability of benthic and pelagic ecosystems and differentiating such variability from impacts induced by MRE devices when impact assessment and monitoring surveys only span a couple of years (Wilding et al. 2017). Extreme changes (either natural or anthropogenically induced) are more likely to be detected over a short survey timeframe, while subtle changes are more likely to take longer to observe. Some authors recommend that monitoring studies last more than three years to enable accurate measurement of extreme and subtle changes (Wilding et al. 2017), if not six to eight years to cover the recovery timeframe of some cable sites (Kraus and Carter 2018; Sheehan et al. 2018; Taormina et al. 2018).

In addition, attention needs to be given to the extent of the spatial scale to provide enough strength in detecting potential impacts (Bicknell et al. 2019). The diversity and spatial variability of benthic habitats are more likely to be characterized if the baseline sampling design during the EIA process involves a large-scale regular-spaced grid supplemented with randomly selected additional stations, in order to identify local patches and gradients in habitats and communities

(Kregting et al. 2016; O'Carroll et al. 2017b; Wilding et al. 2017). Follow-up monitoring surveys may sample a subset of the baseline survey as long as they cover the diversity of habitats and communities initially identified (O'Carroll et al. 2017b; Wilding et al. 2017).

Using a modeling approach may be helpful in highlighting some potential changes in benthic and/or pelagic habitats and species that can then be specifically looked for. Habitat suitability models (e.g., MaxEnt) are particularly valuable when it comes to identifying areas that feature the appropriate ecological requirements for a species to establish itself, and these models may help track the settlement of non-native species (Adams et al. 2014; du Feu et al. 2019). Regarding pelagic communities such as nekton organisms, parametric models (e.g., state-space model) work best for detecting changes, time-series models and semi-parametric models are better fitted for quantifying such changes, and nonparametric models are preferred for forecasting changes (Linder and Horne 2018; Linder et al. 2017). Among food web models, the EwE modeling approach is one of the most easily accessed and commonly used approaches for modeling human-induced ecosystem-wide changes over long periods of time, particularly in data-poor systems like MRE sites (Alexander et al. 2016; Raoux et al. 2017). However, many other model types also exist, such as size-based models (Rogers et al. 2014) or agent-based models (Fulton et al. 2015). Modelers interested in MRE would benefit from consulting with experienced ecological and fisheries modelers to determine what approach would be better suited given their specific questions and the available data. Experience drawn from modeling associated with an ecosystem approach to fisheries or coastal management would also suggest that an ensemble modeling approach is likely an effective option to pursue given the current levels of uncertainty (Cheung et al. 2016; Fulton et al. 2019).

6.6. RECOMMENDATIONS

While several questions have been addressed over the four years since publication of the previous State of the Science report, numerous authors have highlighted recommendations for conducting research and monitoring to reduce the uncertainty around some of the changes in benthic and pelagic habitats and to move the industry forward (Bray et al. 2017; Dannheim et al. 2019; Linder and Horne 2018; Loxton et al. 2017; Macleod et al. 2016; O'Carroll et al. 2017b; Wilding et al. 2017). Suggestions for the path forward include the following:

- Define relevant spatial and temporal scales for EIAs and monitoring surveys.
- Identify justified and acceptable thresholds for changes in benthic and pelagic environments, including the extent of loss or the level of colonization by biofouling and artificial reef organisms.
- Use modeling approaches to define habitat suitability and connectedness during the siting process.
- Characterize the diversity and ecological characteristics of biofouling communities and common non-native biofouling and artificial reef species.
- Use (transfer) as much as possible knowledge and lessons learned from other offshore industries such as offshore wind, oil and gas extraction, and fisheries.
- Identify the cumulative effects of MRE devices and other activities occurring in the same area, especially relative to the artificial reef, reserve, and stepping stone effects.

6.7. REFERENCES

Adams, T. P., Miller, R. G., Aleynik, D., and Burrows, M. T. 2014. Offshore marine renewable energy devices as stepping stones across biogeographical boundaries. *Journal of Applied Ecology*, 51(2), 330-338. doi:10.1111/1365-2664.12207 *https://tethys.pnnl.gov/publications/offshore-marine-renewable-energy-devices-stepping-stones-across-biogeographical*

Alexander, K. A., Meyjes, S. A., and Heymans, J. J. 2016. Spatial ecosystem modelling of marine renewable energy installations: Gauging the utility of Ecospace. *Ecological Modelling*, 331, 115-128. doi:10.1016/j.ecolmodel.2016.01.016 *https://tethys.pnnl.gov/publications/spatial-ecosystem-modelling-marine-renewable-energy-installations-gauging-utility*

Arena, P. T., Jordan, L. K. B., and Spieler, R. E. 2007. Fish assemblages on sunken vessels and natural reefs in southeast Florida, USA. *Hydrobiologia*, 580, 157–171. doi:10.1007/s10750-006-0456-x *https://tethys.pnnl.gov/publications/fish-assemblages-sunken-vessels-natural-reefs-southeast-florida-usa*

Bailey, H., Brookes, K. L., and Thompson, P. M. 2014. Assessing environmental impacts of offshore wind farms: lessons learned and recommendations for the future. *Aquatic Biosystems*, 10(1), 8. doi:10.1186/2046-9063-10-8 *https://tethys.pnnl.gov/publications/assessing-environmental-impacts-offshore-wind-farms-lessons-learned-recommendations*

Bender, A., Francisco, F., and Sundberg, J. 2017. A Review of Methods and Models for Environmental Monitoring of Marine Renewable Energy. Paper presented at the 12th European Wave and Tidal Energy Conference, Cork, Ireland. *https://tethys.pnnl.gov/publications/review-methods-models-environmental-monitoring-marine-renewable-energy*

Bicknell, A. W. J., Sheehan, E. V., Godley, B. J., Doherty, P. D., and Witt, M. J. 2019. Assessing the impact of introduced infrastructure at sea with cameras: A case study for spatial scale, time and statistical power. *Marine Environmental Research*, 147, 126-137. doi:10.1016/j.marenvres.2019.04.007 *https://tethys.pnnl.gov/publications/assessing-impact-introduced-infrastructure-sea-cameras-case-study-spatial-scale-time*

Bray, L., Kassis, D., and Hall-Spencer, J. M. 2017. Assessing larval connectivity for marine spatial planning in the Adriatic. *Marine Environmental Research*, 125, 73-81. doi:10.1016/j.marenvres.2017.01.006 *https://tethys.pnnl.gov/publications/assessing-larval-connectivity-marine-spatial-planning-adriatic*

Broadhurst, M., Barr, S., and Orme, C. D. L. 2014. In-situ ecological interactions with a deployed tidal energy device; an observational pilot study. *Ocean & Coastal Management*, 99, 31-38. doi:10.1016/j.ocecoaman.2014.06.008 *https://tethys.pnnl.gov/publications/situ-ecological-interactions-deployed-tidal-energy-device-observational-pilot-study*

Broadhurst, M., and Orme, C. D. L. 2014. Spatial and temporal benthic species assemblage responses with a deployed marine tidal energy device: A small scaled study. *Marine Environmental Research*, 99, 76-84. doi:10.1016/j.marenvres.2014.03.012 *https://tethys.pnnl.gov/publications/spatial-temporal-benthic-species-assemblage-responses-deployed-marine-tidal-energy*

Causon, P. D., and Gill, A. B. 2018. Linking ecosystem services with epibenthic biodiversity change following installation of offshore wind farms. *Environmental Science & Policy*, 89, 340-347. doi:10.1016/j.envsci.2018.08.013 *https://tethys.pnnl.gov/publications/linking-ecosystem-services-epibenthic-biodiversity-change-following-installation*

Cheung, W. W. L., Frölicher, T. L., Asch, R. G., Jones, M. C., Pinsky, M. L., Reygondeau, G., Rodgers, K. B., Rykaczewski, R. R., Sarmiento, J. L., Stock, C., and Watson, J. R. 2016. Building confidence in projections of the responses of living marine resources to climate change. *ICES Journal of Marine Science*, 73(5), 1283-1296. doi:10.1093/icesjms/fsv250 *https://tethys.pnnl.gov/publications/building-confidence-projections-responses-living-marine-resources-climate-change*

Clynick, B. G., Chapman, M. G., and Underwood, A. J. 2008. Fish assemblages associated with urban structures and natural reefs in Sydney, Australia. *Austral Ecology*, 33(2), 140-150. doi:10.1111/j.1442-9993.2007.01802.x *https://tethys.pnnl.gov/publications/fish-assemblages-associated-urban-structures-natural-reefs-sydney-australia*

Coates, D. A., Kapasakali, D.-A., Vincx, M., and Vanaverbeke, J. 2016. Short-term effects of fishery exclusion in offshore wind farms on macrofaunal communities in the Belgian part of the North Sea. *Fisheries Research*, 179, 131-138. doi:10.1016/j.fishres.2016.02.019 *https://tethys.pnnl.gov/publications/short-term-effects-fishery-exclusion-offshore-wind-farms-macrofaunal-communities*

Coolen, J., Lengkeek, W., Degraer, S., Kerckhof, F., Kirkwood, R., and Lindeboom, H. 2016. Distribution of the invasive *Caprella mutica* Schurin, 1935 and native *Caprella linearis* (Linnaeus, 1767) on artificial hard substrates in the North Sea: separation by habitat. *Aquatic Invasions*, 11(4), 437-449. doi:10.3391/ai.2016.11.4.08 *https://tethys.pnnl.gov/publications/distribution-invasive-caprella-mutica-schurin-1935-native-caprella-linearis-linnaeus*

Coolen, J. W. P., van der Weide, B., Cuperus, J., Blomberg, M., Van Moorsel, G. W. N. M., Faasse, M. A., Bos, O. G., Degraer, S., and Lindeboom, H. J. 2018. Benthic biodiversity on old platforms, young wind farms, and rocky reefs. *ICES Journal of Marine Science*. doi:10.1093/icesjms/fsy092 *https://tethys.pnnl.gov/publications/benthic-biodiversity-old-platforms-young-wind-farms-rocky-reefs*

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewski, G., Staines, G., Gill, A., Hutchison, I., O'Hagan, A., Simas, T., Bald, J., Sparling, C., Wood, J., and Masden, E. 2016. Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. *https://tethys.pnnl.gov/publications/state-of-the-science-2016*

Dannheim, J., Bergström, L., Birchenough, S. N. R., Brzana, R., Boon, A. R., Coolen, J. W. P., Dauvin, J.-C., De Mesel, I., Derweduwen, J., Gill, A. B., Hutchison, Z. L., Jackson, A. C., Janas, U., Martin, G., Raoux, A., Reubens, J., Rostin, L., Vanaverbeke, J., Wilding, T. A., Wilhelmsson, D., and Degraer, S. 2019. Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. *ICES Journal of Marine Science*. doi:10.1093/icesjms/fsz018 *https://tethys.pnnl.gov/publications/benthic-effects-offshore-renewables-identification-knowledge-gaps-urgently-needed*

De Backer, A., Van Hoey, G., Coates, D., Vanaverbeke, J., and Hostens, K. 2014. Similar diversity-disturbance responses to different physical impacts: Three cases of small-scale biodiversity increase in the Belgian part of the North Sea. *Marine Pollution Bulletin*, 84(1), 251-262. doi:10.1016/j.marpolbul.2014.05.006 *https://tethys.pnnl.gov/publications/similar-diversity-disturbance-responses-different-physical-impacts-three-cases-small*

du Feu, R. J., Funke, S. W., Kramer, S. C., Hill, J., and Piggott, M. D. 2019. The trade-off between tidal-turbine array yield and environmental impact: A habitat suitability modelling approach. *Renewable Energy*, 143, 390-403. doi:10.1016/j.renene.2019.04.141 *https://tethys.pnnl.gov/publications/trade-between-tidal-turbine-array-yield-environmental-impact-habitat-suitability*

Dunham, A., Pegg, J. R., Carolsfeld, W., Davies, S., Murfitt, I., and Boutillier, J. 2015. Effects of submarine power transmission cables on a glass sponge reef and associated megafaunal community. *Marine Environmental Research*, 107, 50-60. doi:10.1016/j.marenvres.2015.04.003 *https://tethys.pnnl.gov/publications/effects-submarine-power-transmission-cables-glass-sponge-reef-associated-megafaunal*

Ellis, J. I., and Schneider, D. C. 1997. Evaluation of a gradient sampling design for environmental impact assessment. *Environmental Monitoring and Assessment*, 48(2), 157-172. doi:10.1023/A:1005752603707 *https://tethys.pnnl.gov/publications/evaluation-gradient-sampling-design-environmental-impact-assessment*

Floeter, J., van Beusekom, J. E. E., Auch, D., Callies, U., Carpenter, J., Dudeck, T., Eberle, S., Eckhardt, A., Gloe, D., Hänselmann, K., Hufnagl, M., Janßen, S., Lenhart, H., Möller, K. O., North, R. P., Pohlmann, T., Riethmüller, R., Schulz, S., Spreizenbarth, S., Temming, A., Walter, B., Zielinski, O., and Möllmann, C. 2017. Pelagic effects of offshore wind farm foundations in the stratified North Sea. *Progress in Oceanography*, 156, 154-173. doi:10.1016/j.pocean.2017.07.003 *https://tethys.pnnl.gov/publications/pelagic-effects-offshore-wind-farm-foundations-stratified-north-sea*

Fowler, A. M., Jørgensen, A.-M., Svendsen, J. C., Macreadie, P. I., Jones, D. O., Boon, A. R., Booth, D. J., Brabant, R., Callahan, E., Claisse, J. T., Dahlgren, T. G., Degraer, S., Dokken, Q. R., Gill, A. B., Johns, D. G., Leewis, R. J., Lindeboom, H. J., Linden, O., May, R., Murk, A. J., Ottersen, G., Schroeder, D. M., Shastri, S. M., Teilmann, J., Todd, V., Van Hoey, G., Vanaverbeke, J., and Coolen, J. W. 2018. Environmental benefits of leaving offshore infrastructure in the ocean. *Frontiers in Ecology and the Environment*, 16(10), 571-578. doi:10.1002/fee.1827 *https://tethys.pnnl.gov/publications/environmental-benefits-leaving-offshore-infrastructure-ocean*

Fraser, S., Williamson, B. J., Nikora, V., and Scott, B. E. 2018. Fish distributions in a tidal channel indicate the behavioural impact of a marine renewable energy installation. *Energy Reports*, 4, 65-69. doi:10.1016/j.egyr.2018.01.008 *https://tethys.pnnl.gov/publications/fish-distributions-tidal-channel-indicate-behavioural-impact-marine-renewable-energy*

Fulton, E. A., Blanchard, J. L., Melbourne-Thomas, J., Plagányi, É. E., and Tulloch, V. J. D. 2019. Where the Ecological Gaps Remain, a Modelers' Perspective. *Frontiers in Ecology and Evolution*, 7(424). doi:10.3389/fevo.2019.00424 *https://tethys.pnnl.gov/publications/where-ecological-gaps-remain-modelers-perspective*

Fulton, E. A., Boschetti, F., Sporcic, M., Jones, T., Little, L. R., Dambacher, J. M., Gray, R., Scott, R., and Gorton, R. 2015. A multi-model approach to engaging stakeholder and modellers in complex environmental problems. *Environmental Science & Policy*, 48, 44-56. doi:10.1016/j.envsci.2014.12.006 *https://tethys.pnnl.gov/publications/multi-model-approach-engaging-stakeholder-modellers-complex-environmental-problems*

Greaves, D., and Iglesias, G. 2018. Wave and Tidal Energy. Hoboken, NJ: John Wiley & Sons Ltd. *https://tethys.pnnl.gov/publications/wave-tidal-energy-0*

Henkel, S. 2016. Assessment of Benthic Effects of Anchor Presence and Removal. Report by Northwest National Marine Renewable Energy Center for Oregon Wave Energy Trust, Portland, Oregon. *https://tethys.pnnl.gov/publications/assessment-benthic-effects-anchor-presence-removal*

Keenan, G., Sparling, C., Williams, H., and Fortune, F. 2011. SeaGen Environmental Monitoring Programme: Final Report. Report by Royal Haskoning for Marine Current Turbines, Edinburgh, UK. *https://tethys.pnnl.gov/publications/seagen-environmental-monitoring-programme-final-report*

Kramer, S., Hamilton, C., Spencer, G., and Ogston, H. 2015. Evaluating the Potential for Marine and Hydrokinetic Devices to Act as Artificial Reefs or Fish Aggregating Devices, Based on Analysis of Surrogates in Tropical, Subtropical, and Temperate U.S. West Coast and Hawaiian Coastal Waters. Report by H. T. Harvey & Associates for U.S. Department of Energy Efficiency and Renewable Energy, Golden, CO. *https://tethys.pnnl.gov/publications/evaluating-potential-marine-hydrokinetic-devices-act-artificial-reefs-or-fish*

Kraus, C., and Carter, L. 2018. Seabed recovery following protective burial of subsea cables - Observations from the continental margin. *Ocean Engineering*, 157, 251-261. doi:10.1016/j.oceaneng.2018.03.037 *https://tethys.pnnl.gov/publications/seabed-recovery-following-protective-burial-subsea-cables-observations-continental*

Kregting, L., Elsaesser, B., Kennedy, R., Smyth, D., O'Carroll, J., and Savidge, G. 2016. Do Changes in Current Flow as a Result of Arrays of Tidal Turbines Have an Effect on Benthic Communities? *PLoS ONE*, 11(8), e0161279. doi:10.1371/journal.pone.0161279 *https://tethys.pnnl.gov/publications/do-changes-current-flow-result-arrays-tidal-turbines-have-effect-benthic-communities*

Krone, R., Dederer, G., Kanstinger, P., Krämer, P., Schneider, C., and Schmalenbach, I. 2017. Mobile demersal megafauna at common offshore wind turbine foundations in the German Bight (North Sea) two years after deployment - increased production rate of *Cancer pagurus*. *Marine Environmental Research*, 123, 53-61. doi:10.1016/j.marenvres.2016.11.011 *https://tethys.pnnl.gov/publications/mobile-demersal-megafauna-common-offshore-wind-turbine-foundations-german-bight-north*

Krone, R., Gutow, L., Joschko, T. J., and Schröder, A. 2013. Epifauna dynamics at an offshore foundation – Implications of future wind power farming in the North Sea. *Marine Environmental Research*, 85, 1-12. doi:10.1016/j.marenvres.2012.12.004 *https://tethys.pnnl.gov/publications/epifauna-dynamics-offshore-foundation-implications-future-wind-power-farming-north-sea*

Langhamer, O. 2010. Effects of wave energy converters on the surrounding soft-bottom macrofauna (west coast of Sweden). *Marine Environmental Research*, 69(5), 374-381. doi:10.1016/j.marenvres.2010.01.002 *https://tethys.pnnl.gov/publications/effects-wave-energy-converters-surrounding-soft-bottom-macrofauna-west-coast-sweden*

Langhamer, O. 2012. Artificial Reef Effect in relation to Offshore Renewable Energy Conversion: State of the Art. *The Scientific World Journal*, 8. doi:10.1100/2012/386713 *https://tethys.pnnl.gov/publications/artificial-reef-effect-relation-offshore-renewable-energy-conversion-state-art*

Langhamer, O. 2016. The location of offshore wave power devices structures epifaunal assemblages. *International Journal of Marine Energy*, 16, 174-180. doi:10.1016/j.ijome.2016.07.007 *https://tethys.pnnl.gov/publications/location-offshore-wave-power-devices-structures-epifaunal-assemblages*

Langhamer, O., Dahlgren, T. G., and Rosenqvist, G. 2018. Effect of an offshore wind farm on the viviparous eelpout: Biometrics, brood development and population studies in Lillgrund, Sweden. *Ecological Indicators*, 84, 1-6. doi:10.1016/j.ecolind.2017.08.035 *https://tethys.pnnl.gov/publications/effect-offshore-wind-farm-viviparous-eelpout-biometrics-brood-development-population*

Langhamer, O., and Wilhelmsson, D. 2009. Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes – A field experiment. *Marine Environmental Research*, 68(4), 151-157. doi:10.1016/j.marenvres.2009.06.003 *https://tethys.pnnl.gov/publications/colonisation-fish-crabs-wave-energy-foundations-effects-manufactured-holes-field*

Lindeboom, H., Degraer, S., Dannheim, J., Gill, A. B., and Wilhelmsson, D. 2015. Offshore wind park monitoring programmes, lessons learned and recommendations for the future. *Hydrobiologia*, 756(1), 169-180. doi:10.1007/s10750-015-2267-4 *https://tethys.pnnl.gov/publications/offshore-wind-park-monitoring-programmes-lessons-learned-recommendations-future*

Lindeboom, H. J., Kouwenhoven, H. J., Bergman, M. J. N., Bouma, S., Brasseur, S., Daan, R., Fijn, R. C., de Haan, D., Dirksen, S., van Hal, R., Hille Ris Lambers, R., ter Hofstede, R., Krijgsveld, K. L., Leopold, M., and Scheidat, M. 2011. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environmental Research Letters*, 6(3). doi:10.1088/1748-9326/6/3/035101 *https://tethys.pnnl.gov/publications/short-term-ecological-effects-offshore-wind-farm-dutch-coastal-zone-compilation*

Linder, H. L., and Horne, J. K. 2018. Evaluating statistical models to measure environmental change: A tidal turbine case study. *Ecological Indicators*, 84, 765-792. doi:10.1016/j.ecolind.2017.09.041 *https://tethys.pnnl.gov/publications/evaluating-statistical-models-measure-environmental-change-tidal-turbine-case-study*

Linder, H. L., Horne, J. K., and Ward, E. J. 2017. Modeling baseline conditions of ecological indicators: Marine renewable energy environmental monitoring. *Ecological Indicators*, 83, 178-191. doi:10.1016/j.ecolind.2017.07.015 *https://tethys.pnnl.gov/publications/modeling-baseline-conditions-ecological-indicators-marine-renewable-energy*

Loxton, J., Macleod, A. K., Nall, C. R., McCollin, T., Machado, I., Simas, T., Vance, T., Kenny, C., Want, A., and Miller, R. G. 2017. Setting an agenda for biofouling research for the marine renewable energy industry. *International Journal of Marine Energy*, 19, 292-303. doi:10.1016/j.ijome.2017.08.006 *https://tethys.pnnl.gov/publications/setting-agenda-biofouling-research-marine-renewable-energy-industry*

Maar, M., Bolding, K., Petersen, J. K., Hansen, J. L. S., and Timmermann, K. 2009. Local effects of blue mussels around turbine foundations in an ecosystem model of Nysted off-shore wind farm, Denmark. *Journal of Sea Research*, 62(2), 159-174. doi:10.1016/j.seares.2009.01.008 *https://tethys.pnnl.gov/publications/local-effects-blue-mussels-around-turbine-foundations-ecosystem-model-nysted-shore*

Macleod, A. K., Stanley, M. S., Day, J. G., and Cook, E. J. 2016. Biofouling community composition across a range of environmental conditions and geographical locations suitable for floating marine renewable energy generation. *Biofouling*, 32(3), 261-276. doi:10.1080/08927014.2015.1136822 *https://tethys.pnnl.gov/publications/biofouling-community-composition-across-range-environmental-conditions-geographical*

Mendoza, M., and Henkel, S. K. 2017. Benthic effects of artificial structures deployed in a tidal estuary. *Plankton and Benthos Research*, 12(3), 179-189. doi:10.3800/pbr.12.179 *https://tethys.pnnl.gov/publications/benthic-effects-artificial-structures-deployed-tidal-estuary*

Methratta, E. T., and Dardick, W. R. 2019. Meta-Analysis of Finfish Abundance at Offshore Wind Farms. *Reviews in Fisheries Science & Aquaculture*, 27(2), 242-260. doi:10.1080/23308249.2019.1584601 *https://tethys.pnnl.gov/publications/meta-analysis-finfish-abundance-offshore-wind-farms*

Mineur, F., Cook, E., Minchin, D., Bohn, K., Macleod, A., and Maggs, C. 2012. Changing Coasts: Marine Aliens and Artificial Structures. In R. N. Gibson, R. J. A. Atkinson, J. D. M. Gordon, and R. N. Hughes (Eds.), *Oceanography and Marine Biology: An Annual Review* (Vol. 50, pp. 189-234). Boca Raton, FL: CRC Press. *https://tethys.pnnl.gov/publications/changing-coasts-marine-aliens-artificial-structures*

O'Carroll, J. P. J., Kennedy, R. M., Creech, A., and Savidge, G. 2017a. Tidal Energy: The benthic effects of an operational tidal stream turbine. *Marine Environmental Research*, 129, 277-290. doi:10.1016/j.marenvres.2017.06.007 *https://tethys.pnnl.gov/publications/tidal-energy-benthic-effects-operational-tidal-stream-turbine*

O'Carroll, J. P. J., Kennedy, R. M., and Savidge, G. 2017b. Identifying relevant scales of variability for monitoring epifaunal reef communities at a tidal energy extraction site. *Ecological Indicators*, 73, 388-397. doi:10.1016/j.ecolind.2016.10.005 *https://tethys.pnnl.gov/publications/identifying-relevant-scales-variability-monitoring-epifaunal-reef-communities-tidal*

Page, H. M., Dugan, J. E., Dugan, D. S., Richards, J. B., and Hubbard, D. M. 1999. Effects of an offshore oil platform on the distribution and abundance of commercially simportant crab species. *Marine Ecology Progress Series*, 185, 47-57. doi:10.3354/meps185047 *https://tethys.pnnl.gov/publications/effects-offshore-oil-platform-distribution-abundance-commercially-important-crab*

Raoux, A., Lassalle, G., Pezy, J.-P., Tecchio, S., Safi, G., Ernande, B., Mazé, C., Loc'h, F. L., Lequesne, J., Girardin, V., Dauvin, J.-C., and Niquil, N. 2019. Measuring sensitivity of two OSPAR indicators for a coastal food web model under offshore wind farm construction. *Ecological Indicators*, 96, 728-738. doi:10.1016/j.ecolind.2018.07.014 *https://tethys.pnnl.gov/publications/measuring-sensitivity-two-ospar-indicators-coastal-food-web-model-under-offshore-wind*

Raoux, A., Tecchio, S., Pezy, J.-P., Lassalle, G., Degraer, S., Wilhelmsson, D., Cachera, M., Ernande, B., Le Guen, C., Haraldsson, M., Grangeré, K., Le Loc'h, F., Dauvin, J.-C., and Niquil, N. 2017. Benthic and fish aggregation inside an offshore wind farm: Which effects on the trophic web functioning? *Ecological Indicators*, 72, 33-46. doi:10.1016/j.ecolind.2016.07.037 *https://tethys.pnnl.gov/publications/benthic-fish-aggregation-inside-offshore-wind-farm-which-effects-trophic-web*

Rogers, A., Blanchard, Julia L., and Mumby, Peter J. 2014. Vulnerability of Coral Reef Fisheries to a Loss of Structural Complexity. *Current Biology*, 24(9), 1000-1005. doi:10.1016/j.cub.2014.03.026 *https://tethys.pnnl.gov/publications/vulnerability-coral-reef-fisheries-loss-structural-complexity*

Schuchert, P., Kregting, L., Pritchard, D., Savidge, G., and Elsäßer, B. 2018. Using Coupled Hydrodynamic Biogeochemical Models to Predict the Effects of Tidal Turbine Arrays on Phytoplankton Dynamics. *Journal of Marine Science and Engineering*, 6(2), 58. doi: 10.3390/jmse6020058 *https://tethys.pnnl.gov/publications/using-coupled-hydrodynamic-biogeochemical-models-predict-effects-tidal-turbine-arrays*

Sheehan, E. V., Bridger, D., Nancollas, S. J., and Pittman, S. J. 2020. PelagiCam: a novel underwater imaging system with computer vision for semi-automated monitoring of mobile marine fauna at offshore structures. *Environmental Monitoring and Assessment*, 192(1), 11. doi:10.1007/s10661-019-7980-4 *https://tethys.pnnl.gov/publications/pelagicam-novel-underwater-imaging-system-computer-vision-semi-automated-monitoring*

Sheehan, E. V., Cartwright, A. Y., Witt, M. J., Attrill, M. J., Vural, M., and Holmes, L. A. 2018. Development of epibenthic assemblages on artificial habitat associated with marine renewable infrastructure. *ICES Journal of Marine Science*. doi:10.1093/icesjms/fsy151 *https://tethys.pnnl.gov/publications/development-epibenthic-assemblages-artificial-habitat-associated-marine-renewable*

Slavik, K., Lemmen, C., Zhang, W., Kerimoglu, O., Klingbeil, K., and Wirtz, K. W. 2019. The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea. *Hydrobiologia*, 845(1), 35-53. doi:10.1007/s10750-018-3653-5 *https://tethys.pnnl.gov/publications/large-scale-impact-offshore-wind-farm-structures-pelagic-primary-productivity-southern*

Smokorowski, K. E., and Randall, R. G. 2017. Cautions on using the Before-After-Control-Impact design in environmental effects monitoring programs. *FACETS*, 2(1), 212-232. doi:10.1139/facets-2016-0058 *https://tethys.pnnl.gov/publications/cautions-using-after-control-impact-design-environmental-effects-monitoring-programs*

Taormina, B. 2019. Potential impacts of submarine power cables from marine renewable energy projects on benthic communities. Doctoral Dissertation, University of Western Brittany, Brest, France.

Taormina, B., Bald, J., Want, A., Thouzeau, G., Lejart, M., Desroy, N., and Carlier, A. 2018. A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions. *Renewable and Sustainable Energy Reviews*, 96, 380-391. doi:10.1016/j.rser.2018.07.026 *https://tethys.pnnl.gov/publications/review-potential-impacts-submarine-power-cables-marine-environment-knowledge-gaps*

van Hal, R., Griffioen, A. B., and van Keeken, O. A. 2017. Changes in fish communities on a small spatial scale, an effect of increased habitat complexity by an offshore wind farm. *Marine Environmental Research*, 126, 26-36. doi:10.1016/j.marenvres.2017.01.009 *https://tethys.pnnl.gov/publications/changes-fish-communities-small-spatial-scale-effect-increased-habitat-complexity*

van der Molen, J., Ruardij, P., and Greenwood, N. 2016. Potential environmental impact of tidal energy extraction in the Pentland Firth at large spatial scales: results of a biogeochemical model. *Biogeosciences*, 13(8), 2593-2609. doi:10.5194/bg-13-2593-2016 *https://tethys.pnnl.gov/publications/potential-environmental-impact-tidal-energy-extraction-pentland-firth-large-spatial*

Vaselli, S., Bulleri, F., and Benedetti-Cecchi, L. 2008. Hard coastal-defence structures as habitats for native and exotic rocky-bottom species. *Marine Environmental Research*, 66(4), 395-403. doi:10.1016/j.marenvres.2008.06.002 *https://tethys.pnnl.gov/publications/hard-coastal-defence-structures-habitats-native-exotic-rocky-bottom-species*

Viola, S. M., Page, H. M., Zaleski, S. F., Miller, R. J., Doheny, B., Dugan, J. E., Schroeder, D. M., and Schroeter, S. C. 2018. Anthropogenic disturbance facilitates a non-native species on offshore oil platforms. *Journal of Applied Ecology*, 55(4), 1583-1593. doi:10.1111/1365-2664.13104 *https://tethys.pnnl.gov/publications/anthropogenic-disturbance-facilitates-non-native-species-offshore-oil-platforms*

Vodopivec, M., J Peliz, Á., and Malej, A. 2017. Offshore marine constructions as propagators of moon jellyfish dispersal. *Environmental Research Letters*, 12(8), 084003. doi:10.1088/1748-9326/aa75d9 *https://tethys.pnnl.gov/publications/offshore-marine-constructions-propagators-moon-jellyfish-dispersal*

Want, A., Crawford, R., Kakkonen, J., Kiddie, G., Miller, S., Harris, R. E., and Porter, J. S. 2017. Biodiversity characterisation and hydrodynamic consequences of marine fouling communities on marine renewable energy infrastructure in the Orkney Islands Archipelago, Scotland, UK. *Biofouling*, 33(7), 567-579. doi:10.1080/08927014.2017.1336229 *https://tethys.pnnl.gov/publications/biodiversity-characterisation-hydrodynamic-consequences-marine-fouling-communities*

Want, A., and Porter, J. 2018, 28-31 May 2018. BioFREE: An International Study of Biofouling Impacts on the Marine Renewable Energy Industry. Paper presented at the 2018 OCEANS - MTS/IEEE Kobe Techno-Oceans (OTO), Kobe, Japan. doi:10.1109/OCEANSKOBE.2018.8559322 *https://tethys.pnnl.gov/publications/biofree-international-study-biofouling-impacts-marine-renewable-energy-industry*

Wehkamp, S., and Fischer, P. 2013. Impact of coastal defence structures (tetrapods) on a demersal hard-bottom fish community in the southern North Sea. *Marine Environmental Research*, 83, 82-92. doi:10.1016/j.marenvres.2012.10.013 *https://tethys.pnnl.gov/publications/impact-coastal-defence-structures-tetrapods-demersal-hard-bottom-fish-community*

Wilding, T. A., Gill, A. B., Boon, A., Sheehan, E., Dauvin, J. C., Pezy, J.-P., O'Beirn, F., Janas, U., Rostin, L., and De Mesel, I. 2017. Turning off the DRIP ('Data-rich, information-poor') – rationalising monitoring with a focus on marine renewable energy developments and the benthos. *Renewable and Sustainable Energy Reviews*, 74, 848-859. doi:10.1016/j.rser.2017.03.013 *https://tethys.pnnl.gov/publications/turning-drip-data-rich-information-poor-rationalising-monitoring-focus-marine*

Wilhelmsson, D., Malm, T., and Öhman, M. C. 2006. The influence of offshore windpower on demersal fish. *ICES Journal of Marine Science*, 63(5), 775-784. doi:10.1016/j.icesjms.2006.02.001 *https://tethys.pnnl.gov/publications/influence-offshore-windpower-demersal-fish*

Williamson, B., Fraser, S., Williamson, L., Nikora, V., and Scott, B. 2019. Predictable changes in fish school characteristics due to a tidal turbine support structure. *Renewable Energy*, 141, 1092-1102. doi:10.1016/j.renene.2019.04.065 *https://tethys.pnnl.gov/publications/predictable-changes-fish-school-characteristics-due-tidal-turbine-support-structure*

NOTES

Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices

Hemery, L.G. 2020. Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 104-125). doi:10.2172/1633182

REPORT AND MORE INFORMATION

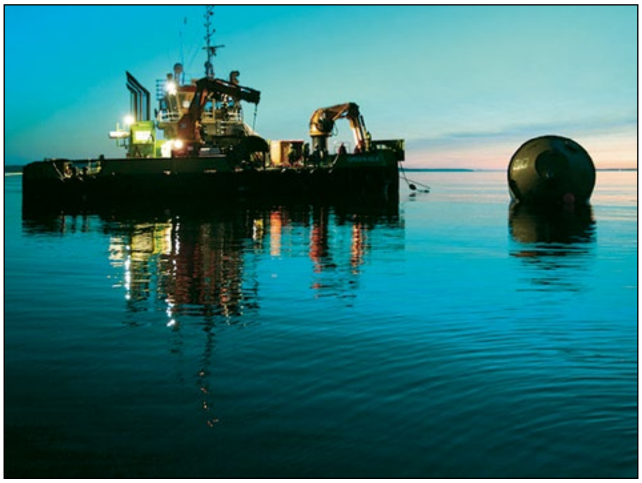
OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

7.0



Chapter authors: Jonathan M. Whiting, Grace Chang
Contributors: Andrea E. Copping, Lysel Garavelli, Hayley K. Farr

Changes in Oceanographic Systems Associated with Marine Renewable Energy Devices

Oceanographic processes define the marine environment: the flow of water determines the concentrations of dissolved gases and nutrients, transports sediments, and maintains the habitats and water quality that support marine organisms and healthy ecosystems. Important physical processes in the ocean include, but are not limited to, tidal circulation and basin flushing, wave action, local and basin-scale ocean currents, temperature and salinity gradients, sediment transport forming and shaping coastlines, and the exchange of heat and dissolved gases at the air-water interface. Harnessing energy with marine renewable energy (MRE) devices has the potential to affect these processes in both the nearfield (within a few device lengths) and the farfield (farther from the device, from the scale of multiple devices to the scale of an enclosed basin) by removing energy from the system, changing natural flow patterns around devices, and/or decreasing wave heights.

7.1. IMPORTANCE OF THE ISSUE

MRE devices are most commonly sited in locations that feature high-energy densities where there is potential to extract energy. Channels that are constricted by depth and/or width increase water velocity and flow rates and may be well suited for harnessing tidal energy. The energy and configuration of waves are dependent on the fetch over which the wind can generate waves, the configuration of the continental slope and shelf, and in some cases, the geometry of the incident coastline. Ocean currents are formed along continental boundaries, driven by the rotation of the Earth, temperature gradients, and global winds, with narrower focused currents on the western side of ocean basins (western intensification). These are the regions where MRE devices may be able to most effectively harness energy from the ocean (Yang and Copping 2017). However, some areas may be too energetic for successful deployment and operation of devices, particularly in tidal areas characterized by high levels of turbulence (Chen and Lam 2015).

While the blockage of natural flow caused by tidal turbines is not as significant as hydropower dams and tidal barrages, tidal turbines will reduce the tidal range or the flushing of contaminants from an enclosed coastal system, but the effect will almost certainly be negligible until large arrays are deployed and operated (De Dominicis et al. 2017; Nash et al. 2014). Tides are a primary driver of sediment transport in enclosed basins, moving and suspending sediments that shape seabed morphology and support nearshore habitats. In addition, tidal currents play a role in water column mixing, changing the nutrient concentrations and plankton aggregations, and transporting fish and invertebrate larvae.

Wave energy converters (WECs) have the potential to alter wave propagation and under-currents, thereby affecting natural processes such as the transport of sediment in coastal waters and the shaping of coastlines. The transport of sediments supports the formation and protection of beaches and other coastal features (González-Santamaría et al. 2012), but can also lead to the erosion of shorelines and destruction of coastal infrastructure (Caldwell 1967). Waves are also responsible for vertical mixing of salinity, temperature, suspended sediments, dissolved nutrients in the water column, and plankton, further supporting marine life.

Ocean currents (e.g., the Gulf Stream current in the North Atlantic Ocean) are responsible for the transport of organisms and nutrients worldwide. Large arrays of ocean current turbines may have the potential to slow or alter the direction of ocean currents (e.g., Haas et al. 2014).

Large-scale MRE deployments have the potential to disrupt natural processes driven by tides, waves, and ocean currents. Yet these disruptions need to be viewed within the context of the ocean as a rapidly changing system, comparing the magnitude of potential disruptions caused by MRE development to the natural variation of key parameters in the marine systems.

7.2. SUMMARY OF KNOWLEDGE THROUGH 2016

Changes in oceanographic systems caused by single MRE devices or small MRE arrays (~20 MW or less) are likely to be small compared to the natural variability of the system (Robins et al. 2014). In the absence of large-scale arrays, insight gained into the changes in the oceanographic system has relied on numerical model simulations to estimate potential farfield effects. These models need to be validated, but the scarcity of oceanographic data about these high-energy environments and the scarcity of device deployments worldwide make model validation impossible at this time (Copping et al. 2016).

As of 2016, studies that attempted to measure oceanographic conditions before and after deployment and operation of MRE devices were limited (Copping et al. 2016). However, many numerical models had been developed to study energy removal and changes in flow around MRE devices. Modeling investigations of the effects of tidal energy generation saw considerable advances prior to 2016, with the placement of economically and socially reasonable numbers of turbines for an estuary or coastal embayment (Martin-Short et al. 2015; Yang et al. 2014), more accurate modeling of sediment transport processes (Fairley et al. 2015; Robins et al. 2014; Smith et al. 2013), and the inclusion of water-quality constituents (Wang et al. 2015; Yang and Wang 2015). Although the complexity of wave regimes and the number of different WEC designs under development posed challenges to wave modeling, numerical models have provided insight into beach erosion profiles (Abanades et al. 2014) and nearshore changes (Chang et al. 2014).

As of 2016, a small number of field and laboratory studies on the changes in oceanographic systems caused by MRE devices had been conducted. Research in the Bay of Fundy, Canada used natural variability as a proxy for the perturbations caused by tidal devices, to look at the changes in sediment dynamics and deposition in tidal creeks (O'Laughlin and van Proosdij 2013; O'Laughlin et al. 2014; van Proosdij et al. 2013). Experiments carried out in a flume, using a small-scale turbine and an artificial sediment bed, used simulated field conditions and identified the characteristics of erosion (Ramírez-Mendoza et al. 2015).

By 2016, significant progress had been made toward understanding and evaluating the potential effects of MRE devices on natural systems, yet five specific needs remained (Copping et al. 2016):

- validation of models with more field measurements around deployed devices
- reduction of model uncertainty with targeted research on turbulence
- variation of model inputs to account for differences in device designs
- creation of better linkages between the nearfield and farfield effects of MRE devices
- evaluation of the cumulative effects in relation to natural variability and anthropogenic activities.

7.3. KNOWLEDGE GENERATED SINCE 2016

Literature that advances the state of the science relative to changes in oceanographic systems is summarized here by field, laboratory, and modeling studies. Although a substantial body of literature focuses on power extraction potential and resource characterization for wave and tidal energy, only studies that explicitly address the environmental effects of MRE devices are included. Studies of the turbulence downstream of offshore wind turbines that have monopile foundations have been conducted (Baeye and Fettweis 2015; Miles et al. 2017; Rogan et al. 2016; Schultze 2018), but a structure spanning the full water column is not representative of MRE devices. Instead, future studies conducted around floating offshore wind foundations will be valid analogs to inform MRE deployments.

7.3.1. FIELD STUDIES

Field studies have focused on measuring changes in flow and turbulence near MRE development sites to provide for the calibration or validation of numerical models. As of 2020, few field studies have measured the effects of MRE devices, because potential changes are unlikely to be measurable within a system's natural variability for the current size of deployments (Petrie et al. 2014).

The greatest number of MRE devices worldwide has been deployed and tested at the European Marine Energy Centre (EMEC) in the United Kingdom (UK) but only a few projects have focused on measuring changes in oceanographic systems. Using the Flow, Water Column and Benthic Ecology (FLOWBEC) platform, Fraser et al. (2017) measured velocity in the wake of the bottom-mounted foundation for a tidal turbine to quantify turbulent interactions with the seabed. Compared to nearby control measurements, observations showed a 31 percent decrease in flow velocity and a 10–15 percent increase in turbulence intensity over two days of measurements. As part of the Reliable Data Acquisition Platform for Tidal (ReDAPT) project, two instrumentation platforms were deployed to characterize the EMEC Fall of Warness Tidal site and monitor flow and wave fields around a 1 MW Alstrom DEEPGEN IV tidal turbine (Sellar and Sutherland 2016; Sellar et al. 2017). Analyses of flow velocity and turbulence highlighted site-specific differences between ebb and flood tides, which can be used to optimize power production while minimizing likely environmental effects (Sellar et al. 2018). Wake recovery measurements around a deployed river turbine in Alaska, United States (U.S.), showed that the wake was persistent and did not show significant recovery downstream of the turbine (Guerra and Thomson 2019). Observations around deployments of three CETO5 point-absorber WECs off Perth, Australia, between November 2014 and December 2015, supported model predictions of reduced wave height leeward of the devices (Contardo et al. 2018). Key findings included that wave height reductions in the swell band were comparable to those in the wind-sea band, observations were greater than those simulated by the model, and some of the differences in the local wave climate were attributable to natural variability at the site. Turbulence was also measured at potential tidal extraction sites (Garcia Novo and Kyozuka 2019; Togneri et al. 2017). The results of these field studies inform numerical models that assist with device design and siting, but they also have implications for how MRE devices may affect the nearfield and farfield mixing of water and entrainment of sediment within the marine ecosystem.

7.3.2. LABORATORY STUDIES

Studies conducted in flumes to understand wake recovery and turbulence due to tidal energy extraction can provide insight into the effects of MRE extraction (Mycek et al. 2014a, 2014b). Acoustic instrumentation was used to characterize flow and sediment transport in the wake of a scaled turbine, and the results indicated an increase in suspended sediment as far as 15 rotor diameters downstream, deposition along the centerline, and a horseshoe-shaped scour pit in the near wake region (Ramírez-Mendoza et al. 2018). Wake effects characterize the environment in the immediate area of turbines but might also have more distant effects with the development of large arrays. Close lateral spacing within an array causes significantly reduced velocity recovery, suggesting that spacing could be optimized for wake recovery (Nuernberg and Tao 2018). Three distinct wake regions were identified in a flume study (Ouro et al. 2019), which allowed for more detailed examination of changes that might affect the environment (Figure 7.1).

Experiments in wave tanks were also used to better understand the mechanics of reflected waves and the wave spectrum. Five cylindrical floating WECs were tested in a wave basin with different spacing, and it was determined that one wavelength distance apart reduced the changes in hydrodynamics (O'Boyle et al. 2017). Stereo-videogrammetry has been shown to demonstrate accuracy similar to wave gauges when measuring waves reflecting from walls (Winship et al. 2018).

7.3.3. MODELING STUDIES – TIDAL ENERGY

Until large arrays are deployed in the marine environment and field measurements are collected to determine whether MRE devices are affecting oceanographic processes, numerical models provide the best insight into what might occur as the MRE industry advances.

Literature addressing the effects of tidal energy extraction on the hydrodynamics of oceanographic systems has reported changes in velocity and residence times, without much elaboration about the environmental implications of such changes. Gallego et al. (2017) and Side et al. (2017) summarize a large collaborative modeling project, known as TeraWatt, that uses hydrodynamic, wave, and sediment transport models to examine the effects of tidal arrays in Pentland Firth and Orkney waters, UK, thereby demonstrating the application of numerical models to assessing the oceanographic changes in a system. Li et al. (2019) assessed the theoretical effects of a single tidal device on waves in shallow waters and showed a three percent reduction in wave

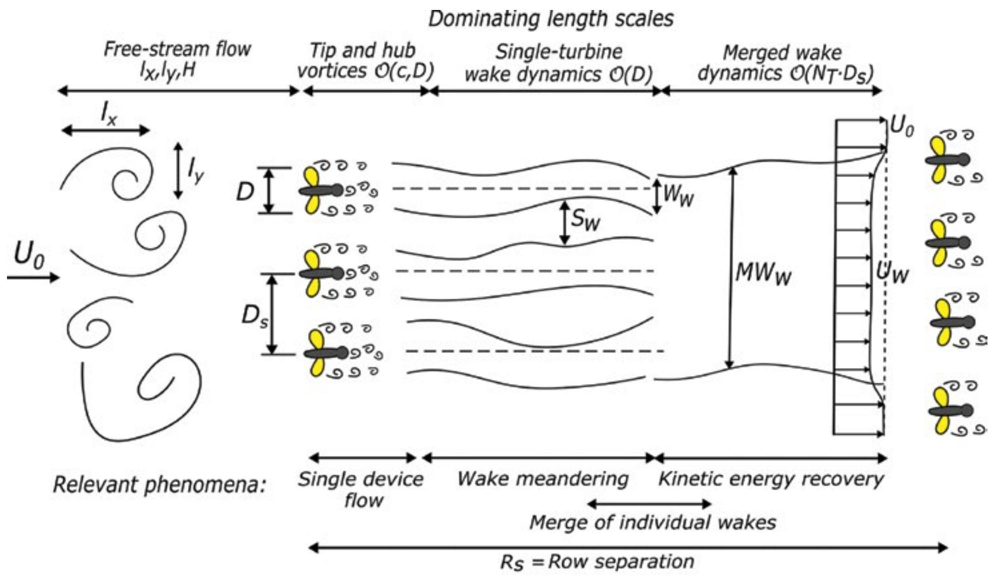


Figure 7.1. Schematic of the hydrodynamics of an array of tidal turbines. (From Ouro et al. 2019)

height and a slight increase in wavelength, where the magnitude of change was highly dependent on turbine size and water depth. Wang and Yang (2017) explored power extraction scenarios extracting 250 kW to 1.8 MW from tidal inlets in Puget Sound, Washington State, U.S., and showed that system-wide environmental effects were unlikely to be a concern for small arrays. A model of a large 480-device tidal array in northeast China showed reduced velocities as far as 10 km downstream (Liu et al. 2019). Guillou and Chapalain (2017) modeled a full-extraction scenario in the Passage du Fromveur, France that showed alterations to existing circulation patterns and displaced recirculation eddies near the tidal extraction site, determined using tracer experiments, and resulted in a 5 percent decrease in residence time across the Ouessant-Molène archipelago (Guillou et al. 2019).

The removal of energy or alterations to water circulation patterns have the potential to change sediment transport processes that result in shoreline erosion, replenishment of beaches and shorelines, scour around infrastructure installations, and sediment accumulation nearshore. Sediment bed-shear stress is quadratically related to changes in the amplitude of tidal currents, indicating that the extraction of tidal energy could strongly affect sediment transport (Neill et al. 2017). Several models have assessed changes in sediment transport under large tidal energy extraction scenarios, and highlighted morphological change in sandbanks, including long-term movement and alteration that may disturb the sensitive benthic ecology (Chatzirodou et al. 2019; Fairley et al. 2017, 2018). Localized sediment accumulation was predicted around a proposed 10 MW array in Ramsey Sound (UK) using a 2D hydrodynamic model (Haverson et al. 2018). Modeling of suspended sediments around two large idealized energy extraction scenarios of 770 MW and 5.6 GW in the upper Bay of Fundy indicated that suspended sediment may decrease by an average of 5.6 percent and 37 percent, respectively, across the basin because of increased sedimentation, which could affect habitat particularly on fine-grained intertidal areas of the basin (Ashall et al. 2016). A dampening of the flood-ebb asymmetry driven by tidal energy extraction was simulated in a channel, resulting in a reduction of the gross volume of sediment transported (Potter 2019). Finally, Nelson et al. (2018) developed a framework for optimizing tidal energy device siting while considering environmental effects such as sediment transport.

Changes in flow caused by the introduction of tidal turbines also has the potential to affect biogeochemical processes. A 2D model of a 1000 m idealized channel with 55 turbines indicated that the operation of the turbines increased the residence time of phytoplankton within a waterbody by five percent but resulted in a decrease of mean phytoplankton concentrations by 18 to 28 percent (Schuchert et al. 2018). Using the backdrop of Pentland Firth, coupled hydrodynamics and biogeochemical models were used to examine nutrient cycles and responses by microorganisms in the presence of large tidal extraction scenarios of 800 MW and 8 GW (van der Molen et al. 2016). The results showed an initial increase in particulate carbon content in the seabed as detrital material settled, although an equilibrium was reached after the first year.

Because of the natural variability in the movement and constituents of seawater, exacerbated by variability induced by climate change, oceanographic changes attributable to the presence of large arrays of MRE devices in the water may not be detectable at a level that is biologically important. A model of the two-way interaction between a 1 m sea level rise predicted for 2090 and tidal energy extraction at the entrance to the Bay of Fundy showed that the impact of sea level rise even exceeded that of a 3 GW tidal extraction scenario (Kresning et al. 2019). García-Oliva et al. (2017) modeled three large tidal extraction scenarios (240 MW to 2.2 GW) to assess changes in water level within the Solway Firth estuary (UK). Changes in low tide were most prominent within and around the farm, while changes in high tide were most prominent at the inner part of the estuary, potentially decreasing flood risk. Another study modeled a high-emissions 2050 climate change scenario to include a 3.8 GW tidal extraction across 10 arrays in Scotland (De Dominicis et al. 2017, 2018). This scenario indicated that tidal velocities were reduced by both climate change and tidal energy extraction locally, although the impact of climate change was an order of magnitude larger, resulting in reduced mixing and increased stratification. However, tidal energy extraction was shown to locally reduce extreme water levels, countering some impacts of sea level rise (Figure 7.2).

Most tidal energy extraction modeling studies explore farfield effects from large arrays on the order of 1 GW or more (Ashall et al. 2016; Chatzirodou et al. 2019; De Dominicis et al. 2017, 2018; Fairley et al. 2017; Gallego et al. 2017; García-Oliva et al. 2017; Guillou and Chapalain 2017; Guillou et al. 2019; Kresning et al. 2019; van der Molen et al. 2016), but some focus on nearfield effects from small arrays on the order of 20 MW or less (Haverson et al. 2018; Li et al. 2019; Wang and Yang 2017). There has been some technology convergence for tidal devices; the greatest number of tidal deployments to date have been horizontal-axis turbines, either mounted on the seabed or suspended in the water column (floating).

7.3.4. MODELING STUDIES – WAVE ENERGY

As with tidal energy extraction, wave energy effects in the farfield physical environment cannot be measured until large arrays are deployed, but numerical models may provide estimates of potential future effects.

Array configurations significantly vary the impact on the nearshore wave climate. Three array configurations of 12 WECs—a single row, two rows, and three rows—were modeled to determine the potential effects of the Westwave array on the west coast of Ireland (Atan et al. 2019). The three-row configuration produced the least power extraction per device and led to a greater change in significant wave height, implying that array configuration can be modified to reduce impacts. Work summarized by Gallego et al. (2017) demonstrated the utility of numerical models to investigate wave arrays in Pentland Firth and Orkney waters, and showed localized effects on coastal morphology that decreased with distance. Several array designs and incident wave conditions were modeled for two hypothetical 60-device wave arrays at a test site off Newport, Oregon, U.S., to determine the threshold for wave-induced longshore force that may affect beaches and nearshore features (O'Dea et al. 2018). This study showed that wave arrays located close to shore and spaced close together will have greater effects, especially as wave heights and periods increase. Using a probabilistic framework, Jones et al. (2018) modeled the changes in shear stress and bed elevation caused by the introduction of a hypothetical 18-device wave farm consisting of oscillating water column WECs off Newport, Oregon. From this study, a Spatial Environmental Assessment Tool risk analysis was developed to visualize the potential impacts on different habitat types along the coast.

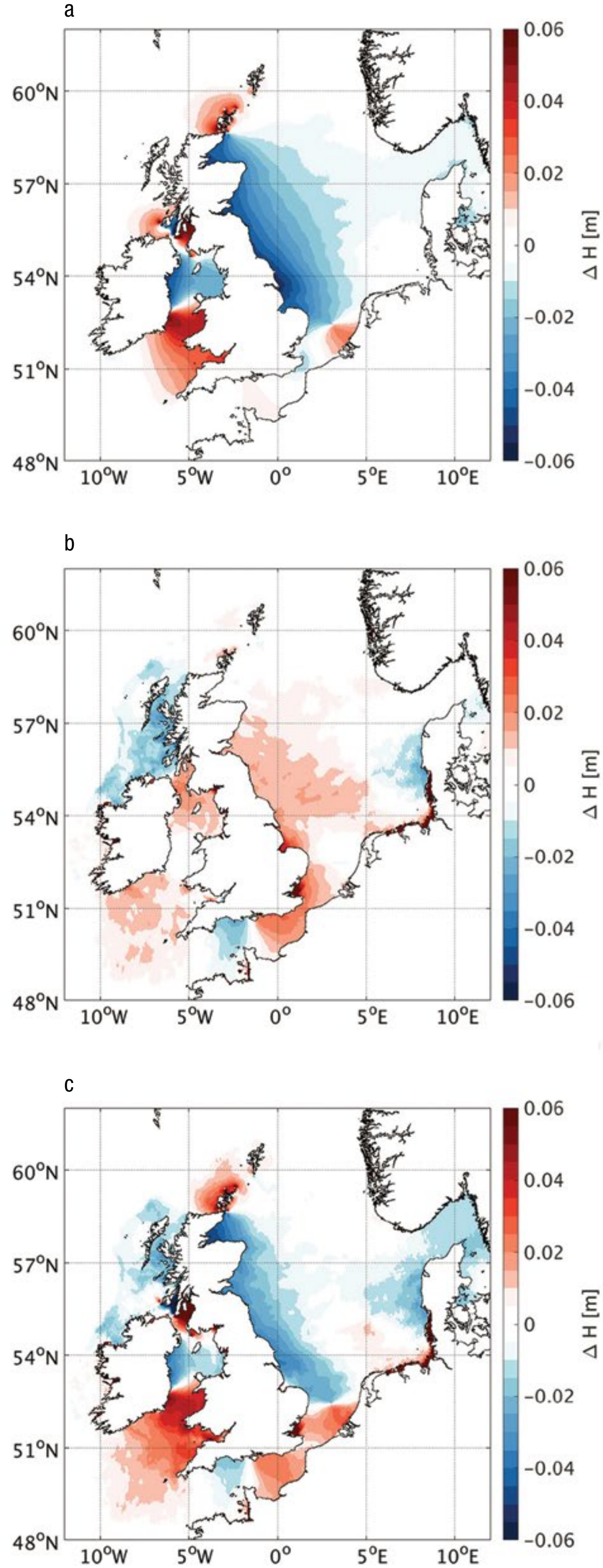


Figure 7.2. Change in spring peak tidal range, shown as the change in tidal height in meters, due to (a) tidal stream energy extraction during present conditions, (b) future climate conditions, and (c) tidal-stream energy extraction and future climate conditions. (Adapted from De Dominicis et al. 2018)

Because wave devices are often located in coastal waters, modeling studies have explored their effects on beach erosion, often analyzing the potential use of WECs for coastal protection. A staggered two-row array of overtopping devices at eight locations along an eroding gravel-dominated deltaic beach in Guidalfeo, Spain, was found to decrease the average significant wave heights by 18.3 percent, wave run-up by 10.6 percent, and beach erosion by 23.3 percent along the coast and by 44.5 percent at the central stretch of beach (Bergillos et al. 2018). In addition, a 44.6 percent decrease in longshore sediment transport and an increased amount of dry beach surface at the optimal array location were shown—significant because the array was located close to shore (Rodriguez-Delgado et al. 2018). Declines in the wave climate, caused by a floating wave array near an eroding beach-dune system in Asturias, Spain, were modeled to alleviate erosion of the dune front and support the dual use of WECs for coastal protection and energy generation (Abanades et al. 2018). However, for most open coastlines, WECs are unlikely to assist with coastal protection because the devices would be locked down during large storms that cause the most significant erosion.

Most wave models assess small arrays of 20 or fewer devices and the resulting nearfield effects (Abanades et al. 2018; Atan et al. 2019; Bergillos et al. 2018; Jones et al. 2018; Rodriguez-Delgado et al. 2018), likely because of the complexity of modeling diffracted and radiated waves around multiple devices or arrays. However, two studies looked at farfield effects around large wave arrays (O'Dea et al. 2018; Venugopal et al. 2017). There has been little technology convergence for wave devices; a plethora of WEC designs are under consideration, including attenuators, oscillating water columns, overtopping devices, and point absorbers. Each WEC design captures different aspects of wave energy and may affect the wave climate in different ways. Representing these different device designs accurately in numerical models adds a layer of complexity to the models, but several methods for parameterizations have emerged, including geometry solvers (Gallego et al. 2017; Venugopal et al. 2017) and idealized power matrices (Chang et al. 2016; Smith et al. 2012).

7.4. GUIDANCE ON MEASURING CHANGES IN OCEANOGRAPHIC SYSTEMS CAUSED BY MRE

The study of physical oceanographic processes is essential for assessing and ultimately quantifying the potential effects of MRE development on the physical environment, as well as for characterizing the tidal or wave resources available for extraction (Bergillos et al. 2019; González-Santamaría et al. 2013; Jones et al. 2018; Palha et al. 2010; Rusu and Guedes Soares 2009, 2013). Accurate measurements of the physical oceanographic environment before and after the deployment and operation of MRE devices can help understand potential effects on processes and resources such as water quality, sediment transport, and ecosystem processes.

7.4.1. ACOUSTIC DOPPLER TECHNOLOGIES

Measurements of subsurface current velocity are typically obtained using acoustic methods. Transducers transmit and receive sound signals at specific frequencies and ocean current velocities are computed based on sound travel time and the frequency shift (Doppler shift) of the echo (e.g., Simpson 2001). Multiple transducers enable resolution of 3D current velocity and direction. Because the principles of operation for the acoustic Doppler current profilers (ADCPs) rely on sound scattering, these instruments can also provide information about particle concentrations, including total suspended sediment (Gartner 2004; Wall et al. 2006), plankton biomass (Cisewski et al. 2010; Jiang et al. 2007), and fish school swimming speeds (Lee et al. 2014; Patro et al. 2000).

ADCPs (Figure 7.3a) are available in a wide range of acoustic frequencies, enabling measurement distances of up to hundreds of meters and at various spatial resolutions (from centimeters to meters). Acoustic Doppler velocimeters (ADVs; Figure 7.3a), which operate based on Doppler-based measurement principles similar to those of ADCPs, sample a small volume of water at a single point in the water column. Many ADVs are capable of sampling at a high rate of frequency (>8 Hz) to quantify forcing parameters such as shear stress, vertical sediment flux, dissipation rate of the kinetic energy of turbulence, and particle settling velocity (e.g., Fong

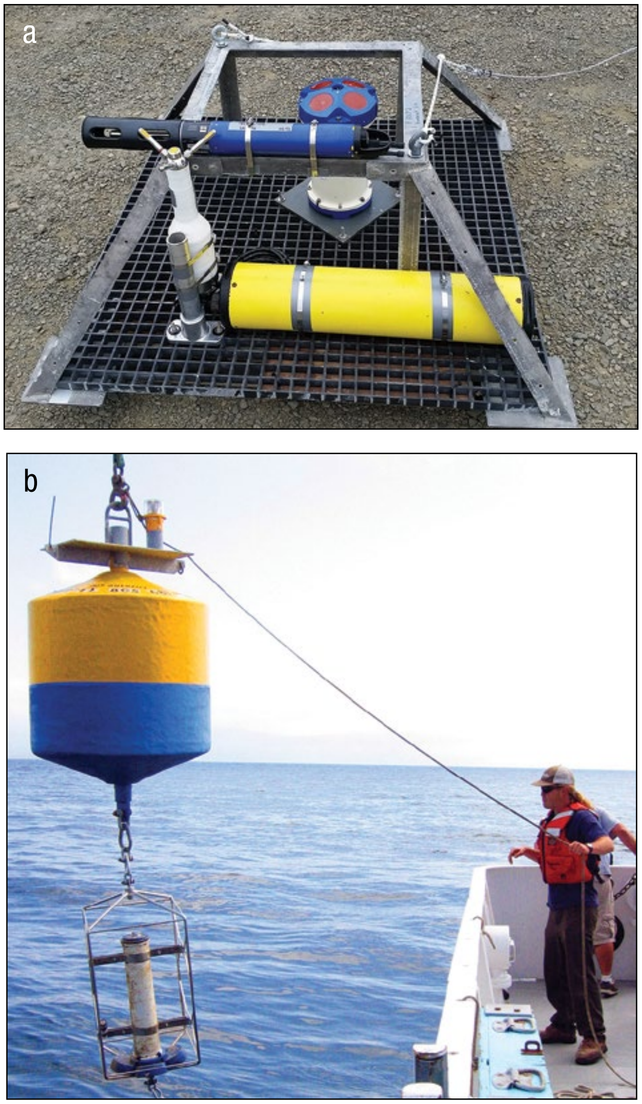


Figure 7.3. (a) An ADCP (background), ADV (foreground), and water-quality sensor (middle) mounted on a bottom platform, upward looking; and **(b)** a downward-looking ADCP mounted in-line on a coastal mooring. (Photos courtesy of Frank Spada [a] and Grace Chang [b])

et al. 2009; Fugate and Friedrichs 2002; Kim et al. 2000; Thorne and Hay 2012; Voulgaris and Throwbridge 1997). These types of measurements are critical for sediment transport monitoring and model parameterization (i.e., choosing appropriate parameters and values of parameters in models such as erosion rate) in the vicinity of MRE devices and may be useful for determining MRE design criteria and operational controls. A recent study demonstrated the utility of ADVs for evaluating the geomorphic effects of tidal turbine arrays under a variety of array designs and different environmental conditions (Musa et al. 2019). Laboratory results quantified local and non-local hydrodynamic and morphodynamic changes in response to different tidal turbine siting strategies to inform future turbine deployments for optimizing power production while minimizing environmental effects.

Acoustic Doppler current meters are self-contained (internal power and data storage) and can be deployed on a variety of sensing platforms, including real-time systems, from fixed and profiling moorings to manned and unmanned surface and underwater vehicles. They can be oriented with transducers pointed upward, downward (Figure 7.3b), or horizontally in the water column. Further, acoustic measurements are largely immune to the effects of biofouling (biological growth is generally acoustically transparent), making ADCPs and ADVs ideal systems for long-term (months), near-continuous measurements of 3D current velocities and particle concentrations. These types of sensors have been widely used for MRE environmental monitoring. Jones et al. (2014) employed ADCPs in combination with conductivity-temperature-depth (CTD) profiles and marine mammal observations to investigate the distribution of harbor porpoises (*Phocoena phocoeana*) in relation to fine-scale hydrodynamics in support of MRE development in Europe. Fine-scale features were identified in ADCP and CTD data and related to harbor porpoise density and distribution.

Some ADCPs are equipped with surface tracking and/or pressure transducers to enable co-located measurements of water elevation and spectral wave parameters (e.g., height, period, and direction) when mounted with transducers pointed upward. Wave measurements can also be obtained from bottom-mounted pressure gauges and wave staffs (e.g., Grogg 1986), or surface wave measurement buoys whose measurement principles are based on inertial measurement units (Earle 1996) or global positioning systems (Herbers et al. 2012). Although wave staffs and pressure gauges are depth-limited and more commonly used in wave tanks for MRE applications, wave buoys may be moored or allowed to passively drift in virtually any body of water (Raghukumar et al. 2019) (Figure 7.4).

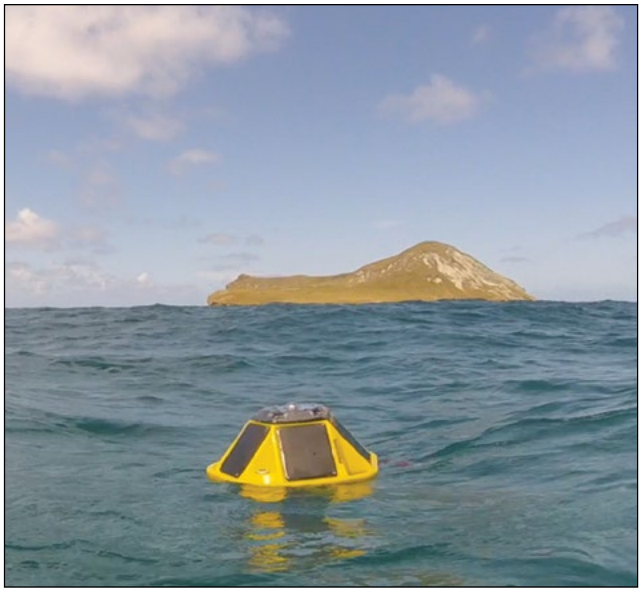


Figure 7.4. Spotter (Sofar Ocean) real-time wave measurement buoy. (Photo courtesy of Grace Chang)

7.4.2. REMOTE SENSING TECHNIQUES

Surface waves and currents can also be measured using remote-sensing techniques (e.g., radar altimetry, high-frequency radar, synthetic aperture radar, light detection and ranging [LiDAR]), or stereo photogrammetry. The primary advantage of remote-sensing technologies is that they provide synoptic measurements over relatively large spatial extents. The disadvantages may include poor spatial resolution, accuracy, range of detection, and/or limitations in measurement parameters (e.g., some technologies provide wave height but not direction or period).

Marine radar techniques are increasingly being employed for assessment, evaluation, and environmental monitoring in support of MRE projects (Bourdier et al. 2014). In The Crown Estate lease areas for MeyGen Ltd. and Scottish Power Renewables in Scotland, marine radar was used to obtain maps of surface currents in support of tidal turbine array deployments (Bell et al. 2014). This technique provided synoptic and accurate, high spatial resolution measurements of tidal currents for resource characterization and array design. Marine radar can also provide information about the potential downstream effects of tidal turbines, such as sea surface roughness modulations (turbulent wakes) in relation to tidal turbine foundation structures (Bell et al. 2015).

Remotely sensed optical technologies such as LiDAR show great promise for near-continuous observations of oceanographic processes in support of MRE environmental monitoring. While LiDAR techniques are more traditionally used for measurement of bathymetry (used as inputs in numerical models), they can also provide accurate assessment of waves, currents, and coastal morphology. Automated terrestrial LiDAR devices are effective tools for analyzing coastal processes at a wide range of spatial and temporal scales, from detailed investigation of individual wave propagation to long-term evaluation of hydrodynamic and morphodynamic variability in coastal zones (O'Dea et al. 2019). When deployed in the vicinity of WEC or tidal turbine arrays, LiDAR systems can satisfy the ocean parameter measurement criteria for high relevance and impact, feasibility, and cost.

7.5. RESEARCH AND MONITORING NEEDS TO RESOLVE THE ISSUE

Most regulators accept the fact that single MRE devices are unlikely to disrupt the oceanographic system into which they are deployed, and that we cannot expect to gather conclusive data about the potential effects of arrays until commercial MRE development progresses (Jones et al. 2016). In the meantime, improvements in numerical modeling capabilities and the validation of those models can help set the stage for evaluating future monitoring and research needs for larger arrays. Although progress has been made, key research and monitoring needs identified in the *2016 State of the Science* report (Copping et al. 2016) remain relevant. Recommendations for research and monitoring to advance the knowledge of MRE effects on oceanographic systems and move the industry forward are listed in the following sections.

7.5.1.
IMPROVING MODEL VALIDATION

Given the general lack of commercial-scale MRE deployments, few field data are being collected with which to validate model simulations. Oceanographic measurements collected for the purpose of characterizing the power potential at MRE sites are being used to verify model assumptions and outcomes from the UK and other regions where tidal turbines and WECs have been deployed (e.g., Sellar et al. 2017, 2018). Comprehensive monitoring was performed, mostly in the nearfield, at the sites of several single devices or small arrays located at EMEC, UK (Fraser et al. 2017; Sellar and Sutherland 2016; Sellar et al. 2017) and Perth, Australia (Contardo et al. 2018). As large arrays are deployed in the future, pre- and post-deployment farfield measurements will be needed to provide data for model validation.

Numerical models are steadily improving in resolution and realism, yet these improvements increase their dependency on high-quality measurements. Many geographic locations lack high-resolution bathymetry data that drive model realism. Models often use basic bottom drag or momentum sinks for tidal turbines or basic parameterizations for WECs, so fine-tuned device parameterizations are needed to accurately represent energy removal and changes in water flow (e.g., Apsley et al. 2018). To address the need for datasets, research should target the enhanced accuracy and resolution of sensors and remote technology, more consistent methodologies for data collection, and better sharing of existing datasets.

7.5.2.
ASSESSING CUMULATIVE EFFECTS: NATURAL VARIABILITY AND ANTHROPOGENIC ACTIVITIES

Assessing energy removal in the context of natural variability and other anthropogenic activities is particularly challenging and hampers estimation of the potential effects of MRE on the environment. Ocean circulation and sediment transport patterns naturally shift seasonally and over multi-year patterns such as the North Atlantic Oscillation, Pacific Decadal Oscillation, and El Niño Southern Oscillation. Extreme events like hurricanes or winter storms are also capable of causing significant acute change. Other anthropogenic activities such as the placement of offshore structures or dredging may also directly affect localized physical processes. Other anthropogenic pressures may be more indirect, such as a dam reducing coastal sediment supply from rivers and increasing coastal erosion. Similarly, MRE arrays may cumulatively interact with one another (Waldman et al. 2019). And all these local changes exist against the backdrop of a changing climate experiencing warming oceans and rising sea levels.

Cumulative effects studies will reduce uncertainty by isolating the effects of MRE extraction from natural and anthropogenic pressures. The effects of MRE extraction must also be compared to the impact of non-renewable energy sources that are being offset. A methodology for carrying out effective cumulative impact assessment is elusive but is sorely needed as additional use of ocean spaces come online. The MRE community needs to be a partner in developing and implementing methods that address cumulative impacts.

7.5.3.
UNDERSTANDING ENVIRONMENTAL IMPLICATIONS

Models predict changes in physical parameters, which may cascade into changes in the environment. To be meaningful, these predictions must be linked to potential impacts on specific organisms and ecosystem processes. These types of linkages are elusive but some insight can be gathered using proxies such as changes in sediment deposition rates to indicate changes in habitat structures (e.g., O'Laughlin et al. 2014), by comparing potential changes to natural variability (e.g., Kregting et al. 2016), or by coupling physical models to biogeochemical models (e.g., van der Molen et al. 2016). Learning from industry analogs may provide some early insights about the environmental effects of arrays. Environmental implications are often site-specific, but trends may be identified that apply across multiple bodies of water, different MRE device designs, and specific organisms. Studies that explore these trends can provide valuable guidance for the interpretation of model results and for device developers to minimize the potential effects of MRE devices on the oceanographic system.

7.6. REFERENCES

Abanades, J., Flor-Blanco, G., Flor, G., and Iglesias, G. 2018. Dual wave farms for energy production and coastal protection. *Ocean & Coastal Management*, 160, 18-29. doi:10.1016/j.ocecoaman.2018.03.038 *https://tethys.pnnl.gov/publications/dual-wave-farms-energy-production-coastal-protection*

Abanades, J., Greaves, D., and Iglesias, G. 2014. Wave farm impact on the beach profile: A case study. *Coastal Engineering*, 86, 36-44. doi:10.1016/j.coastaleng.2014.01.008 *https://tethys.pnnl.gov/publications/wave-farm-impact-beach-profile-case-study*

Apsley, D. D., Stallard, T., and Stansby, P. K. 2018. Actuator-line CFD modelling of tidal-stream turbines in arrays. *Journal of Ocean Engineering and Marine Energy*, 4(4), 259-271. doi:10.1007/s40722-018-0120-3 *https://tethys-engineering.pnnl.gov/publications/actuator-line-cfd-modelling-tidal-stream-turbines-arrays*

Ashall, L. M., Mulligan, R. P., and Law, B. A. 2016. Variability in suspended sediment concentration in the Minas Basin, Bay of Fundy, and implications for changes due to tidal power extraction. *Coastal Engineering*, 107, 102-115. doi:10.1016/j.coastaleng.2015.10.003 *https://tethys.pnnl.gov/publications/variability-suspended-sediment-concentration-minas-basin-bay-fundy-implications*

Atan, R., Finnegan, W., Nash, S., and Goggins, J. 2019. The effect of arrays of wave energy converters on the nearshore wave climate. *Ocean Engineering*, 172, 373-384. doi:10.1016/j.oceaneng.2018.11.043 *https://tethys.pnnl.gov/publications/effect-arrays-wave-energy-converters-nearshore-wave-climate*

Baeye, M., and Fettweis, M. 2015. In situ observations of suspended particulate matter plumes at an offshore wind farm, southern North Sea. *Geo-Marine Letters*, 35(4), 247-255. doi:10.1007/s00367-015-0404-8 *https://tethys.pnnl.gov/publications/situ-observations-suspended-particulate-matter-plumes-offshore-wind-farm-southern*

Bell, P., McCann, D., Lawrence, J., and Norris, J. 2015. Remote detection of sea surface roughness signatures related to subsurface bathymetry, structures and tidal stream turbine wakes. Paper presented at the 11th European Wave and Tidal Conference, Southampton, UK. *https://tethys.pnnl.gov/publications/remote-detection-sea-surface-roughness-signatures-related-subsurface-bathymetry*

Bell, P. S., McCann, D. L., Crammond, S., McIlvenny, J., Dufaur, J., and Archer, P. 2014. Marine radar derived current vector mapping at a planned commercial tidal stream turbine array in the Pentland Firth. Paper presented at the 2nd International Conference on Environmental Interactions of Marine Renewable Energy Technologies, Stornoway, Scotland. *https://tethys.pnnl.gov/publications/marine-radar-derived-current-vector-mapping-planned-commercial-tidal-stream-turbine*

Bergillos, R. J., López-Ruiz, A., Medina-López, E., Moñino, A., and Ortega-Sánchez, M. 2018. The role of wave energy converter farms on coastal protection in eroding deltas, Guadalfeo, southern Spain. *Journal of Cleaner Production*, 171, 356-367. doi:10.1016/j.jclepro.2017.10.018 *https://tethys.pnnl.gov/publications/role-wave-energy-converter-farms-coastal-protection-eroding-deltas-guadalfeo-southern*

Bergillos, R. J., Rodriguez-Delgado, C., and Iglesias, G. 2019. Wave farm impacts on coastal flooding under sea level rise: A case study in southern Spain. *Science of The Total Environment*, 653, 1522-1531. doi:10.1016/j.scitotenv.2018.10.422 *https://tethys.pnnl.gov/publications/wave-farm-impacts-coastal-flooding-under-sea level-rise-case-study-southern-spain*

Bourdier, S., Dampney, K., Fernandez, H., Lopez, G., and Richon, J.-B. 2014. Non-intrusive wave field measurement. (Report No. D4.05). Report by Energy Research Centre of the Netherlands for Marine Renewables Infrastructure Network. *https://tethys.pnnl.gov/publications/d405-non-intrusive-wave-field-measurement*

Caldwell, J. M. 1967. Coastal Processes and Beach Erosion. U.S. Army Coastal Engineering Research Center. *https://tethys.pnnl.gov/publications/coastal-processes-beach-erosion*

Chang, G., Magalen, J., Jones, C., and Roberts, J. 2014. Wave Energy Converter Effects on Wave Fields: Evaluation of SNL-SWAN and Sensitivity Studies in Monterey Bay, CA (Report No. SAND2014-17460). Sandia National Laboratories, Albuquerque, New Mexico. Report by SANDIA for U.S. Department of Energy. *https://tethys-engineering.pnnl.gov/publications/wave-energy-converter-effects-wave-fields-evaluation-snl-swan-sensitivity-studies*

Chang, G., Ruehl, K., Jones, C. A., Roberts, J., and Chartrand, C. 2016. Numerical modeling of the effects of wave energy converter characteristics on nearshore wave conditions. *Renewable Energy*, 89, 636-648. doi:10.1016/j.renene.2015.12.048 *https://tethys.pnnl.gov/publications/numerical-modeling-effects-wave-energy-converter-characteristics-nearshore-wave*

Chatzirodou, A., Karunarathna, H., and Reeve, D. E. 2019. 3D modelling of the impacts of in-stream horizontal-axis Tidal Energy Converters (TECs) on offshore sandbank dynamics. *Applied Ocean Research*, 91, 101882. doi:10.1016/j.apor.2019.101882 *https://tethys.pnnl.gov/publications/3d-modelling-impacts-stream-horizontal-axis-tidal-energy-converters-tecs-offshore*

Chen, L., and Lam, W.-H. 2015. A review of survivability and remedial actions of tidal current turbines. *Renewable and Sustainable Energy Reviews*, 43, 891-900. doi:10.1016/j.rser.2014.11.071 *https://tethys-engineering.pnnl.gov/publications/review-survivability-remedial-actions-tidal-current-turbines*

Cisewski, B., Strass, V. H., Rhein, M., and Krägefsky, S. 2010. Seasonal variation of diel vertical migration of zooplankton from ADCP backscatter time series data in the Lazarev Sea, Antarctica. *Deep Sea Research Part I: Oceanographic Research Papers*, 57(1), 78-94. doi:10.1016/j.dsr.2009.10.005 *https://tethys.pnnl.gov/publications/seasonal-variation-diel-vertical-migration-zooplankton-adcp-backscatter-time-series*

Contardo, S., Hoeke, R., Hemer, M., Symonds, G., McInnes, K., and O'Grady, J. 2018. In situ observations and simulations of coastal wave field transformation by wave energy converters. *Coastal Engineering*, 140, 175-188. doi:10.1016/j.coastaleng.2018.07.008 *https://tethys.pnnl.gov/publications/situ-observations-simulations-coastal-wave-field-transformation-wave-energy-converters*

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewski, G., Staines, G., Gill, A., Hutchison, I., O'Hagan, A., Simas, T., Bald, J., C., S., Wood, J., and Masden, E. 2016. Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development around the World. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. *https://tethys.pnnl.gov/publications/state-of-the-science-2016*

De Demonicis, M., Wolf, J., and Murray, R. 2018. Comparative Effects of Climate Change and Tidal Stream Energy Extraction in a Shelf Sea. *Journal of Geophysical Research*, 123(7), 5041-5067. doi:10.1029/2018JC013832 *https://tethys.pnnl.gov/publications/comparative-effects-climate-change-tidal-stream-energy-extraction-shelf-sea*

De Dominicis, M., O'Hara Murray, R., and Wolf, J. 2017. Multi-scale ocean response to a large tidal stream turbine array. *Renewable Energy*, 114, 1160-1179. doi:10.1016/j.renene.2017.07.058 *https://tethys.pnnl.gov/publications/multi-scale-ocean-response-large-tidal-stream-turbine-array*

Earle, M. D. 1996. Nondirectional and directional wave data analysis procedures. NDBC Technical Document 96-01. National Data Buoy Center, National Oceanic and Atmospheric Administration U.S. Department of Commerce. *https://tethys-engineering.pnnl.gov/publications/nondirectional-directional-wave-data-analysis-procedures*

Fairley, I., Karunarathna, H., and Chatzirodou, A. 2017. Modelling the Effects of Marine Energy Extraction on Non-Cohesive Sediment Transport and Morphological Change in the Pentland Firth and Orkney Waters. Marine Scotland Science, Aberdeen, United Kingdom. Report by Swansea University for Marine Scotland Science. doi:10.7489/1913-1 *https://tethys.pnnl.gov/publications/modelling-effects-marine-energy-extraction-non-cohesive-sediment-transport*

Fairley, I., Karunarathna, H., and Masters, I. 2018. The influence of waves on morphodynamic impacts of energy extraction at a tidal stream turbine site in the Pentland Firth. *Renewable Energy*, 125, 630-647. doi:10.1016/j.renene.2018.02.035 *https://tethys.pnnl.gov/publications/influence-waves-morphodynamic-impacts-energy-extraction-tidal-stream-turbine-site*

Fairley, I., Masters, I., and Karunarathna, H. 2015. Sediment Transport in the Pentland Firth and Impacts of Tidal Stream Energy Extraction. Paper presented at the 11th European Wave and Tidal Energy Conference, Nantes, France. *https://tethys.pnnl.gov/publications/sediment-transport-pentland-firth-impacts-tidal-stream-energy-extraction*

Fong, D. A., S. G. Monismith, M. T. Stacey, and Burau, J. R. 2009. Turbulent stresses and secondary currents in a tidal-forced channel with significant curvature and asymmetric bed forms. *Journal of Hydraulic Engineering*, 135(3): 198-208. doi:10.1061/(ASCE)0733-9429(2009)135:3(198) *https://tethys-engineering.pnnl.gov/publications/turbulent-stresses-secondary-currents-tidal-forced-channel-significant-curvature*

Fraser, S., Nikora, V., Williamson, B. J., and Scott, B. E. 2017. Hydrodynamic Impacts of a Marine Renewable Energy Installation on the Benthic Boundary Layer in a Tidal Channel. *Energy Procedia*, 125, 250-259. doi:10.1016/j.egypro.2017.08.169 *https://tethys.pnnl.gov/publications/hydrodynamic-impacts-marine-renewable-energy-installation-benthic-boundary-layer-tidal*

Gallego, A., Side, J., Baston, S., Waldman, S., Bell, M., James, M., Davies, I., O'Hara Murray, R., Heath, M., Sabatino, A., McKee, D., McCaig, C., Karunarathna, H., Fairley, I., Chatzirodou, A., Venugopal, V., Nemalidinne, R., Yung, T. Z., Vögler, A., MacIver, R., and Burrows, M. 2017. Large scale three-dimensional modelling for wave and tidal energy resource and environmental impact: Methodologies for quantifying acceptable thresholds for sustainable exploitation. *Ocean & Coastal Management*, 147, 67-77. doi:10.1016/j.ocecoaman.2016.11.025 *https://tethys.pnnl.gov/publications/large-scale-three-dimensional-modelling-wave-tidal-energy-resource-environmental*

García-Oliva, M., Djordjević, S., and Tabor, G. R. 2017. The impacts of tidal turbines on water levels in a shallow estuary. *International Journal of Marine Energy*, 19, 177-197. doi:10.1016/j.ijome.2017.07.006 *https://tethys.pnnl.gov/publications/impacts-tidal-turbines-water-levels-shallow-estuary*

Garcia Novo, P., and Kyozuka, Y. 2019. Analysis of turbulence and extreme current velocity values in a tidal channel. *Journal of Marine Science and Technology*, 24(3), 659-672. doi:10.1007/s00773-018-0601-z *https://tethys-engineering.pnnl.gov/publications/analysis-turbulence-extreme-current-velocity-values-tidal-channel*

Gartner, J. W. 2004. Estimating suspended solids concentrations from backscatter intensity measured by acoustic Doppler current profiler in San Francisco Bay, California. *Marine Geology*, 211(3), 169-187. doi:10.1016/j.margeo.2004.07.001 *https://tethys-engineering.pnnl.gov/publications/estimating-suspended-solids-concentrations-backscatter-intensity-measured-acoustic*

González-Santamaría, R., Zou, Q., and Pan, S. 2012. Modelling of the Impact of a Wave Farm on Nearshore Sediment Transport. Proceedings of 33rd Conference on Coastal Engineering, Santander, Spain. doi:10.9753/icce.v33.sediment.66 *https://tethys.pnnl.gov/publications/modelling-impact-wave-farm-nearshore-sediment-transport*

Gonzalez-Santamaria, R., Zou, Q. P., and Pan, S. 2013. Impacts of a Wave Farm on Waves, Currents and Coastal Morphology in South West England. *Estuaries and Coasts*, 38(1), 159-172. doi:10.1007/s12237-013-9634-z *https://tethys.pnnl.gov/publications/impacts-wave-farm-waves-currents-coastal-morphology-south-west-england*

Gotelli, C., Musa, M., Guala, M., and Escauriaza, C. 2019. Experimental and Numerical Investigation of Wake Interactions of Marine Hydrokinetic Turbines. *Energies*, 12(16), 17. doi:10.3390/en12163188 *https://tethys.pnnl.gov/publications/experimental-numerical-investigation-wake-interactions-marine-hydrokinetic-turbines*

Guerra, M., and Thomson, J. 2019. Wake measurements from a hydrokinetic river turbine. *Renewable Energy*, 139, 483-495. doi:10.1016/j.renene.2019.02.052 *https://tethys-engineering.pnnl.gov/publications/wake-measurements-hydrokinetic-river-turbine*

Guillou, N., and Chapalain, G. 2017. Assessing the impact of tidal stream energy extraction on the Lagrangian circulation. *Applied Energy*, 203, 321-332. doi:10.1016/j.apenergy.2017.06.022 *https://tethys.pnnl.gov/publications/assessing-impact-tidal-stream-energy-extraction-lagrangian-circulation*

Guillou, N., Thiébot, J., and Chapalain, G. 2019. Turbines' effects on water renewal within a marine tidal stream energy site. *Energy*, 189, 116113. doi:10.1016/j.energy.2019.116113 *https://tethys.pnnl.gov/publications/turbines-effects-water-renewal-within-marine-tidal-stream-energy-site*

Haas, K., Yang, X., and Fritz, H. 2014. Modeling Impacts of Energy Extraction from the Gulf Stream System. Paper presented at the Marine Energy Technology Symposium, Seattle, Washington. *https://tethys.pnnl.gov/publications/modeling-impacts-energy-extraction-gulf-stream-system*

Haverson, D., Bacon, J., Smith, H. C. M., Venugopal, V., and Xiao, Q. 2018. Modelling the hydrodynamic and morphological impacts of a tidal stream development in Ramsey Sound. *Renewable Energy*, 126, 876-887. doi:10.1016/j.renene.2018.03.084 *https://tethys.pnnl.gov/publications/modelling-hydrodynamic-morphological-impacts-tidal-stream-development-ramsey-sound*

Herbers, T. H. C., Jessen, P. F., Janssen, T. T., Colbert, D. B., and MacMahan, J. H. 2012. Observing Ocean Surface Waves with GPS-Tracked Buoys. *Journal of Atmospheric and Oceanic Technology*, 29(7), 944-959. doi:10.1175/jtech-d-11-00128.1 *https://tethys-engineering.pnnl.gov/publications/observing-ocean-surface-waves-gps-tracked-buoys*

Jiang, S., Dickey, T. D., Steinberg, D. K., and Madin, L. P. 2007. Temporal variability of zooplankton biomass from ADCP backscatter time series data at the Bermuda Testbed Mooring site. *Deep Sea Research Part I: Oceanographic Research Papers*, 54(4), 608-636. doi:10.1016/j.dsr.2006.12.011 *https://tethys.pnnl.gov/publications/temporal-variability-zooplankton-biomass-adcp-backscatter-time-series-data-bermuda*

Jones, A. R., Hosegood, P., Wynn, R. B., De Boer, M. N., Butler-Cowdry, S., and Embling, C. B. 2014. Fine-scale hydrodynamics influence the spatio-temporal distribution of harbour porpoises at a coastal hotspot. *Progress in Oceanography*, 128, 30-48. doi:10.1016/j.pocean.2014.08.002 *https://tethys.pnnl.gov/publications/fine-scale-hydrodynamics-influence-spatio-temporal-distribution-harbour-porpoises*

Jones, C., Chang, G., Raghukumar, K., McWilliams, S., Dallman, A., and Roberts, J. 2018. Spatial Environmental Assessment Tool (SEAT): A Modeling Tool to Evaluate Potential Environmental Risks Associated with Wave Energy Converter Deployments. *Energies*, 11(8), 2036. doi:10.3390/en11082036 *https://tethys.pnnl.gov/publications/spatial-environmental-assessment-tool-seat-modeling-tool-evaluate-potential*

Jones, C., McWilliams, S., Chang, G., and Roberts, J. 2016. Wave Energy Converter Array Environmental Evaluation Tools. Paper presented at the 4th Marine Energy Technology Symposium, Washington, D.C. *https://tethys.pnnl.gov/publications/wave-energy-converter-array-environmental-evaluation-tools*

Kim, S.-C., Friedrichs, C. T., Maa, J. P.-Y., and Wright, L. D. 2000. Estimating Bottom Stress in Tidal Boundary Layer from Acoustic Doppler Velocimeter Data. *Journal of Hydraulic Engineering*, 126(6), 399-406. doi:10.1061/(ASCE)0733-9429(2000)126:6(399) *https://tethys-engineering.pnnl.gov/publications/estimating-bottom-stress-tidal-boundary-layer-acoustic-doppler-velocimeter-data*

Kregting, L., Elsaesser, B., Kennedy, R., Smyth, D., O'Carroll, J., and Savidge, G. 2016. Do Changes in Current Flow as a Result of Arrays of Tidal Turbines Have an Effect on Benthic Communities? *PLoS ONE*, 11(8): 1-14. doi:10.1371/journal.pone.0161279 *https://tethys.pnnl.gov/publications/do-changes-current-flow-result-arrays-tidal-turbines-have-effect-benthic-communities*

Kresning, B., Hashemi, M. R., Neill, S. P., Green, J. A. M., and Xue, H. 2019. The impacts of tidal energy development and sea level rise in the Gulf of Maine. *Energy*, 187, 115942. doi:10.1016/j.energy.2019.115942 *https://tethys.pnnl.gov/publications/impacts-tidal-energy-development-sea-level-rise-gulf-maine*

Lee, K., Mukai, T., Lee, D.-J., and Iida, K. 2014. Classification of sound-scattering layers using swimming speed estimated by acoustic Doppler current profiler. *Fisheries Science*, 80(1), 1-11. doi:10.1007/s12562-013-0683-9 *https://tethys.pnnl.gov/publications/classification-sound-scattering-layers-using-swimming-speed-estimated-acoustic-doppler*

Li, X., Li, M., Jordan, L.-B., McLelland, S., Parsons, D. R., Amoudry, L. O., Song, Q., and Comerford, L. 2019. Modelling impacts of tidal stream turbines on surface waves. *Renewable Energy*, 130, 725-734. doi:10.1016/j.renene.2018.05.098 *https://tethys.pnnl.gov/publications/modelling-impacts-tidal-stream-turbines-surface-waves*

Liu, X., Yuan, P., Wang, S., Yuan, S., Tan, J., and Si, X. 2019. Simulation Study of Potential Impacts of Tidal Farm in the Eastern Waters of Chengshan Cape, China. *Journal of Ocean University of China*, 18(5), 1041-1050. doi:10.1007/s11802-019-3975-6 *https://tethys.pnnl.gov/publications/simulation-study-potential-impacts-tidal-farm-eastern-waters-chengshan-cape-china*

Martin-Short, R., Hill, J., Kramer, S. C., Avdis, A., Allison, P. A., and Piggott, M. D. 2015. Tidal resource extraction in the Pentland Firth, UK: Potential impacts on flow regime and sediment transport in the Inner Sound of Stroma. *Renewable Energy,* 76, 596-607. doi:10.1016/j.renene.2014.11.079 *https://tethys.pnnl.gov/publications/tidal-resource-extraction-pentland-firth-uk-potential-impacts-flow-regime-sediment*

Miles, J., Martin, T., and Goddard, L. 2017. Current and wave effects around windfarm monopile foundations. *Coastal Engineering,* 121, 167-178. doi:10.1016/j.coastaleng.2017.01.003 *https://tethys.pnnl.gov/publications/current-wave-effects-around-windfarm-monopile-foundations*

Musa, M., Hill, C., and Guala, M. 2019. Interaction between hydrokinetic turbine wakes and sediment dynamics: array performance and geomorphic effects under different siting strategies and sediment transport conditions. *Renewable Energy,* 138, 738-753. doi:10.1016/j.renene.2019.02.009 *https://tethys.pnnl.gov/publications/interaction-between-hydrokinetic-turbine-wakes-sediment-dynamics-array-performance*

Mycek, P., Gaurier, B., Germain, G., Pinon, G., and Rivoalen, E. 2014a. Experimental study of the turbulence intensity effects on marine current turbines behaviour. Part I: One single turbine. *Renewable Energy,* 66, 729-746. doi:10.1016/j.renene.2013.12.036 *https://tethys.pnnl.gov/publications/experimental-study-turbulence-intensity-effects-marine-current-turbines-behaviour-part*

Mycek, P., Gaurier, B., Germain, G., Pinon, G., and Rivoalen, E. 2014b. Experimental study of the turbulence intensity effects on marine current turbines behaviour. Part II: Two interacting turbines. *Renewable Energy,* 68, 876-892. doi:10.1016/j.renene.2013.12.048 *https://tethys.pnnl.gov/publications/experimental-study-turbulence-intensity-effects-marine-current-turbines-behaviour-0*

Nash, S., O'Brien, N., Olbert, A., and Hartnett, M. 2014. Modelling the far field hydro-environmental impacts of tidal farms – A focus on tidal regime, inter-tidal zones and flushing. *Computers & Geosciences,* 71, 20-27. doi:10.1016/j.cageo.2014.02.001 *https://tethys.pnnl.gov/publications/modelling-far-field-hydro-environmental-impacts-tidal-farms-focus-tidal-regime*

Neill, S., Robins, P., and Fairley, I. 2017. The Impact of Marine Renewable Energy Extraction on Sediment Dynamics. In Yang, Z. and Copping, A. (Eds.), *Marine Renewable Energy* (pp. 279-304). New York, NY: Springer International Publishing. *https://tethys.pnnl.gov/publications/impact-marine-renewable-energy-extraction-sediment-dynamics*

Nuernberg, M., and Tao, L. 2018. Experimental study of wake characteristics in tidal turbine arrays. *Renewable Energy*, 127: 168-181. doi:10.1016/j.renene.2018.04.053 *https://tethys-engineering.pnnl.gov/publications/experimental-study-wake-characteristics-tidal-turbine-arrays*

Nelson, K., James, S. C., Roberts, J. D., and Jones, C. 2018. A framework for determining improved placement of current energy converters subject to environmental constraints. *International Journal of Sustainable Energy,* 37(7), 654-668. doi:10.1080/14786451.2017.1334654 *https://tethys.pnnl.gov/publications/framework-determining-improved-placement-current-energy-converters-subject*

O'Boyle, L., Elsäßer, B., and Whittaker, T. 2017. Experimental Measurement of Wave Field Variations around Wave Energy Converter Arrays. *Sustainability,* 9(1), 70. doi:10.3390/su9010070 *https://tethys.pnnl.gov/publications/experimental-measurement-wave-field-variations-around-wave-energy-converter-arrays*

O'Dea, A., Brodie, K. L., and Hartzell, P. 2019. Continuous Coastal Monitoring with an Automated Terrestrial Lidar Scanner. *Journal of Marine Science and Engineering,* 7(2), 37. doi:10.3390/jmse7020037 *https://tethys-engineering.pnnl.gov/publications/continuous-coastal-monitoring-automated-terrestrial-lidar-scanner*

O'Dea, A., Haller, M. C., and Özkan-Haller, H. T. 2018. The impact of wave energy converter arrays on wave-induced forcing in the surf zone. *Ocean Engineering,* 161, 322-336. doi:10.1016/j.oceaneng.2018.03.077 *https://tethys.pnnl.gov/publications/impact-wave-energy-converter-arrays-wave-induced-forcing-surf-zone*

O'Laughlin, C., and van Proosdij, D. 2013. Influence of varying tidal prism on hydrodynamics and sedimentary processes in a hypertidal salt marsh creek. *Earth Surface Processes and Landforms,* 38(5), 534-546. doi:10.1002/esp.3340 *https://tethys.pnnl.gov/publications/influence-varying-tidal-prism-hydrodynamics-sedimentary-processes-hypertidal-salt*

O'Laughlin, C., van Proosdij, D., and Milligan, T. G. 2014. Flocculation and sediment deposition in a hypertidal creek. *Continental Shelf Research*, 82, 72-84. doi:10.1016/j.csr.2014.02.012 *https://tethys.pnnl.gov/publications/flocculation-sediment-deposition-hypertidal-creek*

Ouro, P., Runge, S., Luo, Q., and Stoesser, T. 2019. Three-dimensionality of the wake recovery behind a vertical axis turbine. *Renewable Energy*, 133, 1066-1077. doi:10.1016/j.renene.2018.10.111 *https://tethys-engineering.pnnl.gov/publications/three-dimensionality-wake-recovery-behind-vertical-axis-turbine*

Palha, A., Mendes, L., Fortes, C. J., Brito-Melo, A., and Sarmento, A. 2010. The impact of wave energy farms in the shoreline wave climate: Portuguese pilot zone case study using Pelamis energy wave devices. *Renewable Energy*, 35(1), 62-77. doi:10.1016/j.renene.2009.05.025 *https://tethys.pnnl.gov/publications/impact-wave-energy-farms-shoreline-wave-climate-portuguese-pilot-zone-case-study-using*

Patro, R., Zedel, L., and Spanu-Tollefsen, C. 2000. Monitoring fish movement using an ADCP. *The Journal of the Acoustical Society of America*, 108(5), 2489-2489. doi:10.1121/1.4743187 *https://tethys.pnnl.gov/publications/monitoring-fish-movement-using-adcp*

Petrie, J., Diplas, P., Gutierrez, M., and Nam, S. 2014. Characterizing the mean flow field in rivers for resource and environmental impact assessments of hydrokinetic energy generation sites. *Renewable Energy*, 69, 393-401. doi:10.1016/j.renene.2014.03.064 *https://tethys.pnnl.gov/publications/characterizing-mean-flow-field-rivers-resource-environmental-impact-assessments*

Potter, D. 2019. Alteration to the shallow-water tides and tidal asymmetry by tidal-stream turbines. Doctoral Dissertation, Lancaster University, Lancashire, England. *https://tethys.pnnl.gov/publications/alteration-shallow-water-tides-tidal-asymmetry-tidal-stream-turbines*

Raghukumar, K., Chang, G., Spada, F., Jones, C., Janssen, T., and Gans, A. 2019. Performance Characteristics of "Spotter," a Newly Developed Real-Time Wave Measurement Buoy. *Journal of Atmospheric and Oceanic Technology*, 36(6), 1127-1141. doi:10.1175/jtech-d-18-0151.1 *https://tethys-engineering.pnnl.gov/publications/performance-characteristics-spotter-newly-developed-real-time-wave-measurement-buoy*

Ramírez-Mendoza, R., Amoudry, L., Thorne, P., Cooke, R., Simmons, S., McLelland, S., Murphy, B., Parsons, D., Jordan, L., and Vybulkova, L. 2015. Impact of Scaled Tidal Stream Turbine over Mobile Sediment Beds. Paper presented at the 11th European Wave and Tidal Energy Conference, Nantes, France. *https://tethys.pnnl.gov/publications/impact-scaled-tidal-stream-turbine-over-mobile-sediment-beds*

Ramírez-Mendoza, R., Amoudry, L. O., Thorne, P. D., Cooke, R. D., McLelland, S. J., Jordan, L. B., Simmons, S. M., Parsons, D. R., and Murdoch, L. 2018. Laboratory study on the effects of hydro kinetic turbines on hydrodynamics and sediment dynamics. *Renewable Energy*, 129, 271-284. doi:10.1016/j.renene.2018.05.094 *https://tethys.pnnl.gov/publications/laboratory-study-effects-hydro-kinetic-turbines-hydrodynamics-sediment-dynamics*

Robins, P. E., Neill, S. P., and Lewis, M. J. 2014. Impact of tidal-stream arrays in relation to the natural variability of sedimentary processes. *Renewable Energy*, 72, 311-321. doi:10.1016/j.renene.2014.07.037 *https://tethys.pnnl.gov/publications/impact-tidal-stream-arrays-relation-natural-variability-sedimentary-processes*

Rodriguez-Delgado, C., Bergillos, R. J., Ortega-Sánchez, M., and Iglesias, G. 2018. Protection of gravel-dominated coasts through wave farms: Layout and shoreline evolution. *Science of The Total Environment*, 636, 1541-1552. doi:10.1016/j.scitotenv.2018.04.333 *https://tethys.pnnl.gov/publications/protection-gravel-dominated-coasts-through-wave-farms-layout-shoreline-evolution*

Rogan, C., Miles, J., Simmonds, D., and Iglesias, G. 2016. The turbulent wake of a monopile foundation. *Renewable Energy*, 93, 180-187. doi:10.1016/j.renene.2016.02.050 *https://tethys.pnnl.gov/publications/turbulent-wake-monopile-foundation*

Rusu, E., and Guedes Soares, C. 2009. Numerical modelling to estimate the spatial distribution of the wave energy in the Portuguese nearshore. *Renewable Energy*, 34(6), 1501-1516. doi:10.1016/j.renene.2008.10.027 *https://tethys-engineering.pnnl.gov/publications/numerical-modelling-estimate-spatial-distribution-wave-energy-portuguese-nearshore*

Schuchert, P., Kregting, L., Pritchard, D., Savidge, G., and Elsäßer, B. 2018. Using Coupled Hydrodynamic Biogeochemical Models to Predict the Effects of Tidal Turbine Arrays on Phytoplankton Dynamics. *Journal of Marine Science and Engineering*, 6(2), 58. doi:10.3390/jmse6020058 *https://tethys.pnnl.gov/publications/using-coupled-hydrodynamic-biogeochemical-models-predict-effects-tidal-turbine-arrays*

Schultze, V. 2018. Natural variability of turbulence and stratification in a tidal shelf sea and the possible impact of offshore wind farms. Doctoral Dissertation, University of Hamburg, Hamburg, Germany. *https://tethys.pnnl.gov/publications/natural-variability-turbulence-stratification-tidal-shelf-sea-possible-impact-offshore*

Sellar, B., and Sutherland, D. 2016. Tidal Energy Site Characterisation at the Fall of Warness, EMEC, UK: Energy Technologies Institute ReDAPT MA1001 (MD3.8). University of Edinburgh, Edinburgh, Scotland. *https://tethys.pnnl.gov/publications/tidal-energy-site-characterisation-fall-warness-emec-uk*

Sellar, B. G., Sutherland, D. R. J., Ingram, D. M., and Venugopal, V. 2017. Measuring waves and currents at the European marine energy centre tidal energy test site: Campaign specification, measurement methodologies and data exploitation. Paper presented at OCEANS 2017 – Aberdeen, UK. doi: 10.1109/OCEANSE.2017.8085001 *https://tethys.pnnl.gov/publications/measuring-waves-currents-european-marine-energy-centre-tidal-energy-test-site-campaign*

Sellar, B. G., Wakelam, G., Sutherland, D. R. J., Ingram, D. M., and Venugopal, V. 2018. Characterisation of Tidal Flows at the European Marine Energy Centre in the Absence of Ocean Waves. *Energies*, 11(1), 176. doi:10.3390/en11010176 *https://tethys.pnnl.gov/publications/characterisation-tidal-flows-european-marine-energy-centre-absence-ocean-waves*

Side, J., Gallego, A., James, M., Davies, I., Heath, M., Karunarathna, H., Venugopal, V., Vögler, A., and Burrows, M. 2017. Developing methodologies for large scale wave and tidal stream marine renewable energy extraction and its environmental impact: An overview of the TeraWatt project. *Ocean & Coastal Management*, 147, 1-5. doi:10.1016/j.ocecoaman.2016.11.015 *https://tethys.pnnl.gov/publications/developing-methodologies-large-scale-wave-tidal-stream-marine-renewable-energy*

Simpson, M. 2001. Discharge Measurements Using a Broad-Band Acoustic Doppler Current Profiler (OPEN-FILE REPORT 01-1). United States Geological Survey, Sacramento, California. Report by United States Geological Survey. *https://tethys-engineering.pnnl.gov/publications/discharge-measurements-using-broad-band-acoustic-doppler-current-profiler*

Smith, P., Bugden, G., Wu, Y., Mulligan, R., and Tao, J. 2013. Impacts of Tidal Energy Extraction on Sediment Dynamics in Minas Basin, Bay of Fundy, NS. Report by Bedford Institute of Oceanography. *https://tethys.pnnl.gov/publications/impacts-tidal-energy-extraction-sediment-dynamics-minas-basin-bay-fundy-ns*

Thorne, P. D., and Hay, A. E. 2012. Introduction to the Special Issue of Continental Shelf Research on 'The application of acoustics to sediment transport processes'. *Continental Shelf Research*, 46, 1. doi:10.1016/j.csr.2012.08.005 *https://tethys.pnnl.gov/publications/introduction-special-issue-continental-shelf-research-application-acoustics-sediment*

Togneri, M., Lewis, M., Neill, S., and Masters, I. 2017. Comparison of ADCP observations and 3D model simulations of turbulence at a tidal energy site. *Renewable Energy*, 114, 273-282. doi:10.1016/j.renene.2017.03.061 *https://tethys.pnnl.gov/publications/comparison-adcp-observations-3d-model-simulations-turbulence-tidal-energy-site*

van der Molen, J., Ruardij, P., and Greenwood, N. 2016. Potential environmental impact of tidal energy extraction in the Pentland Firth at large spatial scales: results of a biogeochemical model. *Biogeosciences*, 13(8), 2593-2609. doi:10.5194/bg-13-2593-2016 *https://tethys.pnnl.gov/publications/potential-environmental-impact-tidal-energy-extraction-pentland-firth-large-spatial*

van Proosdij, D., O'Laughlin, C., Milligan, T., Law, B., and Spooner, I. 2013. Effects of Energy Extraction on Sediment Dynamics in Intertidal Ecosystems of the Minas Basin. Saint Mary's University, Halifax, Nova Scotia. Report by Acadia University. *https://tethys.pnnl.gov/publications/effects-energy-extraction-sediment-dynamics-intertidal-ecosystems-minas-basin*

Venugopal, V., Nemalidinne, R., and Vögler, A. 2017. Numerical modelling of wave energy resources and assessment of wave energy extraction by large scale wave farms. *Ocean & Coastal Management*, 147, 37-48. doi:10.1016/j.ocecoaman.2017.03.012 *https://tethys.pnnl.gov/publications/numerical-modelling-wave-energy-resources-assessment-wave-energy-extraction-large*

Voulgaris, G., and Trowbridge, J. H. 1998. Evaluation of the Acoustic Doppler Velocimeter (ADV) for Turbulence Measurements. *Journal of Atmospheric and Oceanic Technology*, 15(1), 272-289. doi:10.1175/1520-0426(1998)015<0272:Eotadv>2.0.Co;2 *https://tethys-engineering.pnnl.gov/publications/evaluation-acoustic-doppler-velocimeter-adv-turbulence-measurements*

Waldman, S., Weir, S., O'Hara Murray, R. B., Woolf, D. K., and Kerr, S. 2019. Future policy implications of tidal energy array interactions. *Marine Policy*, 108, 103611. doi:10.1016/j.marpol.2019.103611 *https://tethys.pnnl.gov/publications/future-policy-implications-tidal-energy-array-interactions*

Wall, G., Nystrom, E., and Litten, S. 2006. Use of an ADCP to compute suspended-sediment discharge in the tidal Hudson River, New York. Scientific Investigations Report 2006-5055. U.S. Geological Survey, Reston, Virginia. Report by United States Geological Survey. *https://tethys-engineering.pnnl.gov/publications/use-adcp-compute-suspended-sediment-discharge-tidal-hudson-river-new-york*

Wang, T., and Yang, Z. 2017. A modeling study of tidal energy extraction and the associated impact on tidal circulation in a multi-inlet bay system of Puget Sound. *Renewable Energy*, 114, 204-214. doi:10.1016/j.renene.2017.03.049 *https://tethys.pnnl.gov/publications/modeling-study-tidal-energy-extraction-associated-impact-tidal-circulation-multi-inlet*

Wang, T., Yang, Z., and Copping, A. 2015. A Modeling Study of the Potential Water Quality Impacts from In-Stream Tidal Energy Extraction. *Estuaries and Coasts*, 38(1), 173-186. doi:10.1007/s12237-013-9718-9 *https://tethys.pnnl.gov/publications/modeling-study-potential-water-quality-impacts-stream-tidal-energy-extraction*

Winship, B., Fleming, A., Penesis, I., Hemer, M., and Macfarlane, G. 2018. Preliminary investigation on the use of tank wall reflections to model WEC array effects. *Ocean Engineering*, 164: 388-401. doi:10.1016/j.oceaneng.2018.06.033 *https://tethys-engineering.pnnl.gov/publications/preliminary-investigation-use-tank-wall-reflections-model-wec-array-effects*

Yang, Z., and Copping, A. 2017. Marine Renewable Energy: Resource Characterization and Physical Effects. Springer International Publishing. *https://tethys.pnnl.gov/publications/marine-renewable-energy-resource-characterization-physical-effects*

Yang, Z., and Wang, T. 2015. Modeling the Effects of Tidal Energy Extraction on Estuarine Hydrodynamics in a Stratified Estuary. *Estuaries and Coasts*, 38(1), 187-202. doi:10.1007/s12237-013-9684-2 *https://tethys.pnnl.gov/publications/modeling-effects-tidal-energy-extraction-estuarine-hydrodynamics-stratified-estuary*

Yang, Z., Wang, T., Copping, A., and Geerlofs, S. 2014. Modeling of in-stream tidal energy development and its potential effects in Tacoma Narrows, Washington, USA. *Ocean & Coastal Management*, 99, 52-62. doi:10.1016/j.ocecoaman.2014.02.010 *https://tethys.pnnl.gov/publications/modeling-stream-tidal-energy-development-its-potential-effects-tacoma-narrows*

NOTES

Changes in Oceanographic Systems Associated with Marine Renewable Energy Devices

Whiting, J.M. and G. Chang. 2020. Changes in Oceanographic Systems Associated with Marine Renewable Energy Devices. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 126-145). doi:10.2172/1633183

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

8.0

Chapter author: Lysel Garavelli

Encounters of Marine Animals with Marine Renewable Energy Device Mooring Systems and Subsea Cables

Many marine renewable energy (MRE) technologies, including floating or midwater wave and tidal devices, require mooring systems (i.e., mooring lines and anchors) to maintain their position within the water column or on the sea surface. In the case of some devices such as tidal kites, these lines and cables can be highly dynamic. An array of non-bottom-mounted devices may also include transmission cables within the water column interconnecting devices to one another, or to offshore substations or hubs on the seabed. The potential for these lines and cables to present hazards for marine animals that may become entangled or entrapped in them, or confused by their presence remains an issue of uncertainty (Figure 8.1). The degree to which mitigation to avoid or reduce entanglement risk might be required for future MRE installations is yet to be determined, pending greater understanding of the actual nature of the risk. In this chapter, the entanglement or entrapment of a marine animal is defined as the cause to become caught in a system without possibility of escaping.

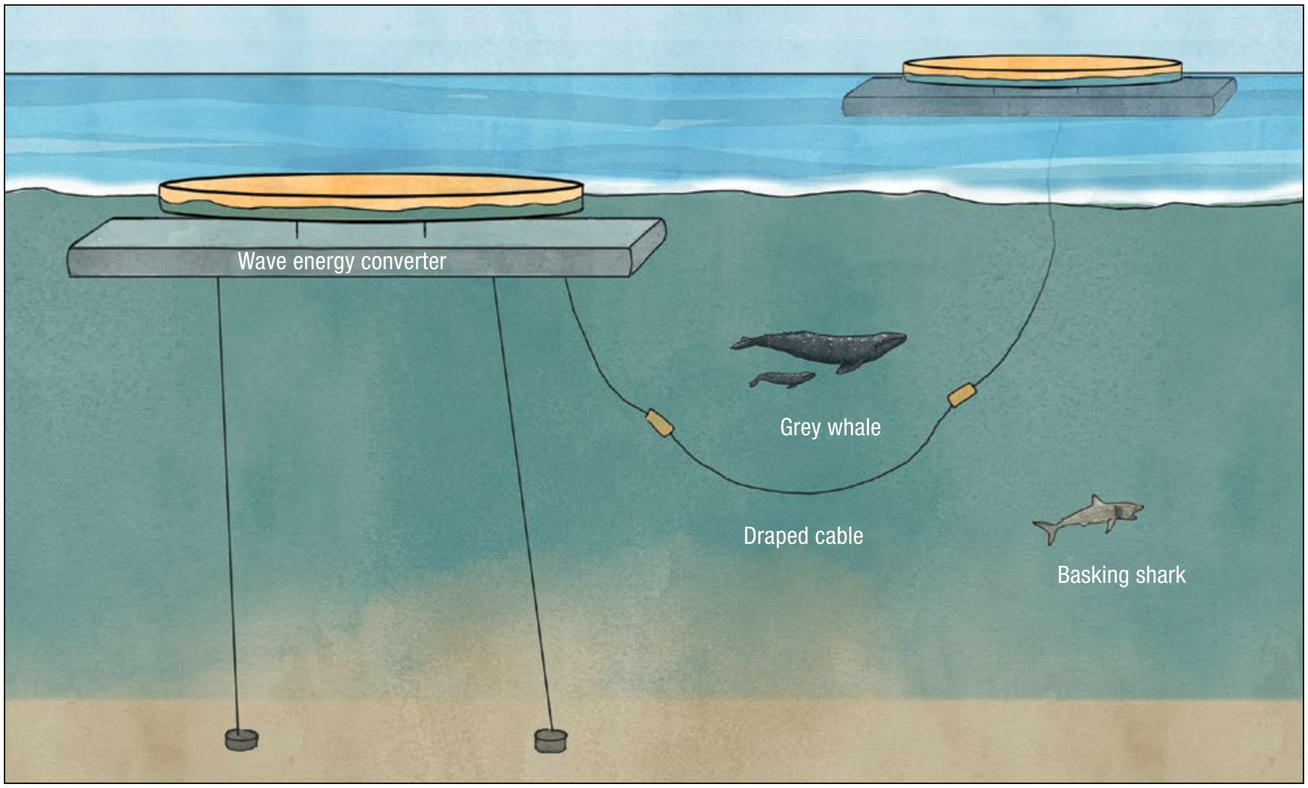


Figure 8.1. Schematic of marine animals' encounters with wave energy devices attached at the bottom by mooring lines and interconnected with a cable. (Illustration by Rose Perry)

8.1. SUMMARY OF KNOWLEDGE

Marine animal encounters with MRE device mooring systems and the associated risk of entanglement and entrapment are emerging topics among the potential environmental effects of MRE; these topics were not discussed in the *2016 State of the Science* report (Copping et al. 2016). Key progress and growth in knowledge and understanding across this topic area are discussed in the following sections.

To date, entanglement has not been considered a significant issue of concern within consenting/permitting (hereafter consenting) processes for single devices and small arrays. However, the extensive legal protection generally afforded to those megafaunal species considered most at risk (e.g., the Marine Mammal Protection Act [1972], in the United States [U.S.]; the Habitats Directive [1992], in the European Union; the Species at Risk Act [2002], in Canada; and the Environment Protection and Biodiversity Conservation Act [1999], in Australia) is likely to lead to precaution in how this issue is considered by regulatory and advisory bodies within consenting processes as the scale of arrays grows.

Large migratory baleen whale species (e.g., humpback whales *[Megaptera novaeangliae]*, minke whales *[Balaenoptera acutorostrata]*, right whales *[Eubalaena glacialis]*) are typically considered to be at the greatest risk of encounters with MRE device mooring systems because of their life history traits (e.g., migration) and feeding behaviors (Benjamins et al. 2014). Large pelagic elasmobranchs (e.g., whale sharks *[Rhincodon typus]*, basking shark whales *[Cetorhinus maximus]*, manta rays) also have greater potential risk of entanglement because of their large body size and feeding habits, but no information about these species' potential entanglement with MRE structures is available. While generally considered to be of lower risk, the risk to diving seabirds, sea turtles, and large fish cannot be completely discounted, particularly when considering the potential effects of larger arrays. The likely consequences of marine animal encounters with these structures, such as risks of injury or death, remain largely unknown, but some parallels can be drawn from studies related to entanglement with fishing gear.

Most of the available literature about the entanglement of marine animals focuses on observations of injury and mortality caused by entanglement with fishing gear such as nets, cables, and traps. Entanglement of large animals with fixed fishing gear can occur in a number of ways, including as a result of swimming through gear fixed to the bottom, or becoming entangled in a loose end or in a loop. When entangled, large whales may be able to pull the gear away, dragging it along with them; these entanglements frequently result in subsequent injury and/or mortality caused by tissue damage, infection, and mobility restrictions that prevent foraging or migration (Moore et al. 2006; Robbins et al. 2015).

Entanglement in submarine telecommunications cables has been reported prior to 1959 (Wood and Carter 2008). Entanglements of whales (mainly sperm whales) were mostly associated with excessive slack in repaired cables and most occurred in deep waters (118 m). The absence of whale entanglement reports since 1959 is likely due to new cable designs that involve cables being buried below the seabed, as well as improved repair techniques (Taormina et al. 2018; Wood and Carter 2008). Modern and improved methods to inform the need for maintenance, such as the use of remotely operated vehicles to inspect cables and detect anomalies, have probably also contributed to the apparent absence of entanglements.

Derelict (i.e., lost, abandoned, discarded) fishing gear and marine debris are known causes of entanglement for elasmobranchs (sharks and rays, Parton et al. 2019) and smaller marine animals (sea turtles, Gunn et al. 2010; fur seals, sea lions, Page et al. 2004; sea turtles, Wilcox et al. 2015). Once entangled, small marine animals do not have the ability to free themselves and the majority of them die without human intervention (Duncan et al. 2017; Schrey and Vauk 1987). Although no part of a mooring line or cable associated with MRE technologies would be abandoned or discarded, indirect entanglement in anthropogenic debris caught on devices is possible and could be a concern for a large range of species (Taormina et al. 2018).

The entanglement risks associated with MRE device mooring systems and transmission cables are poorly understood, largely because of the lack of empirical data and focused studies. Using the available literature on marine mammal entanglement with fishing gear, Kropp (2013) determined that migrating whales off the coast of Oregon (U.S.) would likely be at relatively low risk of entanglement with MRE device mooring systems because of their rare occurrence in the region and their seasonal migration behavior. Benjamins et al. (2014) and Harnois et al. (2015) employed qualitative risk assessments, using the dynamic analysis software OrcaFlex™, to predict the influence of different mooring configurations under various sea states on entanglement risk. The highest entanglement risk was predicted for catenary configurations—freely hanging mooring lines in the water column that have one part lying on the seabed and a large swept water volume. Overall, the model predicted that mooring lines were a low risk for marine animals, although baleen whales were found to be at greater risk because of their large size and feeding behavior (Benjamins et al. 2014). However, all the mooring configurations examined had too much tension to create a loop that could entangle a whale.

The biological characteristics and sensory abilities of marine animals may have a significant effect on entanglement risk. Minke whales seem to visually detect black and white line ropes more than those of other colors (Kot et al. 2012). North Atlantic right whales have been found to best detect vivid color ropes at longer distances (Kraus et al. 2014). However, vivid colors have been suggested to cause entanglement of humpback whales in Australia (How et al. 2015). The species-specific response of whales to rope colors highlights the need to further investigate this topic for the species of interest. Another important biological characteristic of whales is their ability to communicate acoustically. A mitigation strategy to reduce cetacean bycatch in fisheries is the use of acoustic deterrent devices, but their effectiveness is unclear (Hamilton and Baker 2019).

The likelihood of an encounter between marine animals and MRE device systems depends on the line or cable configuration and depth, as well as on the animal size and behavior (Sparling et al. 2013). As part of the environmental impact assessment performed for the Deep Green Utility units, an encounter model was developed to assess the potential of direct collision that could lead to entanglement between the mooring tether of the tidal kite and marine mammals (Minesto 2016). The model predicted that most marine mammals (grey seals *[Halichoerus grypus]*, harbor porpoise *[Phocoena phocoena]*, and bottlenose dolphins) swimming through the swept area of the device would not encounter the mooring tether when the device is operating. Even in the case of an encounter, the tether would remain taut to avoid the risk of entanglement.

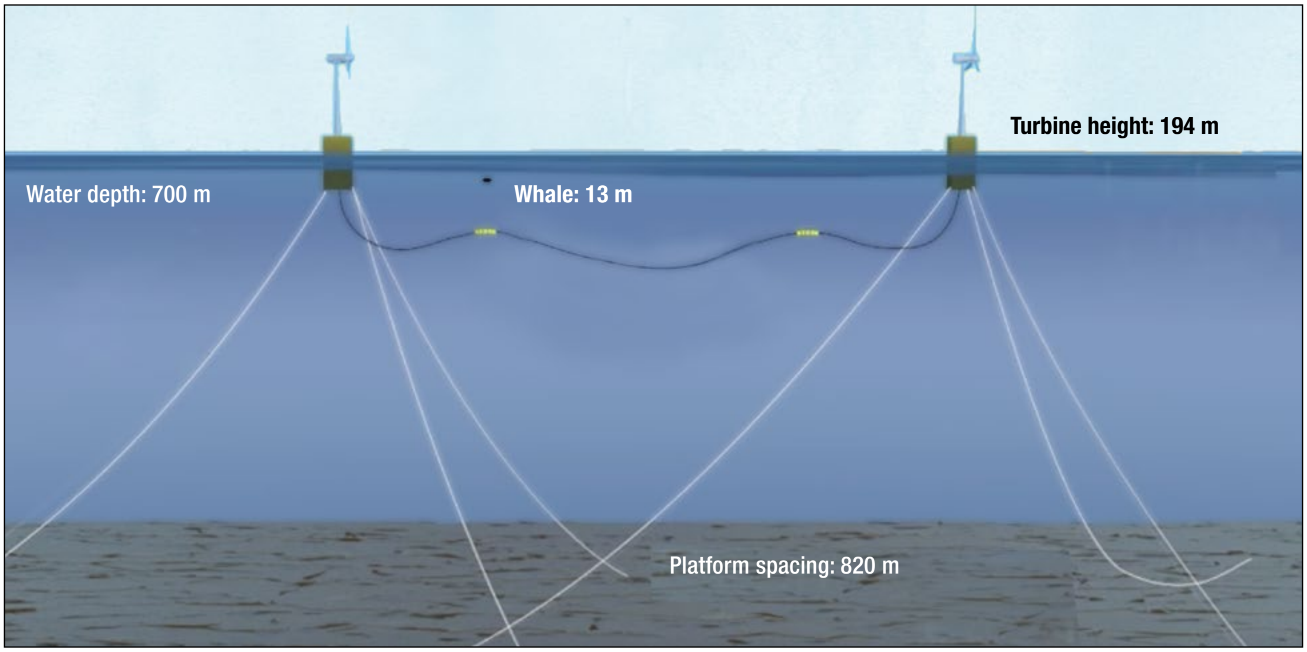


Figure 8.2. Screen capture from the 3D animation on the encounter of a humpback whale with floating offshore wind mooring lines and inter-array cables.[1] (From Copping and Grear 2018)

Overall, for single devices, the probability of encounter is likely to be low because the mooring lines occupy a very small cross section of the marine water column. In a large array of MRE devices, estimating the risk of encountering mooring lines and inter-array cables is less certain. A recent 3D animation developed by Copping and Grear (2018) allows the visualization of a humpback whale female and calf swimming through an offshore floating wind farm array (Figure 8.2). Such tools can provide perspective on the relative spatial scales of MRE devices and associated mooring components, water depth, and the size of marine animals.

8.2. RESEARCH AND MONITORING NEEDS TO RESOLVE THE ISSUE

Additional studies of the habitat preferences and diving behaviors of marine animals are needed to evaluate the risk of encounters that could lead to entanglement. Combining modeling and field observations will enhance the assessment of the risk. While encounter models can help predict the number of animals in the vicinity of MRE devices, empirical data are needed to validate these models. Identifying large whale breeding and feeding habitats as well as assessing their seasonal migration pathways will help inform siting MRE installations, or determine the likelihood of any interactions. Similarly, the identification of crucial habitat for other key migratory species such as turtles and large pelagic elasmobranchs could help manage and mitigate any entanglement risk. Thoughtful approaches to project siting can help to avoid migration corridors and important habitats.

Measures to facilitate routine monitoring of mooring systems, for example with autonomous or remote operating vehicles, could minimize entanglement risk by detecting the malfunction of mooring systems or the presence of derelict fishing gear. If such monitoring detects gear entanglements, the debris can be removed, thereby further reducing the risk of marine animal entanglement. Finally, studies focusing on the development of MRE arrays should be targeted to evaluate the probability of entanglement risk when successive mooring lines or cables are present.

1. See the animation from Copping and Grear (2018) on *https://www.pnnl.gov/news-media/exploring-encounters-between-humpback-and-floating-wind-farms*

8.3. REFERENCES

Benjamins, S., Harnois, V., Smith, H. C. M., Johanning, L., Greenhill, L., Carter, C., and Wilson, B. 2014. Understanding the potential for marine megafauna entanglement risk from marine renewable energy developments (Report No. 791). Report by Scottish Natural Heritage. *https://tethys.pnnl.gov/publications/understanding-potential-marine-megafauna-entanglement-risk-marine-renewable-energy-0*

Copping, A., and Grear, M. 2018. Humpback Whale Encounter with Offshore Wind Mooring Lines and Inter-Array Cables (PNNL-27988). Pacific Northwest National Laboratory, Richland, Washington. Report by Pacific Northwest National Laboratory for Bureau of Ocean Energy Management. *https://tethys.pnnl.gov/publications/humpback-whale-encounter-offshore-wind-mooring-lines-inter-array-cables*

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewski, G., Staines, G., Gill, A., Hutchison, I., O'Hagan, A., Simas, T., Bald, J., Sparling, C., Wood, J., and Masden, E. 2016. Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. *https://tethys.pnnl.gov/publications/state-of-the-science-2016*

Duncan, E. M., Botterell, Z. L. R., Broderick, A. C., Galloway, T. S., Lindeque, P. K., Nuno, A., and Godley, B. J. 2017. A global review of marine turtle entanglement in anthropogenic debris: a baseline for further action. *Endangered Species Research*, 34, 431-448. doi:10.3354/esr00865 *https://tethys.pnnl.gov/publications/global-review-marine-turtle-entanglement-anthropogenic-debris-baseline-further-action*

Environment Protection and Biodiversity Conservation Act 1999 (Cth). [Australia].

Habitats Directive (Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora). OJ L 206, 22.7.1992, p. 7-50. [European Union].

Gunn, R., Hardesty, B. D., and Butler, J. 2010. Tackling 'ghost nets': Local solutions to a global issue in northern Australia. *Ecological Management & Restoration*, 11(2), *88-98.* doi:10.1111/j.1442-8903.2010.00525.x *https://tethys.pnnl.gov/publications/tackling-ghost-nets-local-solutions-global-issue-northern-australia*

Hamilton, S., and Baker, G. B. 2019. Technical mitigation to reduce marine mammal bycatch and entanglement in commercial fishing gear: lessons learnt and future directions. *Reviews in Fish Biology and Fisheries*, 29(2), 223-247. doi:10.1007/s11160-019-09550-6 *https://tethys.pnnl.gov/publications/technical-mitigation-reduce-marine-mammal-bycatch-entanglement-commercial-fishing-gear*

Harnois, V., Smith, H. C. M., Benjamins, S., and Johanning, L. 2015. Assessment of entanglement risk to marine megafauna due to offshore renewable energy mooring systems. *International Journal of Marine Energy*, 11, 27-49. doi:10.1016/j.ijome.2015.04.001 *https://tethys.pnnl.gov/publications/assessment-entanglement-risk-marine-megafauna-due-offshore-renewable-energy-mooring*

Kot, B. W., Sears, R., Anis, A., Nowacek, D. P., Gedamke, J., and Marshall, C. D. 2012. Behavioral responses of minke whales *(Balaenoptera acutorostrata)* to experimental fishing gear in a coastal environment. *Journal of Experimental Marine Biology and Ecology, 413, 13-20.* doi:10.1016/j.jembe.2011.11.018 *https://tethys.pnnl.gov/publications/behavioral-responses-minke-whales-balaenoptera-acutorostrata-experimental-fishing-gear*

Kraus, S., Fasick, J., Werner, T., and McFarron, P. 2014. Enhancing the Visibility of Fishing Ropes to Reduce Right Whale Entanglements. *Bycatch Reduction Engineering Program 1*, 67-74. *https://tethys.pnnl.gov/publications/enhancing-visibility-fishing-ropes-reduce-right-whale-entanglements*

Kropp, R. K. 2013. Biological and existing data analysis to inform risk of collision and entanglement hypotheses (PNNL-22804). Pacific Northwest National Laboratory, Richland, Washington. Report by Pacific Northwest National Laboratory for U.S. Department of Energy. *https://tethys.pnnl.gov/publications/biological-existing-data-analysis-inform-risk-collision-entanglement-hypotheses*

Marine Mammal Protection Act of 1972. 16 U.S.C. ch 31 § 1361 et seq. [United States].

Minesto. 2016. Deep Green Holyhead Deep Project Phase I (0.5 MW) - Environmental Statement. *https://tethys.pnnl.gov/publications/deep-green-holyhead-deep-project-phase-i-05-mw-environmental-statement*

Moore, M. J., Bogomolni, A., Bowman, R., Hamilton, P. K., Harry, C. T., Knowlton, A. R., Landry, S., Rotstein, D. S., and Touhey, K. 2006, 18-21 Sept. 2006. Fatally entangled right whales can die extremely slowly. Paper presented at OCEANS 2006, Washington, D.C. doi:10.1109/OCEANS.2006.306792 *https://tethys.pnnl.gov/publications/fatally-entangled-right-whales-can-die-extremely-slowly*

Page, B., McKenzie, J., McIntosh, R., Baylis, A., Morrissey, A., Calvert, N., Haase, T., Berris, M., Dowie, D., Shaughnessy, P. D., and Goldsworthy, S. D. 2004. Entanglement of Australian sea lions and New Zealand fur seals in lost fishing gear and other marine debris before and after Government and industry attempts to reduce the problem. *Marine Pollution Bulletin*, 49(1), 33-42. doi:10.1016/j.marpolbul.2004.01.006 *https://tethys.pnnl.gov/publications/entanglement-australian-sea-lions-new-zealand-fur-seals-lost-fishing-gear-other-marine*

Parton, K. J., Galloway, T. S., and Godley, B. J. 2019. Global review of shark and ray entanglement in anthropogenic marine debris. *Endangered Species Research*, 39, 173-190. doi:10.3354/esr00964 *https://tethys.pnnl.gov/publications/global-review-shark-ray-entanglement-anthropogenic-marine-debris*

Robbins, J., Knowlton, A. R., and Landry, S. 2015. Apparent survival of North Atlantic right whales after entanglement in fishing gear. *Biological Conservation*, 191, 421-427. doi:10.1016/j.biocon.2015.07.023 *https://tethys.pnnl.gov/publications/apparent-survival-north-atlantic-right-whales-after-entanglement-fishing-gear*

Schrey, E., and Vauk, G. J. M. 1987. Records of entangled gannets *(Sula bassana)* at Helgoland, German Bight. *Marine Pollution Bulletin*, 18(6, Supplement B), 350-352. doi:10.1016/S0025-326X(87)80024-3 *https://tethys.pnnl.gov/publications/records-entangled-gannets-sula-bassana-helgoland-german-bight*

Sparling, C., Coram, A., McConnell, B., Thompson, D., Hawkins, K., and Northridge, S. 2013. Wave and Tidal Consenting Position Paper Series: Marine Mammal Impacts. Report by SMRU Consulting for Natural Environment Research Council. *https://tethys.pnnl.gov/publications/wave-tidal-consenting-position-paper-series-marine-mammal-impacts*

Species at Risk Act, S.C. 2002. c. 29. [Canada].

Taormina, B., Bald, J., Want, A., Thouzeau, G., Lejart, M., Desroy, N., and Carlier, A. 2018. A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions. *Renewable and Sustainable Energy Reviews*, 96, 380-391. doi:10.1016/j.rser.2018.07.026 *https://tethys.pnnl.gov/publications/review-potential-impacts-submarine-power-cables-marine-environment-knowledge-gaps*

Wilcox, C., Heathcote, G., Goldberg, J., Gunn, R., Peel, D., and Hardesty, B. D. 2015. Understanding the sources and effects of abandoned, lost, and discarded fishing gear on marine turtles in northern Australia. *Conservation Biology, 29(1), 198-206.* doi:10.1111/cobi.12355 *https://tethys.pnnl.gov/publications/understanding-sources-effects-abandoned-lost-discarded-fishing-gear-marine-turtles*

Wood, M. P., and Carter, L. 2008. Whale Entanglements With Submarine Telecommunication Cables. *IEEE Journal of Oceanic Engineering*, 33(4), 445-450. doi:10.1109/JOE.2008.2001638 *https://tethys.pnnl.gov/publications/whale-entanglements-submarine-telecommunication-cables*

NOTES

Encounters of Marine Animals with Marine Renewable Energy Device Mooring Systems and Subsea Cables

Garavelli, L. 2020. Encounters of Marine Animals with Marine Renewable Energy Device Mooring Systems and Subsea Cables. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 146-153). doi:10.2172/1633184

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

9.0

Chapter author: Mikaela C. Freeman
Contributor: Deborah J. Rose

Social and Economic Data Collection for Marine Renewable Energy

The social and economic effects of marine renewable energy (MRE) are a necessary consideration for the consenting/permitting (hereafter consenting) of projects (including planning, siting, and project design) and for strategic planning processes. Social and economic effects can include impacts on people, communities, jobs, wages, and revenues (Uihlein and Magagna 2016).

9.1. IMPORTANCE OF THE ISSUE

Fully understanding the effects of MRE developments includes addressing the social and economic aspects (e.g., coastal development, valuation of an area, population, services, cultures, and well-being). For the purpose of this chapter, the focus is on gathering and analyzing information strictly as it is needed for consenting MRE. This chapter does not include an exhaustive list of potential effects, indicators or data types, or assessment methods. Instead, it provides a general overview/description and some examples of social and economic effects and data collection in order to move toward both a better understanding of the effects of MRE and good practices for data collection. While some countries have provided common frameworks, such as the European Union (EU)'s Marine Strategy Framework Directive (Directive 2008/56/EC 2008), they are outside of the purview of this chapter. A large body of knowledge exists about social and economic effects, but not all of it is specific to MRE. As the industry advances and more MRE development occurs, understanding of the social and economics effects of MRE will increase and the information presented in this chapter can be expanded upon.

A number of studies have shown that the MRE sector has the potential to create significant social and economic benefits, including benefits for rural and coastal communities and economies that other sectors cannot reach (Regeneris Consulting Ltd. 2013; Smart and Noonan 2018). The social and economic benefits of MRE projects include low visual impacts (Bailey et al. 2011; Devine-Wright 2011), engagement of the local population (Devine-Wright et al. 2013), and an increase in employment opportunities (Lavidas 2019). Some MRE deployments have provided insight into potential effects and their extents, and indicated the importance of social and economic effects, especially as the industry scales up to array-sized deployments (see Section 9.6). However, because the MRE industry is in the early stages of development globally, some uncertainty regarding potential social and economic benefits or adverse effects of developments remains (Bonar et al. 2015).

Social and economic data and information are needed to support strategic planning for and the consenting of MRE developments, especially in relation to understanding the social and economic effects, dynamics, and values in a community and surrounding areas (Figure 9.1). Commonly, social and economic effects are assessed through cost-benefit analyses or social and economic impact analyses (Uihlein and Magagna 2016). In many countries, these analyses are required as part of consent applications and are often included in environmental impact assessments (EIAs) in Europe or environmental impact statements (EISs) in North America. Furthermore, many countries require the assessment of socioeconomic impacts in their strategic planning processes for marine energy (see Chapter 11, Marine Spatial Planning and Marine Renewable Energy).

To improve how these effects are assessed, there is a need for additional focus on and the development of standardized processes, best practice examples, and guidance for social and data collection and use in MRE consenting and strategic planning. Current practices are inconsistent and could be better developed (Copping et al. 2017). Further, the degree to which social and economic data and assessments have a substantial influence on the outcome of strategic planning or license determination processes is often unclear, even when they are required in support of applications or planning processes.

Ocean Energy Systems (OES)-Environmental has been involved in furthering understanding of the social and economic effects from the perspective of data collection, analysis, and application for consenting, which have been addressed at two international workshops. The first workshop (Copping et al. 2017), hosted at the 2017 European Wave and Tidal Energy Conference, examined frameworks and practical aspects for collecting data that define the social and economic risks and benefits of MRE development. The second workshop (Copping et al. 2018), held in conjunction with the Environmental Interactions of the Marine Renewables 2018 conference, built on the 2017 workshop and examined case studies for social and economic impacts. This chapter builds on the outcomes from both workshops, and much of the information in this chapter comes from discussion and feedback at these workshops. This chapter provides a general overview of the definitions of social and economic effects; requirements for collecting social and economic data in several OES countries, including the responsibility for data collection and stakeholder engagement; needs for data collection; and good practices for data collection, case studies to showcase lessons learned, and recommendations for future data collection improvements.

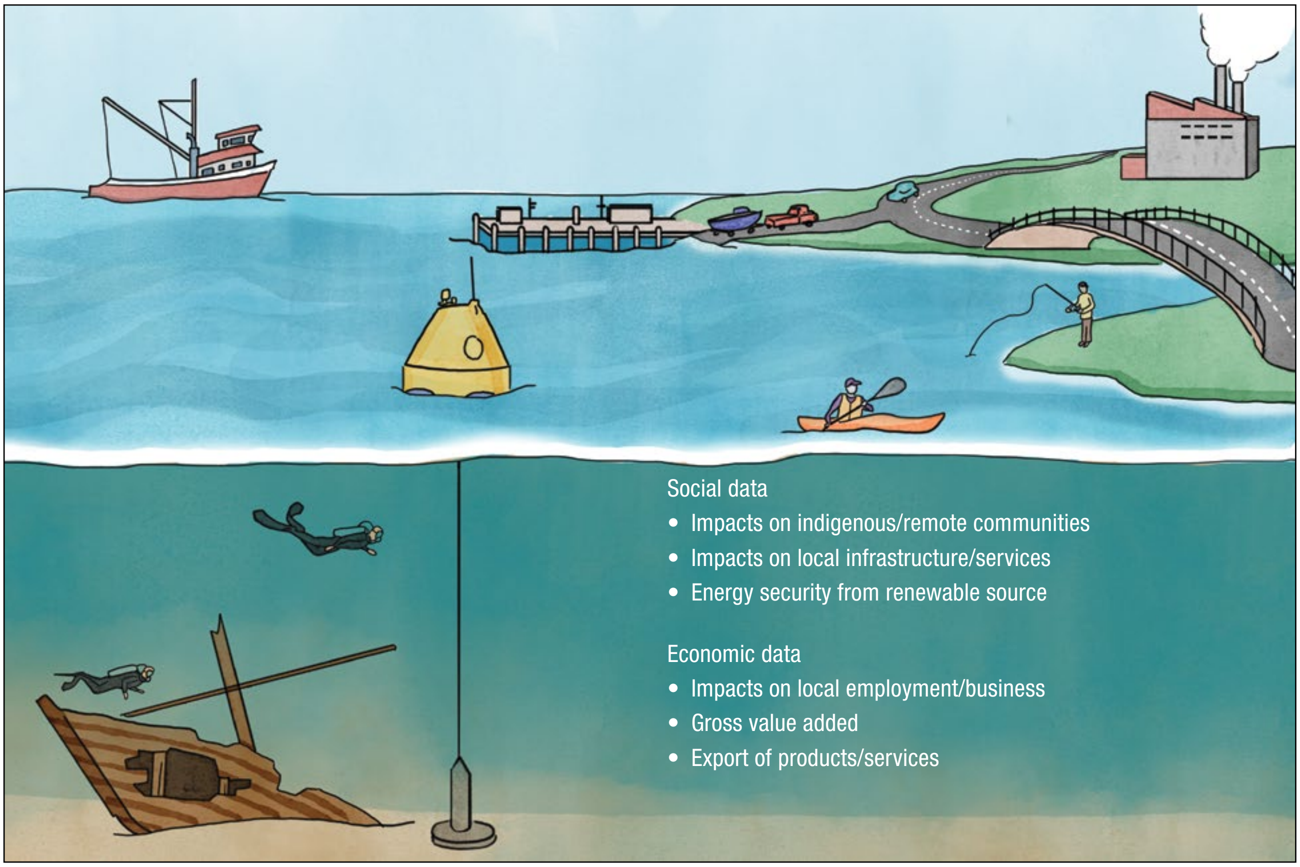


Figure 9.1. Examples of social and economic activities for which data should be collected for consenting and understanding of the potential benefits and adverse effects of marine renewable energy development. (Illustration by Rose Perry)

9.2. DEFINITION OF SOCIAL AND ECONOMIC EFFECTS

Social and economic effects can include benefits to or adverse effects on employment, local infrastructure and services, regional businesses, and communities. Additional examples of social and economic effects can be found in the supplementary material (online at: *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-socio-economics*). Social and economic issues are commonly considered together, but it is important to distinguish between the two because they differ in assessment methods, data types, and scales (both temporal and spatial); for instance, economic data are often quantitative while social data are often qualitative. Key economic indicators include the effects on gross value added[1], employment, wages, exports, businesses, and existing industries, while key social indicators include the effects on infrastructure and facilities, services, cost of living, health and well-being, culture, and populations (Kerr et al. 2014; Vanclay et al. 2015). It is important in any assessment of social and economic effects to include the effects on indigenous and remote communities, because they are often marginalized and may be affected differently than other communities (Kerr et al. 2015).

MRE developments have the potential to provide benefits to local, regional, and national communities. They can stimulate economic development and output, as well as generate revenue and employment opportunities, especially local job creation (including skilled jobs), throughout the different project stages, including manufacturing, transportation, installation, operation, and maintenance (Akar and Akdoğan 2016). MRE developments can provide opportunities for tourism, such as sightseeing and fishing experiences from project structures that serve as artificial reefs/fish-aggregating devices (see Chapter 6, Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices) (Leeney et al. 2014; van den Burg 2019). On the other

1. Gross value added is used to measure the contribution made by an industry or sector and is calculated by the output minus consumption (OECD 2001).

hand, if MRE developments are not carefully located and implemented, they could have adverse effects on communities, economies, and employment. For example, MRE developments may exclude other marine uses, such as reducing access for fisheries, if they are not sited sensitively. In addition, an MRE development could affect the perceived value of an area; for instance, visual components may be negatively perceived by a community or homeowners in the vicinity (Rand and Hoen 2017; Vanclay 2012). Furthermore, the economic effects of an MRE development can vary greatly depending on whether the installation and/or operation are staffed locally or by outside sources. For example, if an MRE development does not use the local supply chain it may fail to create much local benefit or provide direct employment.

Key economic data and information for measuring changes include data about local employment (e.g., job creation potential, employment multiplier, gross wages), inward investment potential, extent of the local and regional supply chain, gross value added, exports of products and services, existing sectors (e.g., commercial fishing, tourism and recreation, shipping and navigation), and economic impacts of MRE on local communities (Copping et al. 2017, 2018; Marine Energy Wales 2020; Smart and Noonan 2018). Some key social data and information to collect include social and cultural context (e.g., social dynamics, cultures and values, traditional activities), demographics and community structure, energy security and carbon offsets (Smart and Noonan 2018), protected or conservation areas, other marine uses (e.g., commercial fisheries, indigenous fisheries, leisure, and recreation), and impacts on local communities (Copping et al. 2017, 2018). Some key metrics for measuring change include business opportunities, net job gain or loss, improvements in existing infrastructure and services, social acceptance and awareness, impacts on local communities, and impacts on existing businesses and marine uses (Copping et al. 2017, 2018).

9.3. REQUIREMENTS FOR COLLECTING SOCIAL AND ECONOMIC DATA TO SUPPORT CONSENTING

Governmental/regulatory or statutory requirements for collecting social and economic data are limited and poorly defined, and regulations can vary from one country to the next as well as within countries, if they exist at all. Several countries and regulatory bodies have requirements for assessing social and economic factors when considering the development of new infrastructure projects. These requirements are primarily addressed in EIAs (also called EISs, environmental statements [ESs], impact assessments [IAs], social impact assessments [SIAs], or environment and social impact assessments [ESIAs], depending on the country). These planning documents are not unique to MRE developments; they are usually required for any full-scale infrastructure project, including device deployment, and few countries have requirements that are specific to the development of MRE projects.

9.3.1. COUNTRY-SPECIFIC SOCIAL AND ECONOMIC REQUIREMENTS FOR MRE

Requirements to consider when assessing social and economic factors are described below for several OES-Environmental countries:

- The EU updated the EIA Directive in 2014 to broaden its scope to include climate change, population and human health, biodiversity, landscape, and risk prevention (Directive 2014/52/EU 2014). Under EU law, these requirements are transposed into member state national EIA legislation by May 2017.
- **France** requires additional analysis of project impacts on cultural heritage that includes architecture and archaeology, impacts on the visual landscape, and the level of nuisance created for humans by project noise, vibration, or light (Environmental Code 2018).
- **Norway** has adopted some components of the EU EIA Directive (Directive 2014/52/EU 2014) to specifically include consideration of conflicts with cultural environments or monuments, traditional reindeer husbandry practices, and other tenets of outdoor life in environmental assessments (Regulations on Impact Assessments 2017).

- In the **United Kingdom** (UK) there is no UK-wide planning process for MRE; there are different systems for Scotland, Northern Ireland, England, and Wales. Consideration of social and economic factors is required in alignment with the EU EIA Directive[2] (Directive 2014/52/EU 2014), which is transposed into UK law (including at a devolved nation level[2]) through specific EIA Regulations. Each devolved administration within the UK has marine planning responsibility, which sits alongside the leasing responsibilities of The Crown Estate Scotland. Marine spatial plans produced within each of the UK devolved nations (see Chapter 11, Marine Spatial Planning and Marine Renewable Energy) generally also include policies related to socioeconomics, which must be taken into account in licensing decisions. Applicants must assure that they have provided sufficient information in support of their license applications for these policies to be considered and permitting authorities must be able to demonstrate that they have taken account of socio-economic policies in their decision-making. A description of impacts on populations and human health, cultural heritage, and the landscape is required across the UK. Where EIAs have been completed for MRE developments (such as at Pentland Firth and the Orkney Islands), they have included predictions of local job creation as well as possible impacts associated with port congestion, near neighbor issues, etc. However, the guidance provided by local and national governments and agencies about social and economic issues, such as local impacts, has been poorly defined and has not been adequately assessed.

  Some examples of the types of information provided in social and economic assessments are provided below:

  - The ES for the European Marine Energy Centre (EMEC) test center at Billia Croo in Scotland included a section on land use, fisheries, and socioeconomic issues, which required consideration of local economic benefits, traditional fishing regions and access, and harbor congestion (Carl Bro Group Ltd. 2002).
  - The ES for MeyGen in Scotland included a description of social and economic issues, including tourism and recreation, harbor and port facilities assessments, local jobs, and other sea uses. In addition, a full commercial fisheries navigational risk assessment and cultural heritage impact assessment were carried out (MeyGen 2012).
  - At SeaGen in Strangford Lough in Northern Ireland, the EIA included an assessment of cultural heritage, social and economic impacts, and a navigational risk assessment. The social and economic impacts included land use, commercial fisheries, and tourism.

- **India** has required consideration of socioeconomic factors since 2006, including anything that would "affect the welfare of people e.g., by changing living conditions", impacts on vulnerable groups of people, the generation of noise or light nuisance, disturbance of tourist routes or facilities, and impacts on "areas occupied by sensitive manmade land uses (hospitals, schools, places of worship…)" (Environmental Impact Assessment Notification 2006). In addition, India already has a specific procedure in place for monitoring and evaluating renewable energy infrastructure projects, including MRE. The ESIA for renewable energy requires analysis of population characteristics, community and educational structure, political and social resources, individual and family changes, and community resources relevant to any development (Dutta and Bandyopadhyay 2010). For example, a draft ESIA for a 200 MW wind project included an analysis of factors including poverty levels, demographic profile, literacy, cultural values, and religious distribution (Voyants Solutions Pvt. Ltd. 2016).
- SIAs have been included in projects in **China** for decades, but they have faced many implementation challenges (e.g., Ip 1990). The first Environmental Impact Assessment Act of the People's Republic of China, passed in 2003, did not explicitly address social issues (Tang et al. 2008). Over time, public participation and social impact assessment have been incorporated more informally into the EIA process (Ren 2013), and China began requiring social risk assessments for major development projects beginning in 2012 (Bradsher 2012; Price and Robinson 2015).

2. Devolution is the concept of delegating power from higher levels of government to lower levels. In the UK devolved nations include Scotland, Northern Ireland, England, and Wales, and while each has statutory powers transferred to them by the UK, some reserved powers remain with the UK. (*https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770709/DevolutionFactsheet.pdf*)

- In the **United States (U.S.)**, SIAs have been a part of the National Environmental Policy Act of 1969 legislation since its initial adoption in 1970 (Burdge and Taylor 2012). Several other pieces of legislation have also included requirements for an SIA, including the Magnuson-Stevens Fishery Conservation and Management Act 1976, the Outer Continental Shelf Lands Act 1978, and others (Burdge and Taylor 2012). In addition, there are coastal requirements that may vary from state to state throughout the U.S. and may be significant.
- **Canada** approved the Impact Assessment Act and the Canadian Energy Regulator Act in August 2019 that adds factors to reflect a more holistic assessment of environmental impacts, specifically in the energy sector. These acts include requirements for assessing the potential negative effects on gender issues in the workforce, exploitation of vulnerable groups, and an increase in cooperative indigenous partnerships and consultations in the development of new projects (Government of Canada 2018, 2019).

9.3.2. DATA COLLECTION RESPONSIBILITY

The responsibility for collecting social and economic data falls to different levels of government, planning authorities, or other responsible parties, such as project developers, depending on the intended purpose and application of the data. However, it is difficult to determine the specifics of who should be responsible for data collection and assessments and, often, any gaps become the burden of the project developer. It is especially challenging to determine the responsibility for long-term baseline data collection and continuing assessments to inform strategic planning for future developments, all of which can be costly. To collect data in a meaningful manner, it is important to come to a consensus on the expectations of the different levels of government (strategic-level data) versus the project developer (project-level data); hence, the two relevant levels of assessments and data collection to be considered are:

- strategic-level activities and measures that should be implemented to meet objectives in line with local, national, and regional policy by government, agencies, and other relevant organizations, and
- project-level activities and measures that should be implemented by the project developer to meet objectives on a local scale, such as within a municipality or community.

Strategic assessments of social and economic effects generally fall to governmental and marine planning entities that can assure that data collection and analysis are completed consistently using appropriate methods to define future effects (Figure 9.2). An advantage of public-sector-collected data is that any results, findings, or reports would be readily accessible. The disadvantage of public data is that results may be outdated, not regularly updated, or relevant data may not have been collected. While developer-collected data are often not shared with the public or easy to access, it may be more contemporary than data from alternative sources. Different levels of government can collaborate to provide information at a strategic level. For instance, higher levels of government could request or provide support for local authorities to collect relevant social and economic information, which could then be scaled up to regional or national levels. In addition, strategic-level assessments carried out by governments can be important to better understanding project-level impacts. For instance, the U.S. Bureau of Ocean Energy Management commissioned two economic impact assessments of wave energy deployments in Oregon, U.S. (Jimenez and Tegen 2014; Jimenez et al. 2015) that showed a significant impact, including an increase in jobs, and identified potential sources of economic development. Both reports are publicly available and can be used to inform future MRE developments and their project-level assessments.

Project-level information would more likely fall to the responsibility of MRE developers (Figure 9.2). Developers will need to collect data and information to support both site-identification and project design and regulatory requirements for consenting. Consulting with regulators is key to defining requirements and data needs from an early stage of project development. This can include discussions about the application of national or regional data to aid project-level assessments. For example, if data are not available at the project-level it may be necessary to downscale strategic-level data to fill in gaps and satisfy regulatory requirements. Developer-collected data are not extensive and can be difficult to track because such data are usually considered private and are often not publicly available. This absence of developer-collected data is likely due to a lack of funds available for data collection that is not based on a regulatory requirement. However, if such information is collated within environmental assess-

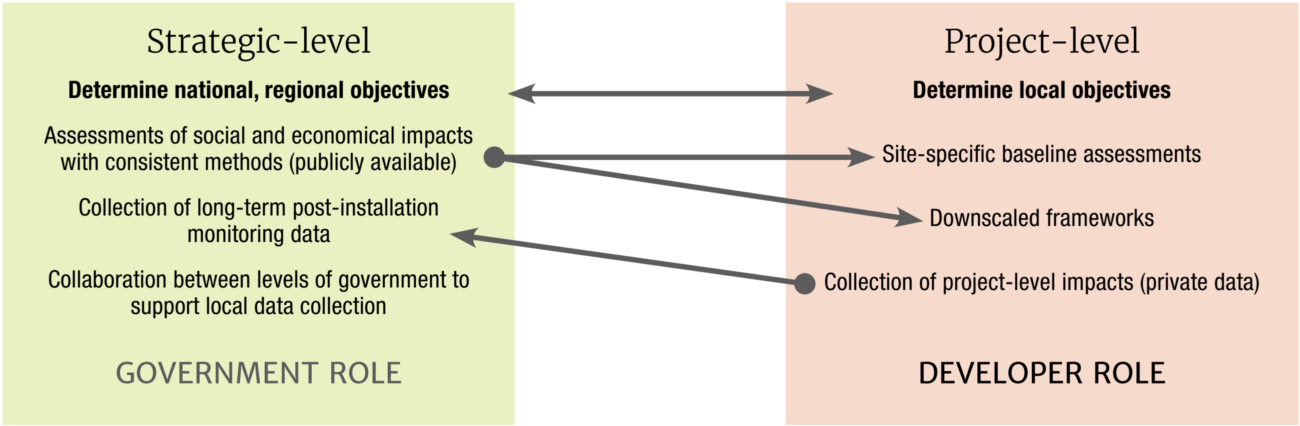


Figure 9.2. Responsibilities of governments and developers in collecting social and economic data, as recommended by expert workshops (Copping et al. 2017, 2018). The arrows indicate which direction data should flow (for example, assessments with consistent methods should inform site-specific baseline assessments and downscaled frameworks).

ments and consent/license applications, it may be made available in the public domain. Trade associations, data portals, test sites, or universities could play an important role as intermediaries that could collate such data and publish results that may not be available directly from developers. The MRE industry can also provide collated information to reveal the potential impacts of MRE, which can then be used by developers to present the likely effects of a project. Two examples include a state of the sector report detailing the economic benefits of MRE for Wales (Marine Energy Wales 2020) and a report about the cost reduction and industrial benefits of MRE for the UK (Smart and Noonan 2018). While these highlight potential impacts, the most effective option is to deploy devices and collect data as projects progress to understand the true social and economic effects of MRE and adapt or mitigate where necessary.

9.3.3. STAKEHOLDER OUTREACH AND ENGAGEMENT

To be successful at all stages of MRE project development, there must be a well-planned process for stakeholder outreach, engagement, and consultation (Equi-Mar 2011; Kerr et al. 2015) that begins early in project planning (Simas et al. 2013). This is especially important because there is relatively little public familiarity with, knowledge of, or awareness of MRE, including the different types of technologies and potential impacts of MRE developments (Dalton et al. 2015), and there may be misconceptions or misunderstandings of MRE and its impacts (Stokes et al. 2014). A study of local perceptions of the Wave Hub deployment in Cornwall, England, found that stakeholders had firm views (such as concern about the wave device affecting waves for surfing) based on intuitions that were generally not influenced by technical understanding or impact assessments (Stokes et al. 2014).

Communicating with stakeholders provides a range of benefits to developers. It is crucial to have the support of stakeholders and local communities, both for individual projects and for the long-term acceptance of the MRE industry. In this sense, stakeholders can include political leaders, local businesses, members of the supply chain, nongovernmental organizations, social program staff, and community members, and especially indigenous and local communities (Isaacman et al. 2012). MRE projects are often located in rural and sometimes remote areas where development pressures have not been previously experienced. MRE developments are relatively new and unproven commercially and therefore they can be seen as both pioneering or experimental. A partnership approach, with full communication (listening as well as information sharing), practical engagement (using local resources as a priority), and options for local participation (such as investment once risk levels are appropriate) can help align local community and project-related interests.

Stakeholders will differ between communities, regions, and countries, and, while it can be difficult to define the stakeholders, identifying main groups and involving local communities is crucial. Stakeholders (especially local knowledge-holders) can supply a wealth of knowledge and information, and help assure that the data collected and the metrics used are relevant to the project and the community. They can be important allies and supporters of MRE development if they are engaged early in the process through transparent and timely communication. Sharing success stories or positive case studies from other projects or analogous industries, such as offshore wind, can be an especially useful tool to aid outreach efforts and can provide insight into best approaches and lessons learned (Box 9.1). In addition, developer awareness of prior projects (both MRE or other industries) that have not been successful or failed to deliver on promises or commitments can aid in understanding community perceptions of a new MRE project. Building trust by engaging stakeholders early in the development process and being transparent throughout project development is key to successful stakeholder engagement efforts. Involving stakeholders can be challenging and often lengthens the process, especially because all stakeholders may not initially be in favor of MRE development. In circumstances where a project or particular development strategy may be irreconcilable with local interests, concerns, and aspirations, it may not be appropriate for a proposed development to proceed. While difficult, such successful engagement and participatory processes can lead to consensus building, help manage conflict and build trust, and gain better cooperation (Drake 2012).

9.4. DATA COLLECTION AND NEEDS

Social and economic information is needed to understand baseline and long-term assessments at all scales, economic changes (e.g., employment, wages, local supply chain, etc.), and social changes (e.g., social structures, schools, housing, services, etc.), as well as the success of projects that maximize benefits and limit adverse effects.

For social and economic data to be useful, they must be collected (by developers, researchers, industry, etc.) consistently and comparably over time (both before and after a project), to the extent possible, so that they can be comparable (Leeney et al. 2014) and put into context to demonstrate potential impacts. Qualitative data should be used in addition to quantitative data (Vanclay 2012). Providing a cultural context, history of events, and narratives from communities can help understand initial attitudes and expected responses to potential developments. These social characterizations must include spatial and temporal factors for any assessment.

Value maps (e.g., Figure 9.3) can also be a useful tool to represent the stakeholders, cultures, or jobs, and provide important context for assessments to help determine the best approach to MRE development.

9.4.1. DATA COLLECTION CONSISTENCY AND REGULATORY GUIDANCE

It can be difficult to predict or analyze the effects of MRE projects. For example, understanding local impacts is difficult for smaller projects because the associated number of jobs alone may be minimal, may not be truly indicative of the change, and will necessitate other data, information, or context to show the full effect (Copping et al. 2018), and in the end these impacts may still be small at the MRE prototype and demonstration scale. Gathering and analyzing social and economic data to capture and grasp the full spectrum of effects can be challenging because of a lack of

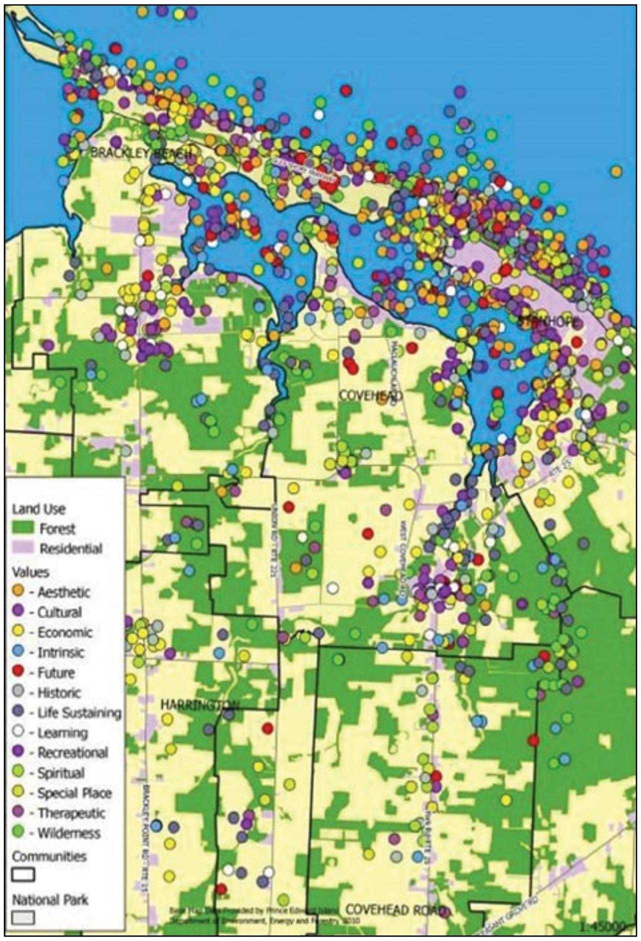
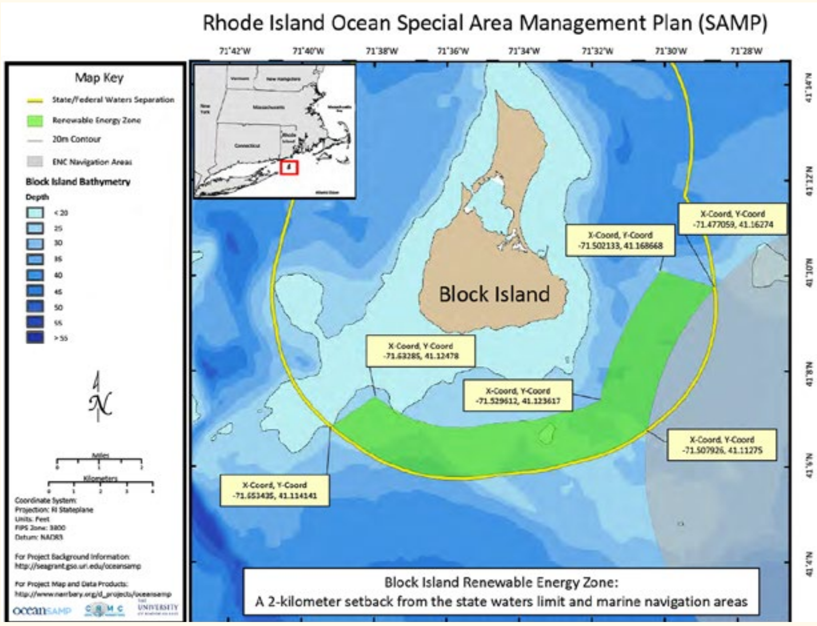


Figure 9.3. A value map created from a study of social and cultural values related to climate change adaptation on Prince Edward Island, Canada. Colored dots note areas where survey participants expressed interest based on the specific values. (From Novaczek et al. 2011)

BOX 9.1

EXAMPLES OF STAKEHOLDER ENGAGEMENT AND OUTREACH FROM THE MARINE RENEWABLE ENERGY (MRE) AND OFFSHORE WIND INDUSTRIES



MRE test centers – A review of environmental impact assessments from several MRE test centers showed that consulting stakeholders (e.g., fishers, surfers, navigation authorities, etc.) early (prior to test center design) introduced an opportunity for stakeholders to voice concerns and provide input. Through this engagement process, test centers were able to choose a location and design that addressed potential concerns, did not require further mitigation, and most important were agreed upon (Simas et al. 2013).

Offshore wind on the United States (U.S.) Atlantic Coast – As Rhode Island developed the Ocean Special Area Management Plan, they conducted a comprehensive stakeholder engagement process to give stakeholders an opportunity to have a say in the process. When an application for wind development came around, stakeholders (i.e., commercial fishery representatives, environmental advocates, and members of the Narragansett Indian Tribe) were able to support the application and encourage siting and consenting because of their early involvement (Smythe et al. 2016).

MRE in Orkney, United Kingdom – MRE development and its ramifications in Orkney involve many individuals and organizations such as Aquatera, European Marine Energy Centre, Heriot Watt University, Marine Scotland, and Xodus. The Orkney Renewable Energy Forum (OREF) provides an example of ongoing engagement efforts. Since 2000, OREF has brought stakeholders together and has become key to developing the industry in Orkney by focusing on the environmental, commercial, community, and research and development aspects of renewables. OREF has consistently advocated for the community, the MRE sector, and environmental interests of MRE, and has dealt with internal and external challenges to balance competing interests. OREF's approach has helped achieve

- more than 50 device deployments
- an investment of about £400 million in projects in (or linked to) Orkney MRE deployments
- an investment of about £150 million by the local community in MRE developments
- a direct supply chain of about 300 individuals
- support from the vast majority of the community and the local authorities for MRE development
- monitoring of ecological effects that have not yielded indications of harm to fish, marine mammals, or seabirds
- the management of leasing authority devolving from The Crown Estate to The Crown Estate Scotland, which is a new organization that has a more community-centric focus.

OREF continues to work with its partners and the community to further the MRE industry and appropriately address issues that arise (OREF 2020).

MRE in Oregon, U.S. – The Oregon Wave Energy Trust (OWET) started in 2007 as a non-profit, public-private partnership established by the Oregon State Legislature to "responsibly develop ocean energy by connecting stakeholders, supporting research and development, and engaging in public outreach and policy work. OWET works with stakeholders, industry, and local communities to explore the balance among existing ocean uses and ocean energy projects." OWET has funded wave and other technology developments, community outreach and engagement, and research studies to address concerns related to regulatory, environmental, education/outreach, market development, and applied research. About 10 of these studies have addressed social and economic issues, which are major concerns for the coastal community and state government, particularly with the emphasis on the importance of fishing to Oregon coastal communities. OWET has worked with stakeholders including fisheries representatives, the military, a nearby liquefied natural gas plant, and the logging industry. While potential and perceived conflicts between fishing and wave energy were not fully resolved, the care and understanding applied to dealing with fisheries issues specifically, and coastal planning issues in general, provided exemplary models that can be exported to other jurisdictions (OWET 2020). OWET became the Pacific Ocean Energy Trust (POET) in 2017.

guidance or standard approaches for collecting, analyzing, and presenting appropriate data or information (Copping et al. 2017). Having governments at the appropriate level provide guidance and standard approaches would lead to more consistent data collection (including methods and metrics) and the ability to compare results across projects. As data become increasingly available and are compared across projects, understanding of social and economic impacts can increase and benefit the industry as a whole. However, standardization of data is complicated because each project, context, region, and country can be unique in its culture, situation, history, demographics, and regulations, and regulatory guidance at an international level is unlikely. While such standardization can be provided through industry standards, to date the only guidance related to environmental or social and economic effects in the MRE industry is for measuring underwater noise (see Chapter 4, Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices).

This scarcity of guidance for conducting proper assessments can cause delays in consenting processes as regulators attempt to interpret impacts, which can hinder strategic planning and license applications. Clarification of how social and economic benefits and adverse effects substantially influence strategic- and project-level decision-making for MRE, and guidance on associated evidence requirements, are needed. Currently, regulatory requirements are driven by the need to respond to legislation and are often focused on numerical data, but numerical data may not be the best way to represent social effects and can involve value judgments. Economic effects may not always be straightforward to represent, but data are frequently collected to understand these effects. Social effects can be even more challenging to properly measure and analyze (Vanclay 2012), so much so that they are often dismissed, left out of assessments, or do not occur on timescales that allow for the effects to be easily understood. Defining success is difficult because there is no standard approach for assessing social and economic effects, regulatory guidance can be hard to provide, and there is not enough data to indicate whether previous efforts to maximize benefits and minimize adverse effects have been successful. To make progress in this area, clear assessment methods and metrics in all locations and the capacity to assess performance relative to those metrics are needed. The responsibility for standard methods and metrics may fall to the research community or industry to develop, while governments may be responsible for creating the impetus for, or requiring the use of, agreed-upon assessments and methods.

9.4.2. SCALES OF DATA COLLECTION

Data collection at all appropriate scales (both spatial and temporal) is important for providing a full picture of the benefits and adverse effects of MRE development. The scales at which data collection should be carried out will vary across projects and countries (and may include spatial scales ranging from the project, city, state, or regional level or temporal scales ranging from a monthly, yearly, or bi-annual basis) based on a variety of factors. Spatial effects are more likely to occur at smaller geographic scales or at the project level. As the MRE industry moves to larger arrays and/or multiple projects in a similar area, it will be important to assess social and economic effects over larger geographic scales. However, most spatial data are collected over a large geographic area or at a strategic level and are not specific to MRE developments. While such data can offer a useful starting point, MRE developers must downscale such data on a project-by-project basis or collect additional project-level data, which can be costly, to gain an understanding of the potential effects. For example, regional and national data are collected at larger geographic scales and will need to be downscaled to inform projects at smaller geographic scales.

Similarly, most assessments and research focus on the shorter-term impacts (Dalton et al. 2015). Having long-term data is equally important, especially as the industry develops. Because of a lack of well-established and coordinated efforts to track the social and economic effects of the MRE industry over time, the onus falls on the project developers, especially those first in the water, to show anticipated benefits and adverse effects. Another issue with temporal data is the lag between the time of data collection and actual implementation of an MRE project (Copping et al. 2018). Demonstrating the benefits of early MRE projects and collectively tracking efforts over time would help future projects plan for impacts, improve consenting processes, and aid in obtaining public acceptance of future MRE projects.

9.5. GOOD PRACTICES FOR COLLECTING DATA AND FOLLOWING TRENDS

Good practices for social and economic data collection for impact assessment and monitoring of MRE developments can contribute to planning and management that will maximize benefits and avoid or minimize adverse effects (Vanclay et al. 2015). However, there is lack of available frameworks or guidance related to good practices. Good practices can provide greater standardization in collecting and assessing baseline, installation, and operational data to be used in consenting MRE projects. Improving the consistency of data collection allows for benefits and adverse effects of projects on communities to be compared, and will foster a better understating of long-term impacts and changes.

OES-Environmental has developed a set of good practices for the collection of social and economic data (see Table 9.1). Because the industry is in the early stages of developing frameworks, guidance, and associated good (or best) practices, these good practices are based on qualitative experiences and will need to be improved as the industry advances.

Table 9.1. Good practices for the collection of marine renewable energy (MRE) social and economic data. (From Copping et al. 2019)

Practice 1:	Strategic-level data collection, analysis, and assessments should be carried out by the appropriate level of local, regional, or national government (or relevant agencies) in order to understand the benefits and adverse effects of MRE projects, and the data should be collected in relation to the size of the development (for example, larger projects may necessitate more data if strategic decisions are involved).	
Practice 2:	Specific questions should be developed by researchers and/or the MRE community and the answers to these questions should elucidate changes in social or economic conditions (either benefits or adverse effects) for the communities and regions in which MRE development is planned. These questions should drive the specific data collection efforts and analyses.	
Practice 3:	Baseline social and economic data should be collected that address the current social and economic attributes, at the appropriate scale, prior to MRE development. For this practice, it is important to differentiate between strategic-level (3A) and project-level (3B) baseline data and who may be responsible for the collection efforts.	
	Practice 3A: Baseline data for strategic assessments should be gathered by the appropriate level of local, regional, or national government, scaled to the closest possible geographic extent for the area of the MRE project, before development occurs.	**Practice 3B:** Project-level baseline data should be gathered by the project developer, assisted by existing supply chain companies and other local stakeholders as part of consenting processes, before development occurs. If multiple projects are occurring on similar time scales, the project developers should be encouraged to collaborate to help gather data to inform strategic assessments.
Practice 4:	Social and economic data should be collected once MRE development has occurred and the devices are operational. To the greatest extent possible, data should be collected using variables/methods similar to those used for baseline data to allow for direct before/after comparison. For this practice, it is important to differentiate who is responsible for such data collection (4A or 4B).	
	Practice 4A: Social and economic data should be collected at the same scales, using the same methodologies for strategic-level assessments, by the appropriate level of local, regional, or national government.[1]	**Practice 4B:** Social and economic data should be collected at the same scales, using the same methodologies for project-level assessment, by the project developer, with assistance from supply chain personnel and other local stakeholders, including local governments.
Practice 5:	Results from both social and economic assessments should be clearly communicated to the communities affected by MRE developments, with a focus on the transparency of methods, analyses, and purpose of the studies. Strategic-level assessment communication is the responsibility of the appropriate level of government, while project-level social and economic assessments should be jointly presented by the project developer and the appropriate level of government.	

1. It is important to note that for good practices that rely on government data collection, resources may not be available for collecting data for all, or in some cases any, MRE projects. This will vary by country, region, and locality.

9.6. CASE STUDIES

Analyzing case studies related to deployed MRE projects can help further the understanding of social and economic effects and provide lessons learned for future projects. The case studies can also be used as reference points for the effects of MRE developments and offer a reliable comparison upon which to base estimates for future projects. Box 9.2 highlights social and economic data that have been collected around three MRE developments and test centers.

9.7. RECOMMENDATIONS

To fully understand the effects of an MRE deployment, social and economic data must be collected and assessed. The good practice examples presented in this chapter provide guidance about collecting data consistently throughout the industry and enabling greater standardization of assessments to support strategic planning for and consenting of MRE projects. These practices will lead to an overall increase in the understanding of the social and economic benefits and adverse effects of MRE developments, improved social acceptance, and could be linked to more favorable regulatory outcomes for the MRE industry.

There are many ways in which data collection could be improved upon. Some recommendations are listed in the following sections.

9.7.1. REVIEW OR DEVELOP TOOLS AND DATABASES

Identifying potential social and economic indicators at both the project- and strategic-level will improve data collection efforts and be useful for developers or other stakeholders. Available tools and databases from MRE and other analogous industries (such as offshore wind, oil and gas, etc.) should be reviewed. If the necessary tools or databases do not exist, there may be a need to develop new tools or a database that could identify key indicators. Doing so would help to understand what data are relevant for a project and should be collected based on the size and potential impact of a project, and would show regulators and governments which data may be important. Reviewing or developing tools and databases can help standardize data collection and assessment as key indicators become agreed upon throughout the MRE industry and across governmental bodies. This recommendation is best carried out by researchers or the MRE community.

9.7.2. GUIDE DATA COLLECTION EFFORTS

Once key indicators of the social and economic impacts of MRE development are better understood, the next step would be to develop a template that establishes the questions that need to be asked and answered and the key data needed to understand impacts that may arise from a specific MRE development. Such a template would guide data collection efforts by developers as well as data collection requirements from governments and regulators (ABPMer 2012). This recommendation is best carried out by researchers or the MRE community.

9.7.3. CONDUCT MEANINGFUL STAKEHOLDER ENGAGEMENT

As described in Section 9.3.3, stakeholder engagement is necessary for successful MRE project development and operation. In addition, stakeholders and groups familiar with the area surrounding a project can provide a wealth of information on key social and economic data to collect. Stakeholders should be engaged in a meaningful manner by listening and learning from important groups to identify evidence needs and key sources of data. These groups will likely include local companies in the MRE supply chain, the fishing industry, the tourism industry, communities that are often marginalized especially indigenous or native populations, and representatives from local and regional groups that are likely to be impacted. This engagement is best carried out by MRE project developers.

9.7.4. PROVIDE AN INCENTIVE TO COLLECT AND PUBLICIZE MRE DATA

To move the industry forward, data and information should be shared between MRE projects so that lessons can be learned from past deployments (see Chapter 13, Risk Retirement and Data Transferability for Marine Renewable Energy). The collection of social and economic data should be included in funding and deployment conditions when possible. Government entities and/or investors who provide funding or test sites who provide funding or deployment opportunities can incentivize (or even require) developers to collect spe-

BOX 9.2

CASE STUDIES OF SOCIAL AND ECONOMIC DATA COLLECTION EFFORTS FROM MARINE RENEWABLE ENERGY (MRE) DEVELOPMENTS OR TEST CENTERS (COPPING ET AL. 2018)

MeyGen Prior to the MeyGen tidal energy deployment at Pentland Firth, United Kingdom (UK), an extensive assessment of social and economic impacts as part of the environmental statement (ES) was undertaken (MeyGen 2012). In addition, a comparison of economic development estimates and data was carried out. Metrics from the gross value added report were used and the information gathered is now regarded as the baseline. The ES included data collected about employment sectors, fisheries, cultural heritage, and shipping and navigation, as well as the mapping of constraints to development such as other marine uses (MeyGen 2012). Outreach to the fishing community resulted in comments and data collected that allowed for the ES to report that impacts on the fishing community would not be significant (MeyGen 2012). In addition, MeyGen took note of potential impacts and made a commitment to have a number of apprenticeships and to use a percentage of local workers (Copping et al. 2018). The developer, DP Energy, also collected social and economic information in two ways that should be noted. They tracked apprenticeships in anticipation of construction and monitoring and also talked to the fishing community in the area; both practices allowed them to gather data that could not have been gained otherwise (Copping et al. 2018).

European Marine Energy Centre (EMEC) Social and economic data have been collected around Orkney's EMEC (established in 2003), to elucidate the potential social and economic impacts of MRE development. One of the main tangible benefits of MRE development is the employment opportunities that EMEC and MRE developments bring to Orkney (Figure 9.4) and beyond. EMEC employs 22 staff, and the average equivalent of 119 jobs in Orkney and 262 jobs across the UK were supported by EMEC activity from 2003 to 2011 (Renewable UK 2014). The local government, understanding the opportunities present, funded the development of ports and additional infrastructure to support the MRE industry, which in turn benefited other marine industries and produced additional job opportunities (EMEC 2019). Orkney residents developed a greater understanding of MRE and how MRE can contribute to the community by investing in energy projects (Copping et al. 2018). It is worth noting that EMEC's development was shown to have boosted the UK economy by over £200M (EMEC 2019). On a local scale, population growth related to increased employment, the increase in average earnings, and job diversification have also been attributed to EMEC (EMEC 2019). An important lessons learned through data collection efforts related to EMEC was to assure that the metrics used are valid. For example, a comparison of jobs in London to jobs in Orkney was not meaningful for understanding the impacts in a small community such as Orkney. It is key to use the proper metrics so that useful data can be collected for meaningful assessments.

Date	Overall total jobs (number)	Annual income from jobs (£000s)	Monthly salary bill (£000s)	Cumulative jobs (job years)	Cumulative income from jobs (£000s)
2000	26	650	54	26	650
2001	27	675	56	53	1,325
2002	32	800	67	85	2,125
2003	40	1,000	83	125	3,125
2004	48	1,200	100	173	4,325
2005	57	1,425	119	230	5,750
2006	69	1,725	144	299	7,475
2007	77	1,925	160	376	9,400
2008	93	2,325	194	469	11,725
2009	124	3,100	258	593	14,825
2010	163	4,075	340	756	18,900
2011	189	4,725	394	945	23,625
2012	229	5,725	477	1,174	29,350
2013	286	7,150	596	1,460	36,500
2014	300	7,500	625	1760	44,000
2015	250	6,250	520	2010	50,250
2016	220	5,750	460	2240	56,000

Figure 9.4. This graph shows the MRE job trend in Orkney over time from 2000 to 2016. The first MRE deployment at EMEC was in 2004 and the number of deployments peaked at 14 in 2014. (From Copping et al. 2018)

Fundy Ocean Research Center for Energy (FORCE) Some social and economic data have also been collected in Nova Scotia (Canada), especially related to the construction of the Fundy Ocean Research Center for Energy (FORCE), which was established in 2009. A value proposition for tidal energy developed in the region showed the economic benefits to include 22000 new full-time equivalent jobs and more than $1.5 billion of additional gross domestic product (Gardner et al. 2015). These figures were due in part to the fact that much of the pre-construction, construction, installation, operation, and maintenance work was sourced locally and that more than 300 companies were involved in the supply chain. FORCE has also become a part of the tourism industry and attracts visitors to its Visitor Center from Nova Scotia and worldwide (Howell and Drake 2012). However, FORCE has run into pushback, mainly in the form of ongoing opposition from the fishing community and concerns about the cumulative effects and potential harm to marine life caused by tidal deployments (CBC News 2017). While it was ruled that FORCE has carefully monitored and is following the precautionary principle, this conflict speaks to the importance of social acceptance and the need for early and transparent outreach and engagement with key stakeholders to understand and address community concerns.

cific social and economic data following the good practices above. In addition, government entities, investors, and test sites can also incentivize or require that data, information, and analyses be shared and provided for public use. For example, the U.S. Department of Energy stipulates that MRE projects that have received government funding have to upload their data to an online data portal (Marine and Hydrokinetic Data Repository 2020). Not only does this help fund and create an impetus for data collection and sharing, but it allows these entities to ask for data collected about key indicators and impacts, thereby further adding to the ability to standardize methods and available data. This recommendation is best carried out by governments, investors, and/or MRE test sites.

9.7.5. USE A FLEXIBLE PLANNING APPROACH

With uncertainty around not only the environmental effects of MRE, but also its social and economic effects, it is important to allow for learning to develop over time and for adjustments to be made as a project is deployed. Considering a flexible approach to planning, such as a design envelope approach (also known as the "Rochdale Envelope") (The Planning Inspectorate 2018; Caine 2018), or an adaptive management approach (see Chapter 12, Adaptive Management Related to Marine Renewable Energy), is necessary. A design envelope approach gives developers flexibility during the consenting and development stages of projects because they can provide a range of project parameters (BOEM 2018). These approaches allow for uncertainty to be addressed and adjustments to be made as the project moves forward, and learning, including understanding of potential social and economic impacts, increases. This recommendation is best carried out by governments allowing a flexible approach to be used and developers using such approaches for their developments.

9.7.6. CORRELATE IMPACTS, DATA COLLECTION, AND PROCESSES TO APPROPRIATE SIZES

With many barriers for the MRE industry to overcome as it advances, one potential barrier is unnecessary requirements. In the case of social and economic data collection, the requirements may be overly burdensome. Instead, when collecting data, the associated impacts need to be strongly correlated to the sensitivity of the receptor. For example, if fishing jobs are lost because of an MRE deployment, the loss would have a smaller impact on a community that does not heavily rely on the fishing industry than it would have on a community that relies significantly on this industry. In addition, consenting processes can create challenges related to long timelines and associated costs. While consenting processes can help limit adverse effects, such processes and the associated evidence burden placed on developers should be proportional to the project size. For example, for a smaller MRE development, adversarial effects will be small and requirements for benefits to offset those should be proportionally smaller too. This recommendation is relevant for regulators who set requirements for data collection and governments who set requirements for consenting processes.

9.8. CONCLUSION

One of the most important areas for future MRE research is the social and economic effects, especially because the social effects are not well understood (Uihlein and Magagna 2016). Improving the collection, collation, and dissemination of data about social and economic effects would greatly aid this developing industry. As more information becomes available, producing social and economic assessments will become easier thanks to lessons learned from previous projects, more existing and accessible data to compare between projects, and data and information that may be used from one project for a future project (see Chapter 13, Risk Retirement and Data Transferability for Marine Renewable Energy).

9.9. REFERENCES

ABPMer. 2012. A Socio-economic Methodology and Baseline for Pentland Firth and Orkney Waters Round 1 Wave and Tidal Developments. Available by request.

Akar, Z., and Akdoğan, D. A. 2016. Environmental and Economic Impacts of Wave Energy: Some Public Policy Recommendations from Implementation in Turkey. In M. M. Erdoğdu, T. Arun, and I. H. Ahmad (Eds.), Handbook of Research on Green Economic Development Initiatives and Strategies (pp. 285-309). Hershey, PA: IGI Global. *https://tethys.pnnl.gov/publications/handbook-research-green-economic-development-initiatives-strategies*

Bailey, I., West, J., and Whitehead, I. 2011. Out of Sight but Not out of Mind? Public Perceptions of Wave Energy. *Journal of Environmental Policy & Planning*, 13(2), 139-157. doi:10.1080/1523908X.2011.573632 *https://tethys.pnnl.gov/publications/out-sight-not-out-mind-public-perceptions-wave-energy*

Bonar, P. A. J., Bryden, I. G., and Borthwick, A. G. L. 2015. Social and ecological impacts of marine energy development. *Renewable and Sustainable Energy Reviews*, 47, 486-495. doi:10.1016/j.rser.2015.03.068 *https://tethys.pnnl.gov/publications/social-ecological-impacts-marine-energy-development*

Bradsher, K. 2012. 'Social Risk' Test Ordered by China for Big Projects. The New York Times. Retrieved from *https://www.nytimes.com/2012/11/13/world/asia/china-mandates-social-risk-reviews-for-big-projects.html*

Burdge, R. J., and Taylor, C. N. 2012. When and Where is Social Impact Assessment Required? Paper presented at the International Association for Impact Assessment Annual Meeting, Porto, Portugal. *https://tethys.pnnl.gov/publications/when-where-social-impact-assessment-required*

Bureau of Ocean Energy Management (BOEM). 2018. Draft Guidance Regarding the Use of a Project Design Envelope in a Construction and Operations Plan. Office of Renewable Energy Programs, U.S. Department of the Interior. *https://tethys.pnnl.gov/publications/draft-guidance-regarding-use-project-design-envelope-construction-operations-plan*

Caine, C. A. 2018. The place of the Rochdale envelope approach in offshore renewable energy. *Environmental Law Review*, 20(2), 74-88. doi:10.1177/1461452918777835 *https://tethys.pnnl.gov/publications/place-rochdale-envelope-approach-offshore-renewable-energy*

Carl Bro Group Ltd. 2002. Marine Energy Test Centre Environmental Statement (REP141-01-03 20071115). Glasgow, UK. *https://tethys.pnnl.gov/publications/billia-croo-environmental-statement*

CBC News. 2017. Fundy fishermen lose bid to stop tidal turbine in Minas Basin. CBC News. Retrieved from *https://www.cbc.ca/news/canada/nova-scotia/tidal-turbine-fundy-fishermen-court-decision-1.4064346*

Code de l'Environnement. 2018. Article L112-1.

Copping, A., Freeman, M., Hutchinson, I., and Fox, J. 2019. Good Management Practices for Social and Economic Data Collection for Marine Renewable Energy. Ocean Energy Systems. *https://tethys.pnnl.gov/publications/good-management-practices-social-economic-data-collection-marine-renewable-energy*

Copping, A., Hutchinson, I., and Fox, J. 2017. Exploring the State of Understanding and Practice Used to Assess Social and Economic Risks and Benefits of Marine Renewable Energy Development. Workshop conducted at the European Wave and Tidal Energy Conference, Cork, Ireland. *https://tethys.pnnl.gov/events/exploring-state-understanding-practice-used-assess-social-economic-risks-benefits-marine*

Copping, A., Hutchinson, I., Fox, J., and Freeman, M. 2018. Case Studies on Social and Economic Effects around MRE Development. Workshop conducted at the Environmental Impacts of Marine Renewables Conference, Kirkwall, UK. *https://tethys.pnnl.gov/events/case-studies-social-economic-effects-around-mre-development*

Dalton, G., Allan, G., Beaumont, N., Georgakaki, A., Hacking, N., Hooper, T., Kerr, S., O'Hagan, A. M., Reilly, K., Ricci, P., Sheng, W., and Stallard, T. 2015. Economic and socio-economic assessment methods for ocean renewable energy: Public and private perspectives. *Renewable and Sustainable Energy Reviews*, 45, 850-878. doi:10.1016/j.rser.2015.01.068 *https://tethys.pnnl.gov/publications/economic-socio-economic-assessment-methods-ocean-renewable-energy-public-private*

Devine-Wright, P. 2011. Enhancing local distinctiveness fosters public acceptance of tidal energy: A UK case study. *Energy Policy*, 39(1), 83-93. doi:10.1016/j.enpol.2010.09.012 https://tethys.pnnl.gov/publications/enhancing-local-distinctiveness-fosters-public-acceptance-tidal-energy-uk-case-study

Devine-Wright, P., Burningham, K., Barnett, J., Devine-Wright, H., Walker, G., Infield, D., Evans, B., Howes, Y., Evans, F., Cass, N., Theobald, K., Parks, J., Barton, J., Thrush, D., and Speller, G. 2013. Beyond Nimbyism: Project Summary Report. School of Environment and Development, University of Manchester, Manchester, UK. https://tethys.pnnl.gov/publications/beyond-nimbyism-project-summary-report

Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). OJ L 164, 25.6.2008, p. 19–40

Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment. OJ L 124, 25.4.2014, p. 1–18

Drake, C. 2012. Understanding socioeconomic issues and opportunities of an emerging tidal energy industry in Nova Scotia. Master's Thesis, University Centre of the Westfjords, Ísafjörður, Iceland. https://tethys.pnnl.gov/publications/understanding-socioeconomic-issues-opportunities-emerging-tidal-energy-industry-nova

Dutta, B., and Bandyopadhyay, S. 2010. Environmental Impact Assessment and Social Impact Assessment - Decision Making Tools for Project Appraisal in India *World Academy of Science, Engineering and Technology*, 39, 1116-1121. https://tethys.pnnl.gov/publications/environmental-impact-assessment-social-impact-assessment-decision-making-tools-project

EquiMar. 2011. Deliverable D5.8: Impacts upon marine energy stakeholders. https://tethys.pnnl.gov/publications/equitable-testing-evaluation-marine-energy-extraction-devices-terms-performance-cost

European Marine Energy Centre (EMEC). 2019. EMEC Socio-Economic Report. Stromness, Orkney. https://tethys.pnnl.gov/publications/emec-socio-economic-report

Gardner, M., MacDougall, S., Taylor, J., Karsten, R., Johnson, K., Kerr, S., Fitzharris, J. 2015. Value Proposition for Tidal Energy Development in Nova Scotia, Atlantic Canada and Canada. Offshore Energy Research Association (OERA), Halifax, Nova Scotia. Report for OERA. https://tethys.pnnl.gov/publications/value-proposition-tidal-energy-development-nova-scotia-atlantic-canada-canada

Government of Canada. 2018. The Proposed Impact Assessment System: A Technical Guide. https://tethys.pnnl.gov/publications/proposed-impact-assessment-system

Government of Canada. 2019. Impact Assessment Agency of Canada. Retrieved from https://www.canada.ca/en/impact-assessment-agency.html

Howell, A., and Drake, C. 2012. Scoping Study on Socio-Economic Impacts of Tidal Energy Development in Nova Scotia: A Research Synthesis & Priorities for Future Action. FERN Technical Report # 2012 – 01. Fundy Energy Research Network (FERN), Wolfville, Nova Scotia. Report by FERN for Nova Scotia Department of Energy. https://tethys.pnnl.gov/publications/scoping-study-socio-economic-impacts-tidal-energy-development-nova-scotia-research

Ip, D. F. 1990. Difficulties in implementing social impact assessment in China: Methodological considerations. *Environmental Impact Assessment Review*, 10(1), 113-122. doi:10.1016/0195-9255(90)90011-N https://tethys.pnnl.gov/publications/difficulties-implementing-social-impact-assessment-china-methodological-considerations

Isaacman, L., Daborn, G., and Redden, A. 2012. A Framework for Environmental Risk Assessment and Decision-Making for Tidal Energy Development in Canada (Report No. 106). Acadia Centre for Estuarine Research (ACER), Acadia University, Wolfville, Nova Scotia. https://tethys.pnnl.gov/publications/framework-environmental-risk-assessment-decision-making-tidal-energy-development

Jimenez, T., and Tegen, S. 2014. Economic Impact of Large-Scale Deployment of Offshore Marine and Hydrokinetic Technology in Oregon (NREL/TP-5000-61727). National Renewable Energy Laboratory, Golden, Colorado. https://tethys.pnnl.gov/publications/economic-impact-large-scale-deployment-offshore-marine-hydrokinetic-technology-o

Jimenez, T., Tegen, S., and Beiter, P. 2015. Economic Impact from Large-Scale Deployment of Offshore Marine and Hydrokinetic Technology in Oregon Coastal Counties (NREL/TP-5000-63506). National Renewable Energy Laboratory, Golden, Colorado. Report by National Renewable Energy Laboratory for Bureau of Ocean Energy Management. *https://tethys.pnnl.gov/publications/economic-impact-large-scale-deployment-offshore-marine-hydrokinetic-technology-oregon*

Kerr, S., Colton, J., Johnson, K., and Wright, G. 2015. Rights and ownership in sea country: implications of marine renewable energy for indigenous and local communities. *Marine Policy*, 52, 108-115. doi:10.1016/j.marpol.2014.11.002 *https://tethys.pnnl.gov/publications/rights-ownership-sea-country-implications-marine-renewable-energy-indigenous-local*

Kerr, S., Watts, L., Colton, J., Conway, F., Hull, A., Johnson, K., Jude, S., Kannen, A., MacDougall, S., McLachlan, C., Potts, T., and Vergunst, J. 2014. Establishing an agenda for social studies research in marine renewable energy. *Energy Policy*, 67, 694-702. doi:10.1016/j.enpol.2013.11.063 *https://tethys.pnnl.gov/publications/establishing-agenda-social-studies-research-marine-renewable-energy*

Lavidas, G. 2019. Energy and socio-economic benefits from the development of wave energy in Greece. *Renewable Energy*, 132, 1290-1300. doi:10.1016/j.renene.2018.09.007 *https://tethys.pnnl.gov/publications/energy-socio-economic-benefits-development-wave-energy-greece*

Leeney, R. H., Greaves, D., Conley, D., and O'Hagan, A. M. 2014. Environmental Impact Assessments for wave energy developments – Learning from existing activities and informing future research priorities. *Ocean & Coastal Management*, 99, 14-22. doi:10.1016/j.ocecoaman.2014.05.025 *https://tethys.pnnl.gov/publications/environmental-impact-assessments-wave-energy-developments-learning-existing-activities*

Marine Energy Wales. 2020. State of the Sector Report: Economic Benefits for Wales. *https://tethys.pnnl.gov/publications/state-sector-report-2020-economic-benefits-wales*

Marine and Hydrokinetic Data Repository. 2020. About DOE's Marine and Hydrokinetic Data Repository. Retrieved from *https://mhkdr.openei.org/about*

MeyGen. 2012. MeyGen Tidal Energy Project Phase 1: Environmental Statement. *https://tethys.pnnl.gov/publications/meygen-tidal-energy-project-phase-1-environmental-statement*

National Environmental Policy Act of 1969. 42 U.S.C. §§4321-4370h.

Novaczek, I., MacFadyen, J., Bardati, D., and MacEachern, K. 2011. Social and Cultural Values Mapping as a decision-support tool for climate change adaptation. Institute of Island Studies, University of Prince Edward Island, Charlottetown, Canada. *https://tethys.pnnl.gov/publications/social-cultural-values-mapping-decision-support-tool-climate-change-adaptation*

Oregon Wave Energy Trust (OWET). 2020. OWET Research. Retrieved from *https://pacificoceanenergy.org/research/owet-research/*

Organisation for Economic Co-operation and Development (OECD). 2001. Glossary of Statistics Terms: Gross Value Added. Retrieved from *https://stats.oecd.org/glossary/detail.asp?ID=1184*

Orkney Renewable Energy Forum (OREF). 2020. Orkney Renewable Energy Forum. Retrieved from *http://www.oref.co.uk/*

The Planning Inspectorate. 2018. Using the Rochdale Envelope. Advice Note Nine: Rochdale Envelope. *https://tethys.pnnl.gov/publications/using-rochdale-envelope*

Price, S., and Robinson, K. 2015. Making a Difference?: Social Assessment Policy and Praxis and Its Emergence in China (Vol. 6). Brooklyn, NY: Berghahn Books. *https://tethys.pnnl.gov/publications/making-difference-social-assessment-policy-praxis-its-emergence-china*

Rand, J., and Hoen, B. 2017. Thirty years of North American wind energy acceptance research: What have we learned? *Energy Research & Social Science*, 29, 135-148. doi:10.1016/j.erss.2017.05.019 *https://tethys.pnnl.gov/publications/thirty-years-north-american-wind-energy-acceptance-research-what-have-we-learned*

Regeneris Consulting Ltd. 2013. The Economic Impact of the Development of Marine Energy in Wales. *https://tethys.pnnl.gov/publications/economic-impact-development-marine-energy-wales*

Regulations on Impact Assessments. Kgl. Res. 21. June 2017. nr. 71.

Ren, X. I. N. 2013. Implementation of environmental impact assessment in China. *Journal of Environmental Assessment Policy and Management*, 15(3), 1350009. doi:10.1142/S1464333213500099 https://tethys.pnnl.gov/publications/implementation-environmental-impact-assessment-china

Renewable UK. 2014. Maximising the Value of Marine Energy to the United Kingdom. Marine Energy Program Board. https://tethys.pnnl.gov/publications/maximising-value-marine-energy-united-kingdom

Simas, T., Magagna, D., Bailey, I., Conley, D., Greaves, D., O'Callaghan, J., Marina, D., Saulnier, J., Sundberg, J., Embling, C. 2013. SOWFIA Deliverable D.4.4 Interim Report: Critical Environmental Impacts for Relevant Socio-economic Activities and Mitigation Measures Including Main Conclusions and Feedback Analysis from Workshop B and Analysis of the Stakeholder Survey. Report by WavEC - Offshore Renewables. https://tethys.pnnl.gov/publications/sowfia-deliverable-d44-interim-report-critical-environmental-impacts-relevant-socio

Smart, G., and Noonan, M. 2018. Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit: Summary Analysis. Offshore Renewables Energy Catapult. https://tethys.pnnl.gov/publications/tidal-stream-wave-energy-cost-reduction-industrial-benefit-summary-analysis

Smythe, T., Andrescavage, N., and Fox, C. 2016. The Rhode Island Ocean Special Area Management Plan, 2008 – 2015: From Inception through Implementation. Coastal Resources Center and Rhode Island Sea Grant College Program, URI Graduate School of Oceanography, Narragansett, Rhode Island. Report by University of Rhode Island for Gordon and Betty Moore Foundation. https://tethys.pnnl.gov/publications/rhode-island-ocean-special-area-management-plan-2008-2015-inception-through

S.O. 1533, Environmental Impact Assessment Notification, 2006, Ministry of Environment and Forests, GAZ. INDIA, New Delhi, 14 Sep 2006.

Stokes, C., Beaumont, E., Russell, P., and Greaves, D. 2014. Anticipated coastal impacts: What water-users think of marine renewables and why. *Ocean & Coastal Management*, 99, 63-71. doi:10.1016/j.ocecoaman.2014.04.003 https://tethys.pnnl.gov/publications/anticipated-coastal-impacts-what-water-users-think-marine-renewables-why

Tang, B., Wong, S., and Lau, M. C. 2008. Social impact assessment and public participation in China: A case study of land requisition in Guangzhou. *Environmental Impact Assessment Review*, 28(1), 57-72. doi:10.1016/j.eiar.2007.03.004 https://tethys.pnnl.gov/publications/social-impact-assessment-public-participation-china-case-study-land-requisition

Uihlein, A., and Magagna, D. 2016. Wave and tidal current energy – A review of the current state of research beyond technology. *Renewable and Sustainable Energy Reviews*, 58, 1070-1081. doi:10.1016/j.rser.2015.12.284 https://tethys.pnnl.gov/publications/wave-tidal-current-energy-review-current-state-research-beyond-technology

van den Burg, S. W. K., Aguilar-Manjarrez, J., Jenness, J., and Torrie, M. 2019. Assessment of the geographical potential for co-use of marine space, based on operational boundaries for Blue Growth sectors. *Marine Policy*, 100, 43-57. doi:10.1016/j.marpol.2018.10.050 https://tethys.pnnl.gov/publications/assessment-geographical-potential-co-use-marine-space-based-operational-boundaries

Vanclay, F. 2012. The potential application of social impact assessment in integrated coastal zone management. *Ocean & Coastal Management*, 68, 149-156. doi:10.1016/j.ocecoaman.2012.05.016 https://tethys.pnnl.gov/publications/potential-application-social-impact-assessment-integrated-coastal-zone-management

Vanclay, F., Esteves, A. M., Aucamp, I., and Franks, D. 2015. Social Impact Assessment: Guidance for assessing and managing the social impacts of projects. International Association for Impact Assessment, Fargo, North Dakota. https://tethys.pnnl.gov/publications/social-impact-assessment-guidance-assessing-managing-social-impacts-projects

Voyants Solutions Pvt. Ltd. 2016. Environmental and Social Impact Assessment of 200 MW Wind Project at Village Aspari, District Kurnool, Andhra Pradesh. Mytrah Energy India. https://tethys.pnnl.gov/publications/environmental-social-impact-assessment-200-mw-wind-project-village-aspari-district

NOTES

NOTES

Social and Economic Data Collection for Marine Renewable Energy

Freeman, M.C. 2020. Social and Economic Data Collection for Marine Renewable Energy. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 154-174). doi:10.2172/1633195

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

Section C

Environmental Monitoring

10.0

Chapter authors: Daniel J. Hasselman, David R. Barclay, Robert Cavagnaro, Craig Chandler, Emma Cotter, Douglas M. Gillespie, Gordon D. Hastie, John K. Horne, James Joslin, Caitlin Long, Louise P. McGarry, Robert P. Mueller, Carol E. Sparling, and Benjamin J. Williamson
Contributor: Garrett J. Staines

Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines

The greatest potential risk from turbine operation continues to be perceived by regulators and other stakeholders to be that of marine animals colliding with turbine blades. These potential interactions are the most difficult to observe using common oceanographic instruments and must be undertaken in parts of the ocean where fast moving water and high waves make studies challenging. However, our collective understanding of the effects of marine renewable energy (MRE) devices on marine animals and their habitats has improved through monitoring and research since the publication of the *2016 State of the Science* report (Copping et al. 2016).

10.1. BACKGROUND TO ENVIRONMENTAL MONITORING TECHNOLOGIES AROUND TURBINES

Technological advancements in different instrument classes, the integration of instruments on subsea monitoring platforms, and improvements of methodologies have increased our understanding of the effects that tidal energy turbines and wave energy converters (WECs) have on marine organisms. Despite these advances, monitoring challenges remain with respect to the durability of monitoring equipment in harsh marine environments, power availability/management of integrated monitoring systems, and continuous data collection, storage, and analysis. This chapter focuses on the state of the science in environmental monitoring technologies and techniques, in particular (1) the instrument classes used for monitoring MRE devices (Section 10.2)[1], (2) the challenges of monitoring around MRE devices (Section 10.3), and (3) integrated monitoring platforms that are currently used to monitor MRE devices (Section 10.4). This chapter also provides an overview of lessons learned from monitoring activities (Section 10.5) and recommendations for quality data collection, management, and analysis (Section 10.6).

An additional challenge to developing and operating environmental monitoring instruments and platforms around MRE devices is the need to have available instrumentation packages that can be safely and effectively used by MRE developers around active wave or tidal projects. MRE developers invest time and resources to design against device failure; the same investments are likely needed for monitoring instruments. There is a need to design and implement simple, robust environmental monitoring packages because many consenting/permitting (hereafter consenting) decisions are contingent upon the operation and provision of data streams from the instruments. Many of the instruments described here were developed for research purposes; additional effort will be needed to further marinize and harden the platforms and instruments to assure that the engineering designs are capable of withstanding the purpose for which they may be used in the high-energy waters where the harvesting of tidal and wave energy is planned.

1. Mention of commercial instruments or other equipment and software throughout this chapter is meant to illustrate the gear in use and does not constitute endorsement of any commercial products.

10.2. INSTRUMENT CLASSES USED FOR MONITORING MRE DEVICES

A suite of environmental monitoring instruments has been used to monitor the potential environmental effects of MRE devices. The most common instrumentation used to document interactions of marine animals and habitats with MRE devices include passive acoustic instruments, active acoustic instruments, and optical cameras, while other instrumentation is used to help define the physical environment in which these interactions may occur. Here, we provide an overview of the different classes of instrumentation used for monitoring marine animal interactions with MRE devices.

10.2.1. PASSIVE ACOUSTICS

Within the context of monitoring MRE devices, passive acoustic monitoring (PAM) instruments have primarily been used to (1) characterize the soundscape of energetic marine environments (e.g., ambient sound and MRE device-associated noise; for details, see Chapter 4, Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices), and (2) monitor for echolocating marine mammals (e.g., detection and localization; for details, see Chapter 3, Collision Risk for Animals around Turbines). PAM of MRE devices is important because these devices may generate underwater noise (e.g., cavitation and motor/mechanical noise [Wang et al. 2007]) that could affect animal navigation, communication, predation, and life cycles (Lombardi 2016; Pine et al. 2012). Despite a growing body of PAM effort around MRE devices, no commercially available acoustic monitoring systems have been designed specifically for monitoring in the highly energetic marine environments that are sought for MRE extraction. Instead, various PAM technologies designed for more benign marine environments have been experimentally deployed in high-flow environments to assess their suitability for monitoring in these conditions. These technologies include conventional cabled or autonomous hydrophone and analog-to-digital instrument packages, internally recording hydrophones with digital interfaces, cabled and autonomous hydrophones or vector instrument arrays, and integrated hydrophone and data processing systems for marine mammal detection. In this section, we first consider the challenges faced by PAM in high-flow environments, and then provide an overview of the state of the science with respect to the use of PAM technologies for monitoring marine sound and marine mammals.

Challenges

A variety of factors (e.g., flow noise, natural ambient sound, instrument size and geometry, and deployment method) influence the detection efficiency of PAM instruments. However, the primary challenge for PAM in highly energetic marine environments is the identification and mitigation of flow noise (Bassett et al. 2014; Lombardi 2016; Thomson et al. 2012) generated by pressure fluctuations caused by turbulent flow on the surface of the hydrophone, or the noise made by water moving rapidly across the surface of the hydrophone. In energetic marine environments, flow noise can mask true propagating sound over a large bandwidth (i.e., 0–1 kHz), with increasing intensity and decreasing frequency, while sediment movement can generate noise in the 10s of kilohertz, depending on grain size and material (Bassett 2013; Raghukumar et al. 2019). This complicates the accurate characterization of ambient sound and the quantification of anthropogenic noise and reduces the effective detection range for echolocating marine mammals.

A suite of mechanical solutions to mitigate flow noise have been proposed. For instance, linear arrays of hydrophones have been used to reduce flow noise when monitoring tidal energy turbines in open channel turbulent flow (Auvinen and Barclay 2019; Worthington 2014). Because the flow noise is generated locally on each instrument, it is independent from one instrument to the next, but true propagating sound will appear to be coherent across the array. By coherently averaging the signals across the array, the flow noise may be suppressed while the true sound is amplified. Another commonly used option is the deployment of instrumentation on Lagrangian drifting floats in place of fixed moorings, and the use of flow shields, baffles, and vibration isolation mounts to minimize flow noise. However, none of these approaches are entirely effective at removing flow noise, and some options (e.g., flow shields) can degrade the detection of propagating sound if they are not designed appropriately.

Marine Sound Monitoring

Copping et al. (2013) and Robinson and Lepper (2013) provided comprehensive reviews of all published acoustic environmental monitoring activity for MRE devices up to 2013. Online supplementary Table S10.1 (online at: *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-environmental-monitoring*) provides an update and expansion of the two previously mentioned 2013 reports and summarizes the various PAM efforts used to characterize (1) ambient noise baseline measurements, (2) operational noise, (3) construction and installation associated noise, and (4) planned transmissions, and includes selected publications describing the results. Monitoring for marine noise around MRE sites should follow the protocol of the International Electrotechnical Commission Technical Specification (IEC TS) 62600-40:2019, which provides uniform methodologies for consistently characterizing the sound produced by the operation of marine energy converters that generate electricity from wave, current, and thermal energy conversion (IEC 2019; for details, see Chapter 4, Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices).

Marine noise at MRE sites has been characterized most often using a combination of drifting buoy or boat-based measurements; moored/bottom-mounted systems and directional arrays or paired hydrophones have been used less frequently. However, many of the early studies that used drifting boat-based measurements suffered from significant contamination of the acoustic recordings by noise generated by surface motion, including waves lapping against the boat hull and topside activity. Subsequent studies deployed hydrophones under floating buoys using isolation and suspension systems, drogues, or catenary sections to reduce noise contamination (Figure 10.1). These hydrophone deployments are described as having the highest fidelity relative to the true sound field—a claim that is frequently substantiated by the reduction of flow noise and motion-induced noise levels in subsequently collected datasets.

Operationally, moored/bottom-mounted systems provide the ability to monitor a single point in space for extended periods of time, whereas drifting systems measure a snapshot (typically on the order of minutes) of the noise field over a wider geographic area. There are advantages and disadvantages to each

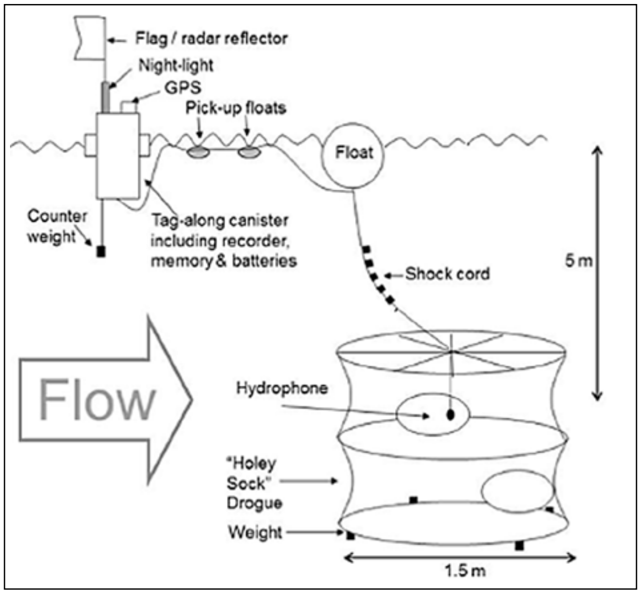


Figure 10.1. Schematic of the components of the "drifting ears" autonomous recording drifter specifically developed for use in tidal streams. This system was designed to keep the hydrophone in a fixed position relative to the body of moving water and is placed in a submerged underwater drogue. (From Wilson et al. 2014)

approach, depending on the context of the monitoring program being considered. For instance, for quantifying MRE device-generated noise, flow noise detected by a moored/bottom-mounted system typically masks the frequencies of interest (10s–100s of hertz), necessitating a labor-intensive and carefully executed drift-based measurement campaign. However, in the case of continuous real-time monitoring, a moored/bottom-mounted system is the only realistic option at this time, and methods of flow noise suppression (e.g., a flow shield) must be used if the objective includes quantifying MRE device-generated noise. However, there is no standard flow shield design available. Results from flow shield experiments have provided mixed results; some studies confirm a reduction in flow noise (Bassett 2013; Raghukumar et al. 2019), and others demonstrate a reduction in system sensitivity with no effect on flow noise in the band of interest (Malinka et al. 2015; Porskamp et al. 2015).

Digital hydrophones are widely available from a suite of manufacturers, are relatively compact in form, and are preferable for long-term deployments of moored/bottom-mounted observation systems because of their ability to transfer data at high speeds with little signal attenuation. The future automation of drifting PAM systems using unmanned aerial vehicles (UAVs) to take underwater noise measurements (Lloyd et al. 2017) may alleviate the laborious nature of previous drift-based monitoring campaigns, but these techniques are yet to be demonstrated. The use of a station-keeping autonomous hovercraft with a deployable acoustic instrument has also been proposed (Barclay 2019), and both of these technologies could provide duty-cycled long-term monitoring of MRE sites without interference from flow noise.

Marine Mammal Monitoring

A variety of PAM technologies are used for monitoring the presence of vocalizing marine mammals and their interactions with MRE devices. Most marine mammal monitoring programs that employ PAM technologies use porpoise and dolphin echolocation clicks to detect, classify, and localize the various species. These short-duration signals have reasonably wide bands (10–50 kHz) and are centered at relatively high frequencies (90–130 kHz). However, the detection efficiency of PAM instruments for monitoring marine mammals is affected by a variety of factors, including the vocalization bandwidth for the species being monitored and the potential masking of these sounds by flow noise and ambient noise (e.g., sediment transport on the seafloor), as well as by the propagation environment, reverberation, instrument placement, and instrument deployment methodology (Bassett et al. 2013; Porskamp et al. 2015; Tollit and Redden 2013). By understanding the relative effects of these factors, the performance of PAM technologies for monitoring marine mammals around MRE devices can be assessed. For instance, some frequently observed baleen whales in the Bay of Fundy, Nova Scotia, Canada, (e.g., humpback, fin, and minke whales) produce low-frequency sounds (below 1 kHz), and masking by flow and sediment transport noise may contribute to the absence of their detections using PAM technologies. In addition, a modeling exercise found that the passive acoustic detection range for southern resident killer whale (*Orcinus orca*) frequently observed in Admiralty Inlet, in Washington State, United States (U.S.) (Snohomish Public Utility District 2012), was reduced by 90 percent during flood and ebb tides suitable for turbine operation in a tidal channel because of flow noise (Bassett 2013).

Because the primary signal of interest for monitoring marine mammals around MRE devices is echolocation clicks, the data recording packages suitable for detection must have high sampling rates (>250 kHz) and large memory capacities for storing the raw pressure time series. The resulting data must then be processed for detection, classification, and localization using either commercially available software or custom-designed detection algorithms. A popular choice for this task is PAMGuard (Gillespie et al. 2008a) — an open-source software that automates detection and classification of sounds in the time series and permits localization. While "conventional" PAM instruments (Figure 10.2a) frequently require separate hardware (recording) and software (detection and classification) systems, alternative "stand-alone" instruments (Figure 10.2b) allow the pressure time series to be analyzed in real time (following some prescribed criteria for detection and classification), thereby permitting the raw data to be discarded while storing the associated metadata.

Figure 10.2. Examples of a "conventional" PAM instrument (Ocean Instruments NZ SoundTrap ST300 HF) (a) and a "stand-alone" PAM instrument (b). (Photos courtesy of Daniel Hasselman)

These two classes of PAM instruments (i.e., "conventional" and "stand-alone") have been deployed in drifting, moored, bottom-mounted, and MRE device-mounted configurations to detect, classify, and localize various echolocating marine mammals, but have been shown to have different performance depending on a variety of factors, including the metric being assessed. For instance, a study in the Baltic Sea found that a stand-alone instrument detected 21 to 94 percent of the click trains detected by PAMGuard when applied to the recordings made with a co-located conventional instrument (Sarnocinska et al. 2016). The reduced rate of detections (i.e., clicks per minute) was due to several factors, but primarily the fact that PAMGuard detected individual clicks, whereas the proprietary software on the stand-alone instrument detected click trains. However, data collected as clicks per minute by conventional and stand-alone PAM instruments cannot be directly compared, because there is large spread in the detection ratio of these systems and no consistent linear relationship between the detection rates for these instruments (Sarnocinska et al. 2016). Alternative metrics such as "detection positive minutes per unit time" (Roberts and Read 2015) and "echolocation clicks per hour" (Jacobson et al. 2017) have revealed greater agreement (i.e., higher accuracy and lower spread in detection ratio) between classes of PAM instruments. However, prior studies have shown that co-located conventional instruments record five to ten times more detection minutes per day than stand-alone instruments (Adams 2018; Porskamp et al. 2015; Tollit and Redden 2013), and the differences are attributed to the detection algorithm employed and the greater impact of flow-induced noise (i.e., sediment transport) when using stand-alone instruments.

One concern with the use of stand-alone PAM instruments in high-flow environments centers around the issue of "lost time" (or time when the system is not operational) and the potential for under-reported click trains. Flow-induced noise can cause the maximum number of recordable clicks per minute to be exceeded on a stand-alone instrument, resulting in saturation of the detection buffer, and generating lost time (Tollit and Redden 2013). Comparative studies in high-flow environments have shown the effect of lost time from flow-induced noise for bottom-mounted and moored stand-alone instruments (Porskamp et al. 2015; Wilson et al. 2013). Bottom-mounted stand-alone instruments generally have more detection minutes per day than moored systems, during which noise generated by the mooring system being "blown down" against the seabed during periods of high flow may have saturated the detection buffer of the instrument (Porskamp et al. 2015). Alternatively, drifting stand-alone instruments suspended from Lagrangian drogues or floats do not appear to suffer from lost time, suggesting that flow-induced noise has less of an impact on the detection buffer in this configuration (Adams 2018; Benjamins et al. 2016; Wilson et al. 2013).

Detection efficiency also differs between PAM technologies; conventional instruments generally have greater detection ranges (0–500 m) than stand-alone instruments (0–300 m), depending on the conditions under which the tests are conducted (Benjamins et al. 2017;

Kyhn et al. 2008, 2012; Polagye et al. 2012; Porskamp et al. 2015; Roberts and Read 2015; Tollit and Redden 2013).

Three three-dimensional (3D) localization studies have been conducted to date. The first involved a vertical array of eight large-aperture hydrophones combined with a small quad array. This system was deployed from a drifting ship to localize echolocating marine mammals, and provided a detection range of 200 m (Macaulay et al. 2017). The second study involved a 3D distribution of seven hydrophones mounted on a tidal turbine in Ramsey Sound, Wales, and was used to detect and localize dolphins and porpoises (Malinka et al. 2018). The estimated detection range of this system was 20 to 200 m for sound sources with source levels of 178 to 208 dB re 1 µPa, respectively. However, there was an estimated 50 percent probability of detection and localization for ranges >20 m, and only an estimated 10 percent probability at 50 m. The third study involved a PAM array for the commissioning of a tidal kite in the Holyhead Deep, Wales, to detect porpoises and dolphins. It was composed of an 8-channel system containing two clusters of four hydrophones that would together localise cetacean echolocation clicks in 3D and monitor near-field movement and evasion around the kite. A second array of six single channel SoundTraps (Ocean Instruments) surrounded the kite to detect mid-field activity that may inform avoidance. Recorders for the 8-channel array included long-endurance batteries and 4 TB of removable data storage which resulted in a predicted recording duration of approximately 56d while sampling at 312 kHz.

Although conventional PAM instruments record the entire pressure time series and provide advantages over stand-alone systems for the detection, classification, and localization of echolocating marine mammals in high-flow environments, important factors to consider when pairing PAM technology with monitoring objectives are the deployment configuration and associated costs. While signal masking by flow noise, sediment noise, and mooring noise can limit the utility of moored or bottom-mounted PAM instruments, PAM instruments suspended below floats or drogues limit flow noise. Although deploying floating PAM instruments requires a large field effort upfront, data collection can occur over a protracted timeframe (days) to reduce overall costs. The development of flow noise reduction strategies could aid marine mammal monitoring with PAM instruments from bottom-mounted systems and reduce the confounding effects of noise in high-flow environments.

10.2.2.
ACTIVE ACOUSTICS – IMAGING SONARS

Active acoustics, as opposed to passive acoustics, generate a sound that is received as a return from the object of interest. For environmental monitoring at MRE sites, imaging sonars provide the advantage of high-resolution imagery in turbid waters without the need for artificial illumination (Hastie et al. 2019b). Although imaging sonars have several advantages over optical imagery, classification of targets is generally more difficult, and data processing methods to allow real-time target detection, tracking, and classification relative to current flows are currently under development. Because the environmental conditions and instrument configurations vary among monitoring projects, target-detection algorithms require "tuning" relative to current flow, and the final target classification step generally requires information from a secondary instrument, such as an optical camera, an echosounder, or an acoustic Doppler current profiler (ADCP), for validation.

There are currently more than a dozen commercially available imaging sonars that have been developed for use in high-energy marine environments (each differing in functional range, resolution, field of view, and mechanical configuration), but the typical application is for underwater vehicle navigation and situational awareness. Further, not all imaging sonars have been designed for long-term deployments without regular maintenance. Most uses do not require the sonar control software to be integrated on a multi-instrument platform with other active acoustics. Thus, many of the commercially available imaging sonars are not well suited for monitoring MRE devices, but several have been demonstrated on previous projects. This section provides an overview of the most frequently used and commercially available imaging sonars for monitoring MRE devices.

The use of imaging sonars for environmental monitoring in high-flow environments has been documented in approximately 20 journal publications and project reports, and is spread across a range of applications that may be categorized by deployment type (i.e., downward looking from a surface vessel, mounted on a subsea platform, or integrated into turbine substructure), deployment duration (i.e., from less than one day to several months), target monitoring goals (i.e., as defined by regulatory requirements, or project developer's interest in retiring perceived risks), and method of data acquisition (i.e., often continuous collection) and processing (i.e., a combination of manual review and automated approaches). Given that every monitoring project has distinct requirements, which may change over the course of the project, the most appropriate sonar for each application will also vary. The technical specifications for different sonars affect their suitability for monitoring MRE devices. The specifications that have the greatest impact on the capabilities of imaging sonars for monitoring include (1) the operating frequency, (2) the field of view or swath angles, (3) the functional range, (4) the input/output (I/O) trigger option, and (5) the software development kit (SDK). In general, the sonar functional range is determined by the operational frequency, while the field of view and resolution are functions of the number of beams. The option for an input trigger or SDK is crucial for integration on a multi-instrument platform. A summary of the technical specifications for the six most common imaging sonars used for monitoring MRE devices and examples of specific applications are provided in online supplementary Table S10.2 (online at: https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-environmental-monitoring).

Applications

Imaging sonars have been used in a variety of configurations and applications relevant to monitoring MRE devices (Hastie et al. 2019a, 2019b). Several studies have mounted imaging sonars on a pole and deployed the sonar over the side of a vessel to conduct mobile surveys (Grippo et al. 2017; Melvin and Cochrane 2015; ORPC Maine 2014; Parsons et al. 2014, 2017). Parsons et al. (2017) conducted a vessel survey using a Tritech Gemini and used the native software for data collection and processing. The sonar configuration and vertical field of view (Figure 10.3) and sample data from Parsons et al. (2014, 2017) (Figure 10.4) are provided below. While the relatively short duration of vessel surveys and the constantly changing field of view complicate background subtraction for automated data processing, vessel surveys can cover large areas and the motion of the sonar can be used for 3D reconstruction. Further, the relatively short duration of deployments simplifies sonar

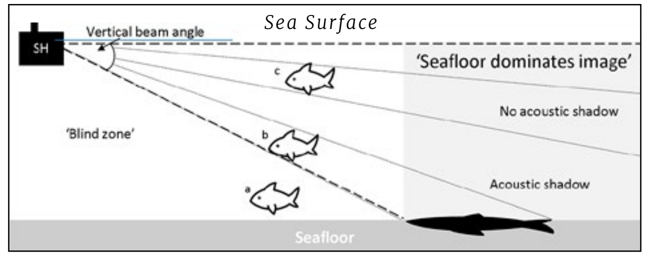


Figure 10.3. Example of a vessel-based sonar configuration. (From Parsons et al. 2017)

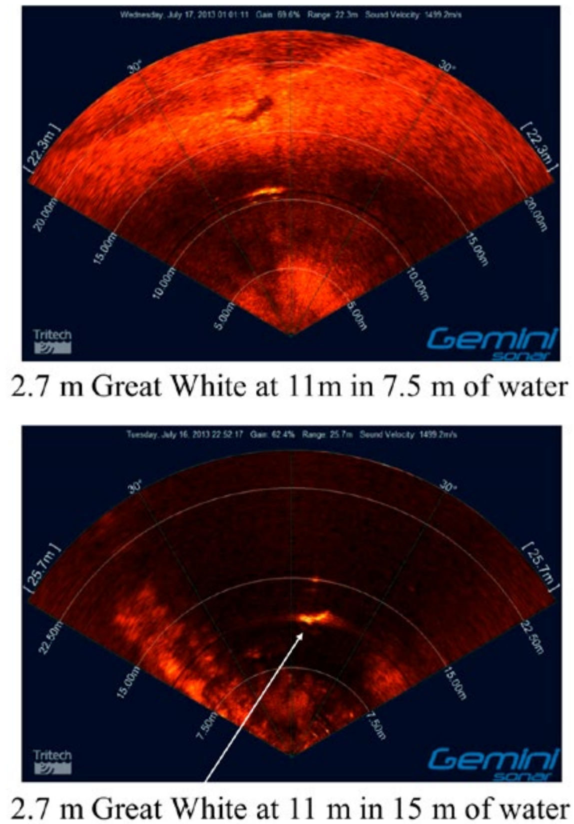


Figure 10.4. Example data from a vessel-based survey using Tritech Gemini. (From Parsons et al. 2014)

maintenance and allows for continuous data collection; eliminating the need for real-time target-detection and -tracking algorithms. When vessel surveys with imaging sonars are conducted in conjunction with fisheries echosounders, the combination of techniques allows for fish classification (echosounders) and tracking (imaging sonars) when targets can be co-registered between the data streams.

Imaging sonars have also been integrated into a variety of subsea platforms that have been deployed near MRE devices. The Flow, Water Column and Benthic Ecology (FLOWBEC)-4D platform (Section 10.4.3) integrates an Imagenex 837B Delta T imaging sonar with a suite of instruments and a large battery bank to facilitate con-

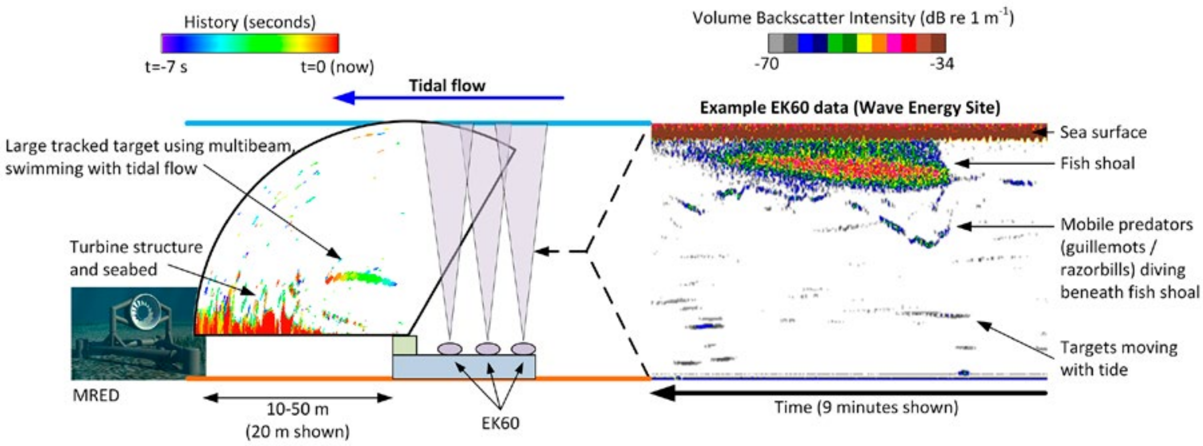


Figure 10.5. Example data from the Flow, Water Column, and Benthic Ecology (FLOWBEC)-4D deployment at the European Marine Energy Centre. (From Williamson et al. 2016a)

tinuous data collection during two-week autonomous deployments. The Imagenex 837B Delta T sonar was chosen for this platform because of previous experience with the instrument and its relatively low cost, low power consumption, and low data bandwidth. Experience with this sonar simplified integration with the platform and synchronization with a Simrad EK60 echosounder, and the low power consumption and low bandwidth requirements made this imaging sonar better suited for autonomous deployments. The sonar is mounted on the FLOWBEC-4D platform so that the field of view allows for target co-registration with the echosounder and tracking capabilities. Although the narrow beam angle for both the imaging sonar and the echosounder results in only a narrow horizontal region being monitored concurrently, deployments to date have facilitated the development of target-detection and -tracking algorithms to simplify data post-processing. Figure 10.5 provides an example of a processed data sequence with the imaging sonar and echosounder tracking biological targets on their approach to a turbine structure.

The Adaptable Monitoring Package (AMP) (Section 10.4.1) is an integrated instrumentation platform developed by the University of Washington for monitoring tidal energy devices (Cotter et al. 2017, Polagye et al. 2020), but it has also been used for monitoring at wave energy test sites, although without WECs (i.e., PacWave site in Oregon, U.S., and Wave Energy Test Site [WETS] in Hawaii, U.S.). Imaging sonars that have higher frequencies have shorter ranges, while lower frequencies extend the range of target detection. While an earlier version of the AMP included a Kongsberg M3 imaging sonar (Cotter et al. 2017), subsequent generations of the platform have included a Tritech Gemini and a Teledyne BlueView imaging sonar to take advantage of the long and short relative ranges of these instruments. Because of the high bandwidth of the instruments on the AMP, imaging sonar data are processed in real time to detect targets and trigger the optical camera lights and data-archiving process. This approach avoids data mortgages (Section 10.3.2) and simplifies any post-processing steps required.

Beyond their inclusion on integrated monitoring platforms, imaging sonars have also been deployed as stand-alone instruments. For instance, a Sound Metrics Dual-Frequency Identification Sonar (DIDSON) imaging sonar was deployed on a cabled platform approximately 12 m from the base of the tidal turbine used for the Verdant Roosevelt Island Tidal Energy project (Bevelhimer et al. 2016). The platform was equipped with a pan-and-tilt system to allow dynamic positioning of the sonar so that the field of view could be adjusted as required. The monitoring objective of the sonar was to observe fish behavior relative to the turbine and look for evidence of avoidance. Although the turbine failed soon after its deployment, the sonar collected data continuously for 19 days.

Imaging sonars have also been mounted directly on turbine structures for monitoring purposes. The SeaGen project in Strangford Lough used imaging sonars for monitoring the interactions of marine mammals with tidal energy turbines for the greatest length of time. This project used the Tritech Gemini imaging sonar for monitoring harbor porpoises (*Phocoena phocoena*) and harbor seals (*Phoca vitulina*) (Hastie 2013), and allowed Tritech International Ltd. to implement autonomous real-time target detection and tracking in their software. Two Sound Metrics DIDSON imaging sonars were mounted on the Ocean Renewable Power Company (ORPC) vessel-based turbine test platform deployed in Cobscook Bay, Maine, U.S., in 2012 to monitor fish (Viehman and Zydlewski 2014). Data were collected continuously for 22 hours and included manual post-processing. Although these sonars have the highest resolution of all commercially available imaging sonars, they have a short range and narrow field of view.

Key Considerations

The successful use of imaging sonars and their integration with multi-instrument platforms for monitoring MRE devices will depend on a variety of factors (i.e., mounting and orientation, electrical and communication connections, software for instrument control and data acquisition, and software for data processing). Here, we provide an overview of some of these key considerations.

The ideal orientation for an imaging sonar depends on the location and size of the MRE device and the monitoring objectives. The sonar swath may be oriented to look across, in front of, or behind a device, with a vertical or horizontal orientation, and either from a bottom or surface platform. Each of these configurations has its own challenges and benefits that are difficult to predict prior to testing. If the monitoring objective includes individual fish passage, then a high-resolution sonar will need to be deployed close to (or mounted on) the MRE device. If the monitoring objective is to cover the full area of an MRE device, then the deployment of one (or more) sonars with suitable range and resolution may need to be deployed on a cabled or autonomous subsea platform.

Custom software for controlling the imaging sonar and acquiring data are provided by instrument manufacturers. Customization beyond the native software capabilities is required for integration of multiple instruments into monitoring platforms, and when data are processed in real time or acquired on a duty cycle. For these reasons, sonars with manufacturer-supported SDKs are more suitable for platform integration. For instance, instrument control and data acquisition software for the AMP was developed using National Instruments LabView for both the Teledyne BlueView and Tritech Gemini imaging sonars.

Lessons Learned

Many of the key considerations for the successful use of imaging sonars and their integration with multi-instrument platforms come from previous failures that often remain undocumented by the teams who have deployed them. The most common challenges stem from the durability of the imaging sonar for lengthy deployments, or from the software for data collection and processing.

Long-term deployments of instruments in the marine environment will result in biofouling that can inhibit data collection (see Chapter 6, Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices). Although biofouling of an imaging sonar's transducer does not always degrade the imagery, it can damage sensitive components over time. While instituting a regular maintenance schedule that prevents the biofouling of sensitive components from becoming established is the best solution, it may not always be possible. Alternatives for sensitive components include using biofouling wipers (e.g., ZibraTech Inc.) for optical view ports, ultraviolet lights, antifouling paint, or highly concentrated zinc oxide paste (exception: stainless-steel surfaces). For less sensitive components, copper or vinyl tape may be used to coat surfaces to inhibit growth or easily remove biofouling.

The integration of imaging sonars on multi-instrument platforms can reveal interference with other active acoustic sources and electrical noise. For instance, thin radial lines appeared on the BlueView imaging sonar when strobe lights for an optical camera on the AMP were activated (Figure 10.6). This kind of interference is typically due to direct current (DC) power converters that operate at frequencies similar to the imaging sonar and produce noise in the sonar imagery. This can be remedied by isolating and filtering the power supplied to the imag-

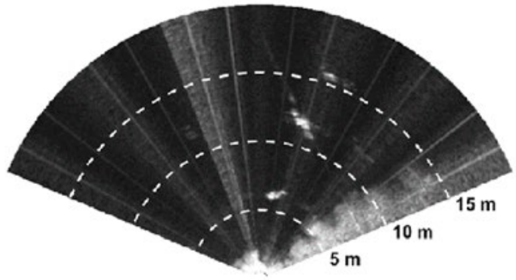


Figure 10.6. Example of electrical interference in data from a BlueView imaging sonar on the Adaptable Monitoring Package (AMP). Thin radial lines are observed when strobe lights for optical cameras are active. (From Joslin 2019)

ing sonar. To avoid "cross-talk" between active acoustic instruments, synchronization of instrument controls is necessary to interweave pings, and doing so typically requires the imaging sonar to have an input trigger option that can be synched with a central controller.

The presence of non-biological targets (e.g., debris) and environmental artifacts (e.g., turbulent vortices, entrained air in the water column) that typify MRE sites presents challenges for environmental monitoring, because these conditions can mask actual targets of interest and impede automatic target-detection algorithms. Similarly, moving targets in the sonar field of view (e.g., turbine blades, water surface) or a sonar mounted on a moving platform can result in large changing acoustic artifacts in the sonar image (Urban et al. 2017). For these reasons, integration of imaging sonars mounted on subsea platforms, and deployed to the side of MRE devices, are most likely to yield the highest quality sonar imagery.

Another consideration for use of imaging sonars for monitoring is the response of marine animals to the noise produced by the sonar. While the operating frequencies of most imaging sonars are well above the hearing levels of marine mammals, they can produce sound at lower frequencies, and it is possible that marine animal behavior may be affected (Cotter et al. 2019; Hastie 2013). Although the sound levels are not high enough to be of concern, additional research is needed to fully characterize behavioral changes that are detected by imaging sonars (and echosounders).

10.2.3. ACTIVE ACOUSTICS – ECHOSOUNDERS

High-fidelity echosounders are a standard tool in fisheries science and are routinely used to quantify fish abundance and distribution (Simmonds and MacLennan 2007). They are also valuable for monitoring the interactions of fish with MRE devices and have been used in a variety of configurations, including mobile hydroacoustic surveys (McGarry and Zydlewski 2019; Melvin and Cochrane 2014, 2015) and stationary deployments both at the sea surface (Viehman et al. 2015) and on the seabed (Viehman and Zydlewski 2017; Viehman et al. 2017; Williamson et al. 2016a).

The suite of scientific echosounders that are commercially available can be categorized by (1) those that have been used and found to be effective by the scientific community, (2) those that can be calibrated, and (3) those that have digital output; these echosounders constitute instruments that have the desired features for quantitative monitoring (Demer et al. 2017; Horne 2019). These characteristics combined with packaging flexibility, transmission pulse types, and processing software options, all vetted by the international community, make the current generation of commercial scientific echosounders the instruments of choice for monitoring fish at MRE sites (Horne 2019). Some manufacturers also offer a line of scientific echosounders that have common architecture and design features, and include a series of instruments that can actively transmit in narrowband, single-frequency, continuous wave or wide-bandwidth, frequency-modulated mode. When equipped with split-beam transducers, individual targets can be tracked, and their scattering strength compensated for based on their location in the beam. These echosounders can be used in traditional vessel deployments for mobile surveys, with transducers mounted on the hull of a ship, on a pole, or in a towbody, deployed autonomously on moorings and subsea platforms, integrated into autonomous or cabled subsea monitoring packages, or used on remotely operated underwater vehicles (ROVs) and autonomous underwater vehicles with an external power supply.

Challenges and Mitigation Techniques

The primary challenge for using scientific echosounders to monitor fish interactions with MRE devices in high-flow environments is acoustic signal scattering from air entrained in the water column — a physical feature common to MRE sites. Because sound energy emitted from a transducer will be reflected when the acoustic impedance (product of sound speed and density) differs from the surrounding water, scattering from entrained air affects the ability to detect targets of interest and subsequently discriminate between the targets that are biological and those that are non-biological. In addition, when volume scattering from physical sources such as bubbles is sufficiently high, the presence of biological and other non-biological targets of interest can be masked (Figure 10.7).

Generally, the probability of detecting a target can be maximized by a combination of (1) increasing the source level (i.e., power of the signal emitted from the transducer), (2) reducing the range to targets, (3) matching the transmit frequency to the intended target

(Simmonds and MacLennan 2005), (4) increasing the signal-to-noise ratio (e.g., using matched filter and pulse compression techniques for broadband echosounders [Ehrenberg and Torkelson 2000; Chu and Stanton 1998] or increasing the pulse length for narrow band), and (5) processing raw data to remove noise. While these techniques can improve the detection of targets that have weak scattering properties, or targets at such great distance from the transducer that the returned echo is not sufficiently greater than the level of the background ambient noise present in the sea, other techniques are required to classify echo returns from the targets of interest (fish) and the returns from other unwanted targets in the water column (bubbles).

The challenge of the presence of bubbles in the water column fundamentally complicates the interpretation of hydroacoustic data. Hydroacoustic methods work well when the medium (seawater) is fairly uniform, but they can be severely challenged at MRE sites in the presence of the confounding or masking factor of air bubbles (Melvin and Cochrane 2015; Trevorrow 2003; Vagle and Farmer 1992). The ability to discriminate between targets depends on a combination of factors. The most important are the scattering intensity and the frequency response. Bubbles, turbulent microstructure (if present), suspended sediments, zooplankton, and fish have scattering spectra that can be modeled and used to distinguish between them. However, it can be difficult to distinguish bubbles and fish, based on the frequency content alone, because they have similar spectra. If the bubble field is sufficiently large and the backscatter sufficiently strong, the backscatter from biological targets within the bubble field will be indistinguishable from the bubble backscatter.

Work has been ongoing to develop methodologies for reducing the ambiguity in the classification of acoustic signal scatterers, whether among species or size classes (De Robertis et al. 2010; Horne 2000; Korneliussen 2018), or distinguishing biological sound scatterers (fish, zooplankton) from physical sources of scattering (entrained air, microstructure) (Lavery et al. 2007, 2010; Ross and Lueck 2003; Warren and Wiebe 2008). The echo amplitude of energy backscattered from biological and physical sources is a complex, frequency-dependent function of the material properties (e.g., gas [bubbles] or gas-inclusions [swim bladders], fluid-like, or hard parts [bony skeleton or shell]), shape, and orientation; a complete list is available in Table 4.1 of Korneliussen (2018). Exploiting the frequency-dependent response of scatterers has the potential to reduce ambiguities in the interpretation of scattering data. To that end, instrumentation and techniques have been under development for collecting and interpreting backscattering data across a wide band of frequencies, whether the acoustic signal consists of a single continuous band (i.e., broadband), multiple broadband signals, multiple narrow bandwidth signals, or a combination of broadband and narrowband signals (Bassett et al. 2018; Jech et al. 2017; Stanton et al. 2012).

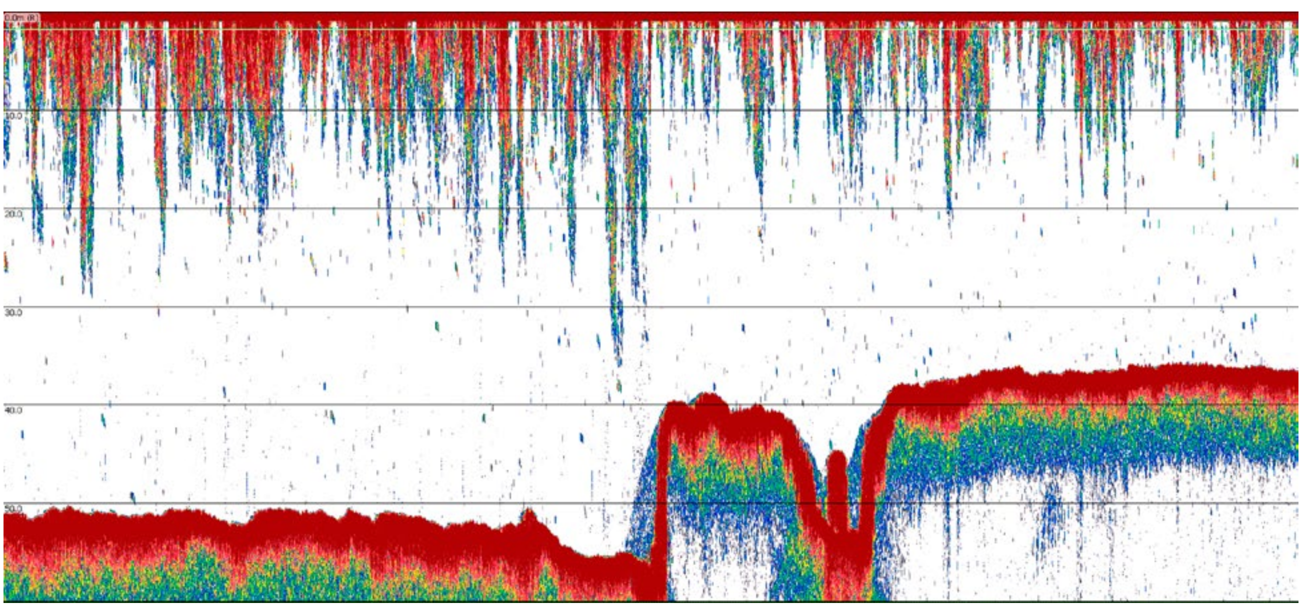


Figure 10.7. Echogram from a single transect during a mobile hydroacoustic survey in Minas Passage, Nova Scotia, Canada, showing the extent and variability of air entrainment during peak flow conditions. (Image courtesy of FORCE)

However, acoustically distinguishing swim-bladdered fish from air bubbles is an ongoing area of research because of the similarity in echo amplitudes caused by the presence of gas in both (Melvin and Cochrane 2015). With continued development of commercially available software packages (e.g., Echoview, ESP3, LSSS, Macheto, SonarX), a variety of filtering techniques are available for removing unwanted targets. A diversity of techniques have been developed to remove noise (De Robertis and Higginbottom 2007; Korneliussen 2000) and isolate target groups (De Robertis et al. 2010; Fernandes 2009; Kloser et al. 2002; Sato et al. 2015). To address the analytical challenges that arise when the background acoustic characteristics are extremely variable, multifrequency methodologies capable of target detection within some of the challenging conditions at MRE sites have been developed. They include the application of a bitmap to isolate targets of interest from backscatter data and automating the use of multifrequency acoustic data to delineate turbulent regions and then extract biological targets from within those regions (Fraser et al. 2017a; Williamson et al. 2017).

Applications

Although scientific echosounders have been mounted on vessels and used for mobile hydroacoustic surveys around MRE sites (McGarry and Zydlewski 2019; Melvin and Cochrane 2014, 2015; Shen et al. 2016), these surveys are subject to a suite of inherent challenges associated with strong currents and turbulent water that affect their efficacy (e.g., vessel control and positioning, ship noise, intermittent signal loss, and the influence of surface conditions on the extent of entrained air in the water column) (Melvin and Cochrane 2015). Nonetheless, this approach is valuable for generating metrics of fish density from the acoustic backscatter of fish in the water column and understanding fish distribution near MRE devices (Staines et al. 2019). An alternative configuration for monitoring MRE devices is stationary deployment of echosounders—both on the surface (Viehman et al. 2015), and on the seabed (Fraser et al. 2018; Viehman et al. 2017; Viehman & Zydlewski 2017; Williamson et al. 2016b). The advantage of a stationary deployment is the potential for persistent monitoring throughout the duration of the deployment. This approach is useful for generating long-term, high-resolution sampling for understanding biological processes at MRE sites where large changes may occur over multiple, wide-ranging time scales (Viehman & Zydlewski 2017). However, observations from stationary deployments are spatially limited as a set of point measurements, and understanding how to set interpolation distances between replicated stationary instruments (e.g., representative range) is important for collecting meaningful spatiotemporal data across equivalent spatial and temporal scales (Horne and Jacques 2018).

A downward-looking single-beam Simrad ES60 echosounder (operating at 38 and 200 kHz simultaneously) was deployed from the side of a moored vessel and used to characterize patterns of fish presence and distribution at the ORPC tidal energy site in Cobscook Bay, Maine, U.S. (Shen et al. 2016; Staines et al. 2019; Viehman et al. 2015). The density of fish was found to vary seasonally; the greatest densities were observed in the spring and late fall (consistent with migratory periods), and the greatest densities were consistently detected near the sea floor (Viehman et al. 2015). These stationary data were combined with mobile survey data collected at the ORPC site using a Simrad EK60 split-beam echosounder to understand fish behavior around MRE devices and generate an encounter probability model (Shen et al. 2016). The study suggested that fish can avoid tidal turbines from 140 m away, and the encounter probability varied depending on month, diel condition, and tidal stage (Shen et al. 2016).

Viehman and Zydlewski (2017) examined data collected by a bottom-mounted, horizontally oriented Simard EK60 split-beam echosounder deployed near a tidal energy turbine (TidGen® Power System) at the ORPC site in Cobscook Bay. Two years of continuously collected data were used to characterize patterns in fish presence at the tidal energy site, and revealed that the abundance of fish near the device varied greatly with tidal and diel cycles in a seasonally changing relationship that was likely linked to the seasonally changing fish community in the region. Contrary to observations at other tidal energy sites, the number of fish detected was not associated with current speed and did not decline with increasing current speed (Viehman and Zydlewski 2017).

An upward-facing ASL Environmental Sciences Acoustic Zooplankton and Fish Profiler (AZFP) with a single-beam transducer was mounted on a subsea platform (FAST-1) and deployed at the Fundy Ocean Research Center for Energy (FORCE) test site in Nova Scotia, Canada, to characterize the density and distribution of fish prior to the deployment of the Cape Sharp Tidal

Venture (OpenHydro) open-center tidal turbine in 2016 (Viehman et al. 2017). This study found that fish density was higher and less variable in winter than in summer (likely due to the presence of migratory vs. overwintering fish), and that fish vertical distribution varied with the sample period, diel stage, and tidal stage (Viehman et al. 2017).

Multifrequency data (38, 120, and 200 kHz) were collected using an upward-facing Simrad EK60 scientific echosounder mounted on the FLOWBEC platform (see Section 10.4.3) and deployed at the European Marine Energy Centre (EMEC) on multiple occasions (Williamson et al. 2016a, 2019; Fraser et al. 2018). Hydroacoustic data were processed using an adaptive processing method (Fraser et al. 2017a) and demonstrated that fish were attracted to a bottom-mounted tidal turbine and its support structure (Williamson et al. 2019). The study also revealed that aggregation and vertical distribution of fish in the modified flow conditions of the turbine was dependent on tidal and diel phase, and provided evidence of some avoidance of turbine depth range during peak flow (Fraser et al. 2018).

10.2.4. VIDEO CAMERAS

Video cameras (VCs) can be used to monitor marine animals' distribution and behavior, and determine the species and size of individuals (Box 10.1). Use of VCs is often needed to assess marine mammal, fish, and diving bird observations as they approach turbine systems; record blade interactions; determine species affected; or to assess the operation of the turbine system. Equipment configurations include single, multiple, or paired stereo cameras; paired lasers for measurement reference; artificial lighting; and autonomous, stationary or traversing data collection platforms. Remotely controlled positioners (pan and tilt) can be incorporated to aid in the collection of data.

VC systems are an important tool for collecting data at all MRE locations. VCs have the ability to document animal behavior and animal interactions with various man-made structures and their natural environment (Booth and Beretta 2002; Mueller et al. 2006). Providing high-resolution imagery that is easily recognizable to a human viewer is advantageous for interpreting and processing data. Even with an easily recognized format, data quality can be a challenge for the measurement objectives (e.g., counting and/or speciating animals, behavior classification, interactions with underwater objects). Numerous parameters (e.g., lighting, frame rate, instrument resolution, field of view) must be considered when using VC to observe animals underwater. The objectives of the VC application must be planned to assure that the observation or measurement goal is achieved. VCs are often used to validate objects and marine life when used in conjunction with active acoustics. Examples include validation of fish species during acoustic surveys using an ROV (Campanella and Taylor 2016).

Numerous vendors specialize in and provide commercial off-the-shelf (COTS) VC systems for research and still imagery, the majority of which are tailored for ROV applications. A wide range of options are available from low resolution (300 to 400 lines of horizontal resolution) to ultra-high resolution (2000 lines of horizontal resolution). Recording resolution is variable and typically consists of 4K, ultra-high definition, 720, 960, and 1080 pixels with variable frame rates. The price can range from inexpensive action VCs (<$1000; Struthers et al. 2015) to very expensive 4K ultra-high definition cameras in high-pressure–rated housings (>$4000). An overview of standard types of optical cameras is provided in online supplementary Table S10.3 (online at: *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-environmental-monitoring*).

Wide-angle field-of-view cameras are best suited for mounting close to structures to capture the largest viewing region. The field of view is mostly controlled by the choice of lens for the VC, specifically the focal length (the shorter the focal length, the wider the field of view). The camera lens size is dependent on the type of survey to be conducted. A wide-angle (2 to 3 mm) lens can be used for fish detection close to the camera, and a 5 to 8 mm fixed or zoom lens is often used for imaging objects at greater distances.

Monochrome VCs (Figure 10.8) are best suited for operating under low-light conditions and accrue smaller data files than color video. In certain conditions, color cameras can be used to help distinguish species. Some systems, such as Sony® Super HAD CCD imagers, support automatically switching to monochrome under low-light conditions, have auto white-balance, or allow users to manually adjust the images.

Figure 10.8. Example of a school of broad whitefish (*Coregonus nasus*) captured with a monochrome video camera. (Photo courtesy of Robert Mueller)

Many VCs are rated for minimum scene illumination, also known as the lux value; the lower the specified lux value, the less light is required to obtain optimal images. Dynamic range is a measure of the difference between the brightest and darkest values an instrument can resolve. High dynamic range is useful for low-light imaging. If a high dynamic range is present, then a higher quality large sensor digital single-lens reflex camera with 10 or more F-stops or raw images produced from the camera in video mode will produce better quality images.

Most commercial-grade cameras are depth rated and are in a waterproof housing made of titanium, Delrin, polyvinyl chloride, acrylic, or aluminum. An alternative to purchasing a camera already in a waterproof housing is to purchase a COTS camera and place it in a housing. The benefits of doing so include the ability to select from a variety of cameras, which often have variable recording rates, variable lens configurations and imagers, and variable control over image acquisition. One drawback is the additional connection cables needed to interface with the wet bulkhead connectors on the outside of the housing. Camera housings are generally pressure-tested to between 60 and 100 m, more available, and less expensive, while marine-grade underwater cameras placed in titanium or stainless-steel housings are more costly and rated to much deeper depths.

Applications

Systems to Measure Object Size and Swimming Speed

Fish size and swimming speed can be determined using stereo-VC systems. This method incorporates two cameras positioned side by side at a set distance. Images are synchronized via computer by using a LED light placed at a set distance and activated on/off and seen on both images (Harvey et al. 2002; Langlois et al. 2012; Lines et al. 2001; Trudel and Boisclair 1996), or by using a narrow-beamed strobe light (Williams et al. 2014). When objects move through both cameras' fields of view, locations in 3D space as well as object sizes can be determined. Camera spacing varies for each application. The stereo camera calibrations may provide in situ challenges in high-energy locations. Images can also be synchronized by hardware triggering of each camera using specialized software. Performing calibrations in a laboratory setting is easier, but the transfer of the cameras and mounting apparatus to the field site can be challenging because the cameras must remain in the same positions they were in during calibration. In the field, real-time tilt instruments can be attached to the cameras to assure they stay at the predetermined location. A recent application had 0.8 m spacing with a maximum range of a 5 to 6 m wide horizontal field of view (Hammar et al. 2013). In another study, camera spacing was 1.4 m, which was used to image objects at 2 to 10 m from the cameras depending on visibility, and it was more accurate when objects were less than 50° from the central axis of the cameras (Harvey and Shortis 1995, 1998). These systems can be effective at determining interactions with turbine blades, species composition, swimming speeds of fish, fish size, and distance of fish to blade interactions, and at estimating the speeds of currents (Harvey et al. 2002).

As an alternative to the use of paired cameras, paired parallel-mounted lasers can be incorporated with a single camera to determine object sizes. These systems are commonly incorporated for use on ROVs. Lasers are mounted on specialized brackets, which hold them parallel to each other so that the laser dot separation is consistent with the variable range to objects. The lasers shine onto animals, substrate, or other structures and allow for the scaling of these objects during later analysis. After VC images are taken in conjunction with the lasers, the size of the animals and other objects can be determined using imaging software. This system is somewhat limiting in that measurements can only be made when lasers appear on the object in contrast to stereo imaging where more objects can be measured per image.

Systems for Long-Term Recording and Storage

For long-term continuous recording, cabled systems of various types with a dedicated recording location on the shore or on a stationary platform have several advantages (online supplementary Table S10.4; online at: *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-environmental-monitoring*).

BOX 10.1

EXAMPLES OF MARINE RENEWABLE ENERGY (MRE) MONITORING USING SUBSEA VIDEO CAMERAS

Nova Innovation, Bluemull Sound, Shetland, Scotland (United Kingdom [UK]) – At the 30 kW demonstrator turbine installed by Nova Innovation in Bluemull Sound, subsea video is used to monitor for potential collisions and nearfield interactions of marine mammals with turbines (Smith and Simpson 2018). The video monitoring uses three cameras per turbine, attached to the nacelle (two directed toward the turbine rotor and one directed toward the seabed). The turbine is not illuminated, so video monitoring is only effective during daylight hours. The camera is connected to a standard closed-circuit television (CCTV) system with a motion trigger to record continuously, and triggered footage is retained for post-hoc analysis.

Sustainable Marine Energy, Grand Passage, Bay of Fundy, Nova Scotia (Canada) – At the PLAT-I tidal energy converter in Grand Passage, Nova Scotia, Canada, four MacArtney LUXUS Compact PUR subsea cameras were installed to collect underwater video to meet requirements under the Environmental Effects Monitoring Plan developed by Sustainable Marine Energy (Canada) Ltd. Each camera was positioned facing downstream, approximately centered on its associated rotor with a field of view approximately 10 percent larger than the rotor diameter. Visibility was generally good, featuring sufficient light and limited suspended particles. A total of 14 hours of video were reviewed by an experienced third-party contractor to screen for potential animal sightings. The video quality was rated as fair to good, and inanimate materials such as seaweed and other debris were noted frequently. Aside from several observations of jellyfish, only one positive identification of marine life was made (a small fish, possibly a rainbow smelt [*Osmerus mordax*]).

Ocean Renewable Power Company, Kvichak River, Iguigig, Alaska (United States [U.S.]) – In the Kvichak River, Alaska, optical cameras were used to understand fish behavior around a horizontal axis helical turbine (Matzner et al. 2017). In more than 42 hours of camera footage reviewed from the Kvichak River, there were only 20 potential contact interactions, of which three were classified as "Maybe" collisions after close visual examination (Matzner et al. 2017). On only one occasion was an actual contact confirmed, and this was an adult fish that contacted the camera, not the turbine itself.

Development of an Ocean Energy Impact Monitoring System, Scotland (UK) – In 2017, as part of the Development of an Ocean Energy Impact Monitoring System project, the statutory advisor to the Scottish Government on nature conservation, Scottish Natural Heritage, commissioned a review of subsea video monitoring data collected around operational tidal energy projects. Further information about this review, which examined footage from three operational projects, and information about other tidal projects that have used subsea video to monitor nearfield interactions of marine wildlife with turbines is provided in Chapter 3 (Collision Risk for Animals around Turbines).

Marine Renewable Energy Installation (MREI) Development Zone (Wave Hub) and Seabed Cable Installation near Cornwall (UK) – Video monitoring studies were conducted off the north coast of Cornwall (UK) between 2011 and 2015 using baited remote underwater video. The deployed system used a weighted aluminum frame, wide-angle lens, housing, and white light-emitting diode (LED) lights, and an aluminum pole, to which bait was attached, was located near the camera. The system was effective at determining the diversity, abundance, and composition of mobile epi-benthic species in highly dynamic conditions. Other advantages included its cost-effectiveness and flexibility to provide spatial and temporal coverage that can be difficult to obtain using other methods (Bicknell et al. 2019).

European Marine Energy Centre offshore tidal energy test site, Isle of Eday, Orkney Islands (UK) – A combination of optical video and acoustic Doppler current profiler (ADCP) survey techniques was used to examine the presence of Pollack (*Pollachius virens*) temporarily aggregating in shoals around the deployed device from 2009 and 2010. The combined use of video/still photography and ADCP sampling techniques proved useful in the offshore and extreme hydrodynamic environments. Study results indicated that the use of such systems provided preliminary ecological quantitative information, which can help regulatory bodies and developers begin to define ecological interactions with marine tidal energy developments (Broadhurst et al. 2014).

U.S. Navy's Wave Energy Test Site (WETS) in Kaneohe, Hawaii, Fred. Olsen Ltd and Sequim Bay, WA (U.S.) – Stereo-optical cameras with artificial illumination and biofouling mitigation have been a critical component of the Adaptable Monitoring Package (AMP). This optical system, which was developed by the Applied Physics Laboratory at the University of Washington uses two machine vision cameras (Allied Vision Technologies, Manta G-507B) that have 5 mm lenses (Kowa LM5JCM) and high-power LED arrays (Cree CXB-3950 and custom 710 nm red LED arrays) for illumination. Each of these components is packaged in custom waterproof housings and configured on the AMP with camera-camera and camera-light separations of approximately 0.4 m, which minimize optical backscatter (Joslin et al. 2014). Biofouling mitigation measures include a copper ring around the planar view ports of the cameras and lights and mechanical brush wipers (Zebra-Tech Ltd.) (Joslin and Polagye 2015). This system has provided high-resolution imagery of targets of interest throughout deployments of up to six months duration in Sequim Bay, Washington, and at the WETS in Hawaii. From fall 2018 to spring 2019 during a deployment at WETS on board the Fred Olsen Lifesaver wave energy converter, images were used to identify species of reef fish that congregated under the surface buoy. Co-registration of targets identified in both the sonar and optical imagery allows for a higher level of target classification and simplifies data review.

These include the ability to view live VC feeds, contain a dedicated power supply, use more robust recording gear, have easy access to recording equipment, and have remote access via the Internet. Some drawbacks include the added cost for cable, and possible cable damage caused by marine life or ocean conditions. Adding a strength member (normally Kevlar) is often used to increase breaking strength and durability.

Digital video recorders (DVRs) offer many advantages, including greater recording resolution, extended recording ability, long-term storage, video overlays, multi-camera inputs, Internet streaming ability, and greater image reproduction capabilities. The DVR uses software to control external cameras and is very flexible in that cameras can be programmed to record at certain intervals or record only events in which motion is detected (i.e., object detection). In addition, triggered systems (although not a common feature of most COTS systems) can be incorporated such that other instruments (e.g., echosounders) can be used to trigger the camera recording. This can help decrease overall data accumulation for long-term deployments. Accessories to VC recording include video overlays, whether embedded with the recording interface or as an added component. The video overlays can include date/time and recording timers, graphical overlays (altimeter, compass, depth), shapes and other superficial objects for custom themes, and various other features.

Challenges

Data Storage

VCs produce large data files compared to other instrument packages, so they require large amounts of data storage space and create significant challenges when transmitting and analyzing the information. Several strategies can be used to decrease the amount of data for storage, transmission, and analysis. When packaged together with active acoustic instruments, algorithms can be developed to identify objects that may be of interest in the water, such as animals, and a trigger can be sent to the VC signaling the need for it to engage (Underwood et al. 2014). In addition, output from the VC and other instruments can be captured on a ring buffer that is overwritten on a short cycle (usually less than one minute) that is triggered to offload and store data only when the active acoustic trigger indicates (Williamson et al. 2016a). Finally, algorithms can be developed and applied to process video data in order to recognize objects of interest (that might resemble the animals or other items seen in the water) and save only those frames that contain the objects, for later analysis. Assuring that time clocks are accurately synchronized across all instruments and storage devices, as well as enabling consistent metadata across instrument outputs, are essential to assure that the data can be interpreted correctly.

Lighting

Nighttime viewing may be required because observations limited to daylight viewing when ambient light levels are sufficient may not yield representative results of animal interactions (Hammar et al. 2013). If nighttime recording is required, cameras may be augmented with various types of white, red/green, or infrared (IR) filtered lights. The most common type of lights used for underwater viewing are LEDs, whose benefits include a broad light spectrum, long life, and cooler operation. Researchers should verify that the light source will not deter or attract animals, which could interfere with the video observations (most impacts would occur during nocturnal periods). IR lights operating at wavelengths longer than 800 nm can be useful for identifying fish because many species are unaffected by IR, which falls beyond their spectral response range (Lythgoe 1988). The visual pigments of freshwater fish have optimal spectral response within the range of 510 to 545 nm, but most freshwater fish have trichromatic vision, and their visual pigments have absorption peaks around 455 nm (blue), 530 nm (green), and 625 nm (red); coastal marine fish are in the 490 to 510 nm range; whereas deep-sea marine fish are more blue-shifted (470 to 490 nm) (Jobling 1995; Lythgoe 1988). However, IR light has high attenuation in water and is only effective at ranges up to 1.5 m for 700 nm (Kyhn et al. 2012; Matsuoka et al. 1997).

Power Supplies

When setting up a video survey, it is important to know the power consumption of each component, which can be estimated by constructing a power consumption list (online supplementary Table S10.5; online at: *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-environmental-monitoring*). Access to reliable alternating current (AC) power is not always available in the field. For remote situations, 12 or 24 V battery or portable generator power may be the only option, although the U.S. Department of Energy (DOE) Powering the Blue Economy initiative is working to address this challenge by supplying power at sea from MRE devices (LiVecchi et al. 2019). A key factor in battery selection is the consumption rated in ampere-hours for a given component. The ampere-hour rating is the total amount of energy that a battery can deliver for 20 hours at 26°C before the battery drops to 10.5 V before becoming fully discharged. Deep-cycle marine batteries are the preferred type because they are designed to withstand frequent cycles of deep discharge and recharge. Light sources usually require a great deal of power. The light duration can be extended by decreasing the intensity (wattage) of the lights, adding battery ampere-hours (e.g., keeping a larger battery at a higher temperature), changing the battery type (using lithium batteries instead of lead or nickel-cadmium types), or adding a generator or solar-powered battery charger. The power requirements for underwater VCs are usually 12 to 24 VDC (volts direct current) at approximately 110 mA for non-lighted models. In addition, if real-time processing is embedded in the VC the power requirement can be significantly increased (Qi et al. 2018).

Conclusion

Optical cameras, both video and still, have many uses for documenting animal interactions with tidal power generation devices. The best results will be obtained when camera capabilities are well matched to the conditions, the subject of observation, and the data needs. There are many commercial options for hardening systems against ocean conditions and depths, as well as for transmitting or retrieving images and video. Other types of monitoring technology, such as ADCP and acoustic imaging, can be incorporated with optical imaging to provide additional context for fish behavior and interactions. Surface observations made from shore, vessel, or aircraft (including drones) can provide information about and context for what animals may be in the area and some common behaviors in the vicinity of MRE devices, particularly for marine mammals and fish. These observations may help to distinguish and identify particular species and allow for comparisons with underwater video.

10.3. CHALLENGES OF MONITORING AROUND MRE DEVICES

Environmental monitoring of MRE devices is made inherently challenging by the harsh conditions under which the monitoring must take place, the need to manage power for multiple instruments to assure continued monitoring, and the volume of data generated by the suite of instruments deployed. This section provides an overview of the various challenges of environmental monitoring around MRE devices.

10.3.1. SURVIVABILITY/DURABILITY AND ROBUST OPERATION

Conditions at locations suitable for the development of marine energy are inherently challenging for engineering durable and robust systems. Namely, forces from high-energy waves and currents compound the customary challenges of working in marine environments including pressure, corrosion, and biofouling. In addition, deployment, maintenance, and recovery operations may be limited because of infrequent calm weather windows, short periods at slack tide, short daylight windows in high latitudes, and safety concerns for personnel associated with swift current and large waves.

Hydrodynamic Forcing

Fluid-structure interactions in flowing water lead to hydrodynamic forces of lift (perpendicular to the direction of flow) and drag (parallel to the direction of flow) acting on submerged bodies. Currents tend to be stronger closer to the surface and weakest at the seabed. Monitoring systems operating in high-flow environments must be secured to prevent sliding, flipping, floating away, or structural failure caused by drag and lift. Three main methods are employed, typically in tandem, to limit these outcomes: reducing the drag and lift coefficients by streamlining exposed components, reducing exposed frontal area, and increasing the weight of the monitoring system. The former two decrease the magnitude of forcing, while the latter one assists in resisting its effects (i.e., by providing friction and leverage). Conversely, monitoring systems may be affixed to more permanent or secure features like pilings, but will likely involve increased cost and complexity. In addition to lift and drag, vibrations or strumming induced by vortex shedding can lead to hardware loosening and increased structural fatigue, and can affect the quality of data derived from acoustic sensors. In all cases, proper engineering analysis and design are critical for system survivability.

Forces from waves manifest through several pathways. Below the surface, waves induce the circular flow or orbital motion of water, decreasing in magnitude with depth, and resulting in lift and drag forces on structures, as described above. The hydrostatic force of a wave is proportional to its height. Designers of monitoring systems built to withstand wave forcing may take several approaches: deploying the system deep enough to avoid orbital motion, designing structures to follow waves instead of absorbing energy from them, avoiding the surf zone, and/or using durable materials and structural designs.

Corrosion and Biofouling

Two environmental effects limit the durability and survivability of submerged structures and instrumentation: corrosion and fouling. Corrosion is the degradation or removal of material as a result of chemical interactions between the environment and structures, and it is typically prevalent on metals. Corrosion occurs naturally in the environment and accelerates in response to the creation of galvanic circuits between coupled dissimilar metals in the presence of an electrolyte, where more "anodic" materials are consumed (The Electrochemical Society 2011). Corrosion rates vary based on many factors and may be hard to predict. Seawater is a particularly corrosive environment because of its high conductivity. Galvanic circuits in seawater yield corrosion rates 5 to 12 times greater than if no electrolytes were present, while rates may increase two to five times in freshwater (The Electrochemical Society 2011). Solutions to corrosion issues include using less reactive or "cathodic" materials such as titanium or certain stainless-steel alloys at increased cost, coatings and anodization, or isolating dissimilar metals using nonconducting materials. Strongly anodic materials should not be used in the presence of strongly cathodic ones. Alternatively, sacrificial anodes made of zinc or other highly reactive metals can be employed to protect more cathodic materials from natural or galvanic corrosion (The Electrochemical Society 2011). Ultimately, experience shows that under certain circumstances, even parts made of titanium can corrode, particularly when exposed to low-oxygen, high-temperature conditions (Pang and Blackwood 2016).

Biological growth on submerged structures, commonly referred to as "biofouling" (see Chapter 6, Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices), may degrade instrument performance or interfere with critical components such as recovery equipment. The fouling process begins with the formation of thin biofilms (microorganisms) on exposed surfaces, followed by the colonization or recruitment of larger macro-organisms (Bixler and Bhushan 2012). Flora and fauna vary by region and depth and may be inconsistent from season to season or year to year. Biofouling can interfere with transducer elements, cover optical ports, clog bearings, and increase drag. Considerable effort over many decades has gone into preventing or mitigating biofouling, yielding solutions including engineering for specialized surface properties, chemical-based coatings or paints, ultraviolet and gamma radiation, ultrasonic vibration, electrical current, and even explosives (Bixler and Bhushan 2012). Mechanical wipers integrated on the AMP have been effective at preventing growth on critical components (Figure 10.9). Regardless of the mitigation method selected, system designers must also be careful not to adversely affect or interfere with the environment they are attempting to study.

Pressure and Sealing

Commercially available instruments and instrumentation subsystems intended for submersion are rated to specific depths and sealed to prevent structural collapse caused by pressure and water ingress. Similarly, individual enclosures may be rated by the level of environmental protection. For example, ingress protection codes and standards, published by the IEC specify ratings indicating protection from splashing, water jets, or submersion (IEC 2013). Sealed enclosures containing instrumentation or electronics introduce additional challenges, including temperature management, connectivity, and maintenance. Common practices to mitigate these including filling housings with mineral oil or other inert incompressible fluids, using wet-mate connectors, and using magnetic or reed switches. Experience to date with MRE monitoring instruments has shown connectors to be the most common point of failure. Many connectors used for offshore oil and gas development are designed to effectively seal at greater depths than is typical for MRE deployments.

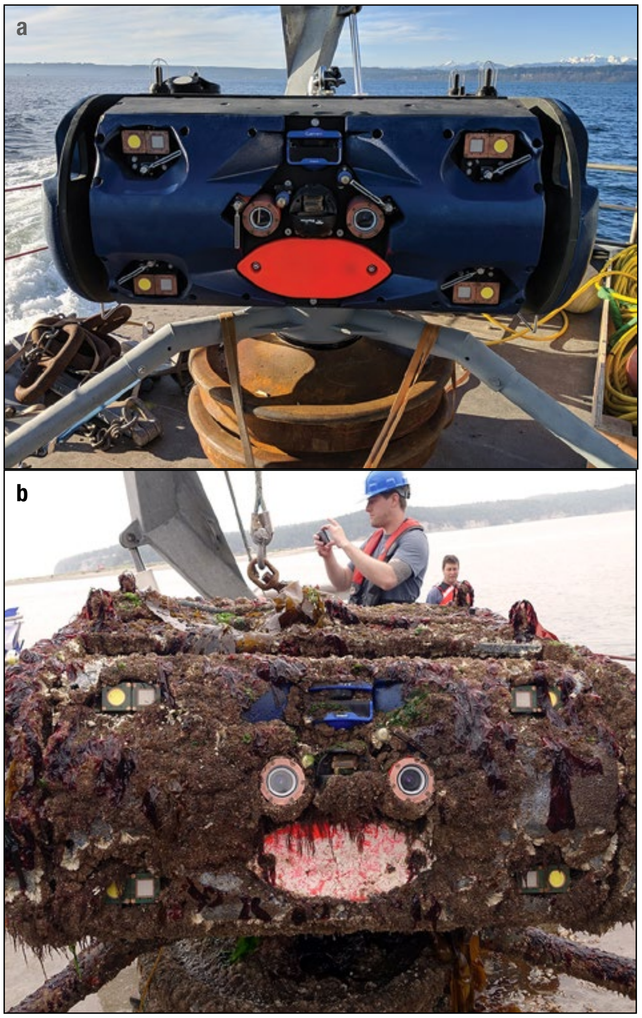


Figure 10.9. The Adaptable Monitoring Package (AMP), before (a.) and after (b.) deployment for 18 weeks in Sequim Bay, Washington, United States. (Photos courtesy of Applied Physics Laboratory, University of Washington)

Deployment, Maintenance, and Recovery

Deployment, maintenance, and recovery of monitoring systems where marine energy resources are strong is a major challenge. Indeed, at sites where the resource is the strongest or most consistent, the access to and ultimately the availability of the systems may be most limited (O'Connor et al. 2013). Scheduling of marine operations depends on vessel and crew availability, which often requires weeks or months of advanced planning. The types of vessels required to operate in high waves or strong currents are often rare and more expensive. For tidal energy sites, the high degree of predictability of the resource aids in planning operations. However, performing tasks during short slack water windows increases risk to personnel and equipment if complications arise. Low wave weather windows are harder to predict, but favorable conditions may last for many hours or days.

10.3.2. DATA MORTGAGES

Reliable detection of rare events, such as interactions between a marine mammal and a tidal turbine, requires monitoring over long periods (on the order of days to years) to satisfy licensing conditions. However, continuous acquisition of data from medium- and high-bandwidth instruments, such as optical cameras or multibeam sonars, results in unmanageable volumes of data (colloquially referred to as a "data mortgage"). For example, a single 5-megapixel camera with a 10 Hz frame rate could accrue more than 2 TB of uncompressed images in a single day. This challenge is compounded when multiple instruments are used in an integrated instrumentation package. While image compression can significantly reduce the data volume, post-processing or human review of the collected data still present a significant challenge. As a result, data mortgages can result in monitoring that is "data-rich, information-poor" (Wilding et al. 2017).

10.3.3. POWER AVAILABILITY AND MANAGEMENT

Providing power to instrumentation is a key challenge to achieving sustained, high-fidelity environmental monitoring at MRE sites. Instruments may be deployed in deep water, far from shore, or in hard to access locations. Power delivery can be accomplished through one or a combination of the following methods: running a power cable to the deployment location, including individual instrument batteries or a centralized battery bank, and coupling to an in situ power generation source.

Cabled Systems

Cabled operation offers the highest level of power and typically enables the ability to stream or easily access data from shore. Cabled observatories currently provide an unprecedented ability to observe the oceans (Smith et al. 2018). The characteristics of the cable are determined by the requirements of the instruments. Depending on these requirements, the cable may conduct AC or DC electricity. Most of the instruments and systems described in this chapter accept external power over a range of 5 to 48 VDC. A higher export voltage than listed for the instruments must be run to account for voltage drop across the cable itself and during startup (inrush current) or high sampling events. Therefore, one or several DC/DC converters are required to step the voltage down to instrument level. If AC power is used, a rectifier or AC/DC converter will be necessary. Additional converters add to system complexity and generate heat. The cable itself and operations to run and secure it represent major project expenses. The cable is a single point of failure for the systems that rely solely on it for power. Ultimately, the major trade-off for employing a cable is access to high-power, high-fidelity, and constant communications at high cost.

Battery-powered Systems

Many of the instruments mentioned in this chapter are designed to be pre-configured and run autonomously using their own internal batteries. Consequently, they have been designed to use small amounts of power and/or have adjustable sampling rates and duty cycles. For many of them, much of their volume is occupied by batteries (e.g., ADCPs). Systems running on batteries can be designed to be deployed anywhere. The major trade-off for relying on internal batteries is broad applicability and reliability countered by limited duration, a lack of operational feedback, and no native synchronization of measurements. Integrated monitoring systems can also employ larger, centralized battery banks to power instruments. This method may extend the duration and enable centralized control of duty cycles. However, similar to cabled systems, DC/DC power converters are necessary, and they add complexity and heat generation to such systems. Other challenges of using batteries are their increased volume and weight, the safety and transportability for certain chemistries (e.g., lithium-ion), and the high cost to seal large volumes.

Marine Energy-powered Systems

Ocean observation systems were identified as a key near-term market for the marine energy industry in the U.S. DOE Powering the Blue Economy report (LiVecchi et al. 2019). This option has the potential to provide power between a cable and a battery bank anywhere there is sufficient resource availability. This concept has been demonstrated for a WEC at the WETS in Kaneohe Bay, Hawaii, U.S. The WEC, when coupled to a battery bank and backup solar panel allowed the AMP to reach 84 percent uptime over a 108-day deployment period (Joslin et al. 2019). Other monitoring systems use marine energy for motion or to perform profiling, thereby offsetting electrical demands (Manley and Willcox 2010; Pinkel et al. 2011). Despite promising potential, challenges remain for this method. First, the maturity and technical readiness of most marine energy systems is still low, and their reliability has not been sufficiently demonstrated. Second, the presence of the converter may interfere with the functioning of instruments or diminish the quality of measurements (e.g., sound from a WEC may dominate hydrophone recordings). Third, other, more mature renewable technologies like solar or wind power may perform similarly or better if a surface presence is possible. Finally, the costs of marine energy systems are high or largely unknown, likely rivaling those of cable installations (depending on the distance from shore). National laboratories, academic universities, and industry are conducting further research and commercial ventures to meet these challenges.

10.4. INTEGRATED MONITORING PLATFORMS CURRENTLY USED TO MONITOR MRE DEVICES

A variety of integrated monitoring platforms have been developed and deployed for monitoring MRE devices. They include a series of autonomous and cabled platforms that have an array of monitoring instruments integrated for power requirements and duty cycles. This section provides an overview of the various integrated monitoring platforms that have been developed and deployed.

10.4.1. ADAPTABLE MONITORING PACKAGE

The AMP (Figure 10.10) is an instrumentation platform developed to provide continuous underwater monitoring for multi-month deployments around marine energy devices using autonomous data processing and real-time target detection and tracking (Cotter et al. 2017, Polagye et al. 2020). Deployments to date have included both cabled and autonomous systems, on both bottom landers and surface buoys. More than two years of sea testing have demonstrated the systems' monitoring capabilities in wave climates, high current channels, and onboard vessels.

The backbone of the AMP hardware is a power and communications system that allows any cabled instrument to be integrated into the platform. To date, these instruments have included stereo-optical cameras with lights and wipers, acoustical cameras, multibeam sonars, echosounders, hydrophones, ADCPs, fish tag receivers, actuators, and water-clarity instruments. The combina-

Figure 10.10. The Adaptable Monitoring Package (AMP). An integrated subsea instrument package developed by the University of Washington that is used to monitor marine renewable energy devices. (Image courtesy of Applied Physics Laboratory, University of Washington)

tions of these instruments can enable a wide range of monitoring and tracking capabilities depending on the objectives. The data acquisition, processing, and management for this system use custom software that integrates the operation and control of each instrument. Real-time algorithms have been implemented to perform target detection, tracking, and classification of data from the imaging sonars and hydrophones, which are used to trigger artificial illumination for the optical cameras and data acquisition from all sensors. This real-time continuous data processing allows the system to capture rare events without accruing a large data mortgage and minimizes bias on marine life related to artificial illumination.

To date, instrument settings and target-detection thresholds have been tuned during the first phase of the deployment to fit the site and monitoring goals. The primary targets of interest that have been detected have been marine mammals (e.g., seals) and diving seabirds in the Puget Sound, Washington, U.S., and large individual fish, squid, and schools of small fish elsewhere. These target-detection and -tracking capabilities have been assessed with the help of cooperative targets in the form of divers, surface vessels and drifters towing targets, and underwater vehicles.

10.4.2. FUNDY ADVANCED SENSOR TECHNOLOGY–ENVIRONMENTAL MONITORING SYSTEM

FORCE in Nova Scotia, Canada, has been pursuing an integrated environmental monitoring platform as part of the Fundy Advanced Sensor Technology (FAST) program for environmental monitoring of tidal turbines in Minas Passage, in the Bay of Fundy. This cabled subsea Environmental Monitoring System (i.e., FAST-EMS) includes (1) a Tritech Gemini 720is multibeam imaging sonar mounted on a Kongsberg pan and tilt device, (2) a NORTEK AWAC ADCP, (3) two Ocean Sonics Ltd. icListen high-frequency hydrophones, and (4) a sculpin subsea camera. The FAST-EMS platform (Figure 10.11) is intended to be deployed near gravity-based tidal turbines deployed at FORCE, but its deployment location is limited by the useful range of the Gemini 720is multibeam sonar (<120 m) and the operational capabilities of the marine assets at the target deployment site. The platform is cabled to shore to provide power and data transferability, and the associated equipment enabling the functioning of the monitoring instruments includes a termination canister and a multiplexer linking to the subsea power cable. Onshore assets at FORCE include a suite of supporting infrastructure for data transferability that has been demonstrated to provide faster upload of multibeam data than the rate at which those data could be collected (i.e., 100 Mbps up/down capabilities).

Multiple short-term trial deployments of the cabled FAST-EMS platform conducted near the FORCE tidal demonstration site to assess system performance revealed that monitoring instruments performed well under relatively benign marine conditions. However, more work with electrical connectors and data transfer with lengthier subsea cables is required to advance FAST-EMS beyond the research and development stage to an integrated monitoring platform that can be used reliably for monitoring interactions of marine animals with tidal turbines at the FORCE tidal demonstration site.

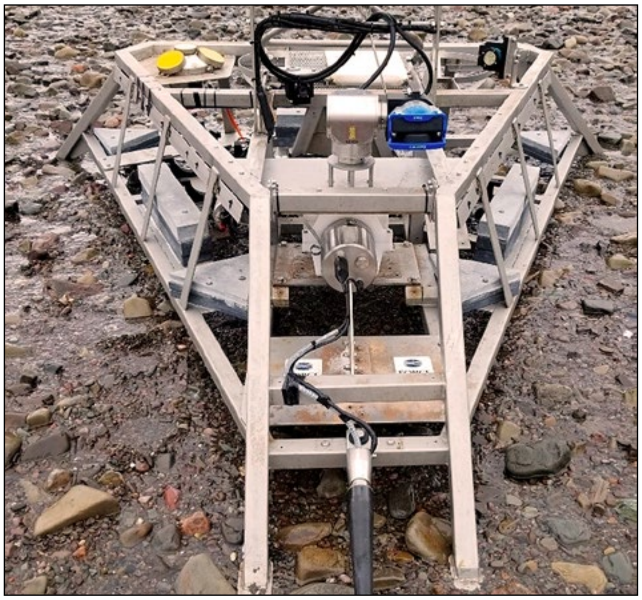


Figure 10.11. Fundy Ocean Research Centre for Energy (FORCE)'s Fundy Advanced Sensor Technology Environmental Monitoring System (FAST-EMS) integrated and cabled monitoring platform positioned on the FORCE beach. (Photo courtesy of FORCE)

10.4.3. FLOW, WATER COLUMN AND BENTHIC ECOLOGY 4D

The FLOWBEC-4D project investigated the environmental and ecological effects of installing and operating MRE devices. The FLOWBEC seabed platform (Figure 10.12) was developed, which integrated multiple instruments to concurrently monitor the physical and ecological environment in marine energy sites (Williamson et al. 2016a). Onboard batteries and data storage provided continuous recording of a 14-day spring/neap tidal cycle to investigate the predictable behavior of animals over tidal and diel cycles (Williamson et al. 2019). The self-contained platform allows measurements to be taken adjacent to marine energy structures and in areas free of such devices to investigate ecological (Fraser et al. 2018) and hydrodynamic changes (Fraser et al. 2017b) around MRE structures. Developments are under way to extend the battery-powered deployments using instrument triggering (i.e., only using higher power instruments during detected periods of interest). A cabled interface providing real-time data and a continuous power supply have also been developed to extend monitoring endurance.

Multiple instruments measure the behavior and interactions of fish, diving seabirds, and marine mammals. An Imagenex 837B Delta T multibeam echosounder (vertical swath aligned with the tidal flow) was synchronized with an upward-facing Simrad EK60 multifrequency (38, 120, 200 kHz) scientific echosounder sampling once per second. A SonTek/YSI ADVOcean 5 MHz Acoustic Doppler Velocimeter was used to measure mean flow and turbulence. A Nortek Signature 500 kHz ADCP was used to take hydrodynamic measurements of flow and turbulence throughout the water column. A camera has recently been integrated to confirm species identification when lighting and visibility permit, and a hydrophone has been integrated to monitor ambient noise and detect vocalizing cetaceans.

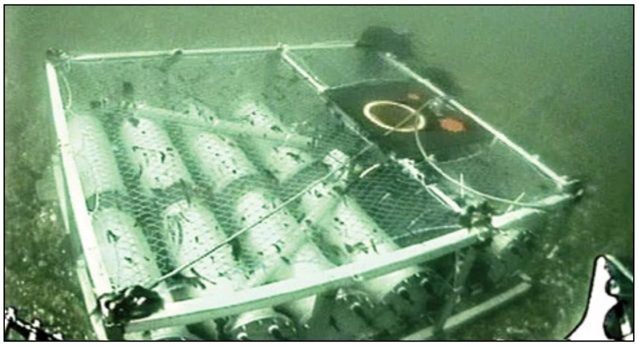


Figure 10.12. The FLOWBEC-4D platform during deployment at the European Marine Energy Center in the United Kingdom. (From Williamson et al. 2016a)

Crucially, these instruments operate simultaneously without interference using a modular and adaptable control system to allow the concurrent measurement of animal behavior and explanatory variables (Williamson et al. 2017), and to investigate comparisons and transferability between sites (Wiesebron et al. 2016). Co-registration between instruments also allows measurements to be validated, and ground-truthing of bird and mammal observations was provided by concurrent shore-based observations or separate ground-truthing surveys.

A total of six battery-powered deployments have been completed at a variety of wave and tidal stream energy sites in Scotland—both EMEC (Orkney, Scotland) and MeyGen (Pentland Firth, Scotland)—including around the Atlantis and OpenHydro tidal turbine support structures and in reference areas, free of devices.

10.4.4. SEA MAMMAL RESEARCH UNIT MONITORING SYSTEM

The Sea Mammal Research Unit (SMRU) at the University of St Andrews in Scotland developed and deployed a 12-hydrophone PAM system on the foundation of an operational tidal turbine at the MeyGen demonstration array in Scotland (Figure 10.13). The hydrophones and acquisition electronics were mounted on the structure prior to its deployment and were connected into the turbine systems for power and data export.

The primary target species was harbor porpoise, which echolocate at 130 kHz, so hydrophones were sampled at 500 kHz, generating ~1 Tb of raw data per day. Data

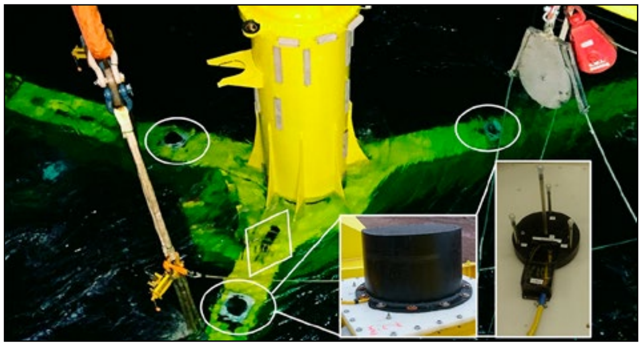


Figure 10.13. Photograph of the MeyGen turbine support structure during installation showing the locations of the three hydrophone clusters. Insets are photographs of a tetrahedral hydrophone cluster and its protective cowling. (Photo courtesy of SIMEC Atlantis Energy)

were sent to the shore via optical fiber in the turbine export cable and processed in real time using PAMGuard software (Gillespie et al. 2008b). The system was operational between October 2017 and October 2019. Data were manually screened offline to confirm species and to localize clicks in three dimensions. Several hundred porpoise tracks around the turbine have been acquired and are being analyzed for evidence of fine-scale avoidance behavior.

The turbine connection system is currently being reconfigured for a new platform, the marine mammal HiCUP (High Current Underwater Platform) (Figure 10.14) to be deployed in late 2020. The new system is built into a gravity-mounted platform that also includes two Tritech Gemini 720i multibeam imaging sonars, which enable the system to also detect and track grey seals (*Halichoerus grypus*) and harbor seals, which rarely vocalize under water.

Two sonars are used to cover the full (~20 m) height of the turbine blades, and also to extract a vertical position for animals based on the relative intensity of the target on the two sonars (Hastie et al. 2019a). Automatic detection and tracking reduces the need for operator screening of large amounts of sonar data (Hastie et al. 2019b). The Tritech system was selected because it is effective at detecting marine mammals at ranges up to ~50 m and does not elicit overt behavioral responses in seals (Hastie et al. 2019a). A single tetrahedral cluster of hydrophones is mounted close to the sonars to give horizontal and elevation angles to sounds, and provides species identification, separating clicks from porpoise and dolphin species, as well as helping to classify seals. Both PAMGuard and software developed for the PAM data acquisition control system are open source and freely available.

10.4.5. INTEGRATED MONITORING POD

Under the Energy Technologies Institute (ETI)'s Reliable Data Acquisition Platform for Tidal (ReDAPT) project, EMEC tested its novel Integrated Monitoring Pod (IMP) at its tidal test site at the Fall of Warness, the Orkney Islands. The first of its kind pre-commercial prototype (Figure 10.15) has been designed to operate in high-velocity tidal flows. It integrates a variety of instruments to undertake comprehensive concurrent environmental measurements, supply real-time data, and provide improved characterization of high-energy marine environments. Instruments onboard the IMP

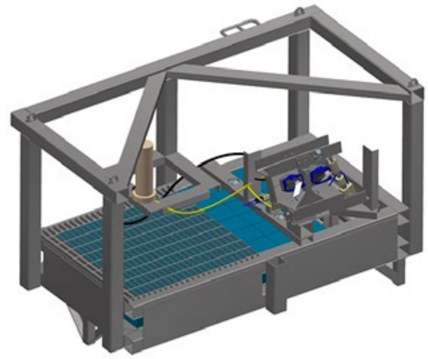


Figure 10.14. Schematic of the marine mammal High Current Underwater Platform (HiCUP) developed by the Sea Mammal Research Unit (SMRU) at the University of St Andrews. (Image courtesy of SMRU, University of St Andrews)

include hydrophones, active sonar system (provided by Ultra Electronics), underwater CCTV, ADCP, and other standard equipment to measure temperature, salinity, and density. It can be connected to the shore via a subsea cable to facilitate 24/7 real-time data collection to deliver live data feedbacks to EMEC for use by clients accessing the test site. Making the real-time data feeds available to clients assists in device design, enabling more accurate assessment of device performance and support during operations and maintenance planning. The ReDAPT project was commissioned to boost public, industry, and regulatory confidence in the tidal energy sector.

The IMP is set up as a plug-and-play prototype in which it is possible to install additional instruments as required. More recently in 2017, through the In Situ Turbulence Replication Evaluation and Measurement project, the pod was reinstalled with a Rockland Scientific turbulence instrument onboard. The instrument

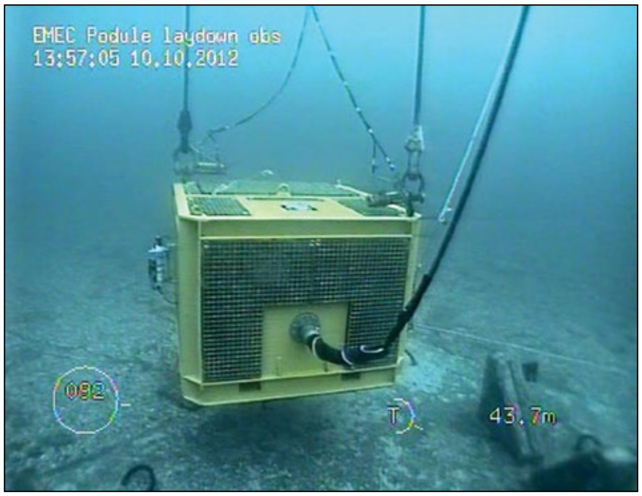


Figure 10.15. The European Marine Energy Centre (EMEC)'s Integrated Monitoring Pod (IMP) during deployment under the Energy Technologies Institute (ETI)'s Reliable Data Acquisition Platform for Tidal (ReDAPT) project. (Photo courtesy of EMEC)

combines standard flow measurement technology (acoustic electromagnetic) with novel non-acoustic measurement technology (shear probes). Plymouth Marine Laboratory has used the pod to test marine coatings designed to prevent biofouling, corrosion, and abrasion, and Heriot-Watt University has installed test panels to characterize biofouling assemblages typical of the high tidally influenced sites. The IMP builds on a comprehensive monitoring system developed by EMEC, which uses marine radar, a meteorological station, VCs, drifting acoustic surveys, ROV surveys, and onshore wildlife observations.

10.5. LESSONS LEARNED FROM MONITORING ACTIVITIES

Building on the information about collision risk to marine animals from Chapter 3 (Collision Risk for Animals around Turbines), our collective understanding of the effects of MRE devices on marine animals has improved because of advances made in methodological processes, innovations in monitoring technologies, the integration of state-of-the-art instrumentation on autonomous and cabled subsea monitoring platforms, and their subsequent deployments in harsh marine conditions. These improvements stem from the series of largely undocumented failures and setbacks experienced by those who pioneered monitoring activities for the nascent MRE industry and initially employed standard oceanographic and remote-sensing technologies in this new context. Although the knowledge gained from this process has greatly advanced monitoring capabilities, ongoing challenges remain, including the need to assure the durability of sensitive equipment; power availability and management for integrated monitoring systems; and continuous data collection, storage, and analysis.

Integrated monitoring platforms, as well as other configurations of remotely mounted instruments can help document the most challenging interactions between marine animals and MRE devices, and especially move collision risk assessments beyond a modeling exercise to the collection of empirical data for quantifying the risk. However, there are currently no commercially available "fit for purpose" instrumentation packages, and monitoring still relies on oceanographic, hydroacoustic, and other instruments that are intended for use in more benign marine conditions. These technologies must be integrated, configured, tested, and validated in new ways to suit dynamic marine environments and to detect critical interactions between marine animals and MRE devices. The electronic integration of instruments on a platform is as important as their physical integration, and despite establishing duty cycles, it is important to recognize that interference between instruments is likely, unless engineering measures are adopted to prevent it, and cannot be ignored. The volume of data collected through monitoring activities and the cost of analyzing the data remain important obstacles. The processes for onboard collection of monitoring data need to be weighed against the collection of excessive amounts of data and the concerns about missing rare events and the future potential use of those data.

10.6. RECOMMENDATIONS FOR QUALITY DATA COLLECTION, MANAGEMENT, AND ANALYSIS

International- and national-level agreements on the suite of instruments required for monitoring MRE devices and for documenting interactions that cannot be resolved by research studies alone are needed. Research studies should be aligned with critical questions posed by licensing requirements and dictated by the results of ongoing monitoring and research campaigns. Modeling studies remain an essential part of understanding the environmental risks of MRE devices and should be employed, as appropriate. For cases where no data currently exist (e.g., changes in oceanographic systems), models can be employed to help guide monitoring programs for when MRE arrays are established. Where few data currently exist (e.g., collision risk), models can be used to iteratively improve monitoring studies. For instances where data are readily available and can be compared to regulatory thresholds or other measures, we should continue to iterate and develop models that will decrease the need for measurements at every site at which an MRE device is deployed.

The data mortgage challenge can be addressed through the collection of data on a sparse duty cycle (e.g., only record five minutes of data every hour). However, this approach would likely miss rare events of interest. Alternatively, automated data processing can be implemented to identify periods of interest in the collected data. When implemented during post-processing, automated data processing can be used to limit human review to periods of interest, reducing the significant effort required to extract insight from large datasets. When implemented in real time, automated data processing can be used to limit data acquisition to periods of interest and reduce the volume of data that requires archival storage. This approach has been used for the AMP (Cotter et al. 2017) and for PAM (Malinka et al. 2018).

Recently, there has been a push to improve automatic data processing methods for environmental data derived from MRE sites to decrease the volume of data that must be analyzed, the rate at which the data can be analyzed, and increase the accuracy of results. Here, we provide a brief overview of recent advancements in the automated processing of passive acoustics, active acoustics, and optical camera data at marine energy sites.

10.6.1. PASSIVE ACOUSTICS

Automated detection and localization of vocalizing marine mammals can be used to quantify the presence and behavior of vocalizing marine mammals. PAMGuard (www.PAMGuard.org; Gillespie et al. 2008b), an open-source software package for automated processing of passive acoustic data, has been widely used for the processing of data from marine energy sites. For example, Malinka et al. (2018) used PAMGuard to detect marine mammal clicks and tonal sounds in real time, and this information was used to limit data acquisition to periods when a vocalization was detected. These detected vocalizations were later manually reviewed for accuracy. Even though mechanical sounds from the monitored tidal turbine caused occasional false detections, the data review effort was significantly reduced compared to review of continuously acquired data. Other examples of automated detection of marine mammal vocalizations using PAMGuard can be found in publications by Fernandez-Betelu et al. (2019), Macaulay et al. (2017), and Wilson et al. (2013).

10.6.2. ACTIVE ACOUSTICS

The most common approach to automatic processing of multibeam sonar data is to detect moving targets in the image and track those targets through the sonar swath (Cotter et al. 2017; Jepp 2017; Lieber et al. 2017; Williamson et al. 2017). In turbulent environments, it may be necessary to first isolate portions of the water column that are dominated by noise (Fraser et al. 2017a). Target-tracking data can be used to narrow down and guide the review that is carried out by humans, allowing them to compare the size, shape, and speed of targets. Cotter et al. (2017) implemented multibeam sonar target tracking in real time and used it to limit data acquisition to periods when targets were predicted to be present. This approach recorded an estimated 99 percent of targets with a 58 percent true positive rate. Cotter and Polagye (2020) evaluated real-time classification of these target tracks and found that a random forest algorithm distinguished between the biological and non-biological targets with a 97 percent true positive rate.

The processing of echosounder data typically involves the separation of pixels that are above a static minimum backscatter strength threshold (Simmonds and MacLennan 2007). However, at marine energy sites, this approach is generally not viable because of variable background backscatter strength levels and the presence of entrained air that has backscatter strength comparable to targets of interest (Fraser et al. 2017a). As a result, the processing of echosounder data at marine energy sites has relied heavily on human review and frequently excludes the top of the water column (Viehman et al. 2018; Wiesebron et al. 2016). To combat this, Fraser et al. (2017a) developed an adaptive filtering approach to suppress background noise in echosounder data using a moving median filter and morphological filtering to separate targets of interest from entrained air. This approach was found to reliably detect fish schools throughout the entire water column in echosounder data collected from a bottom platform at the Fall of Warness in Scotland.

10.6.3. OPTICAL CAMERAS

Automated data processing for optical camera data at marine energy sites is complicated by characteristically low water clarity, high water velocity, and variable ambient light. Most existing algorithms developed for target detection and classification in underwater camera imagery have focused on brightly colored coral fish or deep-water environments with constant artificial illumination, and are not suitable for data collected at marine energy sites (Xu and Matzner 2018). Xu and Matzner (2018) applied a deep neural network, YOLO v3 (Redmon and Farhadi 2018), to automate the detection of fish in optical camera data from two tidal energy sites and one conventional hydropower site. The YOLO algorithm was implemented in EyeSea (Matzner et al. 2019), an open-source application framework for manual or automated annotation of optical camera imagery that can be extended to include new processing algorithms. When the model was trained using optical camera data from the Voith Hydro turbine deployment at EMEC, it was able to identify fish with 75 percent precision and 50 percent recall in validation data from the same test site. However, when trained using data from other sites, the model was found to not generalize well to data collected by different cameras at different locations. Ongoing research at the Applied Physics Laboratory–University of Washington aims to expand upon the work by Xu and Matzner (2018) to develop a generalized stereo camera fish segmentation algorithm for environmental monitoring at marine energy sites. This work uses a stereo camera extrinsic relationship to both increase algorithm robustness and optionally ignore small fish that tend to gather near cameras on marine energy converter environmental monitoring instruments (Mitchell Scott, personal communication).

10.7. REFERENCES

Adams, M. J. 2018. Application of a multi-hydrophone drifter and porpoise detection software for monitoring Atlantic harbour porpoise (*Phocoena phocoena*) activity in and near Minas Passage. Bachelor's Thesis, Acadia University, Wolfville, Nova Scotia. *https://tethys.pnnl.gov/publications/application-multi-hydrophone-drifter-porpoise-detection-software-monitoring-atlantic*

Auvinen, M. F., Barclay, D. R., and Coffin, M. E. W. 2019. Performance of a Passive Acoustic Linear Array in a Tidal Channel. *IEEE Journal of Oceanic Engineering*, 1-10. doi:10.1109/JOE.2019.2944444 *https://tethys.pnnl.gov/publications/performance-passive-acoustic-linear-array-tidal-channel*

Barclay, D. 2019. Noise in the ocean. Presented at Dalhousie University, Halifax, Nova Scotia.

Bassett, C. 2013. Ambient noise in an urbanized tidal channel. Doctoral Dissertation, University of Washington, Seattle, Washington. *https://tethys.pnnl.gov/publications/ambient-noise-urbanized-tidal-channel*

Bassett, C., De Robertis, A., and Wilson, C. D. 2018. Broadband echosounder measurements of the frequency response of fishes and euphausiids in the Gulf of Alaska. *ICES Journal of Marine Science*, 75(3), 1131-1142. doi:10.1093/icesjms/fsx204 *https://tethys.pnnl.gov/publications/broadband-echosounder-measurements-frequency-response-fishes-euphausiids-gulf-alaska*

Bassett, C., Thomson, J., Dahl, P. H., and Polagye, B. 2014. Flow-noise and turbulence in two tidal channels. *The Journal of the Acoustical Society of America*, 135(4), 1764-1774. doi:10.1121/1.4867360 *https://tethys.pnnl.gov/publications/flow-noise-turbulence-two-tidal-channels*

Bassett, C., Thomson, J., and Polagye, B. 2013. Sediment-generated noise and bed stress in a tidal channel. *Journal of Geophysical Research: Oceans*, 118(4), 2249-2265. doi:10.1002/jgrc.20169 *https://tethys.pnnl.gov/publications/sediment-generated-noise-bed-stress-tidal-channel*

Benjamins, S., Dale, A., van Geel, N., and Wilson, B. 2016. Riding the tide: use of a moving tidal-stream habitat by harbour porpoises. *Marine Ecology Progress Series*, 549, 275–288. doi:10.3354/meps11677 https://tethys.pnnl.gov/publications/riding-tide-use-moving-tidal-stream-habitat-harbour-porpoises

Benjamins, S., van Geel, N., Hastie, G., Elliott, J., and Wilson, B. 2017. Harbour porpoise distribution can vary at small spatiotemporal scales in energetic habitats. *Deep Sea Research Part II: Topical Studies in Oceanography*, 141, 191–202. doi:10.1016/j.dsr2.2016.07.002 https://tethys.pnnl.gov/publications/harbour-porpoise-distribution-can-vary-small-spatiotemporal-scales-energetic-habitats

Bevelhimer, M., Colby, J., Adonizio, M., Tomichek, C., and Scherelis, C. 2016. Informing a Tidal Turbine Strike Probability Model through Characterization of Fish Behavioral Response using Multibeam Sonar Output (ORNL/TM-2016-219). Oak Ridge National Laboratory, Oak Ridge, TN. Report by Oak Ridge National Laboratory for U.S. Department of Energy. https://tethys.pnnl.gov/publications/informing-tidal-turbine-strike-probability-model-through-characterization-fish

Bicknell, A. W. J., Sheehan, E. V., Godley, B. J., Doherty, P. D., and Witt, M. J. 2019. Assessing the impact of introduced infrastructure at sea with cameras: A case study for spatial scale, time and statistical power. *Marine Environmental Research*, 147, 126–137. doi:10.1016/j.marenvres.2019.04.007 https://tethys.pnnl.gov/publications/assessing-impact-introduced-infrastructure-sea-cameras-case-study-spatial-scale-time

Bixler, G. D., and Bhushan, B. 2012. Biofouling: lessons from nature. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370(1967), 2381–2417. doi:10.1098/rsta.2011.0502 https://tethys.pnnl.gov/publications/biofouling-lessons-nature

Booth, D. J., and Beretta, G. A. 2002. Changes in a fish assemblage after a coral bleaching event. *Marine Ecology Progress Series*, 245, 205–212. https://tethys.pnnl.gov/publications/changes-fish-assemblage-after-coral-bleaching-event

Broadhurst, M., Barr, S., and Orme, C. D. L. 2014. In-situ ecological interactions with a deployed tidal energy device; an observational pilot study. *Ocean & Coastal Management*, 99, 31–38. doi:10.1016/j.ocecoaman.2014.06.008 https://tethys.pnnl.gov/publications/situ-ecological-interactions-deployed-tidal-energy-device-observational-pilot-study

Campanella, F., and Taylor, J. C. 2016. Investigating acoustic diversity of fish aggregations in coral reef ecosystems from multifrequency fishery sonar surveys. *Fisheries Research*, 181, 63–76. doi:10.1016/j.fishres.2016.03.027 https://tethys.pnnl.gov/publications/investigating-acoustic-diversity-fish-aggregations-coral-reef-ecosystems

Chu, D., and Stanton, T. K. 1998. Application of pulse compression techniques to broadband acoustic scattering by live individual zooplankton. *The Journal of the Acoustical Society of America*, 104(1), 39–55. doi:10.1121/1.424056 https://tethys.pnnl.gov/publications/application-pulse-compression-techniques-broadband-acoustic-scattering-live-individual

Copping, A., Hanna, L., Whiting, J., Geerlofs, S., Grear, M., Blake, K., Coffey, A., Massaua, M., Brown-Saracino, J., and Battey, H. 2013. Environmental Effects of Marine Energy Development around the World: Annex IV Final Report. Pacific Northwest National Laboratory, Richland, Washington. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. https://tethys.pnnl.gov/publications/environmental-effects-marine-energy-development-around-world-annex-iv-final-report

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewski, G., Staines, G., Gill, A., Hutchison, I., O'Hagan, A., Simas, T., Bald, J., Sparling, C., Wood, J., and Masden, E. 2016. Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. https://tethys.pnnl.gov/publications/state-of-the-science-2016

Cotter, E., Murphy, P., and Polagye, B. 2017. Benchmarking sensor fusion capabilities of an integrated instrumentation package. *International Journal of Marine Energy*, 20, 64–79. doi:10.1016/j.ijome.2017.09.003 https://tethys engineering.pnnl.gov/publications/benchmarking-sensor-fusion-capabilities-integrated-instrumentation-package

Cotter, E., and Polagye, B. 2020. Automatic classification of biological targets in a tidal channel using a multibeam sonar. *Journal of Atmospheric and Oceanic Technology.* doi:10.1175/JTECH-D-19-0222.1 *https://tethys.pnnl.gov/publications/automatic-classification-biological-targets-tidal-channel-using-multibeam-sonar*

De Robertis, A., and Higginbottom, I. 2007. A post-processing technique to estimate the signal-to-noise ratio and remove echosounder background noise. *ICES Journal of Marine Science,* 64(6), 1282-1291. doi:10.1093/icesjms/fsm112 *https://tethys.pnnl.gov/publications/post-processing-technique-estimate-signal-noise-ratio-remove-echosounder-background*

De Robertis, A., McKelvey, D. R., and Ressler, P. H. 2010. Development and application of an empirical multifrequency method for backscatter classification. *Canadian Journal of Fisheries and Aquatic Sciences,* 67(9), 1459-1474. doi:10.1139/F10-075 *https://tethys.pnnl.gov/publications/development-application-empirical-multifrequency-method-backscatter-classification*

Demer, D. A., Andersen, L. N., Bassett, C., Berger, L., Chu, D., Condiotty, J., Jr., G. R. C., Hutton, B., Korneliussen, R., Bouffant, N. L., Macaulay, G., Michaels, W. L., Murfin, D., Pobitzer, A., Renfree, J. S., Sessions, T. S., Stierhoff, K. L., and Thompson, C. H. 2017. 2016 USA–Norway EK80 Workshop Report: Evaluation of a wideband echosounder for fisheries and marine ecosystem science (Report No. 336). Report for International Council for the Exploration of the Sea (ICES). *https://tethys.pnnl.gov/publications/evaluation-wideband-echosounder-fisheries-marine-ecosystem-science*

Ehrenberg, J. E., and Torkelson, T. C. 2000. FM slide (chirp) signals: a technique for significantly improving the signal-to-noise performance in hydroacoustic assessment systems. *Fisheries Research,* 47(2), 193-199. doi:10.1016/S0165-7836(00)00169-7 *https://tethys.pnnl.gov/publications/fm-slide-chirp-signals-technique-significantly-improving-signal-noise-performance*

Fernandes, P. G. 2009. Classification trees for species identification of fish-school echotraces. *ICES Journal of Marine Science,* 66(6), 1073-1080. doi:10.1093/icesjms/fsp060 *https://tethys.pnnl.gov/publications/classification-trees-species-identification-fish-school-echotraces*

Fernandez-Betelu, O., Graham, I. M., Cornulier, T., and Thompson, P. M. 2019. Fine scale spatial variability in the influence of environmental cycles on the occurrence of dolphins at coastal sites. *Scientific Reports,* 9(1), 2548. doi:10.1038/s41598-019-38900-4 *https://tethys.pnnl.gov/publications/fine-scale-spatial-variability-influence-environmental-cycles-occurrence-dolphins*

Fraser, S., Nikora, V., Williamson, B. J., and Scott, B. E. 2017a. Automatic active acoustic target detection in turbulent aquatic environments. *Limnology and Oceanography: Methods,* 15(2), 184-199. doi:10.1002/lom3.10155 *https://tethys.pnnl.gov/publications/automatic-active-acoustic-target-detection-turbulent-aquatic-environments*

Fraser, S., Nikora, V., Williamson, B. J., and Scott, B. E. 2017b. Hydrodynamic Impacts of a Marine Renewable Energy Installation on the Benthic Boundary Layer in a Tidal Channel. *Energy Procedia,* 125, 250-259. doi:10.1016/j.egypro.2017.08.169 *https://tethys.pnnl.gov/publications/hydrodynamic-impacts-marine-renewable-energy-installation-benthic-boundary-layer-tidal*

Fraser, S., Williamson, B. J., Nikora, V., and Scott, B. E. 2018. Fish distributions in a tidal channel indicate the behavioural impact of a marine renewable energy installation. *Energy Reports,* 4, 65-69. doi:10.1016/j.egyr.2018.01.008 *https://tethys.pnnl.gov/publications/fish-distributions-tidal-channel-indicate-behavioural-impact-marine-renewable-energy*

Gillespie, D., Mellinger, D. K., Gordon, J., McLaren, D., Redmond, P., McHugh, R., Trinder, P., Deng, X. Y., and Thode, A. 2009. PAMGUARD: Semiautomated, open source software for real-time acoustic detection and localization of cetaceans. *The Journal of the Acoustical Society of America,* 125(4), 2547-2547. doi:10.1121/1.4808713 *https://tethys.pnnl.gov/publications/pamguard-semiautomated-open-source-software-real-time-acoustic-detection-localization*

Grippo, M., Shen, H., Zydlewski, G., Rao, S., and Goodwin, A. 2017. Behavioral Responses Of Fish To A Current-Based Hydrokinetic Turbine Under Mutlipe Operational Conditions: Final Report (ANL-/EVS-17/6129701). Argonne National Laboratory, Argonne, Illinois. Report by Argonne National Laboratory for U.S. Department of Energy. *https://tethys.pnnl.gov/publications/behavioral-responses-fish-current-based-hydrokinetic-turbine-under-multiple*

Hammar, L., Andersson, S., Eggertsen, L., Haglund, J., Gullström, M., Ehnberg, J., and Molander, S. 2013. Hydrokinetic Turbine Effects on Fish Swimming Behaviour. *PLoS ONE*, 8(12), e84141. doi:10.1371/journal.pone.0084141 https://tethys.pnnl.gov/publications/hydrokinetic-turbine-effects-fish-swimming-behaviour

Harvey, E., Fletcher, D., and Shortis, M. 2002. Estimation of reef fish length by divers and by stereo-video A first comparison of the accuracy and precision in the field on living fish under operational conditions. *Fisheries Research* 57: 255–265. doi:10.1016/S0165-7836(01)00356-3 https://tethys.pnnl.gov/publications/estimation-reef-fish-length-divers-stereo-video-first-comparison-accuracy-precision

Harvey, E., and Shortis, M. 1995. A system for stereo-video measurement of sub-tidal organisms. *Marine Technology Society Journal*, 29, 10-22. https://tethys.pnnl.gov/publications/system-stereo-video-measurement-sub-tidal-organisms

Harvey, E., and Shortis, M. 1998. Calibration Stability of an Underwater Stereo Video System: Implications for Measurement Accuracy and Precision. *Marine Technology Society Journal*, 32, 3-17. https://tethys.pnnl.gov/publications/calibration-stability-underwater-stereo-video-system-implications-measurement-accuracy

Hastie, G. 2013. Tracking Marine Mammals Around Marine Renewable Energy Devices Using Active Sonar. Sea Mammal Research Unit, St Andrews, Scotland. Report by Sea Mammal Research Unit for UK Department of Energy and Climate Change. https://tethys.pnnl.gov/publications/tracking-marine-mammals-around-marine-renewable-energy-devices-using-active-sonar

Hastie, G. D., Bivins, M., Coram, A., Gordon, J., Jepp, P., MacAulay, J., Sparling, C., and Gillespie, D. 2019a. Three-dimensional movements of harbour seals in a tidally energetic channel: Application of a novel sonar tracking system. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 29(4), 564-575. doi:10.1002/aqc.3017 https://tethys.pnnl.gov/publications/three-dimensional-movements-harbour-seals-tidally-energetic-channel-application-novel

Hastie, G. D., Wu, G.-M., Moss, S., Jepp, P., MacAulay, J., Lee, A., Sparling, C. E., Evers, C., and Gillespie, D. 2019b. Automated detection and tracking of marine mammals: A novel sonar tool for monitoring effects of marine industry. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 29(S1), 119-130. doi:10.1002/aqc.3103 https://tethys.pnnl.gov/publications/automated-detection-tracking-marine-mammals-novel-sonar-tool-monitoring-effects-marine

Horne, J. K. 2000. Acoustic approaches to remote species identification: a review. *Fisheries Oceanography*, 9(4), 356-371. doi:10.1046/j.1365-2419.2000.00143.x https://tethys.pnnl.gov/publications/acoustic-approaches-remote-species-identification-review

Horne, J. K. 2019. Scientific Echosounder Review for In-Stream Tidal Turbines. Ocean Energy Research Association, Halifax, Nova Scotia. https://tethys.pnnl.gov/publications/scientific-echosounder-review-stream-tidal-turbines

Horne, J. K., and Jacques, D. A. 2018. Determining representative ranges of point sensors in distributed networks. *Environmental Monitoring and Assessment*, 190(6), 348. doi:10.1007/s10661-018-6689-0 https://tethys.pnnl.gov/publications/determining-representative-ranges-point-sensors-distributed-networks

International Electrochemical Commission (IEC). 2013. Degrees of protection provided by enclosures (IP Code). https://tethys-engineering.pnnl.gov/publications/degrees-protection-provided-enclosures-ip-code

International Electrotechnical Commission (IEC). 2019. Marine energy - Wave, tidal and other water current converters - Part 40: Acoustic characterization of marine energy converters (IEC TS 62600- 40:2019). https://tethys-engineering.pnnl.gov/publications/iec-ts-62600-402019-part-40-acoustic-characterization-marine-energy-converters

Jacobson, E. K., Forney, K. A., and Barlow, J. 2017. Using paired visual and passive acoustic surveys to estimate passive acoustic detection parameters for harbor porpoise abundance estimates. *The Journal of the Acoustical Society of America*, 141(1), 219-230. doi:10.1121/1.4973415 https://tethys.pnnl.gov/publications/using-paired-visual-passive-acoustic-surveys-estimate-passive-acoustic-detection

Jech, J. M., Lawson, G. L., and Lavery, A. C. 2017. Wideband (15–260 kHz) acoustic volume backscattering spectra of Northern krill (*Meganyctiphanes norvegica*) and butterfish (*Peprilus triacanthus*). *ICES Journal of Marine Science*, 74(8), 2249-2261. doi:10.1093/icesjms/fsx050 *https://tethys.pnnl.gov/publications/wideband-15-260-khz-acoustic-volume-backscattering-spectra-northern-krill*

Jepp, P. 2017. Target Tracking using Sonars for Marine Life Monitoring around Tidal Turbines. Paper presented at the 12th European Wave and Tidal Energy Conference, Cork, Ireland. *https://tethys.pnnl.gov/publications/target-tracking-using-sonars-marine-life-monitoring-around-tidal-turbines*

Jobling, M. 1994. Environmental Biology of Fishes. Springer Netherlands. *https://tethys.pnnl.gov/publications/environmental-biology-fishes*

Joslin, J. 2019. Imaging sonar review for marine environmental monitoring around tidal turbines. Report by University of Washington for Offshore Energy Research Association of Nova Scotia. *https://tethys.pnnl.gov/publications/imaging-sonar-review-marine-environmental-monitoring-around-tidal-turbines*

Joslin, J., Cotter, E., Murphy, P., Gibbs, P., Cavagnaro, R., Crisp, C., Stewart, A., Polagye, B., Cross, P., Hjetland, E., Rocheleau, A., and Waters, B. 2019. The wave-powered adaptable monitoring package: hardware design, installation, and deployment. Paper presented at the 12th European Wave and Tidal Energy Conference, Naples, Italy. *https://tethys.pnnl.gov/publications/wave-powered-adaptable-monitoring-package-hardware-design-installation-deployment*

Joslin, J., and Polagye, B. 2015. Demonstration of Biofouling Mitigation Methods for Long-Term Deployments of Optical Cameras. *Marine Technology Society Journal*, 49, 88-96. doi:10.4031/MTSJ.49.1.12 *https://tethys-engineering.pnnl.gov/publications/demonstration-biofouling-mitigation-methods-long-term-deployments-optical-cameras*

Joslin, J., Polagye, B., and Parker-Stetter, S. 2012. Development of a stereo camera system for monitoring hydrokinetic turbines. Paper presented at 2012 Oceans, Hampton Roads, VA . doi:10.1109/OCEANS.2012.6405043 *https://tethys.pnnl.gov/publications/development-stereo-camera-system-monitoring-hydrokinetic-turbines*

Kloser, R. J., Ryan, T., Sakov, P., Williams, A., and Koslow, J. A. 2002. Species identification in deep water using multiple acoustic frequencies. *Canadian Journal of Fisheries and Aquatic Sciences*, 59(6), *1065-1077.* doi:10.1139/f02-076 *https://tethys.pnnl.gov/publications/species-identification-deep-water-using-multiple-acoustic-frequencies*

Korneliussen, R. J. 2000. Measurement and removal of echo integration noise. *ICES Journal of Marine Science*, 57(4), 1204-1217. doi:10.1006/jmsc.2000.0806 *https://tethys.pnnl.gov/publications/measurement-removal-echo-integration-noise*

Korneliussen, R. J. (Ed.) 2018. Acoustic target classification. ICES Cooperative Research Report No. 344. Report for International Council for the Exploration of the Sea (ICES). doi:10.17895/ices.pub.4567 *https://tethys.pnnl.gov/publications/acoustic-target-classification*

Kyhn, L. A., Tougaard, J., Teilmann, J., Wahlberg, M., Jørgensen, P. B., and Bech, N. I. 2008. Harbour porpoise (*Phocoena phocoena*) static acoustic monitoring: laboratory detection thresholds of T-PODs are reflected in field sensitivity. *Journal of the Marine Biological Association of the United Kingdom, 88(6), 1085-1091.* doi:10.1017/S0025315408000416 *https://tethys.pnnl.gov/publications/harbour-porpoise-phocoena-phocoena-static-acoustic-monitoring-laboratory-detection*

Kyhn, L. A., Tougaard, J., Thomas, L., Duve, L. R., Stenback, J., Amundin, M., Desportes, G., and Teilmann, J. 2012. From echolocation clicks to animal density—Acoustic sampling of harbor porpoises with static dataloggers. *The Journal of the Acoustical Society of America*, 131(1), *550-560.* doi:10.1121/1.3662070 *https://tethys.pnnl.gov/publications/echolocation-clicks-animal-density-acoustic-sampling-harbor-porpoises-static-o*

Langlois, T. J., Fitzpatrick, B. R., Fairclough, D. V., Wakefield, C. B., Hesp, S. A., McLean, D. L., Harvey, E. S., and Meeuwig, J. J. 2012. Similarities between Line Fishing and Baited Stereo-Video Estimations of Length-Frequency: Novel Application of Kernel Density Estimates. *PLoS ONE*, 7(11), e45973. doi:10.1371/journal.pone.0045973 *https://tethys.pnnl.gov/publications/similarities-between-line-fishing-baited-stereo-video-estimations-length-frequency*

Lavery, A. C., Chu, D., and Moum, J. N. 2010. Measurements of acoustic scattering from zooplankton and oceanic microstructure using a broadband echosounder. *ICES Journal of Marine Science*, 67(2), 379–394. doi:10.1093/icesjms/fsp242 *https://tethys.pnnl.gov/publications/measurements-acoustic-scattering-zooplankton-oceanic-microstructure-using-broadband*

Lavery, A. C., Wiebe, P. H., Stanton, T. K., Lawson, G. L., Benfield, M. C., and Copley, N. 2007. Determining dominant scatterers of sound in mixed zooplankton populations. *The Journal of the Acoustical Society of America*, 122(6), 3304–3326. doi:10.1121/1.2793613 *https://tethys.pnnl.gov/publications/determining-dominant-scatterers-sound-mixed-zooplankton-populations*

Lieber, L., Nilsen, T., Zambrano, C., and Kregting, L. 2017. Optimising multiple multibeam sonars to assess marine life interactions with an underwater kite. Paper presented at the 12th European Wave and Tidal Energy Conference, Cork, Ireland. *https://tethys.pnnl.gov/publications/optimising-multiple-multibeam-sonars-assess-marine-life-interactions-underwater-kite*

Lines, J. A., Tillett, R. D., Ross, L. G., Chan, D., Hockaday, S., and McFarlane, N. J. B. 2001. An automatic image-based system for estimating the mass of free-swimming fish. *Computers and Electronics in Agriculture*, 31(2), 151–168. doi:10.1016/S0168-1699(00)00181-2 *https://tethys.pnnl.gov/publications/automatic-image-based-system-estimating-mass-free-swimming-fish*

LiVecchi, A., Copping, A., Jenne, D., Gorton, A., Preus, R., Gill, G., Robichaud, R., Green, R., Geerlofs, S., Gore, S., Hume, D., McShane, W., Schmaus, C., and Spence, H. 2019. Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets. Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, D.C. *https://tethys.pnnl.gov/publications/powering-blue-economy-exploring-opportunities-marine-renewable-energy-maritime-markets*

Lloyd, S., Lepper, P., and Pomeroy, S. 2017. Evaluation of UAVs as an underwater acoustics sensor deployment platform. *International Journal of Remote Sensing*, 38(8–10), 2808–2817. doi:10.1080/01431161.2016.1259686 *https://tethys.pnnl.gov/publications/evaluation-uavs-underwater-acoustics-sensor-deployment-platform*

Lombardi, A. 2016. Soundscape characterization in Grand Passage, Nova Scotia, a planned in-stream tidal energy site. Master's Thesis, Dalhousie University, Halifax, Nova Scotia. *https://tethys.pnnl.gov/publications/soundscape-characterization-dynamic-acoustic-environment-grand-passage-nova-scotia*

Lythgoe, J. N. 1988. Light and Vision in the Aquatic Environment. In Atema, J., Fay, R. R., Popper, A. N., and Tavolga, W. N. (Eds.), *Sensory Biology of Aquatic Animals* (pp 57–82). New York, NY: Springer. *https://tethys.pnnl.gov/publications/light-vision-aquatic-environment*

Macaulay, J., Gordon, J., Gillespie, D., Malinka, C., and Northridge, S. 2017. Passive acoustic methods for fine-scale tracking of harbour porpoises in tidal rapids. *The Journal of the Acoustical Society of America*, 141(2), 1120–1132. doi:10.1121/1.4976077 *https://tethys.pnnl.gov/publications/passive-acoustic-methods-fine-scale-tracking-harbour-porpoises-tidal-rapids*

Malinka, C., Hay, A., and Cheel, R. 2015. Towards Acoustic Monitoring of Marine Mammals at a Tidal Turbine Site: Grand Passage, NS, Canada. Paper presented at the 11th European Wave and Tidal Energy Conference, Nantes, France. *https://tethys.pnnl.gov/publications/towards-acoustic-monitoring-marine-mammals-tidal-turbine-site-grand-passage-ns-canada*

Malinka, C. E., Gillespie, D. M., Macaulay, J. D. J., Joy, R., and Sparling, C. E. 2018. First in situ passive acoustic monitoring for marine mammals during operation of a tidal turbine in Ramsey Sound, Wales. *Marine Ecology Progress Series*, 590, 247–266. doi:10.3354/meps12467 *https://tethys.pnnl.gov/publications/first-situ-passive-acoustic-monitoring-marine-mammals-during-operation-tidal-turbine*

Manley, J., and Willcox, S. 2010. The Wave Glider: A persistent platform for ocean science. Paper presented at OCEANS'10 IEEE SYDNEY, Sydney, Australia. doi:10.1109/OCEANSSYD.2010.5603614 *https://tethys-engineering.pnnl.gov/publications/wave-glider-persistent-platform-ocean-science*

Matsuoka, T., Ishizuka, S., Anraku, K., and Nakano, M. 1997. Assessment by underwater infrared video of the selectivity of an experimental Danish seine for deep-water prawn. In D. A. Hancock, D. C. Smith, A. Grant, and J. P. Beumer (Eds.), *Developing and Sustaining World Fisheries Resources* (pp. 551–557). Collingwood, Victoria: CSIRO Publishing.

Matzner, S., McBain, A., and Avila, A. 2019. EyeSea. Retrieved from https://github.com/pnnl/EyeSea.

Matzner, S., Trostle, C., Staines, G., Hull, R., Avila, A., and Harker-Klimes, G. 2017. Triton: Igiugig Fish Video Analysis (Report No. PNNL-26576) Pacific Northwest National Laboratory, Richland, Washington. Report by Pacific Northwest National Laboratory for U.S. Department of Energy. https://tethys.pnnl.gov/publications/triton-igiugig-fish-video-analysis

McGarry, L. P., and Gayle B. Zydlewski. 2019. Marine Fish Monitoring at FORCE: Updated Report on Processing and Analysis. Fundy Ocean Research Centre for Energy (FORCE), Halifax, Nova Scotia. Report by University of Maine for Fundy Ocean Research Center for Energy. https://tethys.pnnl.gov/publications/marine-fish-monitoring-force-updated-report-processing-analysis

Melvin, G. D., and Cochrane, N. A. 2014. Investigation of the Vertical Distribution, Movement and Abundance of Fish in the Vicinity of Proposed Tidal Power Energy Conversion Devices. OEER/OETR Research Project 300-170-09-12. Offshore Energy Research Association (OERA), Halifax, Nova Scotia. Report by Fisheries and Oceans Canada for Offshore Energy Research Association of Nova Scotia. https://tethys.pnnl.gov/publications/investigation-vertical-distribution-movement-abundance-fish-vicinity-proposed-tidal

Melvin, G. D., and Cochrane, N. A. 2015. Multibeam Acoustic Detection of Fish and Water Column Targets at High-Flow Sites. *Estuaries and Coasts*, 38(1), 227-240. doi:10.1007/s12237-014-9828-z https://tethys.pnnl.gov/publications/multibeam-acoustic-detection-fish-water-column-targets-high-flow-sites

Mueller, R. P., Brown, R. S., Hop, H., and Moulton, L. 2006. Video and acoustic camera techniques for studying fish under ice: a review and comparison. *Reviews in Fish Biology and Fisheries*, 16(2), 213-226. doi:10.1007/s11160-006-9011-0 https://tethys.pnnl.gov/publications/video-acoustic-camera-techniques-studying-fish-under-ice-review-comparison

O'Connor, M., Lewis, T., and Dalton, G. 2013. Weather window analysis of Irish west coast wave data with relevance to operations & maintenance of marine renewables. *Renewable Energy*, 52, 57-66. doi:10.1016/j.renene.2012.10.021 https://tethys-engineering.pnnl.gov/publications/weather-window-analysis-irish-west-coast-wave-data-relevance-operations-maintenance

Ocean Renewable Power Company (ORPC) Maine. 2014. Cobscook Bay Tidal Energy Project: 2013 Environmental Monitoring Report. Portland, ME. Report by ORPC. https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2013-environmental-monitoring-report

Pang, J., and Blackwood, D. J. 2016. Corrosion of titanium alloys in high temperature near anaerobic seawater. *Corrosion Science*, 105, 17-24. doi:10.1016/j.corsci.2015.12.011 https://tethys-engineering.pnnl.gov/publications/corrosion-titanium-alloys-high-temperature-near-anaerobic-seawater

Parsons, M. J. G., Fenny, E., Lucke, K., Osterrieder, S., Jenkins, G., Saunders, B. J., Jepp, P., and Parnum, I. M. 2017. Imaging Marine Fauna with a Tritech Gemini 720i Sonar. *Acoustics Australia*, 45(1), 41-49. doi:10.1007/s40857-016-0076-1 https://tethys.pnnl.gov/publications/imaging-marine-fauna-tritech-gemini-720i-sonar

Parsons, M. J. G., Parnum, I. M., Allen, K., McCauley, R. D., and Erbe, C. 2014. Detection of sharks with the Gemini imaging sonar. *Acoustics Australia*, 42(2). https://tethys.pnnl.gov/publications/detection-sharks-gemini-imaging-sonar

Pine, M. K., Jeffs, A. G., and Radford, C. A. 2012. Turbine Sound May Influence the Metamorphosis Behaviour of Estuarine Crab Megalopae. *PLoS ONE*, 7(12), e51790. doi:10.1371/journal.pone.0051790 https://tethys.pnnl.gov/publications/turbine-sound-may-influence-metamorphosis-behaviour-estuarine-crab-megalopae

Pinkel, R., Goldin, M. A., Smith, J. A., Sun, O. M., Aja, A. A., Bui, M. N., and Hughen, T. 2010. The Wirewalker: A Vertically Profiling Instrument Carrier Powered by Ocean Waves. *Journal of Atmospheric and Oceanic Technology*, 28(3), 426-435. doi:10.1175/2010JTECHO805.1 https://tethys-engineering.pnnl.gov/publications/wirewalker-vertically-profiling-instrument-carrier-powered-ocean-waves

Polagye, B., Joslin, J., Murphy, P., Cotter, E., Scott, M., Gibbs, P., Bassett, C., Stewart, A. 2020. Adaptable Monitoring Package Development and Deployment: Lessons Learned for Integrated Instrumentation at Marine Energy Sites. *Journal of Marine Science and Engineering*, 8(8), 553. doi:10.3390/jmse8080553 https://tethys.pnnl.gov/publications/adaptable-monitoring-package-development-deployment-lessons-learned-integrated

Polagye, B., Thomson, J., Bassett, C., Wood, J., Tollit, D., Cavagnaro, R., and Copping, A. 2012. Study of the Acoustic Effects of Hydrokinetic Tidal Turbines in Admiralty Inlet, Puget Sound (DOE/EE/0002654-1). Report by Northwest National Marine Renewable Energy Center (NNMREC) for U.S. Department of Energy. doi:10.2172/1039434 https://tethys.pnnl.gov/publications/study-acoustic-effects-hydrokinetic-tidal-turbine-admiralty-inlet-puget-sound

Porskamp, P., Broome, J, Sanderson, B., and Redden, A. 2015. Assessing the Performance of Passive Acoustic Monitoring Technologies for Porpoise Detection in a High Flow Tidal Energy Test Site. *Canadian Acoustics*, 43(3). https://tethys.pnnl.gov/publications/assessing-performance-passive-acoustic-monitoring-technologies-porpoise-detection-high

Qi, B., Shi, H., Zhuang, Y., Chen, H., and Chen, L. 2018. On-Board, Real-Time Preprocessing System for Optical Remote-Sensing Imagery. *Sensors*, 18(5), 1328. doi:10.3390/s18051328 https://tethys.pnnl.gov/publications/board-real-time-preprocessing-system-optical-remote-sensing-imagery

Raghukumar, K., Chang, G., Spada, F. W., and Jones, C. A. 2019. Performance Characteristics of the NoiseSpotter: An Acoustic Monitoring and Localization System. Paper presented at the Offshore Technology Conference, Houston, Texas. doi:10.4043/29425-MS https://tethys.pnnl.gov/publications/performance-characteristics-noisespotter-acoustic-monitoring-localization-system

Redmon, J., and Farhadi, A. 2018. YOLOv3: An Incremental Improvement. Report by University of Washington. https://tethys.pnnl.gov/publications/yolov3-incremental-improvement

Roberts, B. L., and Read, A. J. 2015. Field assessment of C-POD performance in detecting echolocation click trains of bottlenose dolphins (*Tursiops truncatus*). *Marine Mammal Science*, 31(1), 169-190. doi:10.1111/mms.12146 https://tethys.pnnl.gov/publications/field-assessment-c-pod-performance-detecting-echolocation-click-trains-bottlenose

Robinson, S., and Lepper, P. 2013. Scoping Study: Review of Current Knowledge of Underwater Noise Emissions from Wave and Tidal Stream Energy Devices. Report by Loughborough University for The Crown Estate. https://tethys.pnnl.gov/publications/scoping-study-review-current-knowledge-underwater-noise-emissions-wave-tidal-stream

Ross, T., and Lueck, R. 2003. Sound scattering from oceanic turbulence. *Geophysical Research Letters*, 30(6), 6-9. doi:10.1029/2002GL016733 https://tethys.pnnl.gov/publications/sound-scattering-oceanic-turbulence

Sarnocinska, J., Tougaard, J., Johnson, M., Madsen, P. T., and Wahlberg, M. 2016. Comparing the performance of C-PODs and SoundTrap/PAMGUARD in detecting the acoustic activity of harbor porpoises *(Phocoena phocoena). Proceedings of Meetings on Acoustics, 27(1), 070013.* doi:10.1121/2.0000288 https://tethys.pnnl.gov/publications/comparing-performance-c-pods-soundtrappamguard-detecting-acoustic-activity-harbor

Sato, M., Horne, J. K., Parker-Stetter, S. L., and Keister, J. E. 2015. Acoustic classification of coexisting taxa in a coastal ecosystem. *Fisheries Research*, 172, 130-136. doi:10.1016/j.fishres.2015.06.019 https://tethys.pnnl.gov/publications/acoustic-classification-coexisting-taxa-coastal-ecosystem

Shen, H., Zydlewski, G. B., Viehman, H. A., and Staines, G. 2016. Estimating the probability of fish encountering a marine hydrokinetic device. *Renewable Energy*, 97, 746-756. doi:10.1016/j.renene.2016.06.026 https://tethys.pnnl.gov/publications/estimating-probability-fish-encountering-marine-hydrokinetic-device

Simmonds, J., and MacLennan, D. 2007. Fisheries Acoustics: Theory and Practice (Second ed.). Oxford, UK: Blackwell Publishing Ltd. doi:10.1002/9780470995303 https://tethys.pnnl.gov/publications/fisheries-acoustics-theory-practice

Smith, K., and Simpson, N. 2018. Y1 Environmental Monitoring Report (Report No. EnFAIT-EU-0035). Report by Nova Innovation. https://tethys.pnnl.gov/publications/y1-environmental-monitoring-report

Smith, L. M., Barth, J. A., Kelley, D. S., Plueddemann, A., Rodero, I., Ulses, G. A., Vardaro, M. F., and Weller, R. 2018. The Ocean Observatories Initiative. *Oceanography*, 31(1), 16-35. doi:10.5670/oceanog.2018.105 https://tethys.pnnl.gov/publications/ocean-observatories-initiative

Snohomish County Public Utility District No. 1. 2012. Admiralty Inlet Final License Application. FERC Project No. 12690. Report by Northwest National Marine Renewable Energy Center. https://tethys.pnnl.gov/publications/admiralty-inlet-final-license-application

Staines, G., Zydlewski, G., and Viehman, H. 2019. Changes in Relative Fish Density Around a Deployed Tidal Turbine during on-Water Activities. *Sustainability*, 11(22). doi:10.3390/su11226262 *https://tethys.pnnl.gov/publications/changes-relative-fish-density-around-deployed-tidal-turbine-during-water-activities*

Stanton, T. K., Sellers, C. J., and Jech, J. M. 2012. Resonance classification of mixed assemblages of fish with swimbladders using a modified commercial broadband acoustic echosounder at 1–6 kHz. *Canadian Journal of Fisheries and Aquatic Sciences*, 69(5), 854-868. doi:10.1139/f2012-013 *https://tethys.pnnl.gov/publications/resonance-classification-mixed-assemblages-fish-swimbladders-using-modified-commercial*

Struthers, D. P., Danylchuk, A. J., Wilson, A. D. M., and Cooke, S. J. 2015. Action Cameras: Bringing Aquatic and Fisheries Research into View. *Fisheries*, 40(10), 502-512. doi:10.1080/03632415.2015.1082472 *https://tethys.pnnl.gov/publications/action-cameras-bringing-aquatic-fisheries-research-view*

The Electrochemical Society. 2011. Uhlig's Corrosion Handbook (R. W. Revie Ed. Third ed.). Hoboken, NJ: John Wiley & Sons, Inc. doi:10.1002/9780470872864 *https://tethys-engineering.pnnl.gov/publications/uhligs-corrosion-handbook*

Thomson, J., Polagye, B., Durgesh, V., and Richmond, M. C. 2012. Measurements of Turbulence at Two Tidal Energy Sites in Puget Sound, WA. *IEEE Journal of Oceanic Engineering*, 37(3), 363-374. doi:10.1109/JOE.2012.2191656 *https://tethys-engineering.pnnl.gov/publications/measurements-turbulence-two-tidal-energy-sites-puget-sound-wa*

Tollit, D., and Redden, A. 2013. Passive Acoustic Monitoring of Cetacean Activity Patterns and Movements in Minas Passage: Pre-Turbine Baseline Conditions (2011-2012). Report by Acadia Centre for Estuarine Research for Fundy Ocean Research Center for Energy. *https://tethys.pnnl.gov/publications/passive-acoustic-monitoring-cetacean-activity-patterns-movements-minas-passage-pre*

Trevorrow, M. V. 2003. Measurements of near-surface bubble plumes in the open ocean with implications for high-frequency sonar performance. *The Journal of the Acoustical Society of America*, 114(5), 2672-2684. doi:10.1121/1.1621008 *https://tethys.pnnl.gov/publications/measurements-near-surface-bubble-plumes-open-ocean-implications-high-frequency-sonar*

Trudel, M., and Boisclair, D. 1996. Estimation of fish activity costs using underwater video cameras. *Journal of Fish Biology*, 48(1), 40-53. doi:10.1111/j.1095-8649.1996.tb01417.x *https://tethys.pnnl.gov/publications/estimation-fish-activity-costs-using-underwater-video-cameras*

Underwood, M., M. Sherlock, A. Marouchos, J. Cordell, R. Kloser and T. Ryan. 2014. A combined acoustic and optical instrument for industry managed fisheries studies. 2014 Oceans - St. John's, St. John's, NL. doi:10.1109/OCEANS.2014.7003233 *https://tethys.pnnl.gov/publications/combined-acoustic-optical-instrument-industry-managed-fisheries-studies*

Urban, P., Köser, K., and Greinert, J. 2017. Processing of multibeam water column image data for automated bubble/seep detection and repeated mapping. *Limnology and Oceanography: Methods*, 15(1), 1-21. doi:10.1002/lom3.10138 *https://tethys.pnnl.gov/publications/processing-multibeam-water-column-image-data-automated-bubbleseep-detection-repeated*

Vagle, S., and Farmer, D. M. 1992. The Measurement of Bubble-Size Distributions by Acoustical Backscatter. *Journal of Atmospheric and Oceanic Technology*, 9(5), 630-644. doi:10.1175/1520-0426(1992)009<0630:TMOBSD>2.0.CO;2 *https://tethys.pnnl.gov/publications/measurement-bubble-size-distributions-acoustical-backscatter*

Viehman, H., Boucher, T., and Redden, A. 2018. Winter and summer differences in probability of fish encounter (spatial overlap) with MHK devices. Paper presented at the 13th European Wave and Tidal Energy Conference, Napoli, Italy. *https://tethys.pnnl.gov/publications/winter-summer-differences-probability-fish-encounter-spatial-overlap-mhk-devices*

Viehman, H. A., and Zydlewski, G. B. 2014. Fish Interactions with a Commercial-Scale Tidal Energy Device in the Natural Environment. *Estuaries and Coasts*, 38(1), 241-252. doi:10.1007/s12237-014-9767-8 *https://tethys.pnnl.gov/publications/fish-interactions-commercial-scale-tidal-energy-device-natural-environment*

Viehman, H. A., and Zydlewski, G. B. 2017. Multi-scale temporal patterns in fish presence in a high-velocity tidal channel. *PLoS ONE*, 12(5), e0176405. doi:10.1371/journal.pone.0176405 https://tethys.pnnl.gov/publications/multi-scale-temporal-patterns-fish-presence-high-velocity-tidal-channel

Viehman, H. A., Zydlewski, G. B., McCleave, J. D., and Staines, G. J. 2015. Using Hydroacoustics to Understand Fish Presence and Vertical Distribution in a Tidally Dynamic Region Targeted for Energy Extraction. *Estuaries and Coasts*, 38(1), 215-226. doi:10.1007/s12237-014-9776-7 https://tethys.pnnl.gov/publications/using-hydroacoustics-understand-fish-presence-vertical-distribution-tidally-dynamic

Wang, D., Atlar, M., and Sampson, R. 2007. An experimental investigation on cavitation, noise, and slipstream characteristics of ocean stream turbines. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 221(2), 219-231. doi:10.1243/09576509JPE310 https://tethys-engineering.pnnl.gov/publications/experimental-investigation-cavitation-noise-slipstream-characteristics-ocean-stream

Warren, J. D., and Wiebe, P. H. 2008. Accounting for biological and physical sources of acoustic backscatter improves estimates of zooplankton biomass. *Canadian Journal of Fisheries and Aquatic Sciences*, 65(7), 1321-1333. doi:10.1139/F08-047 https://tethys.pnnl.gov/publications/accounting-biological-physical-sources-acoustic-backscatter-improves-estimates

Wiesebron, L. E., Horne, J. K., Scott, B. E., and Williamson, B. J. 2016. Comparing nekton distributions at two tidal energy sites suggests potential for generic environmental monitoring. *International Journal of Marine Energy*, 16, 235-249. doi:10.1016/j.ijome.2016.07.004 https://tethys.pnnl.gov/publications/comparing-nekton-distributions-two-tidal-energy-sites-suggests-potential-generic

Wilding, T. A., Gill, A. B., Boon, A., Sheehan, E., Dauvin, J. C., Pezy, J.-P., O'Beirn, F., Janas, U., Rostin, L., and De Mesel, I. 2017. Turning off the DRIP ('Data-rich, information-poor') – rationalising monitoring with a focus on marine renewable energy developments and the benthos. *Renewable and Sustainable Energy Reviews*, 74, 848-859. doi:10.1016/j.rser.2017.03.013 https://tethys.pnnl.gov/publications/turning-drip-data-rich-information-poor-rationalising-monitoring-focus-marine

Williams, K., De Robertis, A., Berkowitz, Z., Rooper, C., and Towler, R. 2014. An underwater stereo-camera trap. *Methods in Oceanography*, 11, 1-12. doi:10.1016/j.mio.2015.01.003 https://tethys.pnnl.gov/publications/underwater-stereo-camera-trap

Williamson, B., Blondel, P., Armstrong, E., Bell, P. S., Hall, C., Waggitt, J. J., and Scott, B. E. 2016a. A Self-Contained Subsea Platform for Acoustic Monitoring of the Environment Around Marine Renewable Energy Devices–Field Deployments at Wave and Tidal Energy Sites in Orkney, Scotland. *IEEE Journal of Oceanic Engineering*, 41(1), 67-81. doi:10.1109/JOE.2015.2410851 https://tethys.pnnl.gov/publications/self-contained-subsea-platform-acoustic-monitoring-environment-around-marine-renewable

Williamson, B., Fraser, S., Blondel, P., Bell, P., Waggitt, J., and Scott, B. 2016b. Integrating a Multibeam and a Multifrequency Echosounder on the Flowbec Seabed Platform to Track Fish and Seabird Behavior around Tidal Turbine Structures. Paper presented at the 4th Marine Energy Technology Symposium, Washington D.C. https://tethys.pnnl.gov/publications/integrating-multibeam-multifrequency-echosounder-flowbec-seabed-platform-track-fish

Williamson, B., Fraser, S., Williamson, L., Nikora, V., and Scott, B. 2019. Predictable changes in fish school characteristics due to a tidal turbine support structure. *Renewable Energy*, 141, 1092-1102. doi:10.1016/j.renene.2019.04.065 https://tethys.pnnl.gov/publications/predictable-changes-fish-school-characteristics-due-tidal-turbine-support-structure

Williamson, B., Fraser, S., Blondel, P., Bell, P. S., Waggitt, J. J., and Scott, B. E. 2017. Multisensor Acoustic Tracking of Fish and Seabird Behavior Around Tidal Turbine Structures in Scotland. *IEEE Journal of Oceanic Engineering*, 42(4), 948-965. doi:10.1109/JOE.2016.2637179 https://tethys.pnnl.gov/publications/multisensor-acoustic-tracking-fish-seabird-behavior-around-tidal-turbine-structures

Wilson, B., Benjamins, S., and Elliott, J. 2013. Using drifting passive echolocation loggers to study harbour porpoises in tidal-stream habitats. *Endangered Species Research*, 22(2), 125-143. doi:10.3354/esr00538 https://tethys.pnnl.gov/publications/using-drifting-passive-echolocation-loggers-study-harbour-porpoises-tidal-stream

Wilson, B., Lepper, P., Carter, C., and Robinson, S. 2014. Rethinking Underwater Sound-Recording Methods to Work at Tidal-Stream and Wave-Energy Sites. In Shields, M. and Payne, A. (Eds.), *Marine Renewable Energy Technology and Environmental Interactions* (pp. 111-126): Springer, Dordrecht. *https://tethys.pnnl.gov/publications/rethinking-underwater-sound-recording-methods-work-tidal-stream-wave-energy-sites*

Worthington, M. 2014. Acoustic Monitoring of Beluga Whale Interactions with Cook Inlet Tidal Energy Project (Report No. DE-EE0002657). Ocean Renewable Power Company Alaska, Anchorage, Alaska. Report by Ocean Renewable Power Company for U.S. Department of Energy. *https://tethys.pnnl.gov/publications/acoustic-monitoring-beluga-whale-interactions-cook-inlet-tidal-energy-project*

Xu, W., and Matzner, S. 2018. Underwater Fish Detection using Deep Learning for Water Power Applications. Paper presented at the 2018 International Conference on Computational Science and Computational Intelligence, Las Vegas, NV. doi:10.1109/CSCI46756.2018.00067 *https://tethys.pnnl.gov/publications/underwater-fish-detection-using-deep-learning-water-power-applications*

NOTES

Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines

Hasselman, D.J., D.R. Barclay, R.J. Cavagnaro, C. Chandler, E. Cotter, D.M. Gillespie, G.D. Hastie, J.K. Horne, J. Joslin, C. Long, L.P. McGarry, R.P. Mueller, C.E. Sparling, and B.J. Williamson. 2020. Environmental Monitoring Technologies and Techniques for Detecting interactions of Marine Animals with Turbines. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 176-212). doi:10.2172/1633202

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

Section D

Strategies for Accelerating Consenting/Permitting

11.0

Chapter author: Anne Marie O'Hagan
Contributors: Dorian M. Overhus and Mikaela C. Freeman

Marine Spatial Planning and Marine Renewable Energy

Marine spatial planning (MSP) is advocated internationally as an improved approach to managing marine activities that addresses competing sectors and balances environmental, social, and economic interests (Ehler 2008; Ehler and Douvere 2009; SCBD 2012). The benefits of MSP are cited as being increased transparency and certainty for industry, improved environmental protection, reduced sectoral conflicts, and providing opportunities for synergies. Approaches to implementation of MSP vary by country and sometimes within countries. As a relatively new and novel approach to managing marine activities, it can be difficult to determine when success has occurred or what might constitute more effective and efficient management systems. The growth of marine renewable energy (MRE) will result in the increasing use of sea space and potential for conflict with existing marine uses, both of which can be addressed, in part, through implementation of MSP.

11.1. BACKGROUND ON MSP

All MSP systems try to reflect key principles that are science- or evidence-based, integrated, adaptive, strategic, and participatory (Figure 11.1). These principles can present challenges for implementation because they necessitate a departure from traditional forms of marine management, whereby activities are managed on a sectoral basis with limited consideration of other activities occurring in the same space or their potential effects on the receiving environment individually or cumulatively. As such, sectoral management has resulted in a somewhat ad hoc approach to planning, that is, allocation of sea space primarily occurs on a case-by-case basis; hence, it lacks an integrated and strategic approach. While definitions of MSP are numerous, the most widely adopted is that of the United Nations Educational, Scientific and Cultural Organization, which defines MSP as "a public process of analyzing 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" (Ehler and Douvere 2009; Ehler 2014). MSP is a future-oriented process that can be used to assign space to different uses and manage the location of specific human activities in time and space, but practical production of marine goods and services will continue to be conducted through the granting of consents/permits (hereafter consents), permissions, and licenses for specific activities. MSP does not always culminate in the allocation of zones for marine activities but could be used to advocate preferred activities or priorities, reflecting national policy objectives, for example. As a future-oriented process, MSP enables decision-makers to plan and take management actions that should lead to some agreed-upon future spatial vision for marine areas and help to manage potential new uses, such as MRE.

This chapter documents how MSP is currently being used to plan and develop MRE in the 15 countries that are currently involved in Ocean Energy Systems (OES)-Environmental. The information presented in this chapter derives from answers to a questionnaire completed by OES-Environmental participant country representatives or their suggested contacts and, where appropriate, supplemented by relevant external sources. The questionnaire, available online as supplementary material (at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-marine-spatial-planning*), requested input about the approaches to MSP in each country; if and how MRE policies link to MSP; how scientific information informs the process;

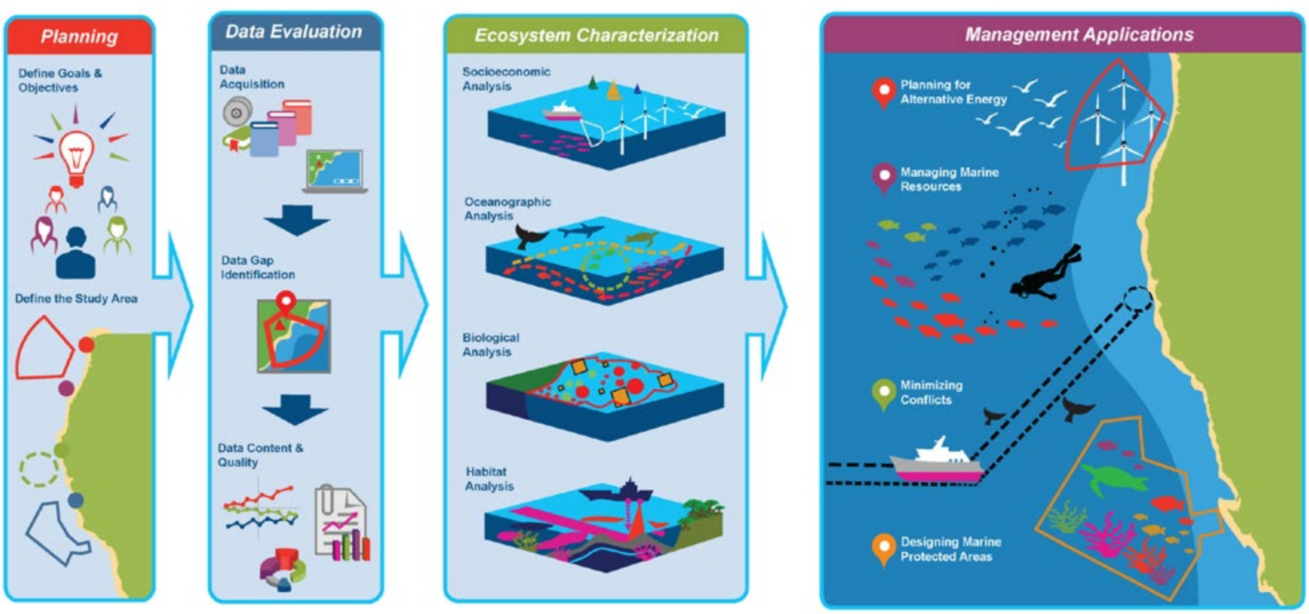


Figure 11.1. Example of a decision support process for marine spatial planning, implemented in a logical sequence of steps in information synthesis: 1) Planning: talking with managers to determine priorities; 2) Data evaluation: assessing the data and identifying data gaps; 3) Ecosystem characterization: describing the ecosystem patterns and processes including human activities across the area of interest; and 4) Management applications: working with managers to support specific management applications. (Image courtesy of the National Oceanic and Atmospheric Administration – National Centers for Coastal Ocean Science)

how potential conflicts are managed; zoning for MRE; tools used to implement MSP; how consenting processes link to MSP; possible challenges to implementation of MSP for MRE; how the public is involved in MSP; and an option to include any further comments.

Each of the questionnaire topic areas is covered thematically in the following sections, closing with a final section about key findings and conclusions derived from questionnaire answers. Given the strong legal basis for MSP in the European Union (EU), findings from participating countries in the EU (Denmark, France, Ireland, Portugal, Spain, and Sweden) are presented first followed by those from the United Kingdom (UK: England, Northern Ireland, Scotland, Wales), Australia, India, Japan, South Africa, and the United States (U.S.). The terminology used reflects that used in the country; for example, certain countries refer to offshore renewable energy in their legislation and policies, covering all forms of marine renewables (wave, tidal, offshore wind, etc.), whereas elsewhere explicit technology types are referred to in policy. In each section, information is given for countries for which respondents provided detailed answers; therefore, not every section addresses each country. For additional details and information about MSP in each of these countries, supplementary information is provided at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-marine-spatial-planning*.

11.2. APPROACHES TO MSP IN OES-ENVIRONMENTAL PARTICIPATING COUNTRIES

Approximately 70 countries worldwide (Marine Spatial Planning Programme 2018) are now estimated to have some form of MSP in varying stages of implementation. Some countries and regions have a legal basis for implementing MSP, whereas others have conducted MSP on a less formal, non-statutory basis. In the EU, MSP has had a basis in law since 2014 because of the adoption of a framework MSP Directive (Directive 2014/89/EU), which requires coastal member states to have maritime spatial plans in place for their waters by March 2021. As a result, all coastal member states are currently at varying stages of progress in implementing MSP. Certain countries had MSP in place before the EU MSP Directive came into force; e.g., Belgium, Scotland, England, the Netherlands, and a number of the Baltic Sea countries. Other EU countries, such as France, Ireland, and Spain, are in the initial stages of plan development. Details about the approaches to MSP for each OES-Environmental country can be found in Table 11.1. More detailed descriptions can be found at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-marine-spatial-planning*.

Table 11.1. Marine spatial planning (MSP)-specific approaches for the Ocean Energy Systems (OES)-Environmental (in alphabetical order by European Union [EU] countries first, then by the other countries).

Country		MSP-Specific Information
EU	Denmark	• Legislation mandating MSP has been in place since 2016, but there is no comprehensive plan. • A range of sectoral plans covering energy infrastructure, fisheries, and nature protection will be used to inform the forthcoming national marine plan.
	France	• MSP is implemented through "Strategic Façade Planning Documents," coordinated by the Ministry for the Solidarity and Ecological Transition for each of four national sea basins[1] (Décret n° 2017-724). • Liaison via a national Façade Maritime Council.
	Ireland	• The first national marine spatial plan is being developed. • The plan will be implemented via the National Marine Planning Framework (NMPF) (DHPLG 2019a). • A draft version of the plan, the NMPF, was published for consultation in November 2019 (DHPLG 2019a). • Information about the progress of the NMPF is publicly available.
	Portugal	• Mechanisms for MSP operate in a complementary manner with strategic mechanisms (such as the National Strategy for the Ocean as the planning and management policy) and operational mechanisms (the Situation Plan [DGRM 2018] and Allocation Plans).
	Spain	• No MSP currently exists; the EU MSP Directive (Directive 2014/89/EU) was transposed into Spanish law through Royal Decree 363/2017 (Real Decreto 363/2017). • The Royal Decree specifies management plans for the North Atlantic, South Atlantic, Estrecho and Alboran, Levantine-Balearic, and Canary Islands. • Progress is being made on the development of and agreement about MSP objectives.
	Sweden	• The Swedish Planning and Building Act (Plan-och bygglag 2010) preceded the EU MSP Directive (Directive 2014/89/EU). • Municipalities must plan throughout the Swedish territory, land, internal waters, and territorial sea out to 12 nautical miles. • Three draft marine spatial plans covering the Gulf of Bothnia, the Baltic Sea, and Western Waters (Skagerrak/Kattegat) were published in 2019 (Swedish Agency for Marine and Water Management 2018; European MSP Platform 2020). • The marine spatial plans being prepared currently will encompass the area one nautical mile from the baseline seaward and will include the Exclusive Economic Zone, but will not cover privately owned sea areas (private waters).
United Kingdom (UK)		• MSP has been in place since 2010 with adoption of the UK Marine and Coastal Access Act 2009. • The Act is complemented by legislation in Scotland and Northern Ireland.
	England	• 11 marine plan regions are to be developed by the Marine Management Organisation. • So far, six plans have been published: the East Marine Plan, North East Marine Plan, North West Marine Plan, South Marine Plans, South East Marine Plan, and South West Marine Plan (Department for Environment, Food and Rural Affairs 2014; 2018; Marine Management Organisation 2020a, 2020b; 2020c; 2020d). • Each plan has vision, objectives, and policies.
	Scotland	• The Scottish National Marine Plan was published in 2015 (Marine Scotland 2015) identifying Marine Scotland as the responsible body. • The key legislation driving MSP are the Marine (Scotland) Act (2010) and the UK Marine and Coastal Access Act (2009). • Under the 2010 Act, Regional Marine Plans are to be developed for 11 regions. • Only the plan for the Clyde and Shetland Isles region has gone forward; the Orkney plan is in development.
	Wales	• The Welsh National Marine Plan (WNMP) was published in 2019 (Welsh Government 2019), developed based on the UK Marine and Coastal Access Act (2009), the UK Marine Policy Statement (HMG 2011), and the EU MSP Directive (Directive 2014/89/EU).
	Northern Ireland	• The Draft Marine Plan for Northern Ireland was published in 2018 (DAERA 2018a). The Department of Agriculture, Environment and Rural Affairs is the responsible authority. • However, the lack of a government from 2017–2019 brought progress to a standstill.[2]

continued

1. For instance: the North Atlantic – West Channel (Nord Atlantique – Manche Ouest) sea basin, see *http://www.dirm.nord-atlantique-manche-ouest.developpement-durable.gouv.fr/IMG/pdf/synthese_vf_cle6e72f2.pdf*; or the Mediterranean sea basin *http://www.dirm.mediterranee.developpement-durable.gouv.fr/la-strategie-de-facade-maritime-est-adoptee-a2892.html*
2. The Northern Ireland Executive and Assembly collapsed in January 2017 owing to ongoing disagreements between the two main political parties and all attempts to restore power-sharing had failed until January 2020, when the Government was restored. Formal adoption of the MSP is therefore anticipated to occur later in 2020.

Country	MSP-Specific Information
Australia	◆ Formal MSP processes exist across several jurisdictions. ◆ Ocean policy established in 1998 is driving marine bioregional planning (Department of the Environment and Heritage 2006). ◆ The existing policy balances social, economic, and environmental objectives, but is not implemented (Vince et al. 2015). ◆ South Australia published the Marine Planning Framework in 2006 (Department for Environment and Heritage 2006). ◆ Along with the Marine and Coastal Reforms Final Transition Plan (State of Victoria DELWP 2018), Victoria enacted the Marine and Coastal Act 2018, which requires the development of an MSP Framework. This was published in 2020 as part of a state-wide Marine and Coastal Policy (State of Victoria DELWP 2020).
India	◆ No MSP is in place and there is no use of specific MSP terminology in legislation or policy. ◆ The principles of MSP and environmental impact assessments (EIAs) are required for developing marine projects in India (Dineshbabu et al. 2019). ◆ Several laws and policies for coastal zone management exist.
Japan	◆ Japan has no formal MSP process. ◆ The Basic Act on Ocean Policy (2007) was enacted in 2007 to assist with marine development, security, scientific knowledge, and governance and to develop a comprehensive ocean policy, to be reviewed on a five-year basis. ◆ In 2018, the Third Basic Plan on Ocean Policy was approved with no specific mention of MSP with objectives for industrial ocean uses, maintenance, and conservation.
South Africa	◆ Implementation of the Marine Spatial Planning Act (2018) began in 2019. ◆ The purpose of the Act is to develop an MSP system for all sectors, for sustainable economic opportunities through coordinated and integrated planning and conservation of the marine environment. ◆ The National Framework for MSP provides high-level direction for MSP within other relevant policies, planning regimes, and developing Marine Area Plans (The Republic of South Africa 2017).
United States (U.S.)	◆ There is no formal MSP process nationally. ◆ Some coastal states (Oregon, Massachusetts, Rhode Island and Washington) enacted MSPs to help guide conservation and use of ocean space through marine plans or MSP principles (Rhode Island State 2020; Commonwealth of Massachusetts 2020; State of Washington 2020; Department of Land Conservation and Development 2020). ◆ Executive Order 13547 (2010) called for regional MSP across the U.S. Two plans were created in 2016 the Northeast Ocean Plan (Northeast Regional Planning Body 2016) and the Mid-Atlantic Regional Ocean Action Plan (Mid-Atlantic Regional Planning Body 2016).

11.3. MRE POLICIES AND LINKS TO MSP

MSP tends to be strategic in nature and often contains broad management principles and objectives that apply to multiple marine sectors rather than being prescriptive about what activity can occur where. As such, it is relevant to document whether countries have national MRE strategies or policies and whether the strategies and policies have been explicitly recognized in the MSP process. Beginning with the EU, and possibly as a result of legislation about renewable energy, a number of countries have dedicated policies specific to offshore wind or MRE (wave and tidal) in particular. Details about MRE policies and the link to MSP for the OES-Environmental country can be found in Table 11.2. More detailed descriptions can be found at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-marine-spatial-planning*.

Table 11.2. Marine renewable energy (MRE) policies and their links to marine spatial planning (MSP) for the Ocean Energy Systems (OES)-Environmental nations (arranged in alphabetical order by European Union [EU] countries first, then by the other countries).

Country		MSP-Specific Information
EU	Denmark	◆ A technical report was published in 2012 focusing on wave energy strategies (Nielsen et al. 2012). ◆ The Danish Wave Power Roadmap was published in 2015 (Nielsen et al. 2015) and produced by a consortium that includes nine Danish wave energy developers.
	France	◆ France has defined targets and quantified objectives to add MRE to the national energy mix. ◆ A 2015 law on energy transition, was supplemented by the French Strategy for Energy and Climate Multi-Annual Energy Plan (PPE [Programmations Pluriannuelles de l'Énergie] in French), updated in 2019 for future contribution of bottom-mounted and floating offshore wind (Ministère de la Transition Écologique et Solidaire 2019a). ◆ There has been no explicit call for MRE, while acknowledging tidal development is maturing.
	Ireland	◆ No specific plan for MRE but the intention is there will be one (DHPLG 2017); development is guided by the Offshore Renewable Energy Development Plan (DCENR 2014; DCCAE 2018). ◆ In 2019, the Climate Action Plan (DHPLG 2019b), together with the NMPF (DHPLG 2019a) and the marine consenting system, will drive MRE development in coming years.
	Portugal	◆ Several strategic government documents since 2007 have highlighted MRE with the intent of optimizing use of available marine space, increasing synergies, and minimizing conflict between all marine activities. ◆ Specific targets for MRE are not included in any of the strategic documents, but the recent MRE roadmap (2017) estimates an installed capacity of 400 MW (260 MW for offshore wind and 140 MW for wave energy) by 2030 (Government of Portugal 2017). ◆ MRE development is reflected in MSP through inclusion of the Aguçadoura test site and designation of a Pilot Zone from San Pedro de Moel to Viana do Castelo.
	Spain	◆ The National Renewable Energy Action Plan (NREAP) 2011–2020 (Ministerio de Industria, Turismo y Comercio 2010) has targets for 100 MW of installed power by 2020, but a feed-in tariff has been suspended since January 2012. ◆ The National Integrated Energy and Climate Plan 2021–2030 (Gobierno de España 2020) and the Draft Bill on Climate Change and Energy Transition (Ministry of the Presidency 2019) were updated in 2018 and presented to European Commission, but have not been enacted into law. The Plan aims to achieve up to 42 percent consumption of renewable energies by 2030 with land-based and offshore wind mainly, but it recognizes MRE. ◆ In 2017, the Basque Government approved an Energy Strategy for 2030 (Basque Energy Agency 2017) which includes support for MRE and a target of 60 MW for offshore wind and MRE by 2030. ◆ MRE is taken into account in the MSP process, and representatives from the sector have participated in meetings related to marine plan development.
	Sweden	◆ The Government intends to transition to 100 percent renewable energy by 2040 (Swedish Government 2016). ◆ MSP includes offshore wind and wave development (Swedish Agency for Marine and Water Management 2019). ◆ Use of the MSP process helped identify sites for offshore wind and testing and development zones for wave energy development. ◆ MSP states that several municipalities are planning for offshore energy development close to the coast by zoning suitable areas in their comprehensive plans under the Planning and Building Act (Plan-och bygglag 2010).

continued

Country		MSP-Specific Information
United Kingdom (U.K.)		• There is a 2050 target to reduce carbon emissions by 80 percent, but there are no specific targets for MRE (The Climate Change Act 2008). • The UK Government in Westminster makes certain legislation and policy but there are four separate legal systems: England, Scotland, Wales, and Northern Ireland, each with legislation of their own. • The Crown Estate manages lands held by the Crown and has legal authority to grant seabed or foreshore rights for uses including MRE.
	Scotland	• There is a Scottish national energy strategy (Scottish Government 2017), but no specific MRE strategy. • Energy policy shows the Scottish Government's commitment to developing MRE, including explicit statements that MRE contributes to achieving the 100 percent renewables target by 2020 (Marine Scotland 2015). • Scottish MSP does not have specific targets for offshore wind, wave, and tidal energy, but indicates their importance in contributing to renewables and decarbonization targets. • MRE is a specific sector in the Scottish National Marine Plan. The Scottish Government is developing plans for offshore wind, wave, and tidal energy in Scottish waters (Scottish Government 2012; 2018).
	Wales	• The Welsh Natural Resources Policy (Welsh Government 2017a), under the Environment (Wales) Act (2016), includes growth in renewables as a priority. • Natural Resources Wales has produced a Marine Area Statement (Natural Resources Wales 2020) to include MRE under the Environment (Wales) Act (2016). • The draft Welsh National Marine Plan identifies MRE as a priority sector for Wales with focus on tidal stream and wave energy over the next 5–10 years.
	Northern Ireland	• The Offshore Renewable Energy Strategic Action Plan 2012–2020 in place was developed in 2012 (DETI 2012). • The initial leasing round has been completed through The Crown Estate for one offshore wind and two tidal projects. • One tidal project is proceeding with the licensing process (DfE 2019). • Currently, Northern Ireland waters have been excluded from further leasing round (DfE 2019).
Australia		• There are no specific ocean energy strategy, targets, incentives, or legislation for MRE. • Some research funding exists for MRE and demonstration projects; the Australian Renewable Energy Agency funds some research into ocean energy, and several demonstrations deployments (<500 kW) have occurred in Australian waters. • The only MRE incorporated into the MSP process is in the Marine and Coastal Policy (State of Victoria DELWP 2020).
India		• The Draft National Renewable Energy Act 2015 (Ministry of New and Renewable Energy 2015) promotes all forms of renewable energy including ocean energy. • Ocean energy is still in demonstration stages in India, but it is now part of the non-solar Renewable Purchase Obligation promoted by the Government of India. • No specific targets have been defined for MRE development.
Japan		• No policies or targets specific to MRE development exist. • A Strategic Energy Plan is reviewed every three years. The most recent, the 5th Strategic Energy Plan, addresses the need for more research and development in ocean energy and covers measures to make wind power a major power source (Ministry of Economy, Trade, and Industry 2018). New legislation in 2019 covers use of sea areas for offshore wind.
South Africa		• No MSP is in place, but it has strong legal and policy bases for marine renewables (Marine Spatial Planning Act, 16 of 2018). • There are no targets in place for MRE development.
United States (U.S.)		• No federal MSP system is in place and MRE is not included as a specific sector. In 2017, the Presidential Executive Order 13783 (Executive Order 13783) established a policy of promoting clean and safe development of domestic energy resources, including renewable energy. • In 2018, the Presidential Executive Order 13840 heavily focused on developments of renewable energy industries, predominantly on offshore wind but also MRE and hydrokinetic technologies (Executive Order 13840). • In 2019, the Bureau of Ocean Energy Management (BOEM) published a new regional offshore wind leasing strategy (BOEM 2019). • Regional ocean partnerships, established in 2016 are heavily focused on developments in renewable energy industries, predominantly offshore wind but also MRE. These partnerships have slowed in recent years.

11.4.
TAKING MRE INTO ACCOUNT IN MSP

MRE has specific requirements from a planning process perspective. For example, MRE needs to link with other infrastructure such as grid provision and access to ports. Any development planning process must be cognizant of the receiving environment. To assure that these aspects are considered before a decision is made, many countries implement some form of environmental assessment (at the strategic or project level) that can then inform future planning processes. As part of environmental assessment requirements, and as a good practice generally, stakeholder consultation is also a fundamental part of the wider planning process. This consultation can occur with the public at large, with individual sectors, or with representative groups and ultimately should lead to a more robust and trusted planning process. These specific requirements of the MRE sector can be taken into account in the development of MSP processes in many ways. Given the implementation status of MSP across the globe, not all countries have addressed these requirements (namely India, South Africa, and the U.S.). In countries and regions where MSP is progressing, specific sectoral requirements are fed into the MSP process, primarily via consultation mechanisms either on an individual sectoral basis or through a dedicated stakeholder mechanism, and are described below. Such consultation is likely to evolve as implementation of MSP begins. The EU countries are most advanced in this respect, probably as a result of the EU MSP Directive (Directive 2014/89/EU) and over-arching climate and energy policies. Under the EU MSP Directive, all marine spatial plans must be subject to a Strategic Environmental Assessment to address environmental impacts at the earliest possible stage in decision-making. The details about each OES-Environmental country can be found in Table 11.3. More detailed descriptions can be found at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-marine-spatial-planning*.

11.5.
DEALING WITH POTENTIAL CONFLICTS BETWEEN MARINE SECTORS/USERS

An important consideration for MSP is potential conflicts between different marine sectors and/or users, especially as the demand for marine space increases and, on occasion, because certain sectors will be interested in the same spatial area. As a relatively new sector, MRE in particular has the potential to overlap with more traditional uses such as fishing and navigation. When multiple-use situations like this arise, it can be challenging to address the different interests and needs of multiple users in mutually satisfying ways. Compatibility between uses and activities depends not only on oceanographic conditions (such as sea turbulence, the nature of the seabed, or the size of the water column), but also on the size and characteristics of each project. Compatibility between activities within the same marine space can still be achieved if, for example, the activities can be carried out at different times of the year. This could be the case, for example, for dredging activities in overlying seawater columns where non-metallic resources could be exploited. One of the rationales for MSP is that it can prevent or minimize conflict, because it clarifies who/what activity can operate within particular spatial areas. Such conflicts tend to be resolved on a case-by-case basis with negotiations between the interested parties (Freeman et al. 2016) and sometimes an independent arbiter. Very few MSP systems contain specific provisions or mechanisms related to conflict resolution, despite the recognition of the potential for conflict in light of the increasing use of marine space and associated competition between uses. Details about how each OES-Environmental country deals with these conflicts can be found in Table 11.4. More detailed descriptions can be found at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-marine-spatial-planning*.

Table 11.3. Consideration of marine renewable energy (MRE) development within marine spatial planning (MSP) processes for the Ocean Energy Systems (OES)-Environmental nations (arranged alphabetically by European Union [EU] countries first, then by the other countries).

Country		MSP-Specific Information
EU	France	• The Programmations Pluriannuelles de l'Énergie (PPE) Strategic Environmental Assessment underlines the need for coherence and compatibility between MRE projects and those from other sectors (Ministère de la Transition Écologique et Solidaire 2019a). • Coordinating prefectures (maritime, regional, and departmental prefectures) provide a connection between regional and local marine sectors. • Stakeholders from socioeconomic sectors (fisheries, maritime transport, tourism, etc.), environmental sectors (marine protected areas [MPAs], nongovernmental organizations), public authorities, scientific and academic sectors, etc. work together on a common regional approach for MRE development.
	Ireland	• Representatives from the MRE sector are part of the National Advisory Board for MSP. • Feedback from the MRE industry helps with development of the policy.
	Portugal	• A final Situation Plan (DGRM 2018) has been developed to identify specific areas for MRE development along the coast. • Input is provided by stakeholders from multiple sectors.
	Spain	• The MSP process is at too early a stage to determine how sectoral MRE interests will be included.
	Sweden	• The presence of a national planning evidence and information system allows sectors to provide input to national government agencies to identify areas of national interest, including MRE.
United Kingdom (UK)	Scotland	• A strong heritage of research and development exists in MRE technologies and associated infrastructure and experience in testing these devices in Scottish waters. • The European Marine Energy Centre, based in Orkney, allows for testing and a pathway to commercialization for tidal and wave devices. • Orkney was selected as location for a Pilot Marine Spatial Plan Case Study (Marine Scotland 2016), including stakeholder engagement to inform Marine Scotland, Council Planners, and the marine community of knowledge regarding requirements for MRE development within a planning construct (Aquatera Ltd. 2015).
	Wales	• During 2017 and 2018, the Welsh National Marine Plan (Welsh Government 2019) was informed by a Stakeholder Reference Group that provided an opportunity for all stakeholders to comment on development of the final plan.
Australia		• The draft MSP framework for Victoria was developed collaboratively with stakeholders using a co-designing process.
Japan		• Environmental Impact Assessments drive consents for MRE. • The Japanese Ministry of Environment has been zoning areas for offshore wind energy development, and takes input from key energy industry players as well as stakeholders, including local fishermen.

11.6. AREAS AVAILABLE FOR MRE DEVELOPMENT

MSP is often interpreted to be synonymous with ocean zoning. Ocean zoning designates a specific space to marine uses and can be used to limit an area to a single activity or to accommodate multiple uses.

While zoning approaches can be used to implement MSP, it is just one tool for delivering the objectives of the MSP process. Some countries have zoned areas of their marine space for specific sectors, activities, and uses. The details about these areas of MRE development as defined for each OES-Environmental country can be found in Table 11.5 (also see Figures 11.2 and 11.3). More detailed descriptions can be found at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-marine-spatial-planning*.

Table 11.4. Information about how the Ocean Energy Systems (OES)-Environmental nations deal with conflicts that often arise during the marine spatial planning (MSP) process (arranged alphabetically by European Union [EU] countries first, then by the other countries).

Country		MSP-Specific Information
EU	France	• Early consultation with marine users and activities in the MSP process and mapping of existing uses of space help reduce and manage potential conflicts. • Strategic phases of MSP implementation rely heavily on mapping specific uses of marine space. • The fisheries sector provides information about fishing areas using geographic information systems to avoid conflicts (Université de Nantes 2019).
	Ireland	• Conflicts between marine users are most likely to be addressed on a case-by-case basis rather than by MSP.
	Portugal	• The Situation Plan (DGRM 2018) favors the multi-use of marine space and compatibility between uses, especially because it enables optimization of the economic potential of a space. • The Direção-Geral de Recursos Naturais, Segurança e Serviços Marítimos (DGRM [Directorate-General for Natural Resources, Safety and Maritime Services]) manages use conflicts for marine activities through the consenting process.
	Spain	• Conflicts between marine users are most likely to be addressed on a case-by-case basis rather than by MSP.
	Sweden	• Activities related to defense and security have priority under Swedish legislation as part of their marine spatial plans (Swedish Agency for Marine and Water Management 2018; European MSP Platform 2020), thereby restricting development of some offshore renewables. • In certain locations, nature conservation has been given priority over other activities as well, while coexistence is promoted in other areas such as some Natura 2000 sites (network of nature protection), with appropriate permits.
United Kingdom	Scotland	• The National Marine Planning system identifies potential conflicts and addresses and reduces these conflicts before they arise. • With only two of several planned Marine Planning Partnerships developed (Clyde and the Shetland Isles), the default is a highly communicative system with different sectors engaging in the planning process, assuring their voices are heard, and incorporating their thoughts in the plan to help reduce conflict.
	Wales	• The Welsh National Marine Plan (WNMP) (Welsh Government 2019) is to be accompanied by implementation guidance, which will include conflict resolution procedures. • The WNMP encourages measures to reduce conflict, such as co-location of activities and sectors.
Australia		• Victoria’s draft MSP Framework provides high-level guidance for considering conflicts between sectors when completing a MSP process.
India		• This situation has not yet been considered
Japan		• Stakeholder consultation is fundamental to minimizing conflict and critical to the successful zoning of marine activities. • When siting MRE developments, conservation areas, shipping routes, and emergency access routes are avoided. • Coexistence with fishing activity is regarded as the most important issue and accordingly, there are frequent meetings with these representatives when carrying out planning.
South Africa		• Addressing conflict between marine users is one of the main drivers of MSP. • Development of marine plans is conducted specifically for the purpose of addressing known and anticipated future conflicts between sectors.
United States (U.S.).		• This situation has not yet been considered

Table 11.5. Areas available for marine renewable energy (MRE) development for the Ocean Energy Systems (OES)-Environmental nations (arranged alphabetically by European Union [EU] countries first, then by the other countries).

Country		**Marine Spatial Planning (MSP)-Specific Information**
EU	France	• MRE projects are strongly excluded from military zones (for training, navigation, or security operations). Marine protected areas (MPAs) are also heavily protected. • For sea basins under the supervision of the Ministry for the Ecological and Inclusive Transition, macro-zones that could potentially host MRE projects have been identified, based largely on physical environmental conditions, geomorphology, risks to maritime security, etc. • Within the macro-zones, stakeholders provide input for siting specific projects.
	Ireland	• No areas have been identified as being prohibited for MRE activities. • It is likely that the new consenting system in the form of the Marine Planning and Development Management Bill (DHPLG 2019c) will enable zoning for different uses in the future.
	Portugal	• Areas are allocated in the marine spatial plan for MRE but require a Title for the Private Use of the Maritime Space. • Other uses are also allowed in this space, based on their compatibility. Compatible uses are illustrated in Figure 11.2. • MRE development approved outside the designated areas will be incorporated into the Situation Plan (DGRM 2018). • Regulations for certain activities create exclusion areas and safety zones.
	Spain	• No areas prohibit wave or tidal energy, nor are there preferred deployment areas.
	Sweden	• No areas are fully prohibited for MRE development, but additional licensing requirements may be needed in areas designated for conservation purposes.
United Kingdom (UK)	Scotland	• Some areas are generally prohibited for MRE development and require consenting requirements that effectively make development impossible. • MRE projects are prohibited from areas designated as firing ranges used by the Ministry of Defence. • Preferred zones and locations for MRE are under development as part of the Sectoral Plans put together by Marine Scotland (Scottish Government 2020; Marine Scotland 2014). • "Preferred areas" will become clearer as more Scottish Marine Regions develop their Regional Marine Plans.
	Wales	• MRE development is constrained in areas used by the Ministry of Defence, as shipping lanes, and designated as safety zones around existing infrastructure, and potential development is managed on a case-by-case basis. • The Welsh National Marine Plan (Welsh Government 2019) identifies Strategic Resource Areas for MRE, based on available energy resources. Consultation on the plan focused on lack of clarity about intended uses. The final marine spatial plan did not include the Strategic Resource Areas but have retained an ambition to move towards spatial specify within future iterations of the plan.
Australia		• No preferred locations for ocean energy have been designated, even with one of the most mature examples of zoning in marine waters (Great Barrier Reef Marine Park Act 1975). • Several existing uses of the marine space are managed by leasing (e.g., petroleum and greenhouse gas titles, aquaculture leases). • In the state of Victoria, MPAs consist of no-take and multiple-use areas.
India		• No preferred areas or zones exist for ocean energy. • MRE and other ocean energy development are prohibited in protected areas around islands as well as coastal areas that feature mangroves, national parks, sanctuaries, and naval bases.
Japan		• MRE development is not prohibited in any area, but development is very challenging in Natural Parks, tidal flats, seaweed beds, coral reefs, and fish spawning grounds. • Reversing past practice, 2016 legislation now allows for future energy developments in ports and harbors. • Designated demonstration sites for MRE research and development have been selected by local governments proposing a demonstration site (see Figure 11.3).
South Africa		• There are no prohibited areas for MRE or preferred locations for its deployment. • The South African National Working Group on MSP is finalizing the Current Status Report, which will provide information about locations for MRE development and other ocean activities.
United States (U.S.)		• No areas have been designated for MRE development, but preferred areas for offshore wind development have been designated in the Atlantic by the Bureau of Ocean Energy Management. • Prohibitions are in place for National Marine Sanctuaries, National Parks, National Monuments, shipping lanes, and MPAs (National Marine Sanctuaries Act of 2000). • Areas identified by the U.S. Department of Defense as critical to their activities require additional layers of consultation and review.

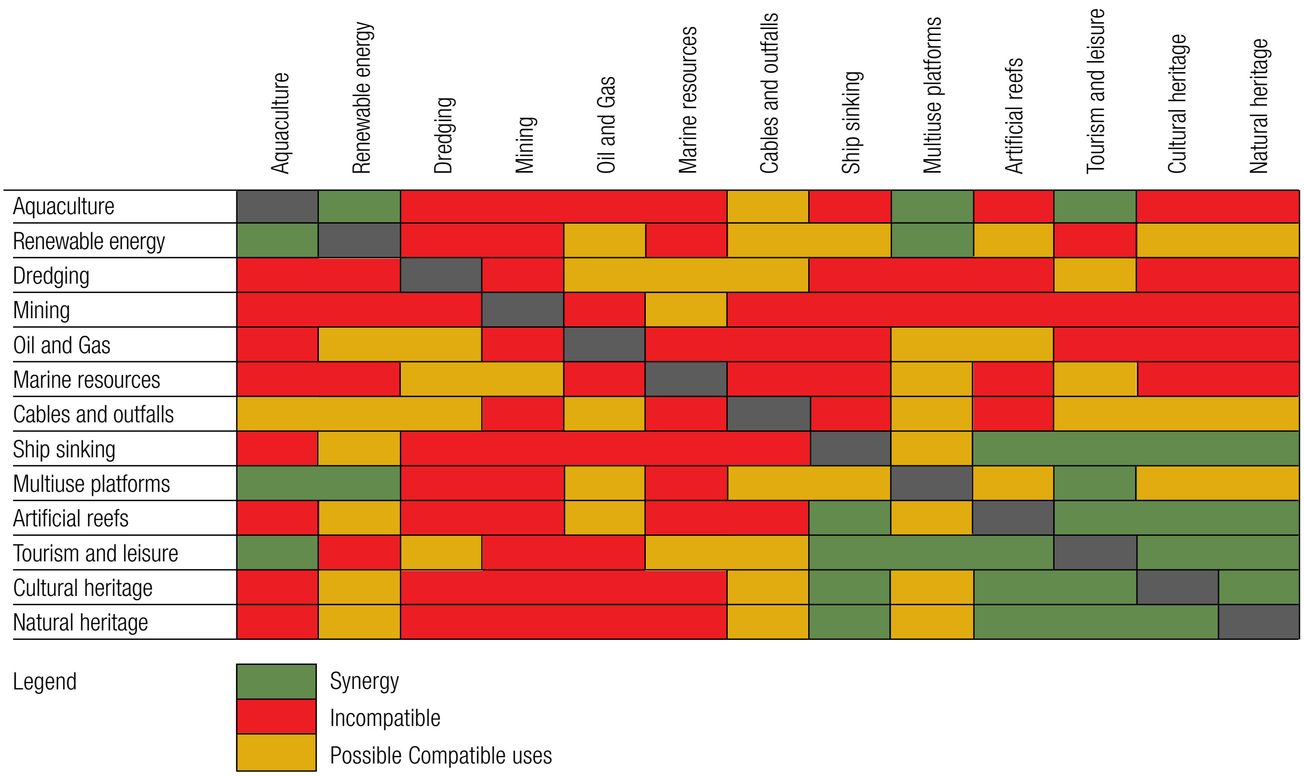


Figure 11.2. Compatible, incompatible, and synergistic marine sectors, as identified in the Portuguese Situation Plan. This figure is theoretical and the fact that two activities are indicated as compatible does not mean that this happens in practice or out of necessity. (Adapted and translated from DGRM 2018)

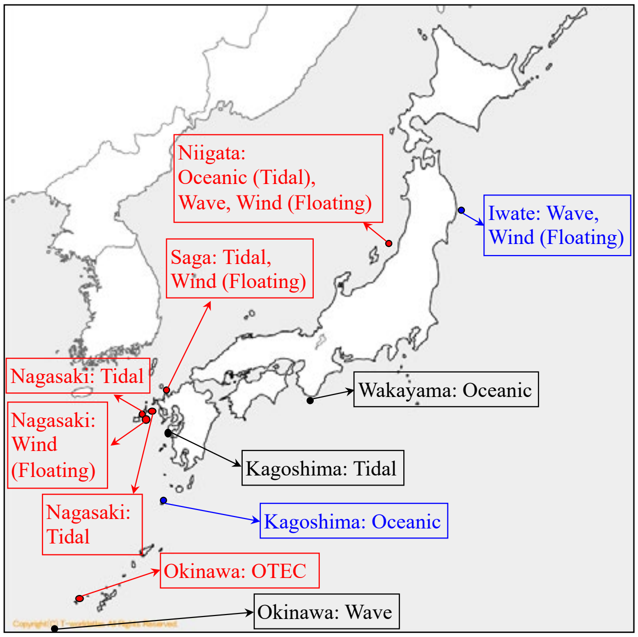


Figure 11.3. Selected demonstration sites for wind, wave, and tidal energy in Japan. Sites shown in red were selected in 2014; the Iwate site, in blue, in 2015; and the Kagoshima site, also in blue, in 2017 as demonstration sites. Sites shown in black text were proposed but not selected. (Image courtesy of Daisuke Kiazawa)

11.7. TOOLS THAT SUPPORT MSP IMPLEMENTATION

Many tools can be used to assist in the implementation of MSP at a variety of scales. These include different spatial management tools such as designated sites and zones (see Section 11.6), as well as more technology-based tools like a dedicated marine atlas or cadastre based on geographic information systems (GISs). In the EU, marine GIS tools are an increasingly popular method of making marine-related information accessible to the public, and a convenient way of illustrating complex data derived from a wide variety of sources. For more details about specific OES-Environmental countries' MSP tools, see Table 11.6 (also see Tables 11.7 and 11.8). More detailed descriptions can be found at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-marine-spatial-planning*.

Table 11.6. Tools that have been developed in the Ocean Energy Systems (OES)-Environmental nations to assist in marine spatial planning (MSP) implementation (arranged alphabetically by European Union [EU] countries first, then by the other countries).

Country		MSP-Specific Information
EU	France	• Implementation of MSP uses geographic information related to marine activities, land-sea interactions, and spatial demands and trends for future maritime activities. • Challenges have arisen related to the appropriate scale at which to operate, how to assess and convey stakeholder perceptions, how to improve coordination on sectoral policies, and how to select available data and to deal with data gaps.
	Ireland	• To fulfill EU Marine Strategy Framework Directive (Directive 2008/56/EC) requirements, the nation's marine atlas is being expanded to support MSP implementation, including tools and data management systems
	Portugal	• A dedicated geoportal was developed and reflects the planning of the national maritime space with a view to private use for the establishment of economic activities (DGRM 2020).
	Spain	• Information about the environment, maritime uses, existing aquaculture zones, anchoring areas, areas for military use, sand extraction zones, and MPAs are being collected into a GIS. • The geographic information system (GIS) will support MSP, as well as the examination of cumulative impacts.
	Sweden	• Uses GIS for MSP purposes as well as the Symphony process (Swedish Agency for Marine and Water Management 2020), a model-based tool developed to support the implementation of ecosystem based maritime spatial planning, to assess cumulative impacts of the plans.
United Kingdom (UK)	England	• The existing Marine Information System, which contained information about plans and policies, supporting data, and information, was replaced with the Explore Marine Plans digital service (Marine Management Organisation 2020e) to improve functionality when using spatial data and information.
	Scotland	• A number of tools are used to implement MSP, as detailed in Table 11.7.
	Wales	• A Marine Planning Portal (Welsh Government 2020a) provides access to the evidence base for MSP in GIS format; an online video provides guidance on the content and its use (Welsh Government 2017b).
	Northern Ireland	• A publicly accessible Marine Mapviewer was developed to show the existing uses and activities in the Northern Ireland Marine Area (DAERA 2018b).
Australia		• Many spatial (GIS-based) mapping tools have been developed to support MSP, as listed in Table 11.8. • Its Assessment of Victoria's Marine Environment report (VEAC 2019) identify current environmental, economic, social, and cultural values of the marine environment and their spatial distribution. • Victoria has also developed a Marine Knowledge Framework to facilitate integrated approaches to research and monitoring efforts in all marine environments across the state (State of Victoria DELWP 2018). • In addition to these GIS-based resources, many other studies have been completed in Australia to assess marine values associated with industries and trends.
India		• No tools have been produced to aid ocean energy development.
Japan		• Layers of information have been organized into a GIS to assist with the zoning that will be used to assess and identify suitable areas for MRE development.
South Africa		• A National Ocean and Coastal Information Management System with accompanying Decision Support Tools is being developed and will be instrumental during the implementation phase of the MSP process and will aid in displaying MSP data and maps (DEFF & DSI 2020).
United States (U.S.)		• The Marine Cadastre website compiles spatial data and information in a user-friendly format throughout U.S. waters to support MSP, MRE siting, and the siting of other ocean-related efforts on the U.S. Outer Continental Shelf (NOAA Office for Coastal Management 2020). • Regional programs are able to use and incorporate data from the Marine Cadastre and apply it to their region of interest (NROC 2020; Mid-Atlantic Ocean Data Portal 2020; West Coast Ocean Partnership 2020).

Table 11.7. Tools that support marine spatial planning implementation in Scotland.

Tool	Contents
Marine Scotland MAPS NMPI *https://marinescotland.atkinsgeospatial.com/nmpi/*	National Marine Plan interactive
Scotland's Marine Atlas: Information for The National Marine Plan *https://www2.gov.scot/Publications/2011/03/16182005/0*	An assessment of the condition of Scotland's seas, based on scientific evidence from data and analysis and supported by expert judgment
Marine Scotland's Regional Locational Guidance *http://marine.gov.scot/information/regional-locational-guidance*	Information related to the search areas for future offshore wind, wave, and tidal energy plan options
Regional Marine Plans *https://www2.gov.scot/Topics/marine/seamanagement/regional/Boundaries*	Only Clyde and Shetland Marine regions have taken this forward to date.
Sectoral Planning *https://www2.gov.scot/Topics/marine/marineenergy/Planning*	Specifically for offshore wind, wave, and tidal energy
Environmental Impact Assessment Regulations *https://www2.gov.scot/Topics/marine/Licensing/marine/guidance/EIARegulations*	Different regulations are used depending on the location of the marine development and the installed capacity of the development. These determine which marine developments are required to undertake production of an Environmental Impact Assessment Report prior to obtaining planning permission and the necessary consents.

Table 11.8. Tools for implementing marine spatial planning (MSP) in Australia.

Mapping Tool	Contents
http://www.nationalmap.gov.au	A spatial database of Australian data, including marine spatial layers in support of MSP at Commonwealth level.
http://www.nationalmap.gov.au/renewables	Spatial information specific to Australia's energy resources and infrastructure.
http://aodn.org.au	Australia's Ocean Data Network, providing Australian marine and climate science data, including spatial layers.
http://www.nespmarine.edu.au/maps	Maps from Australian National Environmental Science Program Marine Biodiversity hub, including maps of pressures on the marine environment and species maps amongst others.
https://marine.ga.gov.au/	Geoscience Australia AusSeabed Marine Data Discovery, providing bathymetry and backscatter data access.
https://www.operations.amsa.gov.au/Spatial/	Includes a spatial database for use in GIS associated with Australia's shipping and maritime safety.
http://maps.ga.gov.au/interactive-maps/#/theme/amsis	The Australian Marine Spatial Information System is a web-based interactive mapping and decision support system that improves access to integrated government and non-government information in Australian marine Jurisdictions.
https://data.marinemammals.gov.au/	National Marine mammal database.
http://seamapaustralia.org	Includes, for example, national marine habitat maps.
https://research.csiro.au/atlantis/home/about-atlantis/	The Atlantis model, used internationally as a decision support tool for MSP.

11.8. THE CONSENTING PROCESS AND MSP

MSP is both strategic and anticipatory. To achieve the objectives of MSP there must be clear links to the project level. All MRE projects will require some form of consent to occupy sea space and generate electricity from natural marine resources. It is therefore imperative that MSP aid decision-making for consenting processes. Every country has a different method of consenting development in their marine space, but the method should align with higher, national-level policy objectives reflected in MSP. In the EU, there is a legal requirement for MSP with a set of common minimum requirements that plans must contain, but there is no similar system for development in marine areas. This remains a member state competence, although requirements of other EU legislation must be adhered to in state practices. In the case of MRE development, for example, depending on the size, location, and nature of the proposed development, most proposed projects will require an environmental impact assessment (EIA) (Commission of the European Communities 2009) based on over-arching EU law on this topic (European Commission – Environment 2009). EU conservation legislation (Habitats and Birds Directives) must also be complied with and such compliance regularly involves the completion of an Appropriate Assessment (Council Directive 92/43/EEC; Directive 2009/147/EC). This interaction of consenting and MSP is not applicable to the current situations in India, South Africa, or the U.S., where consent is granted on a case-by-case basis because there is no over-arching MSP process in place. Details of the interactions of MSP and consenting for MRE are shown for each OES-Environmental country in Table 11.9. More detailed descriptions can be found at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-marine-spatial-planning*.

11.9. FACTORS LIMITING IMPLEMENTATION OF MSP FOR MRE

Across countries, a multitude of factors lead to challenges in implementing MSP. It is important to understand these key challenges in order to provide lessons for other countries to learn from when developing MSP and to tackle challenges that may arise across MSP implementations. Only certain countries, primarily those in the EU that have MSP already in place or are working toward its implementation, were in a position to discuss their limiting factors and challenges. For factors limiting implementation of MSP for MRE in OES-Environmental specific countries, see Table 11.10. More detailed descriptions can be found at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-marine-spatial-planning*.

11.10. PUBLIC INVOLVEMENT IN MSP

It is widely accepted that transparency, accountability, and openness are key principles for successful planning and decision-making processes. Therefore, to achieve the desired planning objectives, it is essential that the parties whose interests may be affected, or who have a role to play, should take part in the design and operation of the planning process. Public and stakeholder involvement can help responsible authorities carry out their responsibilities, set appropriate priorities, and balance environmental, economic, and social objectives. Having contributed to the process, the public and stakeholders are more likely to have a sense of ownership for it and thus be more committed to its successful implementation. Aside from these factors, public participation is regularly a legal requirement in policy- and decision-making processes. The EU MSP Directive (Directive 2014/89/EU) requires member states to create means of public participation by informing all interested parties and consulting with relevant stakeholders, authorities, and the public at an early stage in the development of their marine spatial plans. Public involvement in MSP for MRE in OES-Environmental countries is summarized in Table 11.11. More detailed descriptions can be found at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-marine-spatial-planning*.

Table 11.9. Consenting processes that have been developed in the Ocean Energy Systems (OES)-Environmental nations to assist in marine spatial planning (MSP) implementation (arranged alphabetically by European Union [EU] countries first, then the other countries).

Country		MSP-Specific Information
EU	France	◆ Consenting decisions to deploy MRE devices are granted by the Coordinating Prefectures, which are also responsible for the MSP consultation for their sea basins. ◆ Consenting decisions are based on coherence between the MRE project and • macro-zones identified by the French public authority; • existing marine uses as mapped and defined in the Strategic Façade Planning Documents (Décret n° 2017-724); • the results of an environmental impact assessment clarifying environmental impacts of the project and measures to avoid, reduce, or compensate these impacts, and; • stakeholders providing input on social, economic, and cultural challenges to the MRE project.
	Ireland	◆ The existing consenting system for MRE development is limited to licenses for site investigation, research, or testing facilities. ◆ Legislation has been proposed to modernize the consenting system, including the need to take into account objectives of the National Marine Planning Framework when developing MRE.
	Portugal	◆ The Directorate-General for Natural Resources, Safety and Maritime Services oversees MSP, is responsible for allocation of marine spatial use, and granting a Title for the Private Use of the Maritime Space for licensing any activity that requires a specific spatial area at sea. ◆ The Title for the Private Use of the Maritime Space can only be issued if it is in accordance with the Situation Plan (DGRM 2018).
	Spain	◆ There is no strategic plan in place for MRE, and licensing is done on a case-by-case basis. Currently, a number of consents are needed to deploy an MRE device, taking into account environmental aspects, use of the sea space, and energy production. ◆ Consents need to be approved by the Ministry for Ecological Transition.
	Sweden	◆ The Environment Court is responsible for licensing decisions with guidance from the marine spatial plan, but the plan is not binding
United Kingdom (UK)		◆ All planning decisions must align with UK Government policy, specifically the Marine Policy Statement (HMG 2011), as well as applicable legislation such as the UK Marine and Coastal Access Act (2009). ◆ All licensing applications must take into account the adopted marine plan or the Marine Policy Statement.
	Scotland	◆ A complete review of all the MRE licensing decisions in Scotland has not yet been conducted. ◆ The planning and consenting authorities will consider the objectives and planning recommendations of the Scottish National Marine Plan (Marine Scotland 2015) and the associated Sectoral and Regional Marine Plans (Marine Scotland 2014).
	Wales	◆ All licensing and consenting decisions need to demonstrate compliance with the policies in the Welsh National Marine Plan (Welsh Government 2019). ◆ Implementation guidance is expected from the Welsh Government.
	Northern Ireland	◆ When the Marine Plan is adopted, it will be used by public authorities when making decisions that affect the marine area.
	Australia	◆ Any MRE development has to comply with the federal Environment Protection and Biodiversity Conservation Act (1999) requirements. ◆ Consent is required for MRE development from the Minister responsible for the Marine and Coastal Act (2018) for Victoria. ◆ Ocean energy developments will also be subject to consent conditions, which are site-specific. In issuing a consent, the policies and MSP Framework in the Marine and Coastal Policy (State of Victoria DELWP 2020) must be taken into account, as well as other considerations included in the Marine and Coastal Act (2018).
	Japan	◆ MRE consenting gives priority to the acceptability of other stakeholders, with no involvement of other regulatory authorities in individual project consents.

Table 11.10. Factors that limit the implementation of marine spatial planning (MSP) as it affects marine renewable energy (MRE) development in the Ocean Energy Systems (OES)-Environmental nations (arranged alphabetically by European Union [EU] countries first, then by the other countries).

Country		MSP-Specific Information
EU	France	• Data are needed to improve the knowledge of the environmental impacts of MRE technologies, MRE impacts on the economy, and on social and political interactions. • MSP implementation is limited by the availability of comprehensive marine data, particularly in light of the potential impacts of climate change.
	Ireland	• No commercial-scale MRE can be consented in Irish waters until the National Marine Planning Framework is completed, which is anticipated to occur in 2021. Legislation will be needed to put the plan into effect and provide for a new consenting system.
	Portugal	• The lack of marine data poses a significant challenge to implementing MSP.
	Spain	• Implementation of MSP and its application to MRE development is limited by the lack of human resources.
	Sweden	• Lack of data for some specific aspects of the marine environment hampers implementation of MSP. • A new planning system is under development that could pose challenges because new requirements for MSP and MRE development may be written.
United Kingdom	Scotland	• MSP implementation is limited by financial resources and the willingness of stakeholders to support it.
	Wales	• Applying the marine spatial plan to MRE consenting requires that practical measures be developed to streamline consenting with a proportionate, risk-based approach.
Australia		• Although Australia was an early adopter of MSP, it appears that the ocean policy was too ambitious, suffered from a lack of jurisdictional ownership, lacked sufficient clarity of objectives and integration, lacked sufficient scientific understanding, and had inadequate tools for implementation (Vince et al. 2015). • The focus has turned to making progress in increasing scientific understanding and developing tools, but jurisdictional complexity remains a limitation.
India		• No strong priority is given to ocean energy in the country.
Japan		• MSP implementation to support MSP consenting has been limited by the lack of available data. • Lower technology readiness levels for MRE devices have led to a lack of planning priority, limited financial resources being made available, lack of acceptance by fishermen, and barriers to grid connection.
United States		• The lack of a formal national MSP process, legal framework, or founding legislation limits the effectiveness of MRE consenting.

Table 11.11. Public involvement in marine spatial planning (MSP) processes by the Ocean Energy Systems (OES)-Environmental nations (arranged alphabetically by European Union [EU] countries first, then by the other countries).

Country		**MSP-Specific Information**
EU	France	• The French Code for the Environment requires public consultation on the Strategic Façade Planning Document (Décret n° 2017-724) prior to the commencement of marine renewable energy (MRE) projects. • The EU MSP Directive (Directive 2014/89/EU) demands a greater degree of public consultation, which necessitates earlier public involvement. • Based on these regulatory obligations, there have been two rounds of public consultation on the MSP process for the French North Atlantic sea basin area (Décret n° 2017-724; Ministère de la Transition Écologique et Solidaire 2018; 2019b).
	Ireland	• There is a strong focus on public engagement in the national MSP process, including formal public consultation processes and environmental assessments (DHPLG 2019d). • In addition, a number of public regional workshops, seminars, and interactive web-based workshops have been held (DHPLG 2019d).
	Portugal	• Two consultation periods and a number of public meetings were held during development of the preliminary and draft versions of the Situation Plan (DGRM 2018).
	Spain	• Because of the early stage of MSP implementation, no public involvement has occurred.
	Sweden	• Four rounds of public consultation have been held, in addition to dialog at the outset of the MSP process. • Although invited, the general public has only participated to a limited degree, but most coastal municipalities have participated and been represented.
United Kingdom (UK)	England	• The Marine Management Organisation is responsible for public participation, the agency's engagement with stakeholders, and what to do with the outcomes of any views and opinions received. • This involvement is detailed in a Statement of Public Participation for each marine plan area. • Stakeholder responses are compiled and, where possible, integrated into the plan, provided they align with other laws and policy, and a summary is published (Marine Management Organisation 2019a; 2019b; 2019c; 2019d).
	Scotland	• Marine Scotland and the Scottish Government have a commitment to "[involve] all relevant stakeholders and members of the public in the development of policies that will impact upon them", which is detailed in a Statement of Public Participation (Marine Scotland 2015).
	Wales	• Public consultation on the marine spatial plan, specified in a Statement of Public Participation (Welsh Government 2018), was carried out in 2017 and 2018, but it was largely limited to representatives from environmental nongovernmental organizations. • The Welsh Government produces regular newsletters to provide updates on progress.
	Northern Ireland	• A Statement of Public Participation lays out the public engagement process for the Marine Plan for Northern Ireland (DAERA 2018c). • 12 public information events were held in coastal locations, as well as engagement with primary and secondary school students, six sectoral workshops, and continued engagement with Northern Ireland and UK departments with responsibilities in the Northern Ireland marine areas (DOENI 2012). • Northern Ireland officials meet regularly with officials responsible for MSP in the Republic of Ireland, because they share a marine border.
Australia		• In Victoria, the draft MSP Framework was developed collaboratively using a co-designing process that involved government and partner agencies (such as the Victorian Fisheries Authority) and marine stakeholders (including fishing and boating representative bodies), the resources sector (including the ocean energy sector), environment groups, and academics. • A draft Victorian policy was made available for public comment in 2019.
Japan		• Although there is no formal MSP process, the public is generally involved at the stage of consensus building and environmental impact assessment development when licensing a project.
South Africa		• Stakeholder engagement sessions were held during the initial stages of the MSP process and further stakeholder engagement is planned for other phases. • Once the Current Status Report has been finalized, there will be stakeholder engagement to communicate the progress in the process and to fill gaps in the available information.

continued

Country	MSP-Specific Information
United States (U.S.)	◆ Executive Order 13840 (Executive Order 13840) supports federal agency engagement with stakeholders, including Regional Ocean Partnerships, under existing laws and regulations to address ocean-related matters that may require interagency or intergovernmental solutions. ◆ Regional Ocean Partnerships provide a public forum at which to discuss ocean planning issues in the U.S. The partnerships generally host discussions with members, stakeholders, and the public; provide a shared regional vision; identify regional goals and objectives; analyze data, uses, services, concurrent uses, potential threats, and impacts; and provide work plans and collaborative products for public comment. ◆ Engagement with stakeholders has also been incorporated at multiple points in the Bureau of Ocean Energy Management (BOEM)'s MRE authorization process for leasing on the U.S. Outer Continental Shelf. Through mechanisms like BOEM's Intergovernmental Renewable Energy Task Forces, BOEM carries out its mandate to consult with relevant federal agencies, the Governor of any affected state, the executive of any affected local government, and any affected Tribal Nation within the U.S.

11.11. KEY FINDINGS AND CONCLUSIONS

MSP is an approach that can be used locally, regionally, and nationally as a way of improving marine governance and achieving sustainable development. It is clear from the preceding sections that almost all the countries surveyed are advancing some form of MSP. This progress varies by country and can be attributed to a wide range of factors. In the EU, for example, countries are legally mandated to have maritime spatial plans in place by March 2021 (Directive 2014/89/EU), yet some member states are still at the early stages of plan development, whereas others are already reviewing and adapting their plans. This variability in progress can be attributed to a variety of reasons such as different policy drivers, government priorities, and more operational-level challenges related to human and financial resources. Scale can also be an issue because a number of EU member states have huge maritime jurisdictional areas.

While good practice guidance about how to implement and evaluate MSP exists, it is possibly too early to successfully evaluate the impacts of MSP on any one sector, because of the status of MRE in the studied countries. A number of country respondents stated that marine renewables, and MRE specifically, are still very much a developing sector in their country. The difference in the development of MSP for MRE is probably a reflection of how much importance is placed on the growth of the sector in different administrations and countries. Few countries have allocated zones for MRE development, despite acknowledgment in national and regional energy policies of the potentially transformative role MRE could have in their energy futures. This could be a result of the difficulties involved in spatially zoning areas and the need to avoid conflict with existing users. Often it is more appropriate and easier to have supporting policies and financial assistance.

Once MSP is further along in the implementation process, it would be interesting to look at precisely how, in what way, and at what point MRE and its related infrastructural requirements are incorporated into marine spatial plans. Currently, this seems to occur primarily via stakeholder engagement mechanisms and dedicated meetings with sectoral representatives or their organizations. Development of MSP systems appear to have driven data and information collection and collation in almost every country. This can be motivated by policy requirements, but interestingly can come about as a result of a realization that such data will support other law and policy objectives, putting the principle of "collect data once and use many times" into practice. In the EU, this is particularly the case where implementation of the Marine Strategy Framework Directive (Directive 2008/56/EC) necessitates data collection and environmental monitoring. Research projects, both in terms of funded MSP research projects as well as trial MRE demonstrations and deployments, also act as a scientific data source that can be used in MSP design and implementation. Generation of data and often the requirement to make the data publicly accessible have also driven the development of various web portals and repositories, some of which have been further advanced and refined to become tools to assist in implementing MSP. Such tools are wide-ranging in that, in some cases, their aim is to increase public knowledge about the marine environment and activities that occur there. Elsewhere, these dedicated web tools are designed for use by regulatory authorities when they are making decisions about applications related to developments in the marine space. In the UK, for example, advances have already been made in their online data system to make it more iterative, user-centered, and streamlined.

In terms of moving MSP forward, there is a need to assure that planners and policy-makers are aware of the needs of MRE. This includes up-to-date information from experiences with deployments and their interactions with the marine environment, but also their requirements in terms of supporting infrastructure such as access to ports, transport routes, energy storage options, and grid connections. As the MRE industry looks to both the commercialization and development of large arrays as well as smaller deployments that serve remote or off-grid communities, these needs may vary and MSP will need to address differences such as the appropriate scale for planning processes. Such alignment would assure that key land-based measures to support the MRE sector could be identified at a national, regional, or local scales, and targeted to align with, and support, areas or zones of sectoral potential. If these types of needs are better understood and recognized by planners, they may help to frame MSP going forward. Developing knowledge about environmental interactions could also assist in minimizing the spatial areas where MRE is prohibited or where there are more consenting and licensing obligations. As more and more countries recognize the potentials presented by MRE in meeting renewable energy targets and reducing greenhouse gas emissions, demands on maritime space are likely to increase. To minimize impacts and maximize sustainable development opportunities, it is critical to have a forward-planning process, such as MSP, supported by an efficient and effective development consenting/licensing system and enforcement regime.

11.12. ACKNOWLEDGMENT

The author thanks all the international OES-Environmental participant country representatives for taking the time to complete the questionnaire and garner additional input from their colleagues. The support of the Sustainable Energy Authority of Ireland is also acknowledged. This contribution is based upon projects supported by the Navigate project (Grant-Aid Agreement No. 842 PBA/IPG/17/01), carried out with the support of the Marine Institute, and funded under the Marine Research Programme by the Irish Government, and by Marine and Renewable Energy Ireland: the SFI Research Centre for Energy, Climate and Marine (12/RC/2302).

11.13. REFERENCES

Aquatera Ltd. 2015. Marine and Coastal Tourism and Recreation in the Pentland Firth and Orkney Waters: A Case Study. Stromness, Orkney, Scotland. Report by Aquatera Ltd. for Scottish Government. *https://tethys.pnnl.gov/publications/marine-coastal-tourism-recreation-pentland-firth-orkney-waters-case-study*

Basic Act on Ocean Policy, Act No. 33 of April 27, 2007 [Japan].

Basque Energy Agency. 2017. Basque Energy Strategy 2030. Bilbao, Spain. *https://www.eve.eus/EveWeb/media/EVE/pdf/3E2030/EVE-3E2030-Ingles.pdf*

Bureau of Ocean Energy Management (BOEM). 2019. A Message from BOEM's Acting Director: The Path Forward for Offshore Wind Leasing on the Outer Continental Shelf. Retrieved from *www.boem.gov/newsroom/notes-stakeholders/message-boems-acting-director-path-forward-offshore-wind-leasing-outer*

Commission of the European Communities. 2009. Report from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions - On the application and effectiveness of the EIA Directive (Directive 85/337/EEC, as amended by Directives 97/11/EC and 2003/35/EC). Brussels, Belgium. *https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2009:0378:FIN:EN:PDF*

Commonwealth of Massachusetts. 2020. Massachusetts Ocean Management Plan. Retrieved from *https://www.mass.gov/service-details/massachusetts-ocean-management-plan*

Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. OJ L 206, 22.7.1992, p. 7–50 [European Union].

Décret n° 2017-724 du 3 mai 2017 intégrant la planification maritime et le plan d'action pour le milieu marin dans le document stratégique de façade (Decree n° 2017-724 of 3 May 2017 integrating the maritime planning and action plan for the marine environment in the façade strategic document). *https://www.legifrance.gouv.fr/eli/decret/2017/5/3/DEVH1632060D/jo/texte* (In French).

Department of Agriculture, Environment and Rural Affairs (DAERA). 2018a. Draft Marine Plan for Northern Ireland - Public Consultation. Marine and Fisheries Division, Belfast, Northern Ireland. *https://www.daera-ni.gov.uk/sites/default/files/consultations/daera/Marine%20Plan%20for%20NI%20final%2016%2004%2018.PDF*

Department of Agriculture, Environment and Rural Affairs (DAERA). 2018b. Northern Ireland Marine Mapviewer. Retrieved from *https://appsd.daera-ni.gov.uk/marinemapviewer/*

Department of Agriculture, Environment, and Rural Affairs (DAERA). 2018c. Statement of Public Participation – Marine Plan for Northern Ireland. April 2018. Belfast, Northern Ireland. *https://www.daera-ni.gov.uk/sites/default/files/publications/daera/marine-plan-statement-of-public-participation-final-16-april-18.PDF*

Department of Communications, Climate Action and Environment (DCCAE). 2018. Offshore Renewable Energy Development Plan (OREDP) Interim Review May 2018. Government of Ireland, Dublin, Ireland. *https://www.dccae.gov.ie/documents/OREDP%20Interim%20Review%2020180514.pdf*

Department of Communications, Energy and Natural Resources (DCENR). 2014. Offshore Renewable Energy Development Plan: A Framework for the Sustainable Development of Ireland's Offshore Renewable Energy Resource. Dublin, Ireland. *https://tethys.pnnl.gov/publications/offshore-renewable-energy-development-plan-framework-sustainable-development-irelands*

Department for the Economy (DfE). 2019. Offshore Renewable Energy Strategic Action Plan (ORESAP) 2012-2020 - Progress Report 1 April 2018 to 31 March 2019. Belfast, Northern Ireland. *https://www.economy-ni.gov.uk/sites/default/files/publications/economy/ORESAP-progress-report-to-March%202019.pdf*

Department of Enterprise, Trade and Investment (DETI). 2012. Offshore Renewable Energy Strategic Action Plan (ORESAP) 2012-2020. Belfast, Northern Ireland. *https://tethys.pnnl.gov/publications/ireland-offshore-renewable-energy-strategic-action-plan-2012-2020*

Department of the Environment (DOENI). 2012. Northern Ireland Marine Plan Statement of Public Participation. Marine Plan Team, Belfast, Northern Ireland. *https://www.nienvironmentlink.org/cmsfiles/policy-hub/files/documentation/Marine/NI-Marine-Plan.pdf*

Department for Environment and Heritage. 2006. Marine Planning Framework for South Australia. Adelaide, South Australia. *http://www.environment.sa.gov.au/files/c42d2f66-2230-43b6-8945-9e3001187388/mp_framework.pdf*

Department of the Environment and Heritage. 2006. Marine Bioregional Planning: A new focus for Australia's marine planning. Australian Government. *https://parksaustralia.gov.au/marine/pub/scientific-publications/archive/mbp-brochure.pdf*

Department for Environment, Food and Rural Affairs. 2014. East Inshore and East Offshore Marine Plans. London, England. *https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/312496/east-plan.pdf*

Department for Environment, Food and Rural Affairs. 2018. South Inshore and South Offshore Marine Plan. London, England. *https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/726867/South_Marine_Plan_2018.pdf*

Department of Environment, Forestry and Fisheries (DEFF) and Department of Science and Innovation (DSI). 2020. National Oceans and Coastal Information Management System (OCIMS). Retrieved from *https://www.ocims.gov.za/*

Department of Housing, Planning and Local Government (DHPLG). 2017. Towards a Marine Spatial Plan for Ireland – A Roadmap for the delivery of the national Marine Spatial Plan. Dublin, Ireland. *https://www.housing.gov.ie/planning/marine-spatial-planning/towards-marine-spatial-plan-ireland*

Department of Housing, Planning and Local Government (DHPLG). 2018. National Marine Planning Framework: Baseline Report. Government of Ireland, Dublin, Ireland. *https://www.housing.gov.ie/planning/marine-spatial-planning/national-marine-planning-framework-baseline-report*

Department of Housing, Planning and Local Government (DHPLG). 2019a. National Marine Planning Framework: Consultation Draft. Government of Ireland. *https://www.housing.gov.ie/sites/default/files/public-consultation/files/draft_national_marine_planning_framework_final.pdf*

Department of Housing, Planning and Local Government (DHPLG). 2019b. Climate Action Plan 2019 – To tackle climate breakdown. Government of Ireland. *https://www.dccae.gov.ie/en-ie/climate-action/publications/Pages/Climate-Action-Plan.aspx*

Department of Housing, Planning and Local Government (DHPLG). 2019c. Marine Planning and Development Management Bill – the General Scheme. Beauchamps, Dublin, Ireland. *https://www.beauchamps.ie/sites/default/files/inline-files/Beauchamps%20Client%20Briefing%20note%20on%20the%20MPDM%20Bill.pdf*

Department of Housing, Planning and Local Government (DHPLG). 2019d. Public Consultation on the Draft National Marine Planning Framework. Retrieved from *https://www.housing.gov.ie/planning/marine-planning/public-consultation-draft-national-marine-planning-framework*

Department of Land Conservation and Development. 2020. Ocean Planning. Oregon Coastal Management Program. Retrieved from *https://www.oregon.gov/lcd/OCMP/Pages/Ocean-Planning.aspx*

Dineshbabu, A.P., Thomas, S., Rohit, P., and Maheswarudu, G. 2019. Marine spatial planning for resource conservation, fisheries management and for ensuring fishermen security – global perspectives and Indian initiatives. *Current Science*, 116(4), 561-567. doi:10.18520/cs/v116/i4/561-567 *https://tethys.pnnl.gov/publications/marine-spatial-planning-resource-conservation-fisheries-management-ensuring-fishermen*

Direção-Geral de Recursos Naturais, Segurança e Serviços Marítimos (DGMR). 2018. Ordenamento do Espaço Marítimo Nacional – Plano do Situação [National Maritime Spatial Planning – Situation Plan] (Volumes I to VI). Retrieved from *http://www.psoem.pt/discussao_publica-2/* (In Portuguese).

Direção-Geral de Recursos Naturais, Segurança e Serviços Marítimos (DGMR). 2020. Ordenamento do Mar Português: Plano de Situação do Ordenamento do Espaço Marítimo Nacional [Geoportal/Situation Plan: Portuguese Sea Ordering National Maritime Spatial Situation Plan]. *www.psoem.pt/geoportal_psoem/* (In Portuguese).

Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). OJ L 164, 25.6.2008, p. 19-40.

Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds. OJ L 20, 26.1.2010, p. 7–25.

Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning. OJ L 257, 28.8.2014, p. 135–145

Ehler, C. 2008. Conclusions: Benefits, lessons learned, and future challenges of marine spatial planning. *Marine Policy*, 32(5), 840-843. doi:10.1016/j.marpol.2008.03.014 *https://tethys.pnnl.gov/publications/conclusions-benefits-lessons-learned-future-challenges-marine-spatial-planning*

Ehler, C. and Douvere, F. 2009. Marine Spatial Planning: a step-by-step approach toward ecosystem-based management. Intergovernmental Oceanographic Commission and Man and the Biosphere Programme. IOC Manual and Guides No. 53, ICAM Dossier No. 6. UNESCO, Paris, France. *https://tethys.pnnl.gov/publications/marine-spatial-planning-step-step-approach-toward-ecosystem-based-management*

Ehler, C. 2014. A Guide to Evaluating Marine Spatial Plans. IOC Manuals and Guides No. 70; ICAM Dossier No. 8. UNESCO, Paris, France. *https://tethys.pnnl.gov/publications/guide-evaluating-marine-spatial-plans*

Environment Protection and Biodiversity Conservation Act 1999. Act No. 91 of 1999. 16 Jul 1999. Federal Register of Legislation. Australia.

Environment (Wales) Act 2016, anaw 3. Retrieved from *http://www.legislation.gov.uk/anaw/2016/3/contents/enacted*

Estratégia Industrial para as Energias Renováveis Oceânicas 2017. No 174/2017. (Industrial Strategy for Ocean Renewable Energies (EI-ERO). Portugal.

European Commission – Environment. 2009. Environmental Impact Assessment – EIA. Retrieved from https://ec.europa.eu/environment/eia/eia-legalcontext.htm

European MSP Platform. 2020. Overview of MSP related maritime uses. Sweden. Retrieved from https://www.msp-platform.eu/countries/sweden

Executive Order 13547 of July 9, 2010. The Stewardship of the Ocean, Our Coasts, and the Great Lakes. 3 C.F.R. 13547 [U.S.].

Executive Order 13783 of March 28, 2017. Promoting Independence and Economic Growth. 82 FR 16093 [U.S.].

Executive Order 13840 of June 19, 2018. Ocean Policy To Advance the Economic, Security, and Environmental Interests of the United States. 83 FR 29431 [U.S.].

Freeman, M. C., Whiting, L., and Kelly, R. P. 2016. Assessing potential spatial and temporal conflicts in Washington's marine waters. *Marine Policy*, 70, 137-144. doi:10.1016/j.marpol.2016.04.050 https://tethys.pnnl.gov/publications/assessing-potential-spatial-temporal-conflicts-washingtons-marine-waters

Gobierno de España. 2020. Borrador Actualizado del Plan Nacional Integrado de Energía y Clima [National Integrated Energy and Climate Plan] (PNIEC) 2021-2030. Retrieved from https://energia.gob.es/es-es/Participacion/Paginas/DetalleParticipacionPublica.aspx?k=236

Great Barrier Reef Marine Park Act 1975 Park Act 1975. No. 85 of 1975. Federal Register of Legislation. Australia.

Her Majesty's Government (HGM). 2011. UK Marine Policy Statement: HM Government, Northern Ireland Executive, Scottish Government, Welsh Assembly Government. The Stationary Office, London, England. https://tethys.pnnl.gov/publications/uk-marine-policy-statement

Marine and Coastal Access Act 2009, c.23 [UK].

Marine and Coastal Act 2018 (VIC) [Australia].

Marine Management Organisation. 2019a. North East Marine Plan – Statement of Public Participation: November 2019. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/857072/Revised_SPP_NE_Clean.pdf

Marine Management Organisation. 2019b. North West Marine Plan – Statement of Public Participation: November 2019. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/857074/Revised_SPP_NW_Clean.pdf

Marine Management Organisation. 2019c. South West Marine Plan – Statement of Public Participation: November 2019. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/857078/Revised_SPP_SW_Clean.pdf

Marine Management Organisation. 2019d. South East Marine Plan – Statement of Public Participation: November 2019. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/857092/Revised_SPP_SE_Clean.pdf

Marine Management Organisation. 2020a. North East Inshore and North East Offshore Marine Plan – Draft for consultation. Newcastle upon Tyne, England. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/857247/DRAFT_NE_Marine_Plan.pdf

Marine Management Organisation. 2020b. North West Inshore and North West Offshore Marine Plan – Draft for consultation. Newcastle upon Tyne, England. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/857301/DRAFT_NW_Marine_Plan.pdf

Marine Management Organisation. 2020c. South East Inshore Marine Plan – Draft for Consultation. Newcastle upon Tyne, England. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/857296/DRAFT_SE_Marine_Plan.pdf

Marine Management Organisation. 2020d. South West Inshore and South West Offshore Marine Plan - Draft for consultation. Newcastle upon Tyne, England. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/857299/DRAFT_SW_Marine_Plan.pdf

Marine Management Organisation. 2020e. Map data. Explore Marine Plans. Retrieved from https://explore-marine-plans.marineservices.org.uk/

Marine Scotland. 2014. Planning Scotland's Seas: Sectoral Marine Plans for Offshore Wind, Wave and Tidal Energy in Scottish Waters: Analysis of Consultation Responses. Scottish Government, Edinburgh, Scotland. https://www.gov.scot/publications/planning-scotlands-seas-sectoral-marine-plans-offshore-wind-wave-tidal/

Marine Scotland. 2015. Scotland's National Marine Plan– A Single Framework for Managing Our Seas. Scottish Government, Edinburgh, Scotland. https://tethys.pnnl.gov/publications/scotlands-national-marine-plan-single-framework-managing-our-seas

Marine Scotland. 2016. Pilot Pentland Firth and Orkney Waters Marine Spatial Plan. Scottish Government, Edinburgh, Scotland. https://www.gov.scot/publications/pilot-pentland-firth-orkney-waters-marine-spatial-plan/

Marine (Scotland) Act 2010, asp 5.

Marine Spatial Planning Act 2018. Act No. 16 of 2018. Republic of South Africa.

Marine Spatial Planning Programme. 2018. Status of MSP. Retrieved from http://msp.ioc-unesco.org/world-applications/status_of_msp/

Mid-Atlantic Ocean Data Portal. 2020. Mid-Atlantic Ocean Data Portal. Retrieved from https://portal.midatlanticocean.org/

Mid-Atlantic Regional Planning Body. 2016. Mid-Atlantic Regional Ocean Action Plan. https://www.boem.gov/sites/default/files/environmental-stewardship/Mid-Atlantic-Regional-Planning-Body/Mid-Atlantic-Regional-Ocean-Action-Plan.pdf

Ministerio de Industria, Turismo y Comercio. 2010. Spain's National Renewable Energy Action Plan 2011-2020. Government of Spain. http://pvtrin.eu/assets/media/PDF/EU_POLICIES/National%20Renewable%20Energy%20Action%20Plan/202.pdf

Ministère de la Transition Écologique et Solidaire. 2018. Document Stratégique de Façade: Association du Public. République Française, Paris, France. www.dirm.nord-atlantique-manche-ouest.developpement-durable.gouv.fr/document-strategique-de-facade-association-du-a669.html (In French).

Ministère de la Transition Écologique et Solidaire. 2019a. Stratégie Française Pour L'Énergie et le Climat: Programmation Pluriannuelle de L'Énergie (French Strategy for Energy and Climate: Multi Annual Energy Plan). République Francaise, Paris, France. https://www.ecologique-solidaire.gouv.fr/sites/default/files/Projet%20PPE%20pour%20consultation.pdf (In French).

Ministère de la Transition Écologique et Solidaire. 2019b. Politique Maritime Intégrée – Consultation du public et des instances (Integrated Marine Policy - Public and body consultation). Retrieved from http://www.dirm.nord-atlantique-manche-ouest.developpement-durable.gouv.fr/consultation-du-public-et-des-instances-a966.html (In French).

Ministry of Economy, Trade, and Industry. 2018. 5th Strategic Energy Plan (Provisional Translation). Government of Japan, Tokyo, Japan. https://www.enecho.meti.go.jp/en/category/others/basic_plan/5th/pdf/strategic_energy_plan.pdf

Ministry of New and Renewable Energy. 2015. Draft National Renewable Energy Act 2015. Government of India, New Delhi, India. http://www.indiaenvironmentportal.org.in/files/file/draft-rea-2015.pdf

Ministry of the Presidency. 2019. Government presents Strategic Energy and Climate Framework. Government of Spain. Retrieved from https://www.lamoncloa.gob.es/lang/en/gobierno/councilministers/Paginas/2019/20190222framework.aspx

National Marine Sanctuaries Act of 2000, as amended. 16 U.S.C. ch. 32 § 1431 et seq [U.S.].

National Oceanic and Atmosphere Administration (NOAA) Office for Coastal Management. 2020. Marine Cadastre - An Ocean of Information. Retrieved from https://marinecadastre.gov/

Natural Resources Wales. 2020. Marine Area Statement. Retrieved from https://naturalresources.wales/about-us/area-statements/marine-area-statement/?lang=en

Nielsen, K., Krogh, J., Kofoed, J. P., Jensen, N. E.H., Friis-Madsen, E., Mikkelsen, B. V., and Jensen, A. 2012. Boelgekraftteknologi. Strategi for forskning, udvikling og demonstration 2012 [Wave energy technology. Strategy for research, development and demonstration 2012]. DCE Technical Report No. NEI-DK-5801. Aalborg University, Aalborg, Denmark. https://www.osti.gov/etdeweb/biblio/22005452

Nielsen, K., Krogh, J., Brodersen, H. J., Steenstrup, P. R., Pilgaard, H., Marquis, L., Friis-Madsen, E. and Kofoed, J. P. 2015. Partnership for Wave Power - Roadmaps. DCE Technical Report No. 186. Aalborg University, Aalborg, Denmark. https://tethys.pnnl.gov/publications/partnership-wave-power-roadmaps

Northeast Regional Planning Body. 2016. Northeast Ocean Plan. https://tethys.pnnl.gov/publications/northeast-ocean-plan

Northeast Regional Ocean Council (NROC). 2020. Northeast Ocean Data Portal. Retrieved from https://www.northeastoceancouncil.org/quick-links/

Plan-och bygglag (Planning and Building Act) (2010:900). Retrieved from https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/plan--och-bygglag-2010900_sfs-2010-900 (In Swedish).

Real Decreto 363/2017, de 8 de abril, por el que se establece un marco para la ordenación del espacio marítimo (Decree 363/2017, 8 of April, establishing a framework for the management of the maritime space), BOE 2017, 28802-28810 [Spain].

The Republic of South Africa. 2017. National Framework for Marine Spatial Planning in South Africa. https://iwlearn.net/resolveuid/21f3aa17-e74c-4f3c-8682-9e28af296b20

Rhode Island State. 2020. RI Coastal Resources Management Council (CRMC). Retrieved from http://www.crmc.ri.gov/index.html

Scottish Government. 2012. Planning. Marine and Fisheries. Retrieved from https://www2.gov.scot/Topics/marine/marineenergy/Planning

Scottish Government. 2017. Scottish Energy Strategy: The future of energy in Scotland. Edinburgh, Scotland. https://www.gov.scot/publications/scottish-energy-strategy-future-energy-scotland-9781788515276/

Scottish Government. 2018. Sectoral Marine Plan Offshore Wind Scoping Consultation. Retrieved from https://www2.gov.scot/Topics/marine/marineenergy/Planning/smp-scoping-consultation

Scottish Government. 2020. Marine Renewable Energy – Planning. Scottish Government. Retrieved from https://www2.gov.scot/Topics/marine/marineenergy/Planning

Secretariat of the Convention on Biological Diversity (SCBD). 2012. Marine Spatial Planning in the Context of the Convention on Biological Diversity: A study carried out in response to CBD COP 10 decision X/29. CBD Technical Series No. 68. Montreal, Quebec, Canada. https://tethys.pnnl.gov/publications/marine-spatial-planning-context-convention-biological-diversity

State of Victoria Department of Environment, Land, Water and Planning (DELWP). 2018. Victoria's Marine and Coastal Reforms – Final Transition Plan. Melbourne, Australia. https://www.marineandcoasts.vic.gov.au/__data/assets/pdf_file/0021/330519/Final-Transition-Plan_August-2018.pdf

State of Victoria Department of Environment, Land, Water and Planning (DELWP). 2020. Marine and Coastal Policy. Melbourne, Australia. https://www.marineandcoasts.vic.gov.au/__data/assets/pdf_file/0027/456534/Marine-and-Coastal-Policy_Full.pdf

State of Washington. 2020. Washington Marine Spatial Planning. Retrieved from https://www.msp.wa.gov/

Swedish Agency for Marine and Water Management. 2018. Proposal for the Marine Spatial Plan Baltic Sea: Consultation Document. Gothenburg, Sweden. https://www.havochvatten.se/download/18.47bf2cd7163855d85cae2805/1529995797805/proposal-for-the-marine-spatial-plan-baltic-sea.pdf

Swedish Agency for Marine and Water Management. 2019. Proposals for Marine spatial plans for Sweden: Gulf of Bothnia, Baltic Sea, and Skagerrak/Kattegat. Gothenburg, Sweden. https://www.havochvatten.se/download/18.56d79bf516b232e9db573cab/1560164109554/proposal-marine-spatial-plans-sweden-revieiw.pdf

Swedish Agency for Marine and Water Management. 2020. Symphony – a tool for ecosystem-based marine spatial planning. Retrieved from https://www.havochvatten.se/en/swam/eu--international/marine-spatial-planning/symphony---a-tool-for-ecosystem-based-marine-spatial-planning.html

Swedish Government. 2016. Överenskommelse om den svenska energipolitiken [Agreement on Swedish Energy Policy]. Government Offices of Sweden, Stockholm, Sweden. Retrieved from https://www.regeringen.se/artiklar/2016/06/overenskommelse-om-den-svenska-energipolitiken/

The Climate Change Act 2008 (2050 Target Amendment) Order 2019, SI 2009/1056 [UK].

Université de Nantes. 2019. GIS VALPENA. Retrieved from https://valpena.univ-nantes.fr/accueil-du-gis-valpena-1427390.kjsp?RH=1432731407596&RF=VALPENA (In French).

Victorian Environmental Assessment Council (VEAC). 2019. Assessment of the Values of Victoria's Marine Environment. Melbourne, Victoria. http://www.veac.vic.gov.au/documents/VEAC%20Marine%20Environment%20REPORT.pdf

Vince, J., Smith, A. D. M., Sainsbury, K. J., Cresswell, I. D., Smith, D. C. and Haward, M. 2015. Australia's Oceans Policy: Past, present and future. *Marine Policy*, 57, 1–8. doi:10.1016/j.marpol.2015.02.014 https://tethys.pnnl.gov/publications/australias-oceans-policy-past-present-future

Welsh Government. 2017a. Natural Resources Policy Statement. https://gov.wales/sites/default/files/publications/2019-05/natural-resources-policy-statement.pdf

Welsh Government. 2017b. Wales Marine Planning Portal. Retrieved from https://www.youtube.com/watch?v=JIigdT4J8Ec

Welsh Government. 2018. Statement of Public Participation for the Welsh National Marine Plan. Marine Planning, Cardiff, Wales. https://gov.wales/sites/default/files/publications/2018-10/statement-of-public-participation-for-the-welsh-national-marine-plan.pdf

Welsh Government. 2019. Welsh National Marine Plan. Cardiff, Wales. https://gov.wales/sites/default/files/publications/2019-11/welsh-national-marine-plan-document_0.pdf

Welsh Government. 2020. Wales Marine Planning Portal. Retrieved from http://lle.gov.wales/apps/marineportal/?_ga=2.79479700.1060360826.1565974707-1477372174.1539188259#lat=52.5145&lon=-3.9111&z=8

West Coast Ocean Partnership. 2020. West Coast Ocean Data Portal. Retrieved from http://www.westcoastoceans.org/west-coast-ocean-data-portal.html

NOTES

Marine Spatial Planning and Marine Renewable Energy

O'Hagan, A.M. 2020. Marine Spatial Planning and Marine Renewable Energy. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 214-241). doi:10.2172/1633204

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

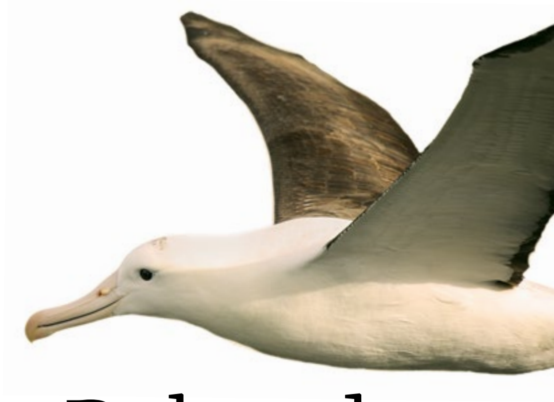
CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

12.0

Chapter author: Célia Le Lièvre
Contributor: Deborah J. Rose



Adaptive Management Related to Marine Renewable Energy

As the marine renewable energy (MRE) industry scales up from single devices to commercial-scale deployments, developers and regulators will need evidence of the environmental effects of MRE to inform project development, strategic planning, and consenting/permitting (hereafter consenting) processes. Uncertainty surrounding the potential impacts of novel MRE technologies on sensitive marine animals, habitats, and ecosystem processes means that even robust baseline environmental information cannot comprehensively address all pre-deployment knowledge gaps (Copping 2018). Tools and practical approaches are needed to help with the sustainable development of the industry. Adaptive management (AM), also referred to as learning by/while doing, enables projects to be deployed incrementally, despite uncertainty, in a way that prevents unacceptable harm to the marine environment. If rigorously implemented, this approach may provide a reliable mechanism for closing knowledge gaps, thereby retiring risks (see Chapter 13, Risk Retirement and Data Transferability for Marine Renewable Energy) for future MRE developments. This chapter explores and suggests a pathway for applying a passive approach to AM for the consenting of single devices and array-scale MRE projects. Complementary information is available online at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-adaptive-management*.

12.1.
INTRODUCTION TO ADAPTIVE MANAGEMENT

AM is best defined as an iterative management process that seeks to reduce scientific uncertainty and improve management through rigorous monitoring and periodic review of management decisions in response to growing knowledge gained from monitoring data (Copping et al. 2019; Williams et al. 2009). Monitoring associated with AM is designed to address specific scientific questions and hence contribute to the wider scientific knowledge base, which can be used to amend decisions, refine policy, and improve consenting processes in light of new information (Le Lièvre 2019).

From a procedural perspective, AM is a six-step cycle (Figure 12.1) (Williams et al. 2009):

1. **Assess the problem.** Conduct baseline monitoring and environmental assessment to assess the problem and define measurable management objectives.
2. **Design management actions.** In the context of MRE, this refers to the design of the project proposals and mitigation plans, compensation, habitat enhancement measures, and monitoring - all which are informed by the environmental assessment.
3. **Implement the project.**
4. **Monitor.** Conduct follow-up monitoring to collect data after the project has been deployed.
5. **Evaluate.** Evaluate the monitoring results.
6. **Adjust.** Adapt management and monitoring methods and scope in light of what has been learned from observations.

AM learning outcomes can be applied to a particular project (changes in monitoring design, mitigation, or compensatory measures), and the learning should provide information that supports planning policies and regulation of future MRE proposals—a learning process called “double-loop” or “institutional” learning (Figure 12.1).

AM seeks to design and apply management actions as testable hypotheses (Walters 1986), to reduce uncertainty and accelerate understanding of ecological processes, which means that certain management actions may be put at risk in order to learn about receptors’ responses to particular actions. However, often this compromise is not possible and AM processes focus on

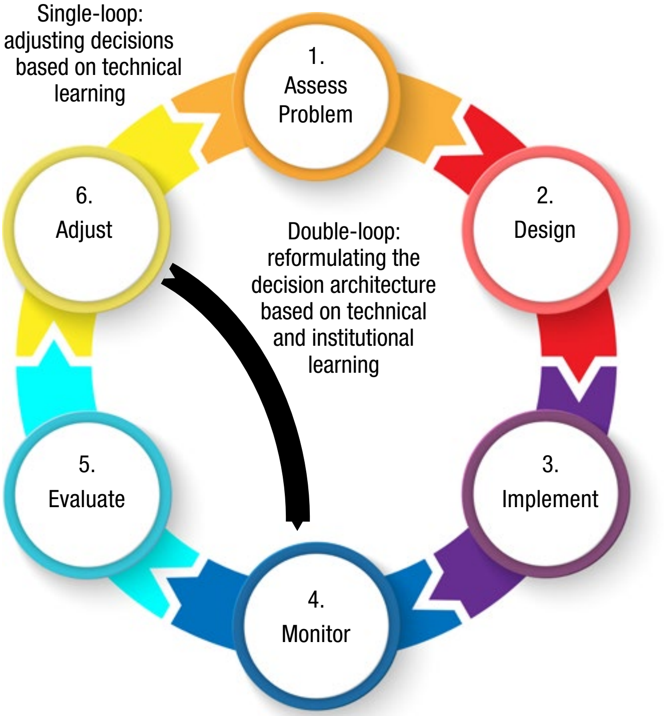


Figure 12.1. The adaptive management (AM) cycle. The original concept of AM concerned single loop learning, while later additions recognize the value of double loop learning, particularly to inform planning and siting for future MRE installations in a region. (Graphic by Robyn Ricks. Adapted from Williams 2011a; Williams and Brown 2018)

monitoring the effects of management measures that reduce uncertainty, and determine whether adjustments are needed to achieve specific mitigation objectives, even in the absence of testable hypotheses. By accounting for scientific uncertainty and providing new observational data to learn about the effects of management and generate new approaches to MRE development and management, this approach may be particularly beneficial for increasing the global understanding of MRE effects and evaluating the effectiveness of monitoring and mitigation actions. This process follows the feedback loops to promote learning for subsequent development phases of specific projects as well as for decision-making for future MRE development.

12.2.
IMPLEMENTING ADAPTIVE MANAGEMENT IN AN MRE CONTEXT

Not a new concept, AM has been used in other natural resource management situations (Copping et al. 2019; Williams 2011a, 2011b; Williams and Brown 2014) and holds promise as a useful tool to support the consenting of MRE projects when the environmental effects are not well understood. It can be used to avoid unacceptable effects through its systematic and iterative approach of learning by doing and adapting as you learn, as well as assisting in determining effects uncovered during the consenting process. While monitoring results collected from single devices may help predict the effects of larger arrays, most environmental interactions may not be properly understood until multiple devices are actually deployed and monitored in real sea conditions (Copping 2018). An AM approach is therefore likely to be needed to address the risks and uncertainties associated with larger commercial arrays and their potential incremental effects on marine ecosystems.

12.2.1.
THE USE OF IMPACT THRESHOLDS IN ADAPTIVE MANAGEMENT

AM can incorporate decision triggers such as thresholds to help guide implementation. Taking an AM approach based on thresholds requires the definition of acceptable and unacceptable risks. In consenting processes, acceptable risks may be quantified by the definition of impact thresholds, which set the level of effect that is acceptable with respect to the ecology, conservation objectives, and the conservation status of the affected species or natural habitats. Project-specific thresholds can determine the safe operating conditions within which MRE developments can be approved and operated, despite uncertainty, without causing unacceptable harm to valuable receptors/features. Results are used to help ensure that ongoing requirements are proportionate to the observed effects. If information from routine monitoring shows that the level of an effect or change is likely to cause an unacceptable impact, corrective mitigation actions should be taken. On the other hand, if the monitoring data indicate that risks have been overestimated during the consenting phase, monitoring and mitigation requirements may then be reduced and progressively removed in subsequent management decisions. The need to develop and adapt modeling approaches and tools that can ascertain thresholds relevant to wave and tidal energy arrays has been identified as a high research priority for addressing risks associated with consenting (ORJIP Ocean Energy 2017). In some jurisdictions, regulatory impact thresholds are already defined numerically for underwater noise exposure levels and direct mortality of sensitive receptors (e.g., National Oceanic and Atmospheric Administration [NOAA] marine mammal acoustic thresholds, Potential Biological Removal [PBR], ASCOBANS [Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas] by-catches reduction target of 1 percent of the population). While threshold levels might be specifically listed for sensitive species (e.g., NOAA/Southall underwater noise thresholds, NMFS 2018), they do not consider cumulative effects from other anthropogenic activities in their implementation.

Threshold levels for lethal and sublethal impacts are rarely prescribed in policy or regulations and, as such, must be determined on a case-by-case basis; for example, through the examination of species conservation status (Le Lièvre et al. 2016). Both lethal and sublethal effects such as changes in animal behavior, density, and distribution are extremely challenging to measure because of the difficulty in confidently measuring direct mortality and monitoring population changes. Identifying and detecting the metrics of concern with the necessary levels of accuracy to inform management decisions is even more difficult to determine with certainty. Population models that seek to translate sublethal impacts to population-level consequences can be applied to MRE developments, but they may not always help identify the appropriate metrics to monitor. Uncertainty and the lack of consistent methods for detecting and estimating acceptable impacts or thresholds are significant limitations to the use of thresholds/triggers in AM (Johnson 2013). Conservative thresholds will help reconcile AM with the precautionary principle (see Section 12.3) and assure that actions are taken before an unacceptable impact occurs. However, at a larger development scale, unfavorable progress toward thresholds may not be detected in time and remedial actions may fail to effectively respond and avoid unacceptable impacts on sensitive receptors. AM-based thresholds may be more appropriate for the early (smaller) scale of the wave and tidal energy sector where project-led monitoring focuses on understanding device-specific stressor-receptor interactions such as collision risk. As the industry moves toward commercial deployment, taking an AM approach would be more acceptable if it were implemented through staged or phased approach to consenting processes, whereby projects are deployed in stages, starting with small numbers of devices or a small spatial area, and followed by subsequent expansion being dependent on monitoring findings. Monitoring should provide meaningful evidence showing that the effects of the larger-scale deployments are properly understood, prior to approving any subsequent phases.

12.2.2. MITIGATION OF RISK

If an MRE development is likely to adversely affect the marine environment, the mitigation hierarchy of the precautionary principle should apply. The mitigation hierarchy is a cautious approach to decision-making that consists of taking a sequence of steps to avoid, reduce, and minimize potential negative impacts and, as a last resort, to compensate for any residual impacts (Figure 12.2) (Elliott et al. 2019). Although the mitigation hierarchy provides a prescribed approach for reducing impacts, it may not reduce uncertainty and facilitate learning as emphasized by AM principles (Hanna et al. 2016). In the face of data gaps and uncertainty, the mitigation hierarchy may instead result in the continuation or reinforcement of mitigation or compensatory measures throughout the project, thereby hampering the generation of useful science for regulatory decision-makers. Conversely, the purpose of AM is to reduce scientific uncertainty through an iterative process of environmental monitoring and adjustment of management actions. As rightly observed by Hanna et al. (2016), "striking the appropriate balance between mitigating and compensating for potential impacts versus detecting change is a dilemma with which regulators and industry must concern themselves if they are to develop AM approaches that meaningfully reduce scientific uncertainty."

AM and the mitigation hierarchy are not incompatible and can be reconciled. The mitigation hierarchy offers a prescribed approach for avoiding unacceptable impacts that may materialize as a result of data gaps, uncertainties, or imperfect monitoring design in an AM process. As more data are gathered through continuous monitoring, the iterative phase of AM provides a mechanism for evaluating the effectiveness of mitigation and compensatory measures, learning from experience, and informing a more effective mitigation toolkit for future developments (Hanna et al. 2016).

Practically speaking, for single devices or small arrays, mitigation takes the form of post-deployment monitoring and feedback mechanisms as integral parts of the project design. At the large development scale, mitigation measures must be considered and, in some cases, implemented from the beginning of the project and not solely when monitoring data indicate an undesirable trend toward impact thresholds. At the top of the mitigation pyramid (Figure 12.2), impacts may be avoided through technology choice and/or by using well-informed designated development areas for MRE projects within an over-arching marine spatial plan (see Chapter 11, Marine Spatial Planning and Marine Renewable Energy). This technique, also known as macro-siting, may not always be feasible where sites with MRE resources correspond to biodiversity hotspots and protected sites. In these cases, the focus of mitigation in AM

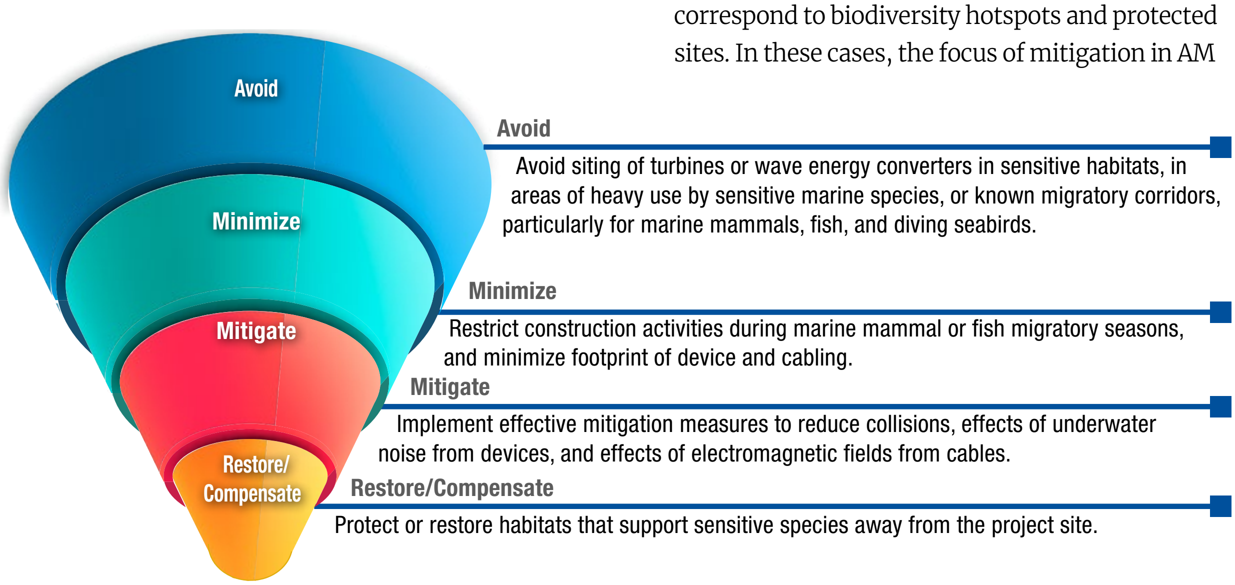


Figure 12.2. The mitigation hierarchy. The mitigation hierarchy is used to avoid impacts when possible, minimize remaining impacts, mitigate to diminish impacts, and provide compensation for unavoidable impacts. (Graphic by Robyn Ricks. Adapted from Elliott et al. 2019)

should be to assure that the impacts of consented MRE projects are reduced and mitigated to acceptable levels. Mitigation measures may consist of spatially arranging the MRE device layout, a mitigation measure also known as "micro-siting" or "smart device positioning".

Curtailment and shutdown protocols have been tested in combination with AM to mitigate and reduce the uncertainty surrounding collision risks with marine mammals (Copping et al. 2016; Fortune 2017). Where no close encounter events are allowed to occur, curtailment could limit the ability of AM to reduce uncertainty and could be poorly suited to undertaking AM. However, the approach taken by SeaGen shows that, despite strict protection of species for which zero tolerance of loss is acceptable, AM may still be employed to decrease uncertainty about collision risks by progressively reducing the precautionary shutdown perimeter of a tidal turbine from an excessive distance of 200 m to less than 30 m (see Section 12.4.2). Curtailment and temporary shutdowns of turbine operation may be overly restrictive in addition to being technically difficult to implement for certain turbine designs. Likewise, these measures are arguably insufficient to address all negative impacts, especially those resulting from displacement and disturbance-related habitat loss or changes in oceanographic systems.

12.2.3. POST-INSTALLATION MONITORING

Creating a successful AM scheme is highly contingent upon the design of monitoring programs that are sufficiently well designed to detect changes, as well as management triggers that can meaningfully inform regulators (Le Lièvre et al. 2016). AM also requires a consenting regime that has the flexibility to encompass such an approach if it is being used as a tool to enable deployments in areas in which the knowledge base is incomplete. Post-installation monitoring is generally required by regulators to validate model predictions in environmental assessments. In the context of AM, the primary purpose of post-installation monitoring is to provide an evidence base for reducing the scientific uncertainty associated with impact assessments and for informing decision-making related to future MRE proposals (Bennet et al. 2016). AM is used to enable deployments when the existing uncertainty causes significant delays in consenting. However, designing and implementing successful AM is contingent on the efficacy of monitoring and the ability to detect change, as well the effectiveness of management actions.

At the project level, post-installation monitoring also serves to verify that project effects do not exceed levels of acceptable change and to adjust the mitigation or compensatory measures initially adopted on the basis of precaution. Likewise, post-consent monitoring design should provide data that can be used to refine the accuracy of both impact thresholds and detected effects, as well as to determine whether additional monitoring and mitigation are required to address predicted and unforeseen impacts.

Poor monitoring precision produces inaccurate evidence leading to inappropriate management decisions. If the statistical power of monitoring data is too low, regulators may make decisions believing that monitoring indicates no change beyond their thresholds of tolerance (Le Lièvre et al. 2016). Monitoring programs will yield more useful information if a question-directed approach is used and data collection methods are designed to answer well-defined and hypothesis-driven environmental questions (Copping et al. 2019). A question-led approach to monitoring will help design surveys that provide useful data for validating model predictions and supporting AM processes (Hanna et al. 2016). Question-directed monitoring also may help address the problem of data-rich information-poor (DRIP), i.e., an undesirable situation in which, despite extensive data collection in the field, post-consent monitoring results do not provide useful information that can be used to reduce scientific uncertainty (Ward et al. 1986; Wilding et al. 2017). This is crucial because DRIP monitoring undermines the success of AM and, in turn, the confidence regulators have in the process.

To date, the application of AM has been primarily directed at reducing uncertainty about the nearfield effects of single or limited numbers of MRE devices and their moving parts. Post-consent monitoring has mainly been implemented to determine whether collisions occur in tidal environments or to assess underwater noise at wave energy sites; hence, monitoring is not necessarily designed to follow a before-after-control impact (BACI) approach. For larger array-scale deployments, the MRE industry may benefit from applying more systematic BACI studies whereby changes in receptors of value to stakeholders are monitored prior to installation, during construction, and during operation of an MRE project (Bennet et al. 2016; Magagna et al. 2012). Embracing a BACI or similar monitoring design will be useful in framing relevant monitoring questions and evaluating changes in response to installation and operation of multiple devices.

AM includes other actions beyond monitoring. For individual projects, additional information gained through single-loop learning may not be sufficient to reduce uncertainty about population impacts, and may not deliver the full benefit that AM has to offer to the MRE sector. Small-scale MRE projects sited in areas where marine animals are widely dispersed will significantly complicate the evaluation of impacts on populations at the individual project level (Fox et al. 2018). By adopting a bottom-up approach where data gained from multiple projects feed into broader marine governance processes through, for example, strategic environmental assessments and strategic research studies supported by government bodies, it may be possible for monitoring to yield additional information, thereby enabling greater regulator confidence and supporting risk retirement during future consenting processes. The MRE sector will particularly benefit from the double-loop learning cycle of AM (Jones 2005), in which lessons learned from past and current projects can inform collective AM for future planning of MRE projects and scientifically informed licensing decisions (Figure 12.1). In principle, double-loop learning in AM may fill many data gaps, allowing developers to save significant time when developing detailed environmental assessments to inform consenting. This will, however, only be possible if monitoring data and methods for data collection, analysis, and presentation are consistent and shared at the appropriate level (Copping 2018).

Examples of MRE applications of AM processes are discussed later. The AM taken in the MeyGen tidal project (Section 12.4.1) in Scotland required phased development with monitoring requirements specifically designed to answer key scientific questions about biological impacts before receiving consents to proceed to the next phase. Similarly, the AM framework for the PacWave project (formerly Pacific Marine Energy Center South Energy Test Site) in the United States (U.S.) required that monitoring results be reviewed by designated regulatory agencies to implement predefined corrective actions, if the project effects exceed certain thresholds or mitigation criteria (Section 12.4.7). The AM approach taken for the Ocean Renewable Power Company's RivGen, U.S. (Section 12.4.6), SeaGen, United Kingdom (UK) (Section 12.4.2), DeltaStream, UK (Section 12.4.3), and Ocean Power Technology's Reedsport Wave Park, U.S. (Section 12.4.5), required that if specific monitoring results were found, a set of triggers could re-start consultation with the regulator and/or an advisory group, in order to adopt changes in project design, operations, and/or monitoring studies. An example of this occurred during consenting with the Reedsport Implementation Committees which had the ability to determine whether a change in the project was required as a result of meeting a screening criterion, and whether the prescribed management practices continued to be appropriate (Section 12.4.5).

12.3. ADAPTIVE MANAGEMENT AND THE PRECAUTIONARY PRINCIPLE

The precautionary principle is used as a preventive action in the face of uncertainty, shifting the burden of proof to the proponents of an activity, exploring a wide range of alternatives to possibly harmful actions, and increasing public participation in decision-making (Kriebel et al. 2001). The primary way the precautionary principle has been applied to MRE is through the mitigation hierarchy of avoidance, reduction, minimization, and compensation (Figure 12.2). While application of the precautionary principle provides a rational approach to avoiding irreversible harm, its implementation through the mitigation hierarchy offers reduced flexibility for addressing scientific uncertainty and promoting iterative learning for future developments. Regulators are faced with an uncertainty paradox, i.e., a paradoxical situation in which regulators take a precautionary approach, requesting an extensive amount of data and information from developers to understand the risks, but the data, in turn, cannot deliver decisive evidence to meet the requested level of certainty (Van Asselt and Vos 2006). While the monitoring of single devices may help understand the incremental effects of sizable arrays, the 2016 State of the Science report stressed that it is unlikely risk will scale in a simple linear fashion as the number of devices increase (Copping et al. 2016). Relying on the precautionary principle alone could lead to situations in which developers and regulators will never understand whether the perceived negative interactions of MRE technologies really exist and, if they do, how they can be resolved and minimized efficiently for future projects (Copping 2018; Todt and Lujan 2014). The purpose of the precautionary principle is the use of rigorous science to prevent unacceptable harm to marine life. Critical to the achievement of rigorous science is the flexibility to integrate scientific methods and data outputs into regulatory decision-making (Tickner and Kriebel 2008). With this in mind, AM may play an important role in the application of the precautionary principle, while working to reduce uncertainty and provide early warnings of adverse effects on marine receptors.

The interplay between AM and the precautionary principle is ambiguous. AM has sometimes been described as an alternative to the paralyzing effect of the precautionary principle (Pembina Institute for Appropriate Development v. Canada 2008). More pragmatic views see AM and the precautionary principle as complementary approaches in biodiversity conservation (Cooney 2006; Morgera 2017). Complementing the application of the precautionary principle with AM is increasingly accepted as a best practice for delivering proportionate and risk-based MRE consenting (Köppel 2014; Le Lièvre 2019). In most nations, reliance on the precautionary principle is subject to the principle of proportionality, which, in simple terms, requires that measures adopted on the basis of precaution must be proportionate to the perceived level of environmental risk. As such, it is generally accepted that precautionary measures should be of a temporary nature pending the availability of additional scientific evidence (Gillespie 2013). As new data are gathered through continuous monitoring, the intensity of monitoring and mitigation requirements should be proportionally responsive to the extent and probability of the environmental threat (Trouwborst 2006). This is the Achilles heel of AM. The use of AM allows for provisional decisions to be made despite uncertainty and responds to knowledge deficits by constantly monitoring and re-evaluating the mitigation initially considered appropriate on the precautionary basis. As such, AM may be viewed as a good practice for applying proportionate precautions and risk management to MRE consenting.

Implementing AM while adhering to the precautionary principle demands the use of rigorous procedural safeguards and a commitment to communicating uncertainty with transparency. AM cannot be used to offer unbounded discretion to decision-makers. AM should not be proposed without any degree of certainty that mitigation measures will be effective. Likewise, AM cannot substitute for demonstrating that substantive legal and regulatory conservation standards will be met throughout the lifespan of MRE projects. The conditions under which AM is acceptable depend on the form of AM and the strength of the application of the precautionary principle in the jurisdiction in which the consenting is taking place. A distinction has been made between prescriptive and flexible AM (Copping et al. 2019). Flexible AM has been predominantly used to address uncertainty about the interactions of single devices that have negligible adverse effects on marine features. At the scale of larger arrays, the value of using prescriptive AM lies in its capacity to incorporate new monitoring feedback into decision-making, while providing regulators with a degree of certainty that corrective mitigation measures will be taken before acceptable thresholds of change or disturbance are exceeded (Hanna et al. 2016). Hanna et al. (2016) also point out that this latter approach would provide developers with greater certainty about the costs of implementing AM. AM may still be used flexibly in larger developments to provide the regulator with a safeguard for prohibiting further deployment phases until specified corrective actions have been taken.

Overall, the question of whether AM is consistent with the precautionary principle should be informed by a case-by-case evaluation of the level of scientific uncertainty and the gravity of the anticipated threat. AM was described as "safe-fail" (Grieg and Murray 2008), meaning that AM should be applied when failure is an acceptable outcome. This suggests that AM may not be appropriate for all receptors, especially at a large deployment scale. If the overriding goal is to protect features of high conservation value, the need to protect these sensitive features may be more important than the desire to address the uncertainty associated with MRE projects. The conservation status of affected species or habitats should always inform the regulator and developers' appetite for risk (Le Lièvre et al. 2016). The adoption of conservative thresholds and trigger levels that incorporate precautionary margins and acknowledge the extant levels of uncertainty will be key for AM to work consistently with the precautionary principle. Implementing AM in this manner offers a relevant response mechanism for reducing scientific uncertainty while assuring that no unintended adverse impacts will occur as a result of insufficient or imprecise data available during the initial approval phase.

12.4.
EVALUATING THE SUCCESS OF ADAPTIVE MANAGEMENT AT SELECTED MRE DEVELOPMENT SITES

AM implementation has supported the deployment of several wave and tidal projects, thereby contributing to the testing of certain monitoring technologies, and it has answered some fundamental questions about the environmental interactions of single devices and small arrays. The case studies described in the following sections demonstrate how AM has been applied to consented projects, including the MeyGen tidal project (Scotland), the SeaGen tidal turbine (Northern Ireland), the DeltaStream tidal turbine (Wales), the Roosevelt Island Tidal Energy project (U.S.), Ocean Power Technology's Reedsport Wave Park (U.S.), and the Ocean Renewable Power Company's TidGen and RivGen turbine power systems (U.S.).

12.4.1.
MEYGEN TIDAL PROJECT

The MeyGen tidal energy demonstration project in Pentland Firth (Scotland) is the world's largest commercial tidal development and has applied an AM approach through a staged consenting process. Development consent was granted by Marine Scotland, on behalf of the Scottish Minister, for the construction and operation of 61 fully submerged turbines with a consented capacity of 86 MW. The Scottish Minister, on the advice of nature conservation bodies, consented the whole project on the condition that the first phase of development was implemented with only six turbines and those turbines were monitored before the deployment of additional turbines (Marine Scotland 2013). The conclusions derived from the environmental assessment process, prescribed under the European Union (EU) Habitats Directive (1992), were that significant adverse effects might occur as a result of predicted levels of collision with protected species, including seabirds, grey seals (*Halichoerus grypus*), harbor seals (*Phoca vitulina*), Atlantic salmon (*Salmo salar*), and sea lampreys (*Petromyzon marinus*).

Phase 1a was limited to six turbines and subject to a comprehensive monitoring program designed to measure the behavior of mobile species near the turbines and the findings were to be used to validate collision risk models. All subsequent project phases are subject to prior approval to assure development consents are given with full knowledge of the potential impacts on protected species. AM enabled the developer to achieve the full project consent necessary for investor confidence, while delivering a phased approach following the survey-deploy-monitor licensing policy for licensing (Marine Scotland 2016). In 2017, Marine Scotland granted development consent to install Phase 1b, which comprised four more turbines of 6 MW each. Deployment of Phase 1c is intended to take place in 2021–2022 and will be highly contingent upon monitoring outcomes from Phases 1a and 1b. If deployed, Phase 1c will consist of a further 49 turbines, bringing the total capacity of Phase 1 to 86 MW. Further information about the specifics of the AM plan and results of environmental monitoring for MeyGen can be found in Chapter 3 (Collision Risk for Animals around Turbines); however, some results are commercially sensitive and not yet publicly available.

12.4.2.
SEAGEN TIDAL TURBINE

The Northern Ireland Environment and Heritage Service and Marine Current Turbines (MCT) installation applied an AM approach to the deployment and operation of MCT's SeaGen turbine in Strangford Lough (Northern Ireland). Strangford Lough is designated as a Special Area of Conservation (SAC) and Special Protection Area (SPA) under the EU Habitats Directive (1992) and Birds Directive (2009). The main environmental concern was whether the turbine would have an adverse impact on the use of the Lough by harbor seals, a feature of the SAC that has an unfavorable conservation status (Keenan et al. 2011). There was also uncertainty about whether there was a risk of collision for harbor seal and harbor porpoises (*Phocoena phocoena*) with the turbine blades. Although not a protected species of the SAC, harbor porpoises are subject to a strict protection regime to keep them from harm, including death, physical injury, and disturbances, under the Habitats Directive (1992). In this case, the key aspects of AM focused on marine mammals. A comprehensive environmental monitoring plan was developed as a condition of the license and was complemented by an AM approach that required continuous review of monitoring data and management measures by an independently chaired Scientific Steering Group. Monitoring objectives for marine mammals included a zero-risk mortality tolerance for collision with the turbine blades (Savidge et al. 2014). Associated mitigation measures included a restriction to daylight operation and the use of Marine Mammal Observers (MMOs) onboard the tidal platform; the MMOs had the ability to shut down the turbine whenever marine mammals were observed to cross the agreed-upon shutdown action perimeter of 200 m (Fortune 2017). The effectiveness of an active experimental sonar system was also tested as a mitigation measure to assist in the detection of marine mammals (Hastie et al. 2014).

After three years of post-installation monitoring, marine mammals appeared to be unlikely to collide with the turbine within the agreed-upon shutdown action perimeter. Monitoring activities showed that seals and harbor porpoises tend to avoid the SeaGen turbine, which reduced the likelihood of marine mammal collisions (Keenan et al. 2011). Field data provided indications that SeaGen did not create a barrier effect for harbor seals transiting through the Strangford Narrows; they continued to use haulout sites during turbine operation (Sparling et al. 2017). Monitoring data also demonstrated that active sonar was effective in mitigating collision risk in a manner comparable to MMOs (Fortune 2017). Mitigation monitoring changed from daylight only with MMOs on the turbine structure to 24-hour manual observation of active sonar, which allowed the turbine to be operated on a 24-hour basis, but with the significant requirement for trained personnel to be on duty whenever the turbine was operating. As knowledge of the environmental effects of SeaGen increased, the precautionary shutdown distance was progressively reduced from 200 m to 100 m, and then to less than 30 m (Savidge et al. 2014). Final removal of the shutdown protocol, with associated fine-scale monitoring around the turbine blades using a new multibeam sonar system, albeit authorized, was not implemented before the device stopped operating in 2015, prior to eventual decommissioning in 2019. The mitigation requirements resulted in missed opportunities to gain relevant knowledge about how marine mammals interact with the operating turbine blades. Despite this, the AM process allowed MCT to install and operate the SeaGen turbine over a period of five years, thereby increasing the developer's confidence in the technology and its capacity to deliver power to the grid (Fortune 2017).

12.4.3. DELTASTREAM TIDAL TURBINE

An AM approach was used to license Tidal Energy Limited's grid-connected 400 kW DeltaStream tidal energy project in Ramsey Sound, off the Pembrokeshire coast in Wales. Ramsey Sound is within a SAC and adjacent to an SPA designated under the EU Habitats Directive (1992) and Birds Directive (2009). The license for installation and operation was granted in 2011 by Natural Resources Wales for a 12-month deployment period of a single 400 kW turbine mounted on a steel triangular gravity-based frame. DeltaStream was successfully deployed and connected to the grid in 2015. The greatest environmental concerns were for the collision with the turbine of a variety of cetacean species protected from killing or disturbance under the Habitats Directive (1992), including harbor porpoise and grey seal. The DeltaStream project relied on a threshold-based approach to AM where acceptable collision thresholds were set using a potential biological removals (PBR) approach (Copping et al. 2016.). PBR is a widely used method of determining the level of additional manmade mortality a population can sustain without adversely affecting its size and stability (Wade 1998). A detailed Collision Monitoring and Adaptive Management Plan established the approach to marine mammal monitoring to determine the real level of collision risks in the face of uncertainty (Copping et al. 2016; Sparling, personal communication). The nearfield monitoring planned for this project included a passive acoustic monitoring system with several hydrophones directly mounted on the turbine substructure together with an active acoustic monitoring system that used a multibeam sonar to detect animals approaching the device (Malinka et al. 2018). Unlike the SeaGen turbine project, the DeltaStream project had no shutdown mitigation requirements, but it applied a flexible AM approach in which the need for mitigation could be identified and required by the Environmental Management Body to reduce the risk of collision-related mortalities and ensure that thresholds were not breached (Copping et al. 2016; Sparling, personal communication). The mitigation steps outlined in the collision risk management plan included the potential for limiting turbine operation during sensitive times and the use of acoustic deterrents. By consenting the project without the need for a shutdown protocol, the deployment of the DeltaStream turbine was designed to provide information about close-range interactions between marine mammals and the operating device to work in conjunction with an acoustic strike detection system that appeared to be highly reliable to detect collisions. However, as the project progressed, the ability of the nearfield monitoring to confidently detect collisions using a strike-detection system became highly uncertain. The DeltaStream project illustrates the challenges of monitoring in the presence of thresholds in AM (as discussed in Section 12.2.1), because these thresholds require the ability to accurately monitor and detect certain metrics of concern to confirm whether an unacceptable impact occurs or a threshold/trigger has been reached. Because of equipment failure and subsequent liquidation of Tidal Energy Limited, the DeltaStream turbine and monitoring system was never operated for any significant length of time.

12.4.4. ROOSEVELT ISLAND TIDAL ENERGY PROJECT

In 2012, the U.S. Federal Energy Regulation Commission (FERC) issued a 10-year Pilot License (FERC No.12611) to Verdant Power for the installation of up to 30 hydrokinetic turbines to be deployed during three phases in the east channel of the East River (New York, U.S.). The first phase of Verdant Power's Roosevelt Island Tidal Energy (RITE) project consisted of three turbines mounted on a tri-frame with a total capacity of 105 kW (Verdant Power 2010a). Three additional redesigned tri-frames and nine turbines will be installed in 2020, with a total capacity of 420 kW. The last phase will culminate with the installation of 6 tri-frames supporting 18 additional turbines, with a total capacity of 1 MW. The project represents the application of AM to support the execution of a series of seven RITE Monitoring of Environmental Effects (RMEE) plans (Verdant Power 2010b). In this particular case, AM was not applied to adapt the management of the project. Instead, AM was directed at reducing scientific uncertainty within the RMEE plans to address key environmental questions related to the characterization of species and the effects of the turbine (and generated operating noise) on the presence, distribution, and abundance of aquatic species. The RMEE plans consisted of seven focal monitoring studies addressing (1) the micro-scale interaction of aquatic species with the turbine, (2) the fish composition in the immediate vicinity of the project, (3) the occurrence of protected fish species under the Endangered Species Act (1973), (4) the potential for turbine impacts on seabirds, (5) the occurrence of underwater noise generated by the project, and (7) the installation's impact on recreation (Verdant Power 2019). During the AM process, the usefulness of the data collected was reviewed to suggest adjustments of the RMEE plans and/or suspend their implementation until the data yielded sufficient information to provide complete understanding of the fundamental questions to be answered under each RMEE plan. Hydroacoustic data enabled Verdant to suspend use of the seasonal Dual-Frequency Identification Sonar (DIDSON) observation plan based on the finding that further DIDSON data collection would not yield additional information about fish interactions (Verdant Power 2018). The DIDSON system also was found to have achieved its objective of providing real-time observation of fish behavior at the micro-scale to enable refinement of the Fish Interaction Model. With these data incorporated, the model suggested that there was a low probability that fish would collide with the turbine blades of the up to 30 turbines planned for installation. AM allowed Verdant to discontinue surveys that do not yield meaningful information and redirect monitoring efforts toward continually enhancing monitoring plans for species of concern.

12.4.5. REEDSPORT WAVE PARK

Ocean Power Technology (OPT)'s Reedsport Wave Park project received a full commercial-scale license in August 2012 to operate up to 10 grid-connected PowerBuoy wave energy converters (WECs), each of which has a capacity of 1.5 MW. A preliminary consent was also secured by OPT to install additional WECs during future phases, which could have brought the overall capacity to 50 MW. Reedsport Wave Park was proposed under a phased consenting approach using AM as a cornerstone. Under terms of the license, Phase 1 consisted of installing a single 150 kW unit largely intended to test the mooring system and the WEC operation, and to collect data about electromagnetic fields (EMFs) and the underwater noise of the device. An AM process was embedded in a Settlement Agreement, which included following a long-term process of engagement with stakeholders and regulatory agencies (OPT 2010). The AM process for OPT aimed at "managing the development and operation of the project in an adaptive manner to avoid and minimize adverse effects to aquatic resources, water quality, recreation, public safety, crabbing and fishing, terrestrial resources and cultural resources" (OPT 2010). Specifically, the project AM was intended to support the implementation of monitoring studies and to identify and adjust measures required to address any unanticipated effects of the project and its potential expansion (OPT 2010). The Settlement Agreement included detailed environmental studies for pinnipeds and cetaceans, EMFs, fish, and seabirds, as well as changes in waves, currents, and sediment transport. The requirements of the agreement relied on the screening criteria that could define changes in project design, monitoring, or management practices if prescribed by an advisory body (or Implementation Committee), to avoid or minimize potential adverse impacts. The screening criteria included detailed baseline characterizations of marine mammal behavior (in the absence of devices) and their response to EMFs and underwater noise. Particular attention was given to whether marine mammals were likely to collide with or become entangled in mooring systems. If the project had an adverse effect on baseline conditions, OPT was required to prepare an avoidance, minimization, and mitigation plan (Response Plan) that included alternative management measures. Alternative management measures were not determined at the start but were left to the later determination of the developer and approval by the competent Implementation Committee. At this point in time, the extent to which AM contributed to reducing uncertainty and informing the future expansion of Reedsport Wave Park cannot be evaluated, because the FERC license was surrendered two years after the project was approved. The license was surrendered mainly because of difficulties related to financing Phase 1 and technical complications resulting from installation of the floating gravity-based anchor, as well as the unfortunate sinking of the subsurface buoyancy float. The project was withdrawn before the AM process could be applied to the full project timeline (O'Neil et al. 2019).

12.4.6
ORPC'S TIDGEN AND RIVGEN POWER SYSTEMS

Ocean Renewable Power Company (ORPC) has a track record of implementing AM to reduce scientific uncertainty when modifying project operations and monitoring methodologies at the scale of single devices (e.g., TidGen and RivGen projects). Using conditional licensing, with AM as a basis, ORPC was granted a Pilot Project License (FERC No. 12711-005) by FERC in 2012 to install and operate TidGen, a single horizontal-axis tidal turbine, in Cobscook Bay, Maine (U.S.) (FERC No. 12711-005). An AM plan that served as the foundation for monitoring and science-based decision-making was required under the Pilot License. The AM plan was developed by ORPC's Adaptive Management Team (AMT) in consultation with regulatory agencies, stakeholders, and local communities. Using the AM process, ORPC, with the support of the AMT, was able to demonstrate that their single tidal unit would have minimal effects on marine wildlife. The process resulted in a number of license modifications that clarified the monitoring requirements and, in some cases, lowered the frequency of monitoring required for specific surveys (ORPC 2017). The core objective of monitoring was to collect data about fisheries and marine life interactions with the turbine and to measure the effects of underwater noise on sockeye salmon (*Oncorhynchus nerka*), marine mammals, and seabirds (ORPC 2013). Data were collected under six monitoring plans; AM provided a strategy for evaluating the monitoring results and making informed decisions about the modification of monitoring plans, as needed.

Initially, the Pilot License for the TidGen project imposed a seasonal restriction window on pile-driving operations because of the presence of migrating Atlantic salmon. Alleviation of seasonal restrictions under the AM plan was dependent on the results of underwater monitoring, which demonstrated that sound levels produced by pile-driving hammer techniques (outside the restriction period) did not exceed the acceptable threshold established by the National Marine Fisheries Service (NMFS 2018). Underwater noise measurements from the installation of TidGen indicated that noise levels were below the thresholds of concern for Atlantic salmon when sound absorption measures, including the placement of plywood between the impact hammer and the follower, were used during pile driving (ORPC 2013). Using these thresholds and transferring underwater noise data from a previous project allowed ORPC to request the removal of seasonal restrictions on pile-driving for Phase 1 operations, which was granted by FERC.

Monitoring for marine mammals during the installation and operational phase included incidental and dedicated observations made by trained MMOs. Incidental observations were performed over several seasons to observe marine mammal presence and behavior around the turbine prior to, during, and after key installation and maintenance activities, including pile-driving (ORPC 2013). Mitigation for the presence of marine mammals entering or approaching a 152 m marine mammal exclusion zone during pile-driving included curtailment and delay of installation activities (ORPC 2013). Cessation of pile-driving activities was required until the marine mammal had moved beyond 305 m (1000 ft) from the exclusion zone or 30 minutes had passed since the last sighting (ORPC 2013). Dedicated marine mammal observations indicated minimal changes in animal presence and behavior as a result of generated noise levels during pile-driving activities (ORPC 2013). Marine mammals were not visually observed to enter the exclusion zone; therefore, the shutdown and delay procedures were not triggered during the installation period (ORPC 2013). Incidental marine mammal sightings did not indicate any behavioral changes or evidence of adverse encounters or collisions during the installation and operation of TidGen (ORPC 2014). These findings resulted in a FERC license order that allowed ORPC to fully transition from dedicated observations, whereby marine mammals are recorded by certified MMOs as part of a dedicated survey effort, to incidental marine mammal observations (ORPC 2014).

In a similar approach, during 2014 and 2015 AM allowed for the deployment of the RivGen demonstration project in the Kvichak River in Alaska, U.S., without requiring a FERC Pilot License. A fish monitoring plan required the use of underwater video cameras to monitor fish interactions with the device and the evaluation and mitigation of possible adverse effects on sockeye salmon. The video footage revealed the absence of physical injuries and no altered behavior of the fish in the immediate vicinity of the turbine. It was determined that mitigation measures were not necessary. In this way, AM was able to contribute to the retirement of collision risk for fish around the single RivGen tidal unit (ORPC 2016). These findings were also presented by ORPC at the Cobscook Bay Tidal Energy Project AMT meeting in 2014 and 2015 (ORPC 2015, 2016), suggesting that transfer of data is a real possibility from the industry perspective and can definitely be used to inform future developments (see Chapter 13, Risk Retirement and Data Transferability for Marine Renewable Energy). The 2015 monitoring project is referenced in the FERC license for the next stage of the Iguigig Hydrokinetic Project (FERC No. 13511-003) and the methods used previously will be implemented again, more extensively (FERC 2019). The short sampling periods in 2014 and 2015 limited broader transferability of the data.

Knowledge gained at the RivGen demonstration project facilitated the issuance of a recent Pilot License authorizing the installation and operation of the current phase of the RivGen project in the Kvichak River, near the village of Iguigig. The RivGen project consists of two in-stream turbine generator units (TGUs), each of 35 kW capacity, to be deployed in two distinct phases. Installation of TGU 1 (Phase 1) was completed in 2019. Installation of TGU 2 (Phase 2) is planned for 2020 (FERC No. 13711-003). The project relies heavily on AM to address environmental unknowns and take corrective actions if monitoring indicates any unanticipated adverse effects on aquatic animals (FERC No. 13711-003, Article 403). The Pilot License includes requirements for real-time video monitoring and the immediate shutdown of the project within one hour if injuries or mortality of outmigrating sockeye smolts are detected as a result of turbine operation. The Emergency Shutdown Plan, which includes provisions for monitoring and reporting, will serve as a source of information for recommending corrective mitigation actions (FERC 2019). If fish monitoring data provide evidence of negative interactions (injuries or mortality) on migrating salmon, the AMT may have to consider additional monitoring efforts and implement work timing windows to reduce and/or eliminate negative impacts on fish populations (FERC No. 13711-003, Article 403). Conversely, if no adverse effects are observed throughout the first year of operation, the AMT may submit recommendations to FERC to modify the monitoring protocol and shutdown plan.

Overall, the RivGen and TidGen projects provide examples of how AM may be used to understand environmental risks, inform best management practices, and modify license requirements based on increased data collection and understanding of environmental effects and species interactions (Johnson 2016).

12.4.7
PACWAVE SOUTH PROJECT

Oregon State University (OSU) developed a detailed AM framework to support a license application to install and operate a grid-connected wave energy test facility: the PacWave South Project, formerly known as Pacific Marine Energy Center South Energy Test Site. The project consists of four grid-connected berths to support testing of up to 20 commercial-scale WECs with a maximum installed capacity of 20 MW. As part of their AM framework, OSU has committed to implementing monitoring programs for underwater noise, habitat changes, and EMFs to confirm assumptions about the levels and durations of potential effects, coupled with processes for taking corrective actions in consultation with competent regulatory agencies (OSU 2019a). The AM framework for PacWave South seems to embody a prescribed approach to AM, whereby monitoring results are evaluated in consultation with an Adaptive Management Committee (AMC) and agency stakeholders to review project effects, make changes to monitoring, and engage specific responsive actions where these effects exceed certain thresholds or mitigation criteria. The AM framework will also inform decisions, including those about the need to adopt additional protection, mitigation, and enhancement measures to assure that the potential effects are within the thresholds and meet the criteria prescribed for the project.

For example, with respect to benthic habitats, if monitoring results indicate that WECs and their components have a statistically significant impact beyond the range of seasonal/interannual variability on macrofaunal species composition or abundance, OSU will be obliged to submit a draft plan to implement the following mitigation actions with accompanying implementation timelines and monitoring provisions to assess the effectiveness of the measures (OSU 2019a):

- Limit use of specific anchor types in future installations.
- Modify and manage the deployment frequency or location to enable recovery of macrofauna.
- Use permanent anchoring systems (e.g., for the life of the project).
- Conduct additional *in situ* monitoring.

Similarly, if underwater noise monitoring results show persistent exceedance of published harassment thresholds (120 dB re 1 µPa) at a distance of 100 m from the WECs or their mooring systems, OSU is obliged to instruct testing clients to diagnose and repair or modify the WECs or mooring systems within 60 days, to continue monitoring activities, and to demonstrate the effectiveness of the noise abatement measures. In addition, OSU is required to notify NMFS about whether further exceedances of harassment thresholds occur after implementation of the corrective actions. If, despite repairs and modifications, the noise level is not reduced below acceptable thresholds, further actions are prescribed, including the provision of a draft plan specifying the following, among other actions:

- alternative or additional methods of monitoring to identify the source and cause of the noise and to inform specific actions necessary to reduce the noise below the threshold
- modifications to the operation of the WECs (e.g., modify controls to change the motion of the WECs)
- necessary repairs and modifications to reduce noise levels.

If after taking these steps, noise levels are not abated within 14 days, the operation of WECs will be temporarily ceased to halt noise threshold exceedances (OSU 2019a).

While it goes beyond the scope of this chapter to detail the catalog of measures and the AM process applied by PacWave South, the approach is relatively similar with respect to EMFs. If post-installation field measurements and modeling results detect EMF emissions greater than biologically relevant levels (e.g., 3 mT), OSU has the obligation to notify the AMC and instruct testing clients to adopt specific actions, including, but not limited to, installing additional shielding of subsea cables or other components such as hubs or subsea connectors. Further *in situ* monitoring is prescribed to verify the abatement of excess EMF levels, and if EMF levels cannot be minimized, a draft mitigation plan must be prepared to implement specified mitigation actions until the source of exceedance is reduced to below the acceptable threshold.

Further information can be found in the FERC license application (OSU 2019a) and the accompanying AM Framework (OSU 2019b).

12.5. CONCLUSIONS AND RECOMMENDATIONS

This chapter provides an explanation of AM and how its underlying principles may be applied to developing effective approaches for addressing uncertainty and knowledge gaps in consenting processes. To date, AM has contributed to risk retirement by allowing single devices or small arrays to be deployed under a structured incremental approach with embedded mitigation and monitoring, thereby providing valuable information about device-specific stressor/receptor interactions. As the industry moves toward commercial deployment, implementation guidance should be issued by responsible governmental bodies to support a common understanding of AM and guide the design of AM plans at the scale of MRE arrays. The industry will particularly benefit from guidance documents that specify the circumstances under which AM is acceptable and establish clear and mandatory elements of AM plans, including the design of and conditions for post-installation monitoring, stakeholder engagement, information sharing, and thresholds for AM intervention.

As the industry moves forward, MRE developers that use AM for marine renewables could learn from their fisheries counterparts by using clearly controlled rules for monitoring and evaluating project effects relative to predefined thresholds, including the ability to adjust mitigation and monitoring as part of a formal structured AM process (McDonald et al. 2017; Sainsbury et al. 2000). Monitoring approaches must be question-driven and the questions must be directly connected to thresholds/triggers to avoid unacceptable impacts. In practice, designing monitoring that informs and works with thresholds may be extremely challenging; it requires the ability to confidently measure and monitor the appropriate metrics of concern with the required levels of accuracy and precision to inform management decisions.

It is important to realize that engaging in an AM approach may not result in quick wins: AM is a long process that requires forethought and commitment, and AM comes with a degree of risk for developers. Developers must accept that the operational schemes of their projects might be altered or terminated if monitoring indicates harm is being done to sensitive species or other valuable uses. Large MRE projects consented on the basis of AM informing project phasing might never achieve full build out, and regulators might require project decommissioning if the related impacts are deemed unacceptable. Likewise, the success of AM largely depends on the regulator's risk acceptance and attitude about proportionality. Before engaging in an AM approach, regulators and developers should undertake an explicit, structured analysis of the resources they have available and consider the need for and practicality of reducing uncertainties. While AM offers some flexibility to consent and deploy MRE projects despite uncertainty, AM at larger deployment scales has the potential to become an onerous process that creates significant financial uncertainty for project developers. To date, AM is the only known method capable of dealing with the levels of existing uncertainty associated with MRE projects as well as the interaction of MRE projects with other industries and other challenges, including climate change. Advancing the use of AM for MRE will require the development of mechanisms that minimize undue financial risks for developers, while assuring adequate protection of the marine environment and consistency relative to the precautionary principle.

12.6. REFERENCES

Bennet, F., Culloch, R., and Tait, A. 2016. Guidance on effective adaptive management and post-consent monitoring strategies (RiCORE Project Report No. RiCORE-D5-2D5-4). Report by Robert Gordon University for European Commission; Aberdeen, Scotland. *https://tethys.pnnl.gov/publications/guidance-effective-adaptive-management-post-consent-monitoring-strategies*

Birds Directive (Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds). OJ L 20, 26.1.2010, p. 7–25. [European Union]

Cooney, R. 2006. A long and winding road? Precaution from principle to practice in biodiversity conservation. In E. Fisher, J. Jones, and R. von Schomberg (Ed.), *Implementing the Precautionary Principle; Perspectives and Prospects* (pp. 223-244). Cheltenham, England: Edward Elgar Publishing Limited. *https://tethys.pnnl.gov/publications/long-winding-road-precaution-principle-practice-biodiversity-conservation*

Copping, A. 2018. The State of Knowledge for Environmental Effects: Driving Consenting/Permitting for the Marine Renewable Energy Industry. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. *https://tethys.pnnl.gov/publications/state-knowledge-environmental-effects-driving-consentingpermitting-marine-renewable*

Copping, A., Gartman, V., May, R., and Bennet, F. 2019. The Role of Adaptive Management in the Wind Energy Industry. In R. Bispo, J. Bernardino, H. Coelho, and J. L. Costa (Eds.), *Wind Energy and Wildlife Impacts* (pp. 1-25). Cham, Switzerland: Springer. *https://tethys.pnnl.gov/publications/role-adaptive-management-wind-energy-industry*

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewski, G., Staines, G., Gill, A., Hutchinson, I., O'Hagan, A., Simas, T., Bald, J., Sparling, C., Wood, J., and Masden, E. 2016. Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. *https://tethys.pnnl.gov/publications/state-of-the-science-2016*

Elliott, K., Smith, H. C. M., Moore, F., van der Weijde, A. H., and Lazakis, I. 2019. A systematic review of transferable solution options for the environmental impacts of tidal lagoons. *Marine Policy*, 99, 190-200. doi:10.1016/j.marpol.2018.10.021 https://tethys.pnnl.gov/publications/systematic-review-transferable-solution-options-environmental-impacts-tidal-lagoons

Endangered Species Act of 1973, as amended. 16 U.S.C. ch. 35 § 1531 et seq. [U.S.]

Federal Energy Regulatory Commission (FERC). 2019. Environmental Assessment for Hydropower License: Igiugig Hydrokinetic Project - FERC Project No. 13511-003. Office of Energy Projects, Washington, D.C. https://tethys.pnnl.gov/publications/environmental-assessment-hydropower-license

Fortune, F., Gilmore, P., and Bennet, F. 2017. Adaptive Management Systems - Don't make the same mistakes twice! Webinar conducted by European Technology and Innovation Platform for Ocean Energy (ETIP) Ocean. https://tethys.pnnl.gov/events/webinar-adaptive-management-systems-dont-make-same-mistakes-twice

Fox, C. J., Benjamins, S., Masden, E. A., and Miller, R. 2018. Challenges and opportunities in monitoring the impacts of tidal-stream energy devices on marine vertebrates. *Renewable and Sustainable Energy Reviews*, 81(2), 1926-1938. doi:10.1016/j.rser.2017.06.004 https://tethys.pnnl.gov/publications/challenges-opportunities-monitoring-impacts-tidal-stream-energy-devices-marine

Gillespie, A. 2013. Conservation, Biodiversity and International Law. Cheltenham, England: Edward Elgar Publishing. https://tethys.pnnl.gov/publications/conservation-biodiversity-international-law

Greig, L., and Murray, C. 2008. Peer Review of Rockfort Quarry Adaptive Management Plan. Jagger Hims Ltd., Collingwood, Ontario. https://www.peelregion.ca/planning/pdf/rockfort/rockfort2.pdf

Habitats Directive (Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora). OJ L 206, 22.7.1992, p. 7-50. [European Union]

Hanna, L., Copping, A., Geerlofs, S., Feinberg, L., Brown-Saracino, J., Bennet, F., May, R., Köpel, J., Bulling, L., and Gartman, V. 2016. Adaptive Management White Paper. IEA Wind Task 34: Assessing Environmental Effects (WREN) Technical Report. Report by Berlin Institute of Technology of International Energy Agency. https://tethys.pnnl.gov/publications/assessing-environmental-effects-wren-adaptive-management-white-paper

Hastie, G. D., Gillespie, D. M., Gordon, J. C. D., Macaulay, J. D. J., McConnell, B. J., and Sparling, C. E. 2014. Tracking Technologies for Quantifying Marine Mammal Interactions with Tidal Turbines: Pitfalls and Possibilities. In M. A. Shields and A. I. L. Payne (Eds.), *Marine Renewable Energy Technology and Environmental Interactions* (pp. 127-139). Dordrecht: Springer Netherlands. https://tethys.pnnl.gov/publications/tracking-technologies-quantifying-marine-mammal-interactions-tidal-turbines-pitfalls

Johnson, C. J. 2013. Identifying ecological thresholds for regulating human activity: Effective conservation or wishful thinking? *Biological Conservation*, 168, 57-65. doi:10.1016/j.biocon.2013.09.012 https://tethys.pnnl.gov/publications/identifying-ecological-thresholds-regulating-human-activity-effective-conservation-or

Johnson, N. 2016. Adaptive Management in the Marine Renewable Energy Industry. Webinar conducted by Ocean Energy Systems Annex IV. https://tethys.pnnl.gov/events/adaptive-management-marine-renewable-energy-industry-webinar

Jones, G. 2005. Is the management plan achieving its objectives? In G. L. Worboys, M. Lockwood, and T. De Lacy (Eds. Second ed.), *Protected Area Management: Principles and Practice* (pp. 555-557). Melbourne, Australia: Oxford University Press. https://tethys.pnnl.gov/publications/management-plan-achieving-its-objectives

Keenan, G., Sparling, C., Williams, H., and Fortune, F. 2011. SeaGen Environmental Monitoring Programme: Final Report. Report by Royal Haskoning for Marine Current Turbines; Edinburgh, Scotland. https://tethys.pnnl.gov/publications/seagen-environmental-monitoring-programme-final-report

Köppel, J., Dahmen, M., Helfrich, J., Schuster, E., and Bulling, L. 2014. Cautious but Committed: Moving Toward Adaptive Planning and Operation Strategies for Renewable Energy's Wildlife Implications. *Environmental Management*, 54(4), 744-755. doi:10.1007/s00267-014-0333-8 *https://tethys.pnnl.gov/publications/cautious-committed-moving-toward-adaptive-planning-operation-strategies-renewable*

Kriebel, D., Tickner, J., Epstein, P., Lemons, J., Levins, R., Loechler, E. L., Quinn, M., Rudel, R., Schettler, T., and Stoto, M. 2001. The precautionary principle in environmental science. *Environmental Health Perspectives*, 109(9), 871-876. doi:10.1289/ehp.01109871 *https://tethys.pnnl.gov/publications/precautionary-principle-environmental-science*

Le Lièvre, C. 2019. Sustainably reconciling offshore renewable energy with Natura 2000 sites: An interim adaptive management framework. *Energy Policy*, 129, 491-501. doi:10.1016/j.enpol.2019.02.007 *https://tethys.pnnl.gov/publications/sustainably-reconciling-offshore-renewable-energy-natura-2000-sites-interim-adaptive*

Le Lièvre, C., O'Hagan, A., Culloch, R., Bennet, F., and Broadbent, I. 2016. Legal feasibility of implementing a risk-based approach to MRE consenting and compatibility with Natura 2000 network (RiCORE Project Report No. 2.3 & 2.4). Report by University College Cork for European Commission; Aberdeen, Scotland. *https://tethys.pnnl.gov/publications/legal-feasibility-implementing-risk-based-approach-mre-consenting-compatibility-natura*

Magagna, D., Greaves, D., Conley, D., O'Hagan, A. M., Holmes, B., Witt, M., Simas, T., Olivares, C. H., Leitão, J. C., Mouslim, H., Torre-Enciso, Y., Sundberg, J., and Rousseau, N. 2012. How Experiences of the Offshore Wind Industry Can Aid Development of the Wave Energy Sector: Lessons Learnt From EIA Studies. Paper presented at the 22nd International Offshore and Polar Engineering Conference, Rhodes, Greece. *https://tethys.pnnl.gov/publications/how-experiences-offshore-wind-industry-can-aid-development-wave-energy-sector-lessons*

Malinka, C. E., Gillespie, D. M., Macaulay, J. D. J., Joy, R., and Sparling, C. E. 2018. First *in situ* passive acoustic monitoring for marine mammals during operation of a tidal turbine in Ramsey Sound, Wales. *Marine Ecology Progress Series*, 590, 247-266. doi:10.3354/meps12467 *https://tethys.pnnl.gov/publications/first-situ-passive-acoustic-monitoring-marine-mammals-during-operation-tidal-turbine*

Marine Scottland. 2013. MeyGen Decision - Decision Letter Consent and Conditions. Scottish Government. *https://tethys.pnnl.gov/publications/consent-granted-scottish-ministers-construct-operate-meygen-tidal-energy-project*

Marine Scottland. 2016. Survey, Deploy and Monitor Licensing Policy Guidance. Scottish Government. *https://tethys.pnnl.gov/publications/survey-deploy-monitor-licensing-policy-guidance*

McDonald, G., Harford, B., Arrivillaga, A., Babcock, E. A., Carcamo, R., Foley, J., Fujita, R., Gedamke, T., Gibson, J., Karr, K., Robinson, J., and Wilson, J. 2017. An indicator-based adaptive management framework and its development for data-limited fisheries in Belize. *Marine Policy*, 76, 28-37. doi:10.1016/j.marpol.2016.11.027 *https://tethys.pnnl.gov/publications/indicator-based-adaptive-management-framework-its-development-data-limited-fisheries*

Morgera, E. 2017. The ecosystem approach and the precautionary principle. In M. Faure, E. Morgera, and J. Razzaque (Eds.), *Elgar Encyclopedia of Environmental Law: Biodiversity and Nature Protection Law* (Vol. III, pp. 70-80). Cheltenham, England: Edward Elgar Publishing. *https://tethys.pnnl.gov/publications/ecosystem-approach-precautionary-principle*

National Marine Fisheries Service (NMFS). 2018. 2018 Revision to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts (NMFS-OPR-59). Report by National Oceanic and Atmospheric Administration for U.S. Department of Commerce; Silver Spring, Maryland. *https://tethys.pnnl.gov/publications/2018-revisions-technical-guidance-assessing-effects-anthropogenic-sound-marine-mammal*

Ocean Power Technologies (OPT). 2010. Reedsport OPT Wave Park Settlement Agreement. Report by Ocean Power Technologies; Reedsport, Oregon. *https://tethys.pnnl.gov/publications/reedsport-opt-wave-park-settlement-agreement*

Ocean Renewable Power Company (ORPC). 2013. Cobscook Bay Tidal Energy Project: 2012 Environmental Monitoring Report. Report by Ocean Renewable Power Company; Portland, Maine. *https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2012-environmental-monitoring-report*

Ocean Renewable Power Company (ORPC). 2014. Cobscook Bay Tidal Energy Project: 2013 Environmental Monitoring Report. Report by Ocean Renewable Power Company; Portland, Maine. *https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2013-environmental-monitoring-report*

Ocean Renewable Power Company (ORPC) 2015. Cobscook Bay Tidal Energy Project: 2014 Environmental Monitoring Report. Report by Ocean Renewable Power Company; Portland, Maine. *https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2014-environmental-monitoring-report*

Ocean Renewable Power Company (ORPC). 2016. Cobscook Bay Tidal Energy Project: 2015 Environmental Monitoring Report. Report by Ocean Renewable Power Company; Portland, Maine. *https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2015-environmental-monitoring-report*

Ocean Renewable Power Company (ORPC). 2017. Cobscook Bay Tidal Energy Project: 2016 Environmental Monitoring Report. Report by Ocean Renewable Power Company; Portland, Maine. *https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2016-environmental-monitoring-report*

Offshore Renewables Joint Industry Programme (ORJIP) Ocean Energy. 2017. The Forward Look: An Ocean Energy Environmental Research Strategy for the UK. Report by Aquatera Ltd for The Crown Estate, Marine Scotland Science, Welsh Assembly Government, Scottish Natural Heritage, Natural Resources Wales; Stromness, Scotland. *https://tethys.pnnl.gov/publications/forward-look-ocean-energy-environmental-research-strategy-uk*

O'Neil, R., Staines, G., and Freeman, M. 2019. Marine Hydrokinetics Regulatory Processes Literature Review. Report by Pacific Northwest National Laboratory for U.S. Department of Energy; Richland, Washington. *https://tethys.pnnl.gov/publications/marine-hydrokinetics-regulatory-processes-literature-review*

Oregon State University (OSU). 2019a. Final License Application for the PacWave South Project (FERC Project No. 14616). Volume III: Appendix I: Potection, Mitigation, and Enhancement Measures. Report by Oregon State University; Corvallis, Oregon. *https://tethys.pnnl.gov/publications/pacwave-south-license-application*

Oregon State University (OSU). 2019b. Final License Application for the PacWave South Project (FERC Project No. 14616). Volume III: Appendix J: Adaptive Management Framework. Report by Oregon State University; Corvallis, Oregon. *https://tethys.pnnl.gov/publications/pacwave-south-license-application*

Pembina Institute for Appropriate Development v. Canada, 2008 FC 302, para. 32. [Canada]

Sainsbury, K. J., Punt, A. E., and Smith, A. D. M. 2000. Design of operational management strategies for achieving fishery ecosystem objectives. *ICES Journal of Marine Science*, 57(3), 731-741. doi:10.1006/jmsc.2000.0737 *https://tethys.pnnl.gov/publications/design-operational-management-strategies-achieving-fishery-ecosystem-objectives*

Savidge, G., Ainsworth, D., Bearhop, S., Christen, N., Elsaesser, B., Fortune, F., Inger, R., Kennedy, R., McRobert, A., Plummer, K. E., Pritchard, D. W., Sparling, C. E., and Whittaker, T. J. T. 2014. Strangford Lough and the SeaGen Tidal Turbine. In M. A. Shields and A. I. L. Payne (Eds.), *Marine Renewable Energy Technology and Environmental Interactions* (pp. 153-172). Dordrecht: Springer Netherlands. *https://tethys.pnnl.gov/publications/strangford-lough-seagen-tidal-turbine*

Sparling, C., Thompson, D., and Booth, C. 2017. Guide to Population Models used in Marine Mammal Impact Assessment. JNCC Report No. 605. Report by Joint Nature Conservation Committee (JNCC), Peterborough, England. *https://tethys.pnnl.gov/publications/guide-population-models-used-marine-mammal-impact-assessment*

Tickner, J., and Kriebel, D. 2008. The role of science and precaution in environmental and public health policy. In E. Fisher, J. Jones, and R. Von Schomberg (Eds.), *Implementing the Precautionary Principle: Perspectives and Prospects* (pp. 58-78). Cheltenham, England: Edward Elgar Publishing. *https://tethys.pnnl.gov/publications/implementing-precautionary-principle*

Todt, O., and Luján, J. L. 2014. Analyzing Precautionary Regulation: Do Precaution, Science, and Innovation Go Together? *Risk Analysis*, 34(12), 2163-2173. doi:10.1111/risa.12246 *https://tethys.pnnl.gov/publications/analyzing-precautionary-regulation-do-precaution-science-innovation-go-together*

Trouwborst, A. 2006. Precautionary Rights and Duties of States. Leiden, Netherlands: Martinus Nijhoff Publishers. *https://tethys.pnnl.gov/publications/precautionary-rights-duties-states*

van Asselt, M., and Vos, E. 2006. The Precautionary Principle and the Uncertainty Paradox. *Journal of Risk Research*, 9(4), 313-336. doi:10.1080/13669870500175063 *https://tethys.pnnl.gov/publications/precautionary-principle-uncertainty-paradox*

van Hees, S. 2018. Large-scale Water-related Innovative Renewable Energy Projects and the Habitats and Birds Directives: Legal Issues and Solutions. *European Energy and Environmental Law Review*, 27(1), 15-36. *https://tethys.pnnl.gov/publications/large-scale-water-related-innovative-renewable-energy-projects-habitats-birds*

Verdant Power. 2010a. Roosevelt Island Tidal Energy Project FERC No. 12611 (Volume 1 of 4). Report by Verdant Power LLC; New York, New York. *https://tethys.pnnl.gov/publications/final-pilot-license-application-roosevelt-island-tidal-energy-project*

Verdant Power. 2010b. Roosevelt Island Tidal Energy Project FERC No. 12611 (Volume 4 of 4). Report by Verdant Power LLC; New York, New York. *https://tethys.pnnl.gov/publications/roosevelt-island-tidal-energy-project-rite-proposed-monitoring-plans-rite-monitoring*

Verdant Power. 2018. Appendix B: P12611- Addendum to Verdant Power RITE Draft License Application. Report by Verdant Power LLC; New York, New York. *https://tethys.pnnl.gov/publications/addendum-verdant-power-rite-draft-license-application*

Verdant Power. 2019. Roosevelt Island Tidal Energy Project, FERC No. P-12611, Article 401 RMEE Plan Amendments. Report by Verdant Power LLC; New York, New York. *https://tethys.pnnl.gov/publications/roosevelt-island-tidal-energy-project-ferc-no-p-12611-article-401-rmee-plan-amendments*

Wade, P. R. 1998. Calculating Limits to the Allowable Human-Caused Mortality of Cetaceans and Pinnipeds. *Marine Mammal Science*, 14(1), 1-37. doi:10.1111/j.1748-7692.1998.tb00688.x *https://tethys.pnnl.gov/publications/calculating-limits-allowable-human-caused-mortality-cetaceans-pinnipeds*

Walters, C. 1986. Adaptive Management of Renewable Resources. Basingstoke, England: MacMillan Publishers Ltd. *https://tethys.pnnl.gov/publications/adaptive-management-renewable-resources*

Ward, R. C., Loftis, J. C., and McBride, G. B. 1986. The "data-rich but information-poor" syndrome in water quality monitoring. *Environmental Management*, 10(3), 291-297. doi:10.1007/BF01867251 *https://tethys.pnnl.gov/publications/data-rich-information-poor-syndrome-water-quality-monitoring*

Wilding, T. A., Gill, A. B., Boon, A., Sheehan, E., Dauvin, J. C., Pezy, J.-P., O'Beirn, F., Janas, U., Rostin, L., and De Mesel, I. 2017. Turning off the DRIP ('Data-rich, information-poor') – rationalising monitoring with a focus on marine renewable energy developments and the benthos. *Renewable and Sustainable Energy Reviews*, 74, 848-859. doi:10.1016/j.rser.2017.03.013 *https://tethys.pnnl.gov/publications/turning-drip-data-rich-information-poor-rationalising-monitoring-focus-marine*

Williams, B. K. 2011a. Adaptive management of natural resources—framework and issues. *Journal of Environmental Management*, 92(5), 1346-1353. doi:10.1016/j.jenvman.2010.10.041 *https://tethys.pnnl.gov/publications/adaptive-management-natural-resources-framework-issues*

Williams, B. K. 2011b. Passive and active adaptive management: Approaches and an example. *Journal of Environmental Management*, 92(5), 1371-1378. doi:10.1016/j.jenvman.2010.10.039 *https://tethys.pnnl.gov/publications/passive-active-adaptive-management-approaches-example*

Williams, B. K., and Brown, E. D. 2014. Adaptive Management: From More Talk to Real Action. *Environmental Management*, 53(2), 465-479. doi:10.1007/s00267-013-0205-7 https://tethys.pnnl.gov/publications/adaptive-management-more-talk-real-action

Williams, B. K., and Brown, E. D. 2018. Double-Loop Learning in Adaptive Management: The Need, the Challenge, and the Opportunity. *Environmental Management*, 62, 995–1006. doi:10.1007/s00267-018-1107-5 https://tethys.pnnl.gov/publications/double-loop-learning-adaptive-management-need-challenge-opportunity

Williams, K., Szaro, R., and Shapiro, C. 2009. Adaptive management: The U.S. Department of the Interior technical guide. Report by U.S. Geological Survey for U.S. Department of the Interior, Washington, D.C. https://tethys.pnnl.gov/publications/adaptive-management-us-department-interior-technical-guide

NOTES

Adaptive Management Related to Marine Renewable Energy

Le Lièvre, C. 2020. Adaptive Management Related to Maritime Renewable Energy. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 242-261). doi:10.2172/1633206

REPORT AND MORE INFORMATION

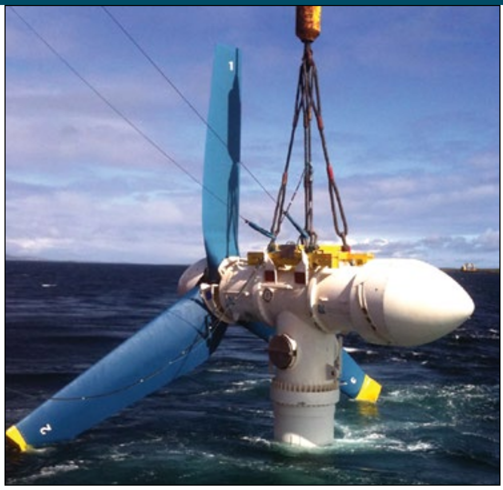
OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

13.0



Chapter authors: Andrea E. Copping, Mikaela C. Freeman, Alicia M. Gorton, Lenaïg G. Hemery

Risk Retirement and Data Transferability for Marine Renewable Energy

WHAT DO WE MEAN BY "RISK RETIREMENT"?

This chapter discusses a process for facilitating consenting for single marine renewable energy (MRE) device deployments, demonstration projects and small arrays, whereby each potential risk need not be fully investigated for every project. Rather we recommend that MRE developers and regulators rely on what is known from already consented projects, from related research studies, or from findings from analogous offshore industries. When larger arrays of MRE devices are planned, or when new information comes to light, these risks can be revisited and new decisions about the level of risk downgrading or retirement can be made.

The intent of the process is to provide assistance to regulators in their decision-making and to inform the MRE community of what is likely to be required for consenting single device deployments, demonstration projects and small arrays, as well as to help distinguish between perceived and actual risk to the marine environment.

Risk retirement will not take the place of any existing regulatory processes, nor will it completely replace the need for appropriate data collection before and after MRE device deployment; baseline data that are not available for a particular site may be needed to enable an assessment of site-specific environmental sensitivities, verify risk retirement findings and add to the overall knowledge base.

Large-scale marine renewable energy (MRE) developments continue to progress slowly, in part because of complicated consenting/permitting (hereafter consenting) processes that invoke the precautionary principle within environmental legislative frameworks. This can lead to broad, poorly scoped environmental assessments, lengthy and expensive environmental data collection requirements, and extended consenting timelines. Much of this delay is associated with uncertainty about the potential effects of MRE on marine animals and habitats (Copping 2018).

This uncertainty may lead regulators and stakeholders to believe that significant risks exist, thereby resulting in a more precautionary approach to consent determination and other decision processes, and possibly lengthy and disproportionate baseline data collection and ongoing monitoring requirements. These, in turn, slow consenting processes and increase costs to the emerging MRE industry and places additional pressure on regulators and their advisors. In addition to being frequently associated with scientific uncertainty, these perceptions of risk may result from lack of familiarity with and access to existing scientific information relevant to the interactions of MRE devices with marine animals or habitats. This chapter documents a path for streamlining consenting processes by examining the potential for risk retirement of specific stressor-receptor interactions, that can help to distinguish between perceived and actual risk to the marine environment. This process has been developed in cooperation with the nations engaged in pursuing environmental effects investigations under the International Energy Agency (IEA) Ocean Energy Systems (OES) task OES-Environmental (see Chapter 1, Introduction).

13.1 DEFINITION OF RISK RETIREMENT

The term "risk retirement" has been used by technology-focused development programs such as geotechnical risk management to delineate circumstances in which key stressor-receptor interactions are sufficiently understood to alleviate the need to carry out detailed investigations for each proposed project (NAS 2018). The term has also been used by the MRE community to describe a means of simplifying the consenting processes by focusing on key issues of concern (Copping et al. 2016; Robertson et al. 2018). However, there is no specific definition and little understanding of how risk might progress to a less active state of investigation or retirement. OES-Environmental aims to examine and define the possibilities of how risk retirement might be manifested and provide a pathway forward that will help streamline consenting processes.

Based on interactions with the MRE industry, regulators, researchers, and other stakeholders, and the scientific evidence set out in this report, it is clear that certain interactions with aspects of operational MRE systems pose little to no risk to the marine environment. For example, the risk of chemical leaching from system components, including oil, is widely considered to be negligible because few such products are used on MRE devices (Copping et al. 2016). Similarly, other stressor-receptor interactions can be informed by established industries, such as aggregation of fish and invertebrates around floats and anchor lines, which has no demonstrable mechanism for harming the marine environment (Copping et al. 2016; Copping 2018). These risks might be considered to be retired, or no longer in need of active investigation for each individual MRE project, but the requirement will always remain at the discretion of the regulatory body. Any indirect effects of some of these interactions observed in the future will need further investigation once large commercial arrays are in operation. With few operational MRE arrays in the water at this time, it is appropriate to focus processes for risk retirement on what is known about single devices, demonstration projects and small arrays.

The risk retirement approach described here follows the concept of stressors and receptors (Boehlert and Gill 2010). The stressor-receptor interactions that are collectively recognized as key issues by regulators, developers, stakeholders and researchers are associated with the following:

- potential collision of marine animals with tidal turbine blades
- effects of underwater noise from MRE operation on marine animal behavior and health
- potential effects of electromagnetic fields (EMFs) from cables and energized devices on sensitive marine species
- changes in benthic and pelagic habitats from MRE anchors, foundations, and mooring lines
- displacement of or barrier effect on migratory animal populations from arrays of MRE devices
- changes in circulation and sediment transport as a result of operational MRE devices, as well as the effects of energy removal from the system
- potential entanglement of marine animals in mooring lines for many wave devices and some tidal turbines.

The appropriate level of risk associated with each of these stressor-receptor interactions can be resolved with the application of rigorous research and monitoring results, as well as lessons learned from other industries (see previous chapters). While interactions with the MRE community of regulators, researchers, developers, and other stakeholders suggest that the effects of underwater noise and EMFs may be good candidates for retiring risks for small numbers of MRE devices (see Section 13.3), other stressor-receptor interactions, like collision risk, may require further research and monitoring, while displacement or barrier effects will not be resolved until larger arrays are deployed and studied. The risk retirement steps described below and depicted in Figure 13.1 are aimed at developing criteria to minimize, downgrade, or retire the risks that are not likely to cause harm to the marine environment.

13.2 THE RISK RETIREMENT PATHWAY

A risk retirement process has been developed with the intent of lowering barriers to consenting and licensing MRE projects for widespread and accelerated development. This approach does not advocate taking shortcuts or lowering standards for environmental protection, but rather is focused on achieving a balance between environmental precaution and the proportional risk created by MRE systems, as well as helping to distinguish between perceived and actual risk to the marine environment. The process begins with a systematic examination and cataloging of datasets from wave and tidal projects that have been consented, assuring that the datasets are accessible and understandable to regulators. If this process is successful, the burden of evidence for projects for which risks have been retired ought to be reduced, and the particular stressor of interest ought to play a less critical role in the overall consenting process. Legislation and regulation in each country will dictate the precise language that regulators must use to conclude the importance of a stressor-receptor interaction, but the overall process of downgrading and retiring risk should be useful in most circumstances.

Based on feedback from surveys of regulators from several countries participating in the OES-Environmental task and direct interactions with United States (U.S.) regulators, a risk retirement pathway (Figure 13.1) was developed to determine whether potential risks from an MRE project can be downgraded or retired. The intent of the process is to provide assistance to regulators in their decision-making and to inform the MRE community of what is likely to be required for the consenting of single devices, demonstration projects and small arrays. Assuring that datasets and knowledge from consented MRE projects are readily available and cataloged is a key aspect of the risk retirement pathway. This accessibility of datasets and knowledge allows a proposed project to be compared to, and utilize evidence from, existing consented projects so that associated lessons learned and knowledge from the latter can be shared. This portion of the process involves the concepts of data and knowledge transferability and data collection consistency (Freeman et al. 2018), explained in more detail in Section 13.4. Adaptive management also plays an important role by allowing regulators and project developers to systematically view monitoring and analysis outputs, and adjust the level of mitigation and monitoring focus accordingly (Wiesebron et al. 2016).

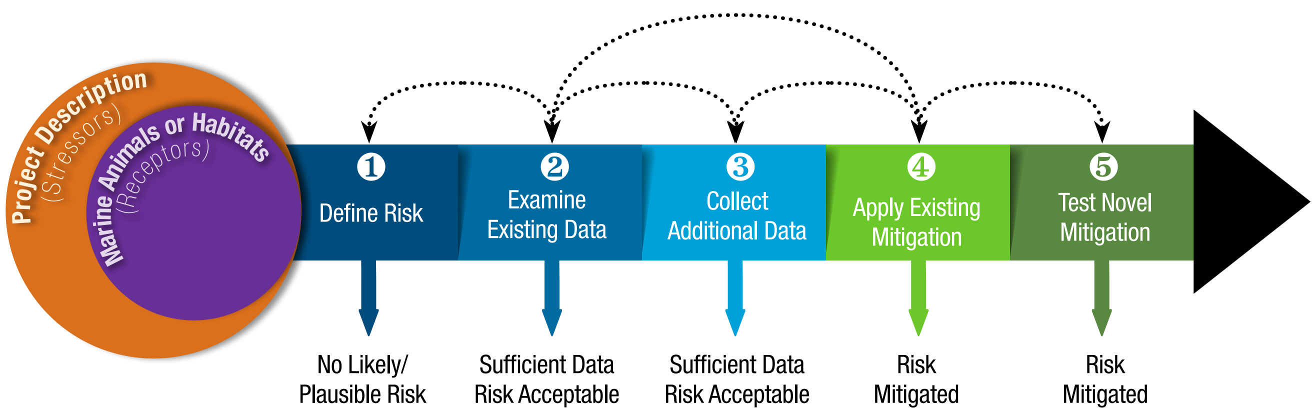


Figure 13.1. Risk retirement pathway. The dotted arrow lines represent the feedback loops between each stage of the pathway. The downward arrows at the bottom of each stage indicate the off ramps where a risk might be considered retired or downgraded. (Graphic by Robyn Ricks)

The risk retirement pathway was developed to provide a method for advancing from determining the level of risk from any stressor-receptor interaction toward a set of solutions based on the best use of available evidence and a proportionate approach to determining any additional evidence needs. The pathway aims to facilitate more streamlined consenting (Figure 13.1). The pathway also implies that a risk can be revisited by following the same process, if additional information suggests further review is needed.

As the risk retirement pathway indicates, the specific project details must first be defined for the project of interest, starting with a description of the project (site characteristics and development type and size) and the animals or habitats that may be affected (Figure 13.1, orange and purple rings). It is essential to include information about the size of the proposed development because single devices are less likely to have significant effects than arrays (see previous chapters). Next in the pathway is a series of stage gates or phases, during which the project is compared to existing data, knowledge, and lessons learned from other consented projects. Each stage incorporates an "off ramp" (implied by the downward-facing arrows in Figure 13.1) to allow the risk to be considered retired if there is sufficient information to do so. As noted, the concept of risk retirement is associated with a decreased need to examine the stressor-receptor interaction at each new project site. If at any stage there is not sufficient information to determine that the risk might be retired (via an off ramp), the risk moves to the next stage to the right. More detail about the stages can be found on the *Tethys* website[1] and in Copping et al. (2020a, 2020b).

In moving from one stage to the next on the risk retirement pathway, available knowledge needs to be examined to determine whether a project can progress to the next stage and to provide feedback among the stages. This application of data to inform the process has been termed "data transferability" (see Section 13.4) and comes into play mainly during stages 1 and 2. In addition to applying existing data (data transfer) to inform progress from stage to stage, the generation of new data from monitoring, research studies, experiments, or development of new effective mitigation measures may require datasets to inform the process (signified by the dotted arrows on the top of the diagram; Figure 13.1).

1. *https://tethys.pnnl.gov/risk-retirement*

13.3 APPLICATION OF THE RISK RETIREMENT PATHWAY TO MRE INTERACTIONS

Based on the understanding of interactions between MRE systems and the marine environment, OES-Environmental identified two stressors (underwater noise and EMFs) as candidates for risk retirement related to small numbers of devices. The evidence base for considering risk retirement for these two stressors is presented here. Additional detail and relevant studies are found in Chapters 4 (Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices) and 5 (Risk to Animals from Electromagnetic Fields Emitted by Electric Cables and Marine Renewable Energy Devices) as well as on the *Tethys* website[2]. During 2019, the evidence base was presented at three workshops to a cross section of experts and practitioners in the MRE community (Box 13.1). Each workshop used hypothetical, but

BOX 13.1.

RISK RETIREMENT WORKSHOPS

An international workshop was held in concert with the European Wave and Tidal Energy Conference 2019 (EWTEC) in Napoli, Italy (September 1–6, 2019), attended by 34 experts from 11 nations. The workshop evaluated the risk retirement pathway using hypothetical examples for underwater noise and electromagnetic fields, mainly focusing on stages 2 (Examine Existing Data) and 3 (Collect Additional Data).

A second workshop, targeted toward a largely American audience, was held at the Ocean Renewable Energy Conference 2019 (OREC) in Portland, Oregon, United States (September 10–12, 2019). The risk retirement pathway was evaluated using two hypothetical examples for underwater noise. Focusing once again on stages 2 (Examine Existing Data) and 3 (Collect Additional Data) of the risk retirement pathway, the workshop experts examined the evidence to determine whether participants felt the risk could be retired for underwater noise for wave and tidal devices.

A third workshop targeted toward an Australian audience was held in Sydney, Australia (December 4, 2019). In addition to presentations to familiarize participants with the current state of the science on environmental effects of marine renewable energy, the risk retirement pathway and data transferability processes related to underwater noise and electromagnetic fields were presented. Similar to the other workshops, two hypothetical examples were used to evaluate risk retirement.

2. *https://tethys.pnnl.gov/events/retiring-risks-mre-environmental-interactions-support-consentingpermitting*

realistic, MRE developments to apply the evidence base and evaluate risk retirement. The consensus among participants was to accept the evidence toward risk retirement, but consider some additional caveats and data collection requirements.

13.3.1 EFFECTS OF UNDERWATER NOISE ON MARINE ANIMALS

As described in Chapter 4 (Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices), monitoring around single devices, as well as field research, indicate that underwater noise emitted from operational MRE devices can be detected by many marine animals but is unlikely to significantly alter their behavior or cause them physical harm (e.g., Baring-Gould et al. 2016). The sound levels of devices, either wave energy devices (WECs) or tidal turbines, appear to fall below existing U.S. regulatory thresholds for marine mammals and fish (NMFS 2018; Tetra Tech 2013). Operational noise from MRE devices also falls below the frequency thresholds at which most marine mammals hear (Haikonen et al. 2013) and has been shown to be of lower amplitude than other industrial activities such as commercial shipping (Lossent et al. 2017).

The evidence base for underwater noise from turbines and WECs includes studies completed by Cruz et al. (2015), Farcas et al. (2016), Hafla et al. (2018), Haikonen et al. (2013), Lepper and Robinson (2016), Lossent et al. (2018), Schmitt et al. (2015, 2018), and Tougaard (2015). To investigate the effects of underwater noise during the three aforementioned workshops (Box 13.2), a selection of hypothetical, but realistic, MRE examples was used. One of the examples included a bottom-mounted axial-flow tidal turbine (Figure 13.2) for which the sound generated by the rotating blades and the power take-off fell in the 118–145 dB re 1 µPa at 1 m range, over frequencies of 40 Hz to 8 kHz (see definitions in Chapter 4, Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices).

BOX 13.2.

FEEDBACK FROM RISK RETIREMENT WORKSHOPS FOR UNDERWATER NOISE

At the EWTEC workshop, participants found the risk retirement pathway intuitive and easy to navigate. They agreed that, in addition to the existing sound at a site, the risk associated with underwater noise from marine renewable energy (MRE) could be retired for single devices and small arrays, with the caveat that a library of standardized noise measurements produced by MRE is needed. The recommendation is to measure *in situ* the underwater noise from each wave or tidal device for which deployment/development consent is sought, using the International Electrotechnical Commission (IEC) Technical Committee (TC) 114 Level B recommendations (IEC 2019). In the United States (U.S.) context, provided that the underwater noise from a device falls below the U.S. thresholds (NMFS 2018; Tetra Tech 2013), the risk could be retired. However, it was noted that different countries have different requirements, so some additional work with regulators is needed to assure that the pathway becomes acceptable under the particular nation's legislation. Gaps in information that would allow a similar analysis for large MRE arrays were noted, including the need to verify noise propagation models because they might apply to underwater noise from large arrays in the high-energy waters in which MRE development is targeted to occur.

At the OREC workshop, participants felt that risks from underwater noise were close to retirement for single devices. In addition to supporting the concept of measuring noise outputs from operational devices and comparing those outputs to U.S. regulatory thresholds, the participants were interested in understanding how marine animals might be using the habitats immediately surrounding the device and how they might behave in response to the noise produced by the device. Acquiring further information about underwater noise from arrays was thought to be important, including the spacing of devices to minimize overall noise inputs to an area and the role that test centers could play in measuring underwater noise under operational conditions.

At the Sydney workshop, participants thought the concept of risk retirement fit well in an Australian regulatory context and that both the risk retirement and data transferability processes added value by providing a systemic analysis that regulators can put into practice. It was noted that additional precautionary steps may be required in specific locations where sensitive species are present. Based on the evidence presented and the U.S. thresholds available for noise effects on marine mammals and fish, participants agreed that underwater noise could be retired for single devices or small arrays. Participants also noted that cumulative effects may become an issue in the future because many sources of anthropogenic noise are already occurring in the marine environment.

13.3.2. EFFECTS OF EMFS ON MARINE ANIMALS

As described in Chapter 5 (Risk to Animals from Electromagnetic Fields Emitted by Electric Cables and Marine Renewable Energy Devices), field research, laboratory studies, and modeling simulations indicate that EMFs from cables are likely a small risk to animals, and one that is easily mitigated by burying the cable if needed (Copping et al. 2016). Given the more than 100-year history of deploying electrical and telecommunications cables in the ocean, EMF signatures are not new to the marine environment. Understanding the effects of EMFs on marine animals can be informed by previous experience with subsea cables used for power and telecommunications, bridges, tunnels, and offshore wind farms that have been deployed and emit measurable EMF signatures in the ocean (Electric Power Research Institute 2013; Meißner et al. 2006).

The evidence base for EMFs from submarine cables includes studies by Hutchison et al. (2018), Kavet et al. (2016), Love et al. (2017), Sherwood et al. (2016), Thomsen et al. (2015), Westerberg and Lagenfelt (2008), Woodruff et al. (2012), and Wyman et al. (2018). To investigate EMFs during two workshops (Box 13.3), a selection of hypothetical, but realistic, examples was used. One of the examples included a floating oscillating water column WEC placed on the sea surface with an energized vertical cable in the water column connected to an offshore substation and an export cable on the seafloor running from the offshore substation to an onshore substation (Figure 13.3).

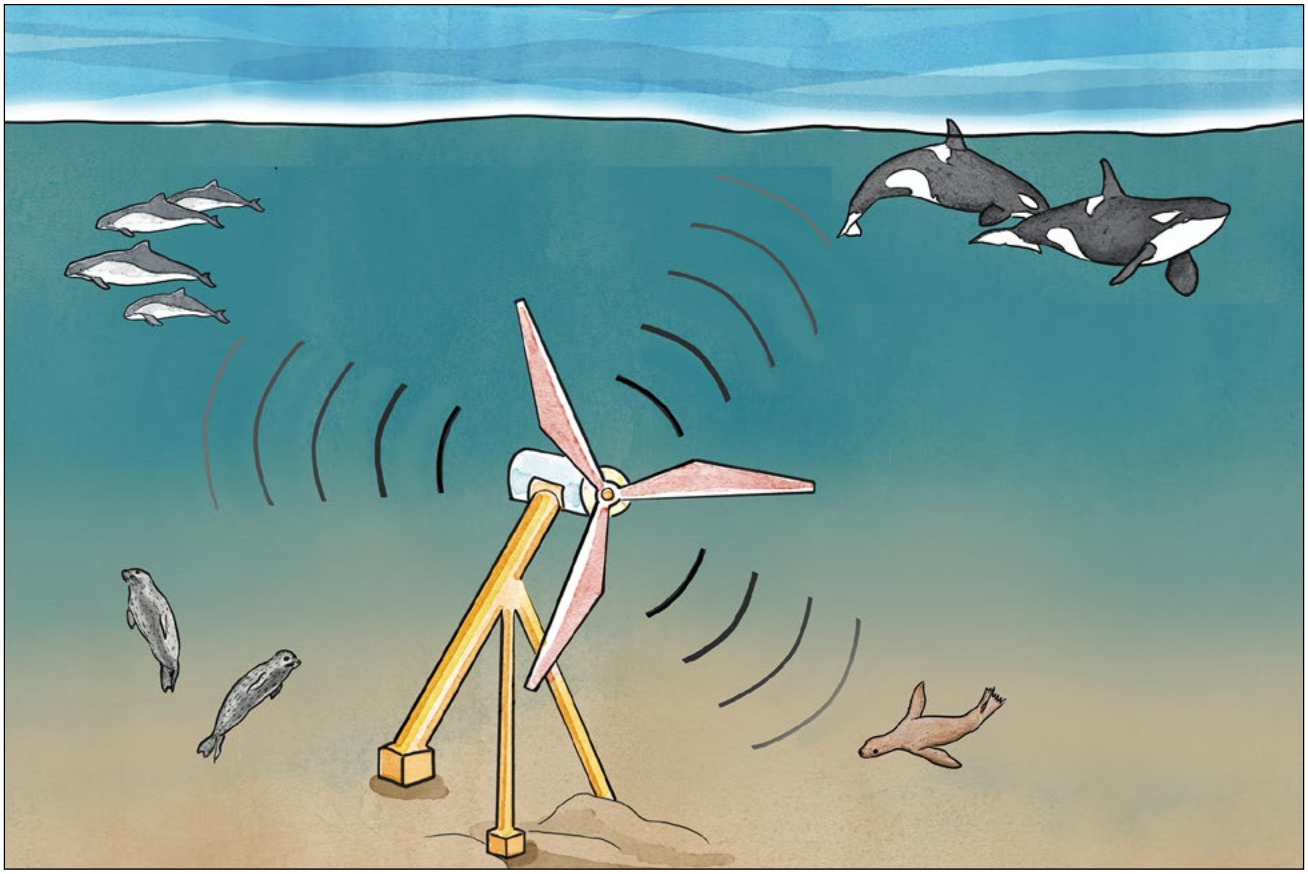


Figure 13.2. Hypothetical example of a tidal turbine emitting noise (represented by the grey semi-circles) in an area used by harbor porpoises, harbor seals, sea lions, and orca whales. Graphics similar to this figure were used at the expert workshops to denote the presence of certain animal species, or receptors, in the vicinity of the turbine, and to help visualize potential stressor-receptor interactions. The animals, turbine, and water depth are not drawn to scale. (Illustration by Rose Perry)

BOX 13.3

FEEDBACK FROM RISK RETIREMENT WORKSHOPS FOR ELECTROMAGNETIC FIELDS

At the EWTEC workshop, participants surmised that electromagnetic fields (EMFs) are not a likely risk, because the level of power carried in marine renewable energy (MRE) cables is very small compared to that from, for instance, offshore wind farms. However, they did agree that some basic information (e.g., baseline data about species and habitats, presence of other cables in the area) would be required to retire the risk for single devices. Participants also highlighted how relatively little is known about EMF-sensitive species and how they might be affected. Some of the strategic gaps identified were the need for field measurements of EMFs to improve and validate models, increased understanding of how EMF emissions vary with power variability, and help in identifying potential risks associated with offshore substations and vertical and draped cables. Participants also expressed concerns regarding the difficulties in establishing EMF thresholds and the cumulative effects of EMFs in the benthic and pelagic environments.

At the Sydney workshop, participants thought that without regulatory thresholds for EMFs it could be challenging to retire this risk, especially because regulators are likely to be risk-averse without guidance. They felt it would be important for EMF experts to put forth some plausible thresholds and work with the MRE industry to help regulators understand that risk will be minimal. Experiences related to consenting an upcoming MRE deployment in Australia demonstrated that burying the export power cable satisfied regulatory needs. Overall, participants agreed that the risk could be retired for single devices, demonstration projects and small arrays, or small arrays, but felt there were effects from EMFs that may still require measurements to be taken.

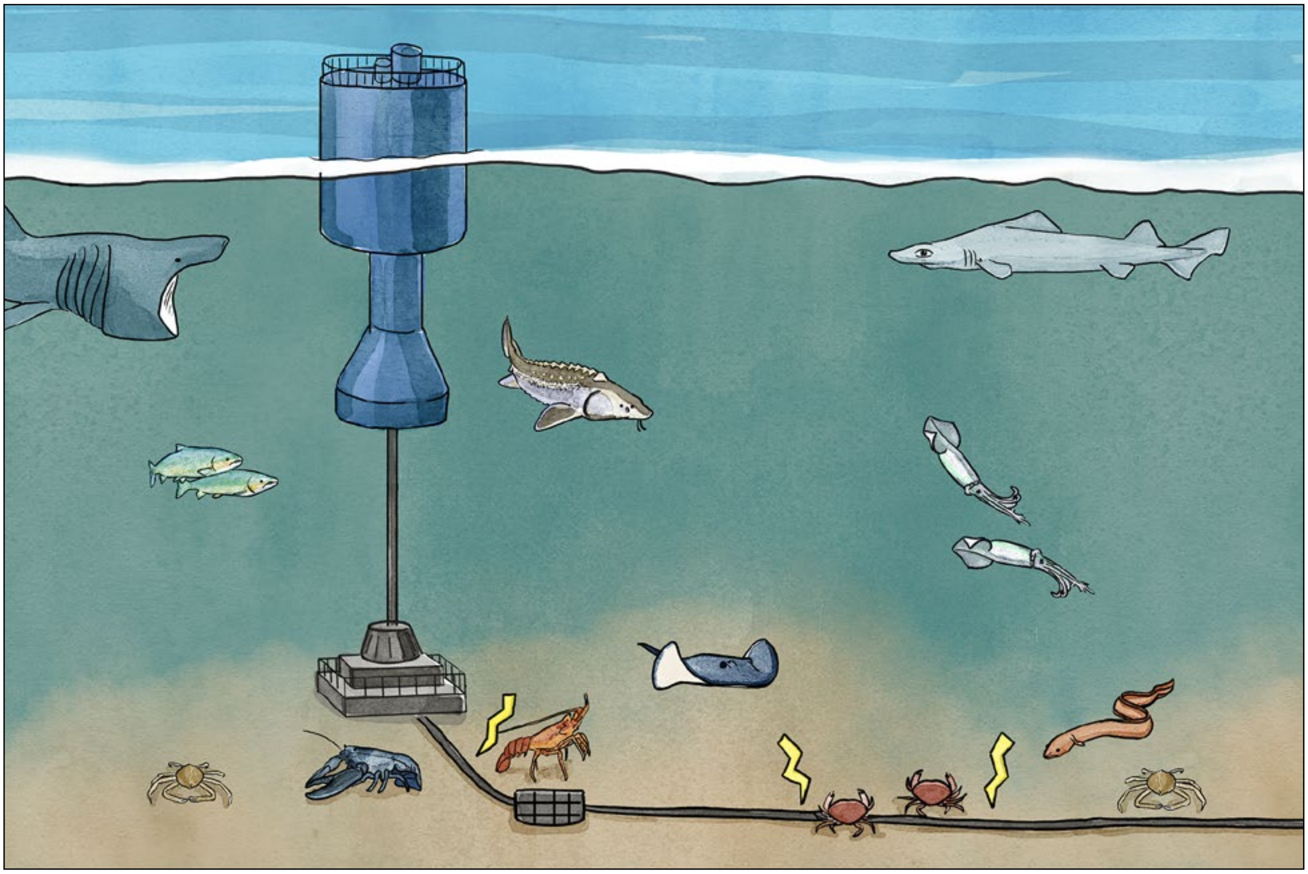


Figure 13.3. Hypothetical example of a wave energy converter (WEC) with cables emitting electromagnetic fields (represented by the lightning bolts along the cable) in an environment used by sharks, skates, bony fishes, crustaceans, and other invertebrates. Graphics similar to this figure were used at the expert workshops to denote the presence of certain animal species, or receptors, in the vicinity of the WEC, and to help visualize potential stressor-receptor interactions. The animals, device, and water depth are not drawn to scale. (Illustration by Rose Perry)

13.4. DATA TRANSFERABILITY PROCESS

In an MRE context, the process of data transferability refers to applying existing learning, analyses, and monitoring datasets from one country to another, among projects, and across jurisdictional boundaries. This process could help satisfy regulatory requirements for MRE developments and subsequently reduce costs and burden to the industry over time, while also protecting the marine environment. To efficiently transfer these datasets, it is advisable for information and data to be comparably collected, analyzed, and interpreted among projects. Currently, information and data are collected around early-stage MRE devices that use many different parameters and methods. If good management practices were applied to standardize methods of collection for baseline and post-installation monitoring around early-stage devices, the results would be more readily comparable, could lead to a decrease in scientific uncertainty, and would support a common understanding of the risk of stressor-receptor interactions. This, in turn, would facilitate more efficient and shorter consenting processes, which would decrease financial risk for MRE project developments, reduce burden and requirement for additional resources for regulators, and subsequently move deployment of wave and tidal devices forward more rapidly. Overall, the purpose of examining the potential for achieving data transferability and data collection consistency is to shorten regulatory timelines and provide greater standardization in baseline and post-installation data requested to support the consenting of MRE projects across multiple jurisdictions.

As a first step toward developing a process for transferring data, the U.S. regulatory community from state and federal jurisdictions responsible for MRE consenting was surveyed to determine the level of understanding of MRE technologies, priorities for consenting risk, and willingness to transfer data (Copping et al. 2018). The regulator engagement outcomes helped tailor materials and methods for future engagement efforts related to the proposed approach to data transferability. U.S. regulators were further engaged through a series of online workshops. The regulators were presented with MRE data from previously consented projects or research studies to provide them with background information and gauge their comfort in using data and information of this nature in their jurisdictions. Based on the feedback received, OES-Environmental developed a data transferability process. The international research and development community was then brought together at a workshop in June 2018 in conjunction with the International Conference on Ocean Energy to gather additional feedback about data transferability, to review and modify proposed best management practices, and to discuss ways to implement the process. Additional details and materials about data transferability outreach and engagement can be found on the *Tethys* website[3].

The data transferability process (described in more detail by Copping et al. 2018, 2020c) consists of four components (Figure 13.4): (1) data transferability framework, (2) data collection consistency table, (3) monitoring datasets discoverability matrix, and (4) best management practices (BMPs). Additional details about applying the process can be found on the *Tethys* website[4]. This process is expected to be useful for regulators, developers, and other stakeholders to help with discovery and comparison of existing datasets that have potential stressor-receptor interactions that may be present in planned MRE projects, and to help provide insight into how the outcome of these interactions might be assessed.

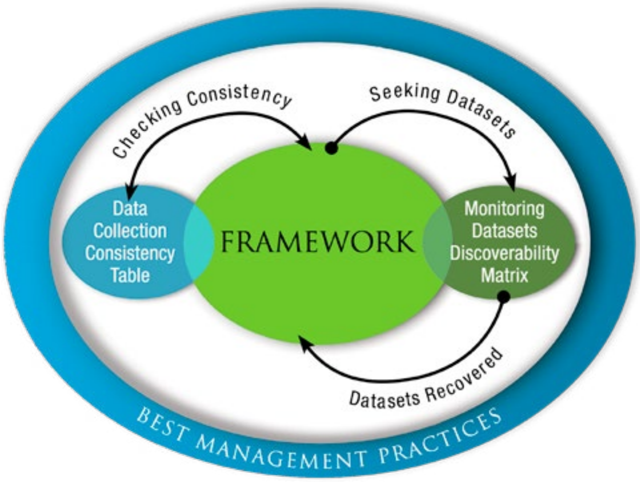


Figure 13.4. The data transferability process consists of a data transferability framework, data collection consistency table, monitoring datasets discoverability matrix, and best management practices. (Graphic by Robyn Ricks)

3. *https://tethys.pnnl.gov/data-transferability#Outreach%20&%20Engagement*

4. *https://tethys.pnnl.gov/data-transferability*

13.4.1. DATA TRANSFERABILITY FRAMEWORK

The data transferability framework (hereafter framework) guides the overall process of data transfer by bringing together datasets (e.g., information, raw data, reports, results) from already consented projects in an organized fashion to facilitate access and assist in the assessment of knowledge for use in consenting future projects. This process may be expedited if datasets are collected in a consistent way using preferred measurement methods or processes.

The framework can be used by regulators, developers, and other stakeholders to develop a common understanding of data types and parameters to determine and address potential effects and set limits and considerations for how the BMPs can be applied to assist with effective and efficient siting, consenting, and post-installation monitoring and mitigation.

The framework uses four variables (stressor, receptor, site condition, and MRE technology type) to define a stressor-receptor interaction. Classifying each project using these four variables is the first step in determining the ability to transfer knowledge from already consented projects to future projects. While the framework is intended to help assess the transferability of information and learning from one consented project to a new project, the tenets are also applicable to knowledge gleaned from research studies and other investigations. Once datasets and other knowledge have been identified as being suitable for transferability, they can be applied to the assessment of new MRE projects.

13.4.2. DATA COLLECTION CONSISTENCY

MRE is an international industry, whose consenting processes and research norms differ from country to country, region to region, and among research and commercial data collection efforts. It would be difficult to enforce the use of specific protocols or instruments to collect pre- or post-installation monitoring data for projects in all jurisdictions. However, encouraging the use of consistent methods and units that have been shown to be effective for the collection of monitoring data can increase confidence in the transfer of data or learning from already consented projects to future projects. Assuring that the information and data from an already consented project are compatible with the needs of future projects, and that knowledge from one or more projects can be aggregated, requires an evaluation of the degree to which collection methods and units are consistent and data are applicable to similar receiving environments.

For six of the stressors, a set of processes, reporting units, and generalized analysis or reporting methods is proposed in the data collection consistency table (Table 13.1). The preferred process (measurement methods) or measurement tools are reported for each stressor, along with preferred reporting units and the most common methods of analysis or interpretation and use of the data. If applied worldwide, the use of this table may enable researchers and developers to effectively collect data in a consistent manner and standardize monitoring methods, as well as allow regulators to evaluate existing data consistently. Over time, this would result in the increased consistency and reliability of monitoring data, as well as the streamlining of data transfer.

13.4.3. MONITORING DATASETS DISCOVERABILITY MATRIX

The monitoring datasets discoverability matrix (hereafter matrix) classifies monitoring datasets from already consented projects by the six stressors previously discussed. The matrix is linked to key features of each dataset, including location, metadata on that site, monitoring or siting reports, links to downloadable data when available, and a contact for discussing or accessing the data. The matrix, developed as an interactive tool on the *Tethys* website[5],will allow regulators, developers, and others in the MRE community to discover datasets by key characteristics (such as stressor, receptor, site condition, MRE technology, etc.). After datasets are identified, there is an opportunity to evaluate the consistency of information and to determine whether the data can be transferred to inform applications and decisions for new projects.

13.4.4. BEST MANAGEMENT PRACTICES

BMPs are defined as practices or procedures that can help to guide implementation of broad guidelines. The BMPs for data transferability underscore the process of evaluating datasets for transfer among the projects and consistency in data collection methods, as well as the useful support of numerical models and application of data collected for other purposes in the project area (for more detail see Copping et al. 2018, 2020c).

5. *https://tethys.pnnl.gov/monitoring-datasets-discoverability-matrix*

The process of implementing the BMPs for data transferability and collection consistency will require the confidence and good will of all parties that play a role in consenting MRE devices. Achieving an appropriate level of acceptance and use will require the following:

- Regulators and other stakeholders must be willing to accept the premise of data transferability so that they apply the principles of data transferability and collection consistency to evaluate and comment on consenting applications.
- Device and project developers must recognize the value of data transferability and commit to collecting and providing data that are consistent with the collection guidelines and that will best fit the framework recommendations from the data collection consistency table.
- Researchers and consultancies should inform themselves of the data consistency needs and potential use of data collected around MRE devices to assure that research data are usable for transfer.

Table 13.1. Data collection consistency table.

Stressor	Process or measurement tool	Reporting unit	Analysis or interpretation
Collision risk	Sensors include: • active acoustic only • active acoustic + video • video only • observations from vessel or shore	Number of visible targets in field of view, number of collisions.	Number of collisions and/or close interactions of animals with turbines, and probability of encounters, used to validate collision risk models. Avoidance or evasion Density of animals that may raise risk (based on subsea observations) vs. predicted densities from models or surface counts to refine collision risk models.
Underwater noise	Fixed or drifting hydrophones	Sound spectrum (amplitude as function of frequency) with units: Amplitude: dB re 1μPa at 1 m Frequency: frequencies within marine animal hearing range	Sound outputs from MRE devices compared against regulatory action levels. Generally reported as broadband noise unless guidance exists for specific frequency ranges. Development of noise propagation models for array projects from monitoring around single devices
Electromagnetic fields	Source: • cable - shielded or unshielded • other	AC or DC Voltage Amplitude in tesla units (μT or mT)	Measured EMF levels used to validate existing EMF models around cables and other energized sources.
Changes in habitats	Underwater mapping with: • sonar • video Habitat or species distribution characterized from: • mapping • existing maps • grabs and other benthic sampling gear	Area of habitat or species distribution altered, specific for each habitat type or species.	Compare potential changes in habitat and/or species distributions to maps of rare and important habitats or species to ensure that these vulnerable species and habitats are not likely to be harmed by the location of the proposed project.
Displacement / barrier effect	Population estimates on or near a project site by: • human observers • passive or active acoustic monitoring • video	Population estimates for species under special protection. Importance of high energy areas for key activities or transit.	Validation of population models, estimates of jeopardy, loss of species for vulnerable populations (locally or globally).
Changes in oceanographic systems	Numerical modeling, with field data validation for currents, turbulence, wave height, wave period, etc.	No preferred units. Indication of datasets used for validation, if any.	Data collected around arrays should be used to validate models.

13.5. APPLYING DATA TRANSFERABILITY TO SUPPORT CONSENTING

Applying the data transferability process will help address the concept of transferring knowledge and information among MRE projects, as well as collecting data consistently.

13.5.1. APPLYING THE PROCESS

The data transferability process was developed to provide a background against which discussions with regulators and other stakeholders can proceed as the key principles and limits of transferability are better understood. The data transferability process will facilitate initial consenting discussions between developers and regulators to guide data collection and monitoring efforts needed for an MRE project and determine operational monitoring needs.

While data transfer often occurs during the consenting process, these instances are rarely documented. To move the data transferability process forward, consenting licenses for which data transfer was used should be highlighted and shared with the MRE community. Through the successful development and implementation of the data transferability process, OES-Environmental will continue its efforts of outreach and engagement with relevant stakeholders to further the knowledge and understanding of the potential environmental effects of MRE devices, thereby accelerating the siting and consenting process for MRE developments.

13.5.2. DATA TRANSFERABILITY CASE STUDIES

A selection of examples from the MRE industry help describe some early successes in the transfer of data and information. We expect that many more examples will become available in the next few years of MRE development.

SME Plat-O #1 *(underwater noise stressor)*

Sustainable Marine Energy (SME) installed their PLAT-O #1 tidal energy device in Yarmouth, England, in preparation for later deployment at EMEC's Fall of Warness test site (Orkney, Scotland). Acoustic monitoring was conducted during anchor installation to measure the sound profile of the operation, specifically to note potential effects on cetaceans, seals, and basking sharks. Using a hydrophone at a depth of approximately 5 m, the sound of seabed drilling was not audible over the vessel plant noise (Aquatera 2015). The outcome of this monitoring was used to inform the development of SME's project environmental management plan for their proposed deployment at EMEC's Fall of Warness test site and, because of the results, SME was not required to implement a mitigation zone, use Marine Mammal Observers, or undertake acoustic monitoring during installation at EMEC (Marine Scotland 2015). This resulted in significant cost savings, streamlined operational planning, and reduced the number of required offshore personnel for the EMEC deployment.

Voith Hydro HyTide and Brims Tidal Array *(changes in habitat stressor)*

Pre- and post-installation underwater video data were collected at the Voith Hydro HyTide project at EMEC in 2011 to determine baseline conditions and the effect of operation on the immediate and surrounding benthic habitat (Aquatera 2011). A report about this high-level assessment was provided to the regulator and advisors, who determined that such drilling activities would have a limited footprint and therefore limited effect on the benthic habitat. These data were then transferred from the Voith Hydro project to inform the environmental impact assessment for the OpenHydro 200 MW Brims Tidal Array near Orkney, Scotland (Aquatera 2011; Brims Tidal Array 2016). Understanding of the extent (footprint) of the direct effects of drilling on benthic habitats allowed a proportionate approach to be adopted during the environmental impact assessment process, enabling developers to focus monitoring and mitigation on topics of greater scientific uncertainty.

Sabella D03 and D10 *(collision risk stressor)*

The Sabella D03 turbine was deployed in 2008 in the Odet estuary in Brittany, France. Video monitoring showed slow-moving turbine speeds that appeared to be "innocuous" to schools of fish (ETIP Ocean 2017; see the video here[6]). Lessons learned from the monitoring of the D03 turbine were transferred to the design and monitoring needs of the D10 model and are proposed to be continued in the scaling up of other Sabella devices (Paboeuf et al. 2016). The low impact and continued low speeds of rotation in the D10 model are considered to also be of minimal effect on fish. The D10 model was deployed in 2015 in Passage du Fromveur, near Ouessant, France, for a demonstration period of one year, and delivered more than 10 MWh of electricity to the grid (Sabella 2020).

Voith Hydro HyTide and EMEC *(marine mammal receptor)*

Voith Hydro installed a 23 m monopile foundation for their HyTide tidal energy device at EMEC's Fall of Warness site in 2011, using a large offshore construction vessel with a dynamic positioning system. Marine Mammal Observers were assigned to monitor within a 1 km radius of the main installation vessel prior to and during monopile drilling activities, and to count hauled-out seals at Seal Skerry throughout the activities. Acoustic monitoring was carried out using drifting hydrophone transects to characterize the ambient noise at the project site and noise generated during monopile installation. Average counts of hauled-out seals on Seal Skerry were slightly lower during and following installation operations, but this correlation was considered likely to be due to the natural diurnal haulout patterns of seals (Aquatera 2011). No evidence of disturbance by the monopile installation operations was observed, and noise levels were found to be unlikely to cause any auditory impairment to harbor seals (Aquatera 2011). Based on these findings, a recommendation was made to EMEC and the regulator that no mitigation or observation zones be established at the test site in the future by individual vessel operators, because there was no observed effect on marine mammals (Aquatera 2011). Data from this project were also used to update EMEC guidance on mitigation of marine mammal disturbance and injury at EMEC test sites (EMEC 2019). The ability to transfer data resulted in significant savings in terms of time and cost for EMEC, as well as for future developers at EMEC test sites.

13.6. CONCLUSION

The concepts of risk retirement and data transferability have been developed by OES-Environmental to inform discussions between developers and regulators in order to reach a common understanding of evidence needs for consenting new MRE projects. This includes assuring that any identified site-specific data needs are proportionate and account for existing relevant knowledge and data, such as assuring that the assumptions made during these processes are correct, and including marine animals and habitats that are particular to the specific location.

The groups that have convened to examine the processes and evidence bases for risk retirement of underwater noise and EMFs were generally in agreement that these stressors could be retired for small MRE projects, but that additional information needs to be added to the evidence base. The data transferability process, particularly the accessibility of datasets from consenting projects, has also received strong support from these groups. The monitoring dataset discoverability matrix will become increasingly useful as more MRE developments are consented in the future and additional datasets become available.

While information and products developed under OES-Environmental are produced in English, there are many countries engaged in MRE development where regulators work primarily in other languages. Processes such as risk retirement and other management strategy tools need to be translated into additional languages to optimize their usefulness.

Additional information about the processes, reports and/or recordings from the various workshops and webinars, and outcomes of risk retirement and data transferability can be found on the *Tethys* risk retirement and data transferability webpages.

6. *https://www.youtube.com/watch?v=MNsKpddt3ew*

13.7. REFERENCES

Aquatera. 2011. Farr Point Wave Farm Development: Request for Scoping Opinion. Report by Aquatera for Pelamis Wave Power, Orkney, Scotland. *https://tethys.pnnl.gov/publications/farr-point-wave-farm-development-request-scoping-opinion*

Aquatera. 2015. SME Project Environmental Monitoring Plan. Orkney, Scotland. Available by request.

Baring-Gould, E., Christol, C., LiVecchi, A., Kramer, S., and West, A. 2016. A Review of the Environmental Impacts for Marine and Hydrokinetic Projects to Inform Regulatory Permitting: Summary Findings from the 2015 Workshop on Marine and Hydrokinetic Technologies, Washington, D.C. (Report No. NREL/TP-5000-66688). Report by National Renewable Energy Laboratory for U.S. Department of Energy, Golden, Colorado. *https://tethys.pnnl.gov/publications/review-environmental-impacts-marine-hydrokinetic-projects-inform-regulatory-permitting*

Boehlert, G. W., and Gill, A. B. 2010. Environmental and Ecological Effects of Ocean Renewable Energy Development: A Current Synthesis. *Oceanography*, 23(2), 68-81. *https://tethys.pnnl.gov/publications/environmental-ecological-effects-ocean-renewable-energy-development-current-synthesis*

Brims Tidal Array Environmental Statement. 2016. *https://tethys.pnnl.gov/publications/brims-tidal-array-environmental-statement*

Copping, A. 2018. The State of Knowledge for Environmental Effects: Driving Consenting/Permitting for the Marine Renewable Energy Industry. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. *https://tethys.pnnl.gov/publications/state-knowledge-environmental-effects-driving-consentingpermitting-marine-renewable*

Copping, A., Freeman, M., Gorton, A., and Hemery, L. 2020a. Risk Retirement—Decreasing Uncertainty and Informing Consenting Processes for Marine Renewable Energy Development. *Journal of Marine Science and Engineering*, 8(3), 21. doi:10.3390/jmse8030172 *https://tethys.pnnl.gov/publications/risk-retirement-decreasing-uncertainty-informing-consenting-processes-marine-renewable*

Copping, A., Freeman, M., and Overhus, D. 2020b. Risk Retirement for Environmental Effects of Marine Renewable Energy (Report No. PNNL-29996). Report by Pacific Northwest National Laboratory, Richland, Washington. *https://tethys.pnnl.gov/publications/risk-retirement-environmental-effects-marine-renewable-energy*

Copping, A., Gorton, A., and Freeman, M. C. 2018. Data Transferability and Collection Consistency in Marine Renewable Energy (Report No. PNNL-27995). Report by Pacific Northwest National Laboratory, Richland, Washington. *https://tethys.pnnl.gov/publications/data-transferability-collection-consistency-marine-renewable-energy*

Copping, A., Gorton, A., Freeman, M., Rose, D., and Farr, H. 2020c. Data Transferability and Collection Consistency in Marine Renewable Energy: An Update to the 2018 Report (Report No. PNNL-27995 Rev. 1). Report by Pacific Northwest National Laboratory, Richland, Washington. *https://tethys.pnnl.gov/publications/data-transferability-collection-consistency-marine-renewable-energy-update-2018-report*

Copping, A., Sather, N., Hanna, L., Whiting, J., Zydlewski, G., Staines, G., Gill, A., Hutchison, I., O'Hagan, A., Simas, T., Bald, J., Sparling, C., Wood, J., and Masden, E. 2016. Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report by Pacific Northwest National Laboratory for Ocean Energy Systems. *https://tethys.pnnl.gov/publications/state-of-the-science-2016*

Cruz, E., Simas, T., and Kasanen, E. 2015. Discussion of the Effects of the Underwater Noise Radiated by a Wave Energy Device - Portugal. Paper presented at the 11th European Wave and Tidal Energy Conference, Nantes, France. *https://tethys.pnnl.gov/publications/discussion-effects-underwater-noise-radiated-wave-energy-device-portugal*

Electric Power Research Institute (EPRI). 2013. EPRI Workshop on EMF and Aquatic Life. Palo Alto, California. *https://tethys.pnnl.gov/publications/epri-workshop-emf-aquatic-life*

European Marine Energy Centre (EMEC). 2019. Marine Mammal Recording SOP074: Protocol for mitigation of marine mammal disturbance and injury at EMEC test sites. Report by European Marine Energy Centre, Orkney, Scotland. *https://tethys.pnnl.gov/publications/protocol-mitigation-marine-mammal-disturbance-injury-emec-test-sites*

European Technology and Innovation Platform for Ocean Energy (ETIP Ocean). 2017. Minimising negative environmental impacts. Webinar conducted by ETIP Ocean. *https://tethys.pnnl.gov/publications/etip-ocean-webinar-minimising-negative-environmental-impacts*

Farcas, A., Thompson, P. M., and Merchant, N. D. 2016. Underwater noise modelling for environmental impact assessment. *Environmental Impact Assessment Review*, 57, 114-122. doi:10.1016/j.eiar.2015.11.012 *https://tethys.pnnl.gov/publications/underwater-noise-modelling-environmental-impact-assessment*

Freeman, M., Copping, A., Gorton, A., and Dreyer, S. 2018. Managing Environmental Effects of Marine Renewable Energy Development through Regulator Engagement, Data Transferability. Paper presented at the Marine Energy Technology Symposium, Washington, D.C. *https://tethys.pnnl.gov/publications/managing-environmental-effects-marine-renewable-energy-development-through-regulator*

Hafla, E., Johnson, E., Johnson, C. N., Preston, L., Aldridge, D., and Roberts, J. D. 2018. Modeling underwater noise propagation from marine hydrokinetic power devices through a time-domain, velocity-pressure solution. *The Journal of the Acoustical Society of America*, 143(6), 3242-3253. doi:10.1121/1.5039839 *https://tethys.pnnl.gov/publications/modeling-underwater-noise-propagation-marine-hydrokinetic-power-devices-through-time*

Haikonen, K., Sundberg, J., and Leijon, M. 2013. Characteristics of the Operational Noise from Full Scale Wave Energy Converters in the Lysekil Project: Estimation of Potential Environmental Impacts. *Energies*, 6(5), 2562-2582. doi:10.3390/en6052562 *https://tethys.pnnl.gov/publications/characteristics-operational-noise-full-scale-wave-energy-converters-lysekil-project*

Hutchison, Z., Sigray, P., He, H., Gill, A., King, J., and Gibson, C. 2018. Electromagnetic Field (EMF) Impacts on Elasmobranch (shark, rays, and skates) and American Lobster Movement and Migration from Direct Current Cables (OCS Study BOEM 2018-003). Report by University of Rhode Island for Bureau of Ocean Energy Management, U.S. Department of the Interior, Sterling, Virginia. *https://tethys.pnnl.gov/publications/electromagnetic-field-emf-impacts-elasmobranch-shark-rays-skates-american-lobster*

International Electrotechnical Commission (IEC). 2019. Marine energy - Wave, tidal and other water current converters - Part 40: Acoustic characterization of marine energy converters (IEC TS 62600-40:2019). *https://tethys.pnnl.gov/publications/acoustic-characterization-marine-energy-converters-iec-ts-62600-402019*

Kavet, R., Wyman, M. T., and Klimley, A. P. 2016. Modeling Magnetic Fields from a DC Power Cable Buried Beneath San Francisco Bay Based on Empirical Measurements. *PLoS ONE*, 11(2), e0148543. doi:10.1371/journal.pone.0148543 *https://tethys.pnnl.gov/publications/modeling-magnetic-fields-dc-power-cable-buried-beneath-san-francisco-bay-based*

Korpinen, S., and Andersen, J. H. 2016. A Global Review of Cumulative Pressure and Impact Assessments in Marine Environments. *Frontiers in Marine Science*, 3(153). doi:10.3389/fmars.2016.00153 *https://tethys.pnnl.gov/publications/global-review-cumulative-pressure-impact-assessments-marine-environments*

Lepper, P. A., and Robinson, S. P. 2016. Measurement of Underwater Operational Noise Emitted by Wave and Tidal Stream Energy Devices. In A. N. Popper and A. Hawkins (Eds.), The Effects of Noise on Aquatic Life II (pp. 615-622), Springer: New York, New York. *https://tethys.pnnl.gov/publications/measurement-underwater-operational-noise-emitted-wave-tidal-stream-energy-devices*

Lossent, J., Gervaise, C., Iorio, L. D., Folegot, T., Clorennec, D., and Lejart, M. 2017. Underwater operational noise level emitted by a tidal current turbine and its potential impact on marine fauna. *The Journal of the Acoustical Society of America*, 141(5), 3923-3923. doi:10.1121/1.4988869 *https://tethys.pnnl.gov/publications/underwater-operational-noise-level-emitted-tidal-current-turbine-its-potential-impact*

Lossent, J., Lejart, M., Folegot, T., Clorennec, D., Di Iorio, L., and Gervaise, C. 2018. Underwater operational noise level emitted by a tidal current turbine and its potential impact on marine fauna. *Marine Pollution Bulletin*, 131, 323-334. doi:10.1016/j.marpolbul.2018.03.024 *https://tethys.pnnl.gov/publications/underwater-operational-noise-level-emitted-tidal-current-turbine-its-potential-impact*

Love, M. S., Nishimoto, M. M., Clark, S., McCrea, M., and Bull, A. S. 2017. Assessing potential impacts of energized submarine power cables on crab harvests. *Continental Shelf Research*, 151, 23-29. doi:10.1016/j.csr.2017.10.002 *https://tethys.pnnl.gov/publications/assessing-potential-impacts-energized-submarine-power-cables-crab-harvests*

Marine Scotland. 2015. SME Marine Licence Number 05684/15/0. Aberdeen, Scotland. *https://www2.gov.scot/Resource/0049/00493389.pdf*

Meißner, K., Schabelon, H., Bellebaum, J., and Sordyl, H. 2006. Impacts of Submarine Cables on the Marine Environment - A Literature Review. Institute of Applied Ecology, Broderstorf, Germany. *https://tethys.pnnl.gov/publications/impacts-submarine-cables-marine-environment-literature-review*

National Academies of Sciences, Engineering, and Medicine (NAS). 2018. Guidelines for Managing Geotechnical Risks in Design–Build Projects. Research Report 884. The National Academies Press, Washington, D.C. *https://tethys.pnnl.gov/publications/guidelines-managing-geotechnical-risks-design-build-projects*

National Marine Fisheries Service (NMFS). 2018. 2018 Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts. NOAA Technical Memorandum NMFS-OPR-59. Report by National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Silver Spring, MD. *https://tethys.pnnl.gov/publications/2018-revisions-technical-guidance-assessing-effects-anthropogenic-sound-marine-mammal*

Nemeth, M., Priest, J., and Patterson, H. 2014. Assessment of Fish and Wildlife Presence Near Two River Instream Energy Conversion Devices in the Kvichak River, Alaska in 2014. Report by LGL Alaska Research Associates for Gray Stassel Engineering, Inc., Anchorage, Alaska. *https://tethys.pnnl.gov/publications/assessment-fish-wildlife-presence-near-two-river-instream-energy-conversion-devices*

Paboeuf, S., Macadré, L.-M., and Yen Kai Sun, P. 2016. A French Application Case of Tidal Turbine Certification. Paper presented at the 35th International Conference on Ocean, Offshore and Arctic Engineering, Busan, South Korea. doi:10.1115/OMAE2016-54834 *https://tethys.pnnl.gov/publications/french-application-case-tidal-turbine-certification*

Robertson, F., Wood, J., Joslin, J., Joy, R., and Polagye, B. 2018. Marine Mammal Behavioral Response to Tidal Turbine Sound. (Report No. DOE-UW-06385). Report by University of Washington for U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, Washington D.C. doi:10.2172/1458457 *https://tethys.pnnl.gov/publications/marine-mammal-behavioral-response-tidal-turbine-sound*

Sabella. 2020. Sabella. Retrieved from *http://www.sabella-d10.bzh/*

Schmitt, P., Elsaesser, B., Coffin, M., Hood, J., and Starzmann, R. 2015. Field Testing a Full-Scale Tidal Turbine Part 3: Acoustic Characteristics. Paper presented at the 11th European Wave and Tidal Energy Conference, Nantes, France. *https://tethys.pnnl.gov/publications/field-testing-full-scale-tidal-turbine-part-3-acoustic-characteristics*

Schmitt, P., Pine, M. K., Culloch, R. M., Lieber, L., and Kregting, L. T. 2018. Noise characterization of a subsea tidal kite. *The Journal of the Acoustical Society of America*, 144(5), EL441-EL446. doi:10.1121/1.5080268 *https://tethys.pnnl.gov/publications/noise-characterization-subsea-tidal-kite*

Sherwood, J., Chidgey, S., Crockett, P., Gwyther, D., Ho, P., Stewart, S., Strong, D., Whitely, B., and Williams, A. 2016. Installation and operational effects of a HVDC submarine cable in a continental shelf setting: Bass Strait, Australia. *Journal of Ocean Engineering and Science*, 1(4), 337-353. doi:10.1016/j.joes.2016.10.001 *https://tethys.pnnl.gov/publications/installation-operational-effects-hvdc-submarine-cable-continental-shelf-setting-bass*

Tetra Tech. 2013. Underwater Acoustic Modeling Report - Virginia Offshore Wind Technology Advancement Project (VOWTAP). Report by Tetra Tech Inc. for Dominion Energy, Glen Allen, Virginia. *https://tethys.pnnl.gov/publications/underwater-acoustic-modeling-report-virginia-offshore-wind-technology-advancement*

Thomsen, F., Gill, A., Kosecka, M., Andersson, M., André, M., Degraer, S., Folegot, T., Gabriel, J., Judd, A., Neumann, T., Norro, A., Risch, D., Sigray, P., Wood, D., and Wilson, B. 2015. MaRVEN - Environmental Impacts of Noise, Vibrations and Electromagnetic Emissions from Marine Renewable Energy (Report No. RTD-K3-2012-MRE). Report by Danish Hydraulic Institute for European Union, Brussels, Belgium. *https://tethys.pnnl.gov/publications/marven-environmental-impacts-noise-vibrations-electromagnetic-emissions-marine*

Tougaard, J. 2015. Underwater Noise from a Wave Energy Converter Is Unlikely to Affect Marine Mammals. *PLoS ONE*, 10(7), e0132391. doi:10.1371/journal.pone.0132391 *https://tethys.pnnl.gov/publications/underwater-noise-wave-energy-converter-unlikely-affect-marine-mammals*

Vandendriessche, S., Derweduwen, J., and Hostens, K. 2015. Equivocal effects of offshore wind farms in Belgium on soft substrate epibenthos and fish assemblages. *Hydrobiologia*, 756(1), 19-35. doi:10.1007/s10750-014-1997-z *https://tethys.pnnl.gov/publications/equivocal-effects-offshore-wind-farms-belgium-soft-substrate-epibenthos-fish*

Westerberg, H., and Langenfelt, I. 2008. Sub-sea power cables and the migration behaviour of the European eel. *Fisheries Management and Ecology*, 15(5-6), 369-375. doi:10.1111/j.1365-2400.2008.00630.x *https://tethys.pnnl.gov/publications/sub-sea-power-cables-migration-behaviour-european-eel*

Wiesebron, L. E., Horne, J. K., and Hendrix, A. N. 2016. Characterizing biological impacts at marine renewable energy sites. *International Journal of Marine Energy*, 14, 27-40. doi:10.1016/j.ijome.2016.04.002 *https://tethys.pnnl.gov/publications/characterizing-biological-impacts-marine-renewable-energy-sites*

Woodruff, D., Schultz, I., Marshall, K., Ward, J., and Cullinan, V. 2012. Effects of Electromagnetic Fields on Fish and Invertebrates Task 2.1.3: Effects on Aquatic Organisms Fiscal Year 2011 Progress Report (Report No. PNNL-20813). Report by Pacific Northwest National Laboratory for U.S. Department of Energy, Washington D.C. *https://tethys.pnnl.gov/publications/effects-electromagnetic-fields-fish-invertebrates-task-213-effects-aquatic-organisms*

Wyman, M. T., Peter Klimley, A., Battleson, R. D., Agosta, T. V., Chapman, E. D., Haverkamp, P. J., Pagel, M. D., and Kavet, R. 2018. Behavioral responses by migrating juvenile salmonids to a subsea high-voltage DC power cable. *Marine Biology*, 165(8), 134. doi:10.1007/s00227-018-3385-0 *https://tethys.pnnl.gov/publications/behavioral-responses-migrating-juvenile-salmonids-subsea-high-voltage-dc-power-cable*

NOTES

Risk Retirement and Data Transferability for Marine Renewable Energy

Copping, A.E., M.C. Freeman, A.M Gorton, and L.G. Hemery. 2020. Risk Retirement and Data Transferability for Marine Renewable Energy. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 262-278). doi:10.2172/1633208

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

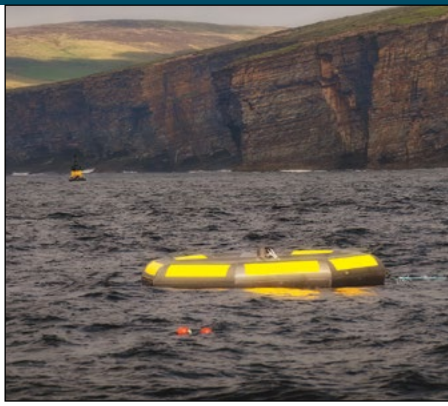
Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

Section E

Looking Ahead

14.0



Chapter author: Andrea E. Copping

Summary and Path Forward

The *2020 State of the Science* report collates and presents the current understanding of interactions between marine renewable energy (MRE) systems and the marine environment, with an emphasis on their effects on marine animals, habitats, and oceanographic systems, using publicly available information. The report places this information in context through lessons learned from research studies in the laboratory and in the field, modeling simulations, and deployments; monitoring around demonstration, pilot, and small commercial MRE projects; identifies gaps in knowledge and makes recommendations for filling those gaps. In addition, strategies for moving toward a consistent and effective consenting or permitting (hereafter consenting) process and management of the potential effects of MRE development are highlighted. The value of the evidence presented in this report will be realized through its application to consenting processes to accelerate the responsible deployment of further MRE devices and arrays. The status and recommendations from each of the priority interactions between MRE devices and the environment are summarized here, and the management strategies for facilitating development are discussed. Finally, a path forward toward commercial MRE development is explored.

14.1. SUMMARY OF FINDINGS

In addition to the detailed reporting and analyses of each set of stressor-receptor interactions, we have attempted to document the continuing level of perceived risk for each interaction. For simplicity, we define risk as the interaction of the likelihood (probability) of an event occurring with the consequences of that event. This documentation takes the form of a simple dashboard and guide for how the level of risk for each interaction might be further understood and lowered. The dashboard consists of an old-fashioned odometer-type dial that uses green to indicate a well understood and relatively low risk from a stressor to yellow and red that indicate increased levels of risk. The dashboard also features a bar graph to indicate what avenues of investigation and sharing are needed to further understand and lower the risk from that stressor (Figure 14.1). These avenues include

- increased sharing of available information
- improved modeling of the interaction
- monitoring data needed to validate models
- new research needed.

Each dashboard represents our estimate of the risk using the best available information collated in this report for each stressor and is broadly proportional to the other stressors. However, it is important to understand that certain risks may be perceived to be high, but may be found to be lower, as more knowledge is acquired. We hope the dashboards will prove valuable as a simple means of visualizing the perceived level of risk, and that they may be updated over time as new information becomes available. Only a limited number of operational devices are in the water, ranging from single turbines to small arrays. Because of the current level of MRE development, the levels of perceived risk reported here are associated with small numbers of devices. As commercial-size arrays are developed and occupy larger areas of the sea, the perceptions of risk for certain stressor-receptor interactions may change.

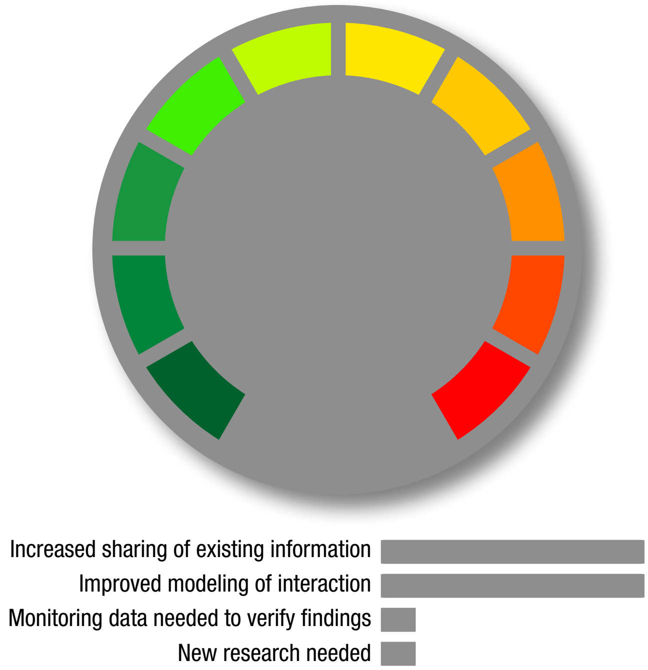


Figure 14.1. Generic version of a dashboard (dial on the top) that demonstrates the broadly understood level of risk for specific stressors, as of 2020, with indication of a pathway forward to further understand and lower the perceived risk of the stressor (bar graph on the bottom). These dashboards were drawn in the style of Copping and Kramer (2017), and updated with information from this report. (Graphic by Robyn Ricks)

The major findings from each of the chapters and topics in this report are summarized in the following sections.

14.1.1. COLLISION RISK FOR ANIMALS AROUND TURBINES

As detailed in Chapter 3 about collision risk, the risk of marine animals colliding with moving parts of tidal and river turbines continues to be the greatest concern for regulators and stakeholders. Among other interactions of concern, this risk has proved to be the most resistant to progressing toward a solution. Considerable effort and resources have gone into modeling, measuring, and observing the potential interactions of marine mammals, fish, and seabirds around turbines; however, fundamental questions remain. One of the greatest barriers to better understanding collision risk stems from the technical challenges related to making observations in the vicinity of turbines in high-energy waters. These observations are particularly challenging because the probability of sightings of marine animals, particularly marine mammals and diving seabirds, is expected to be rare.

Key gaps in knowledge and uncertainty about the potential risk of collision to marine animals remain to be investigated. These gaps include the need for the following:

- determine the probability of a marine animal being struck by a turbine blade while traversing a channel with MRE devices
- determine the likelihood of a collision, based on the characteristics of the turbine blades, the channel morphology, and oceanographic features of the flow
- characterize the seriousness of a blade strike, if it occurs
- understand the impacts on a marine population if individuals are lost as a result of blade strike
- identify sublethal effects of blade strike that may result in significant injury or death at a later time
- assess the ability to scale rates of collision from a single turbine to an array of turbines.

A substantial number of modeling efforts have been carried out to estimate the risk of collision of marine mammals, fish, and birds around turbines. The models have been based on a variety of approaches and geometries, and none of them have been challenged and verified with sufficient post-installation monitoring data to determine which of them best emulate the real world and should be used to estimate potential risk of collision, or whether this is a sensible avenue to pursue for characterizing and quantifying risk. This lack of data continues to hamper estimates of likely collision risk, leading regulators to act conservatively. Models for translating risk to populations based on losses of individuals are commonly used to set regulatory thresholds, but these models have been created to estimate the effects of very different types of risks (such as the risk of entanglement in fishing gear) and have not been applied to potential turbine collisions.

This risk remains relatively high because of the significant uncertainties as well as the very high consequences if a collision occurs (Figure 14.2).

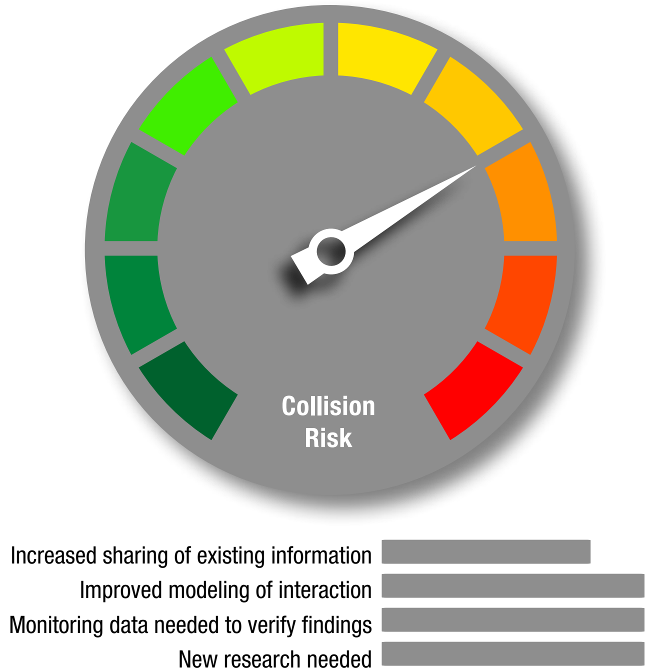


Figure 14.2. Dashboard (dial on the top) that summarizes the broadly understood level of risk that collisions will occur between marine animals and turbines, as of 2020, for small numbers of devices. Risk may vary with larger arrays. The bar graph on the bottom demonstrates a pathway to better understanding and lowering the perceived risk of collision. (Graphic by Robyn Ricks)

14.1.2. UNDERWATER NOISE

Chapter 4, concerning underwater noise, detailed what is known about characterizing underwater noise from MRE devices and estimating how these levels of sound might affect marine animals, especially marine mammals and fishes. Based on the levels of sound that have been measured to date from turbines and wave energy converters (WECs), it appears that sound levels are considerably below those that might be expected to cause physical harm to animal tissues, including those associated with hearing. MRE-generated underwater noise is considered most likely to affect the behavior of marine animals; acoustic pressure is most likely to affect marine mammals and seabirds and perhaps sea turtles (Holt et al. 2009; Jensen et al. 2009; Lesage et al. 1999); while fish are more sensitive to acoustic particle velocities (Popper and Hawkins 2018).

These effects, however, are extremely difficult and costly to investigate, particularly because these intelligent animals adapt and become acclimated to ongoing stimuli (NRC 2003). Research on underwater noise from MRE devices has focused on improving the measurement of MRE device sound emissions and placing those emissions in the context of the ambient soundscapes at existing and planned MRE deployment sites. Measuring sound emissions from MRE devices is challenging because of the high energy of the waters in which devices are deployed; however, the International Electrotechnical Commission Technical Committee 114 standard (IEC TC 114 2019) can be applied to produce accurate measurements. Although few MRE devices have been characterized using this standard, to date all sound emissions have peaked under or near the underwater sound action thresholds for marine mammals (NMFS 2018) or fish (Tetra Tech 2013). The thresholds for underwater noise examined to date consider the likelihood of injury or death to marine mammals; additional thresholds have been developed that also consider lower levels of noise that may disturb or harass marine mammals.

The most critical needs for better understanding the potential effects of underwater noise from MRE devices include the following:

- measuring sound emissions from additional types and models of turbines and WECs across sound frequencies within the hearing range of marine animals
- differentiating between MRE device sounds and ambient sound in the marine environment at MRE sites
- comparing MRE sound emissions to the standards in place in the United States (and any variations accepted in other nations) to determine whether the thresholds are approached or exceeded by particular MRE devices and systems
- observing marine animals around MRE devices when possible, if regulatory thresholds are exceeded
- developing a database of noise signatures from different devices
- developing dose response metrics for behavioral response of marine animals.

This risk is low but some questions remain (Figure 14.3).

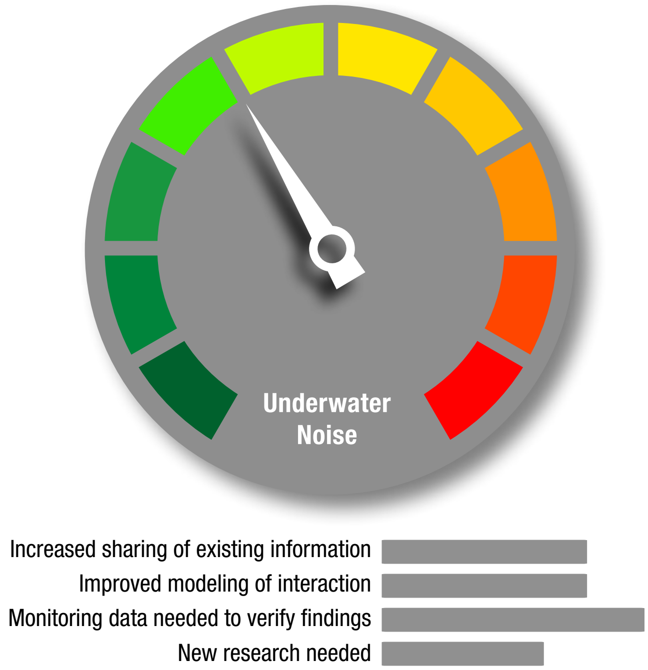


Figure 14.3. Dashboard (dial on the top) that summarizes the broadly understood level of risk from underwater noise from marine renewable energy devices to marine animals, as of 2020, for small numbers of devices. Risk may vary with larger arrays. The bar graph on the bottom demonstrates a pathway to better understanding and lowering the perceived risk of underwater noise. (Graphic by Robyn Ricks)

14.1.3. ELECTROMAGNETIC FIELDS

Chapter 5, about electromagnetic field (EMF) effects on animals, summarized research on the potential effects of MRE power cables and other electrical infrastructure on sensitive marine species. Investigations focused on behavioral, physiological, and developmental/genetic effects. Behavioral investigations have taken place in the laboratory and in the field. While some changes have been noted in sensitive species, none have indicated that crossing EMF at levels typical of MRE-level power cables will significantly alter behavior in a manner likely to be harmful to the individual or the population. Laboratory studies of physiological and developmental changes have been carried out for a wide range of species, many of which are unlikely to encounter MRE cables, but these results are not easily applied in the environment. While it would be easy to dismiss the potential effects of EMFs from cables based on the many cables carrying power in the ocean over many decades, the cumulative effects remain unknown, particularly because future large arrays of MRE devices may be operated in areas already significantly occupied by other EMF sources.

Research and monitoring investigations that will continue to inform this risk include the following:

- developing a reference database that relates power cable configuration, size, and power transmission levels common to MRE cables, to provide EMF output levels
- examining EMF outputs from other underwater infrastructure, such as substations, that will be needed as multiple devices and arrays are deployed in the future
- additional examination of potentially sensitive marine species that are found in the vicinity of MRE project sites for which little research has been done to determine their level of sensitivity to EMF
- better characterizing and modeling of the exact nature of the EMF surrounding cables and other electrical infrastructure as new equipment types are included in MRE development.

Based on research studies, and, in comparison to EMF levels emitted from existing power cables and those associated with offshore wind, this risk can be considered to be relatively low (Figure 14.4).

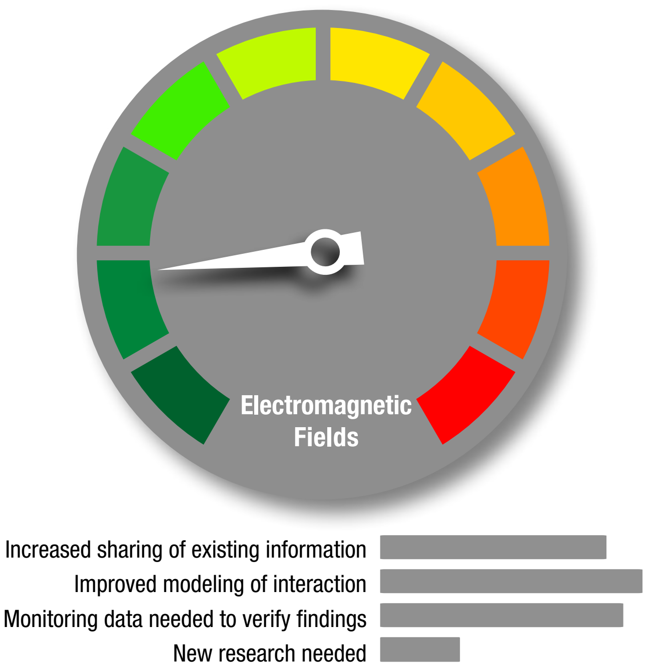


Figure 14.4. Dashboard (dial on the top) that summarizes the broadly understood level of risk from electromagnetic fields (EMFs) from marine renewable energy devices to marine animals, as of 2020 for small numbers of devices. Risk may vary with larger arrays. The bar graph on the bottom demonstrates a pathway to better understanding and lowering the perceived risk of EMFs. (Graphic by Robyn Ricks)

14.1.4. CHANGES IN HABITATS

Chapter 6, concerning changes in habitat, provided insight into the potential effects on benthic and pelagic habitats from the installation and operation of MRE devices, including foundations, anchors, mooring lines, and cables. In addition to changes in habitats, introducing new hard habitats in the form of MRE devices and gear may change the behavior of certain species, especially fishes that are likely to reef around the installations. The footprints of MRE devices and systems, as well as the tendency of marine animals to aggregate around them, does not differ from the effects of other marine installations ranging from navigation and observation buoys, platforms, docks, oil and gas rigs, and piers. These other installations and industries inform us of the potential effects of habitat changes, including the potential for biofouling organisms to give entrée to non-native invasive species in an area.

Research and monitoring investigations that could help resolve the relatively small risks around habitat changes include the following:

- establishing a baseline for the biodiversity and habitat types for each region where MRE devices will be deployed in order to improve the siting of devices and to understand whether changes are taking place over the life of an MRE project
- determining the degree of non-native invasive species penetration into waters and habitats surrounding MRE projects to gauge what possible effect the introduction of new hard habitats might have on the area.

Based on information from analogous offshore industries and the relatively small footprint of MRE foundations, anchors, and mooring lines, this risk can be considered to be low (Figure 14.5). However, the most critical aspect of minimizing harm to habitats is the appropriate siting of MRE projects to avoid all rare or fragile habitat types.

With future expansion of large arrays of MRE devices, the potential to affect common habitats should be revisited.

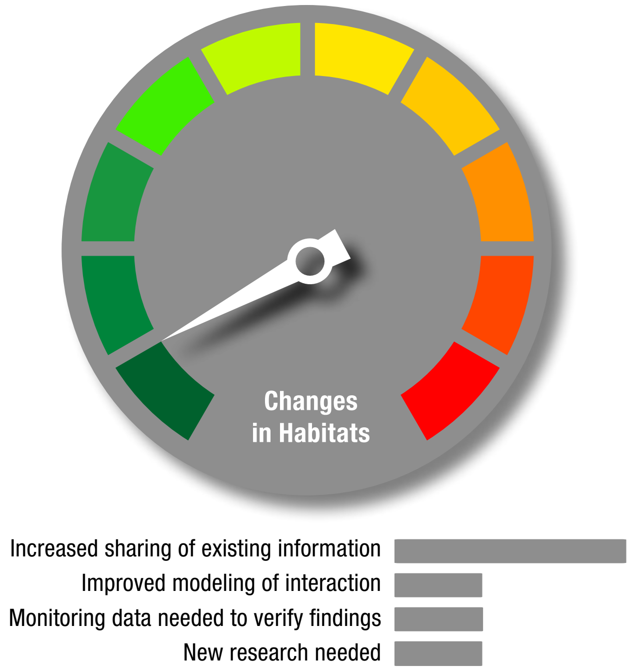


Figure 14.5. Dashboard (dial on the top) that summarizes the broadly understood level of risk from changes in habitats from marine renewable energy devices on marine animals, as of 2020 for small numbers of devices. Risk may vary with larger arrays. The bar graph on the bottom demonstrates a pathway to better understanding and lowering the perceived risk of changes in habitats. (Graphic by Robyn Ricks)

14.1.5. CHANGES IN OCEANOGRAPHIC SYSTEMS

Chapter 7 described the state of knowledge about potential changes in oceanographic systems that could occur as a result of MRE development. Changes in circulation, wave height, and subsequent changes to sediment transport patterns, water quality, and marine food webs are certain to be small for one or two MRE devices, well within the natural variability of the oceanographic systems. Once very large arrays are put in place, the ability to measure these changes and understand their potential ecological consequences will need to be revisited. In the meantime, numerical models allow us to estimate the changes that might occur as large numbers of devices are deployed and operated. To date, the changes estimated using models indicate that they are likely to be localized and revert to background levels within short distances from the devices. The number of devices used in these models to demonstrate change in the environment often exceeds the realistic number that are likely to be consented, based on other concerns such as underwater noise and collision risk.

Research and monitoring that will further resolve the estimates from numerical models include

- collecting monitoring data around operating MRE devices to validate the existing numerical models and to determine that the assumptions are accurate
- improving numerical models to focus on realistic conditions for locations into which MRE devices will be deployed, as well as providing realistic representations of turbines or WECs that include the position in the water column where devices will be deployed
- representing in numerical models the linkages from the potential effects of small numbers of MRE devices to large arrays
- improving these understanding for long-term baseline shifts in oceanographic processes, for example caused by climate change.

Based on modeling studies, this risk can be considered to be low (Figure 14.6).

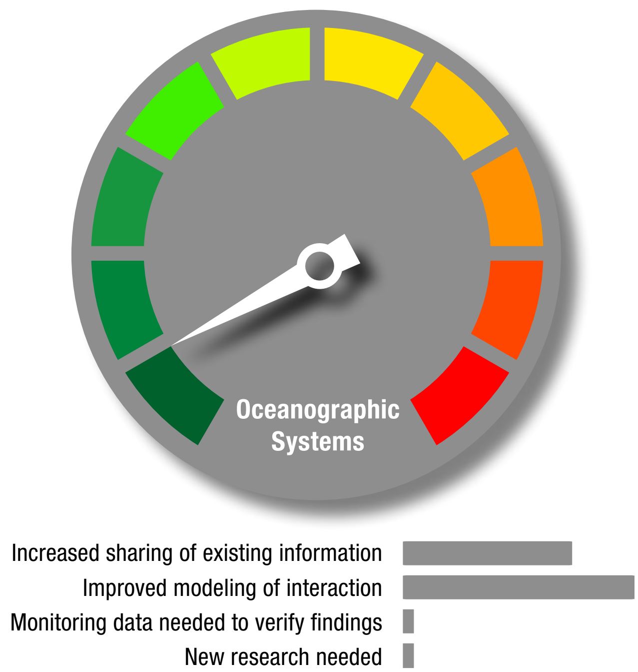


Figure 14.6. Dashboard (dial on the top) that summarizes the broadly understood level of risk from changes in oceanographic systems caused by marine renewable energy devices, as of 2020 for small numbers of devices. Risk may vary with larger arrays. The bar graph on the bottom demonstrates a pathway to better understanding and lowering the perceived risk of changes in oceanographic systems. (Graphic by Robyn Ricks)

14.1.6. MOORING LINES AND SUBSEA CABLES

Chapter 8 described concerns about potential entrapment or entanglement of large marine species such as marine mammals, sharks and other large fishes, and sea turtles, in mooring lines and cables along the seafloor and in the water column. These concerns are largely based on decades-old issues related to submarine cables laid loosely on the seafloor, entangling great whales (a practice that was soon corrected), and the ongoing risk to animals from abandoned and lost fishing gear and lines. MRE mooring lines have no loose ends, nor is there sufficient slack in the lines to create an ensnaring loop. The overall risk from this stressor is likely very low for MRE, but some stakeholders remain concerned that direct interaction, or secondary collection of derelict fishing gear, could cause harm to large animals.

Research and monitoring that could help further elucidate this risk include

- establishing routine maintenance that includes monitoring of mooring lines for derelict gear and their removal in order to reduce potential secondary entanglement
- better understanding of the diving and swimming behavior of animals that might be at risk to help with siting of MRE development away from dense migratory routes and to determine the depths for placement of draped cables in the water column
- describing the relative scales and interactions of marine animals with lines and cables using field measurements and numerical models, which can form the basis for outreach materials to help stakeholders understand this risk.

Based on studies that examine the scale and mechanisms for entanglement, this risk can be considered to be low (Figure 14.7).

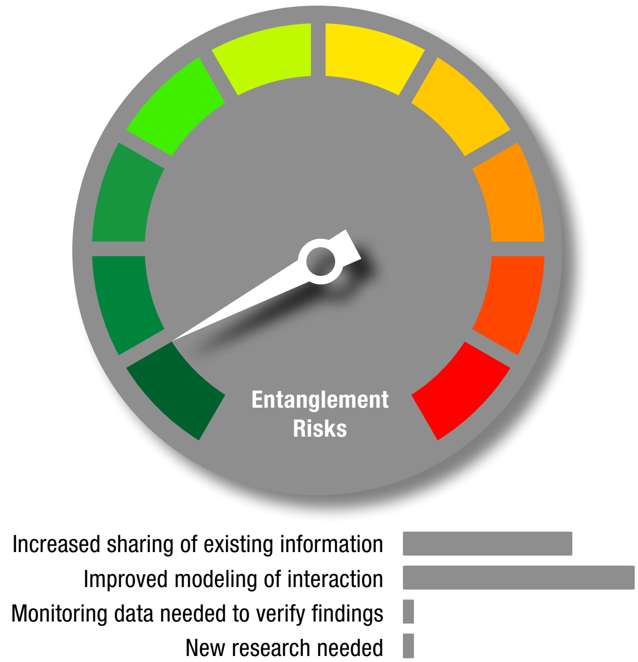


Figure 14.7. Dashboard (dial on the top) that summarizes the broadly understood level of risk to marine animals from mooring lines and cables related to marine renewable energy devices, as of 2020 for small numbers of devices. Risk may vary with larger arrays. The bar graph on the bottom demonstrates a pathway to better understanding and lowering the perceived risk of mooring lines and cables. (Graphic by Robyn Ricks)

14.1.7. SOCIAL AND ECONOMIC INTERACTIONS

Preparation of environmental assessment documents in most nations requires analysis of the social and economic effects that a proposed MRE project may have on a local area or region. Chapter 9, on social and economic data needs, described the data collection and analysis efforts needed to inform these documents, and also considered the need to track these data throughout the life of the project, to determine whether the estimates are accurate, and to inform future projects. Social and economic effects should be examined at the local level as well as at a larger strategic scale.

Efforts that can assist with standardizing social and economic data collection and analysis efforts, making them more transparent and useful, include

- determining what data are available at the local, regional, and national level to support the performance of both project-specific and strategic analyses
- assessing, through agreements with governments at all levels, what data should be collected and tracked by the MRE project developer and what data should be the purview of governments to better understand the strategic implications of MRE development.

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

Chapter 10 of the report delved into the technologies that have been used to detect interactions between marine animals and MRE devices, with an emphasis on the use of existing and emerging technologies to observe and quantify collision risk around turbines. Key instruments that have been used to observe the interactions of marine animals with turbines include passive and active acoustics, as well as optical cameras. Many of these instruments have been mounted and integrated together on platforms, often with data acquisition systems. Challenges in deploying and operating instrument packages to measure animal interactions in the high-energy waters in which tidal and river turbines are deployed include: the need to secure the instrumentation in place either on the seafloor or in the water column; difficulties in operating optical cameras in turbid waters; challenges of controlling biofouling on instrument sensors (particularly optical sensors and lenses); large data mortgages that can be acquired with the use of high-frequency acoustic and optical data collection; the need to operate lights that may change animal behavior for optical image capture in most environments; power management of autonomous integrated packages that rely on batteries, the relatively low densities of animals in fast-moving water; and the cost for developers.

Research and monitoring efforts needed to continue to progress in observing marine animals around turbines include

- establishing collaborative projects among investigators from many nations to develop data collection and analysis methods, particularly for active acoustic data that are prone to interference from ambient conditions at high-energy sites
- pursuing ongoing investigations and trials leading to the standardization of a suite of instruments and instrument packages that have proven to be effective
- continuing the development of strategies to deal with the large quantities of data that are collected and must be analyzed to determine animal interactions through the management of data collection, selective storage of sightings, and development of algorithms to automate analyses.

14.1.9. MARINE SPATIAL PLANNING

Chapter 11 described the application of marine spatial planning (MSP) as it relates to and assists with MRE development. The purpose of MSP is to improve the governance of ocean areas for their sustainable use and to provide equity for all users, while affording environmental protection. Responses to surveys of the OES-Environmental nations described the wide range of MSP programs and applications as they apply to MRE.

Important studies and information are needed to continue improving our understanding of how MSP can support and move forward with MRE development. Needed efforts include

- creating materials for and building contacts with government policy-makers and managers to assure that those tasked with creating national and regional marine spatial plans are aware of the needs of MRE
- making data and information that support MSP processes publicly available and accessible to assure that processes are transparent, including the role that MRE can play in ocean development, ocean space allocations, and governance.

14.1.10. ADAPTIVE MANAGEMENT

Chapter 12 explored the value and application of adaptive management (AM) to MRE siting, development, and management. Using a structured incremental approach to project build-out with embedded monitoring, AM has helped move many consenting processes forward for single MRE devices and small arrays of tidal turbines.

Expanding the value that AM can bring to MRE will require

- publishing guidance on AM implementation within the consenting process, prepared and issued by the appropriate regulatory body
- producing implementation guidance for the MRE industry to clarify the circumstances under which AM is acceptable, and to include requirements for post-installation monitoring, stakeholder engagement, information sharing, and thresholds for AM intervention
- applying AM measures as mechanisms for decreasing financial risk to the industry
- assuring comfort amongst regulators that an AM approach can be fully compliant with regulatory requirements and environmental legislation.

14.1.11. RISK RETIREMENT AND DATA TRANSFERABILITY

Chapter 13 presented the concepts and initial implementation of risk retirement and data transferability as a means of facilitating and accelerating consenting for small numbers of MRE devices (one or two most likely), whereby each potential risk need not be fully investigated for every project. Rather, we recommend that MRE developers and regulators rely on what is already known from already consented and deployed projects, from related research studies, or from findings of analogous offshore industries. When larger arrays of MRE devices are planned, or when new information comes to light, these risks may need to be revisited and new decisions about the level of risk retirement could be made. The intent of the process is to provide assistance to regulators in their decision-making and to inform the MRE community of what is likely to be required for consenting small developments, as well as helping to distinguish between perceived and actual risk to the marine environment. Risk retirement will not take the place of any existing regulatory processes, nor will it completely replace the need for all data collection before and after MRE device deployment; these data are needed to verify the risk retirement findings and add to the overall knowledge base. A process for assuring that appropriate datasets and information are readily available (data transferability) is also discussed. Inherent in the risk retirement and data transferability processes is the necessary protection of the environment and inhabitants of the areas into which MRE devices will be deployed and working within all existing regulatory frameworks.

The concepts of risk retirement and data transferability are relatively new. Considerable work is needed to test whether these concepts have value in MRE development and marine environmental protection, and to see if they can succeed in simplifying these pathways. Necessary activities to further risk retirement include

- increasing outreach and engagement with regulators in many nations to further explain the process and understand their potential for applying risk retirement to consenting processes
- engaging with MRE device and project developers, researchers, consultants, and other stakeholders to gain their trust in the process and to assure they understand what regulators will require of them if risk retirement is applied
- gathering evidence of additional stressors and augmenting the existing evidence base for underwater noise and EMFs as new data become available
- translating into regulatory language the evidence base for each stressor for each participating nation, working closely with regulators.

14.2. CHARTING A PATH FORWARD FOR MRE CONSENTING

By bringing together the information about the potential interactions of marine animals, habitats, and ecosystem processes with MRE devices and systems, this report provides a snapshot of the knowledge in 2020 derived from multiple field, laboratory, and modeling studies conducted around the world. The value of this information is realized as we apply it to consenting processes, and may be informed by applying some of the strategies discussed in the latter chapters of this report: MSP, AM, and risk retirement. Collectively, we might consider this body of information as supporting responsible development of MRE through continued streamlining of consenting processes. In addition, we need to consider how these management strategies support consenting and management of MRE projects through the following lenses:

- proportionate consenting requirements
- sufficiency of evidence
- transferability of evidence
- retirement of specific issues and downgrading of others that may be retired in the future.

14.2.1. PROPORTIONATE CONSENTING REQUIREMENTS

In many parts of the world, the MRE industry has been required to collect significant baseline and post-installation monitoring data for each proposed demonstration, pilot, or commercial project. At times, the requirements for data collection appear to be out of proportion relative to the size of the project and the likely risk to marine receptors. The purpose of the strategies and planning concepts highlighted here (MSP, AM, risk retirement) is to assist in converging on proportionate data collection, analysis, and reporting for consenting. Some site-specific data collection will be required at each proposed MRE project site to assure that models and information collected far from the site are applicable. However, relying on the knowledge of stressor-receptor relationships and likely risk from already consented projects, analogous industries, and research studies can bring these efforts closer to the proportionate consenting that will move the industry forward.

14.2.2. SUFFICIENCY OF EVIDENCE

For each MRE project, it is the duty of regulators to assure that sufficient evidence that is proportionate to the risk is gathered to evaluate the risk to critical marine species and habitats, and the responsibility of stakeholders to question whether the regulatory process is fair and sufficiently protective of the marine environment while not being overly precautionary. At this early stage of MRE development, validating whether the evidence base is sufficient is not a clear and simple process. The process of MSP enables governments and all sectors to come together to identify optimal locations for MRE development, which will allow for the creation of this secure low-carbon energy source, while protecting the marine environment. AM can also play a key role in allowing feedback loops and learning from each subsequent project, granting regulatory bodies and advisors leeway to adjust requirements based on post-installation monitoring data and outcomes from the initial operation of MRE devices.

14.2.3. TRANSFERABILITY OF EVIDENCE

Inherent in determining under what conditions sufficient evidence exists for consenting purposes is the need to examine information collected at other MRE development locations, and to apply lessons learned from analogous offshore industries and targeted research projects. Evaluating and understanding what data and information are valid for application to consenting new MRE sites is challenging. This process will become more transparent as more deployments and evaluations take place worldwide. The data transferability process proposed in this report, as part of the risk retirement pathway, is intended to organize and begin the process of making routine transfer of evidence more efficient.

14.2.4. RETIRING SPECIFIC ISSUES

Some stressor-receptor interactions may be of greater importance in certain countries, based on local sensitivities or other needs. These issues are likely to be given greater attention and inquiry through research investigations or post-installation monitoring requirements. For example, in France, to prevent corrosion of MRE structures, the developers opt to use sacrificial anodes. The use of these metal-based anodes has raised concerns about the potential contamination of nearby waters and habitats, which have resulted in an extensive study of potential concentrations of the metals that might be shed into nearshore waters. The preliminary results of this study show a very limited environmental risk due to metals concentration in nearshore waters, which might result in the risk being retired for France (De Roeck, pers. comm).

As the MRE industry develops and more deployments yield monitoring data and studies, the accurate nature of specific stressor-receptor interactions will become clearer. At this early stage, efforts such as the risk retirement process suggested in this report will help determine for which of these interactions sufficient evidence exists, and where there are still significant uncertainties. By decreasing the need to study each stressor-receptor interaction at each new project site, the focus of project developer funds and scientific expertise can be on the interactions for which not enough is known to clearly judge the associated levels of risk. Understanding of some of the more challenging stressor-receptor relationships, such as collision risk for marine animals around turbines, will progress much faster with this focus. By retiring specific issues for small numbers of devices and planning to re-examine these same interactions with larger arrays, we will move toward a simpler but proportionate protective process for consenting.

14.3. REFERENCES

Copping, A. and Kramer, S. 2017. A snapshot of risk for environmental effects of marine renewable energy development. 6th Annual Marine Energy Technology Symposium. Washington DC. April 30 – May 2, 2017. *https://tethys.pnnl.gov/publications/snapshot-risk-environmental-effects-marine-renewable-energy-development*

Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K. and Veirs, S. 2009. Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. *The Journal of the Acoustical Society of America*, 125(1): EL27-EL32. doi:10.1121/1.3040028 *https://tethys.pnnl.gov/publications/speaking-killer-whales-orcinus-orca-increase-their-call-amplitude-response-vessel*

International Electrotechnical Commission (IEC). 2019. Marine energy - Wave, tidal and other water current converters - Part 40: Acoustic characterization of marine energy converters (IEC TS 62600-40:2019). *https://tethys.pnnl.gov/publications/acoustic-characterization-marine-energy-converters-iec-ts-62600-402019*

Jensen, F. H., Bejder, L., Wahlberg, M., Soto, N. A., Johnson, M. and Madsen, P. T. 2009. Vessel noise effects on delphinid communication. *Marine Ecology Progress Series*, 395: 161-175. doi:10.3354/meps08204 *https://tethys.pnnl.gov/publications/vessel-noise-effects-delphinid-communication*

Lesage, V., Barrette, C., Kingsley, M.C. and Sjare, B., 1999. The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence River estuary, Canada. *Marine Mammal Science*, 15(1): 65-84. doi:10.1111/j.1748-7692.1999.tb00782.x *https://tethys.pnnl.gov/publications/effect-vessel-noise-vocal-behavior-belugas-st-lawrence-river-estuary-canada*

National Marine Fisheries Service (NMFS). 2018. 2018 Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts. NOAA Technical Memorandum NMFS-OPR-59. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, MD. *https://tethys.pnnl.gov/publications/2018-revisions-technical-guidance-assessing-effects-anthropogenic-sound-marine-mammal*

National Research Council (NRC). 2003. Ocean Noise and Marine Mammals. Washington, DC: The National Academies Press. *https://tethys.pnnl.gov/publications/ocean-noise-marine-mammals*

Popper, A. N. and Hawkins, A. D. 2018. The importance of particle motions to fishes and invertebrates. *The Journal of the Acoustical Society of America*, 143(1), 470-488. doi:10.1121/1.5021594 *https://tethys.pnnl.gov/publications/importance-particle-motion-fishes-invertebrates*

Tetra Tech. 2013. Underwater Acoustic Modeling Report - Virginia Offshore Wind Technology Advancement Project (VOWTAP). Report by Tetra Tech Inc. for Dominion Energy, Glen Allen, Virginia. *https://tethys.pnnl.gov/publications/underwater-acoustic-modeling-report-virginia-offshore-wind-technology-advancement*

NOTES

Summary and Path Forward

Copping, A.E. 2020. Summary and Path forward. In A.E. Copping and L.G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 280-292). doi:10.2172/1633209

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at: *https://tethys.pnnl.gov/publications/state-of-the-science-2020*

CONTACT

Andrea Copping
Pacific Northwest National Laboratory

andrea.copping@pnnl.gov

+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

Technical Glossary

Active acoustic measurements: Technique of purposefully producing sound underwater to receive signals (reflections) from multiple sources in the water column. Includes sonar, multi-beam and single-beam echosounders, acoustic cameras.

Adaptive management (AM): Process that seeks to reduce scientific uncertainty and improve management through rigorous monitoring and periodic review of decisions in response to growing knowledge gained from monitoring data.

Alternating current (AC): Electric current that periodically reverses direction.

Ambient noise: Background noise in the environment from multiple sources, and distinct from the noise emitted by a marine renewable energy device or other signals to be measured.

Backscatter: Reflection of a signal (e.g., sound, light) back to its origin.

Benthic: Related to the seafloor habitat; also refers to the animals that inhabit the seafloor.

Biofouling: Accumulation of microorganisms, plants, algae, sessile animals or small mobile animals on underwater structures, generally from pelagic larvae that settle on hard surfaces as part of their life cycle. Biofouling organisms becomes a problem for human structures placed in the ocean (including marine renewable energy devices) as it adds significant weight and can cover and mask important systems or moving parts of a device.

Collision: Direct contact between an animal and a moving device component (blades and rotors).

Consenting/permitting: Providing legal permission for a development, including marine renewable energy projects, based on an existing regulatory pathway that includes analysis and reporting on a range of environmental states and trends that may be affected by the proposed project.

Cumulative impacts: Changes to the environment that are assumed to be damaging, as a result of the combination of past, present, and future human activities and natural processes.

Data transferability: The process of applying datasets and information from established projects or studies that can inform new project applications for regulatory approval. The process will facilitate the discovery and application of existing information and datasets to improve the efficiency and efficacy of transferring the information.

Direct current (DC): Electric current that flows in a single direction.

Ecosystem processes: The physical, chemical, and biological connections that sustain and link the distribution and health of organisms within an environment.

Electromagnetic field (EMF): Force field of electrical and magnetic components that results from the motion of an electrical charge that carries a specific amount of electromagnetic energy.

Entanglement/Entrapment: Result of an animal that became caught or trapped in a device's mooring system without the possibility of escaping.

Farfield: The area of ocean or bay around a marine renewable energy device, generally defined as more than five device diameters from the device or array of devices.

Frequency: Number of vibrations, sound waves, or light waves emitted over a set timeframe.

Light detection and ranging (LiDAR): Technique used to measure distances by illuminating the target with laser light and measuring the time the light takes to return to its source.

Marine Spatial Planning (MSP): An approach to managing multiple marine uses and users within a geographic space, informed by geospatial data on marine resources, human activities, and ecosystem services. MSP seeks to optimize the use of marine resources and space while balancing environmental, social, and economic interests.

Nearfield: The localized area of sea occupied by and in very close proximity to a marine renewable energy, generally considered to be within one to five device diameters.

Passive acoustic measurements: Use of underwater microphones (generally hydrophones) to characterize the soundscape, including vocalization of marine animals.

Pelagic: Related to the water column of the ocean; also refers to the animals that inhabit the water column.

Receptor: Animal, habitat, or ecosystem processes susceptible to stress from an anthropogenic device or process (stressor) that may result in changes in behavior, injury or death of an animal, or removal or deterioration of a habitat.

Stressor: An anthropogenic force or object that can produce stress or injury on marine animals, habitats, or ecosystem processes (receptor). Marine renewable energy systems and subsystems can be stressors in the marine environment.

REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.

OES OCEAN ENERGY SYSTEMS An IEA Technology Initiative

OES ENVIRONMENTAL

Pacific Northwest NATIONAL LABORATORY