



Environmental Effects of Marine Energy Development around the World Annex IV Final Report

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A report prepared by Pacific Northwest National Laboratory for the Ocean Energy Systems Initiative under ANNEX IV on Assessment of Environmental Effects and Monitoring Efforts for Ocean Wave, Tidal and Current Energy Systems

ENVIRONMENTAL EFFECTS OF MARINE ENERGY DEVELOPMENT AROUND THE WORLD

ANNEX IV FINAL REPORT

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Portaferry, Northern Ireland, on the shore of Strangford Lough. Photo courtesy of Scott Butner

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Acronyms and Abbreviations

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
CBTEP	Cobscook Bay Tidal Energy Project
CFD	computational fluid dynamics
cm	centimeter(s)
CPT	Columbia Power Technologies
CTD	conductivity-temperature-depth
DIDSON	Dual-Frequency Identification Sonar
DOE	U.S. Department of Energy
EMEC	European Marine energy Center
EMF	electromagnetic field
EMV	Electromagnetic Velocity Meter
EPRI	Electrical Power Research Institute
EU	European Union
FERC	Federal Energy Regulatory Commission
g	gram(s)
HGE	Hydro Green Energy
HPR	heading, pitch, and roll
Hz	hertz
IEA	International Energy Agency
IHA	Incidental Harassment Authorization
in.	inch(es)
kHz	kilohertz
km	kilometer(s)
m	meter(s)
MHK	marine and hydrokinetic
mm	millimeter(s)
m/s	meter(s) per second
MW	megawatt
NNMREC	Northwest National Marine Renewable Energy Center
NOAA	National Oceanic and Atmospheric Administration
OES	Ocean Energy Systems Initiative
ORNL	Oak Ridge National Laboratory
ORPC	Ocean Renewable Power Company

μPa	micropascal(s)
PNNL	Pacific Northwest National Laboratory
PTS	permanent threshold shift
RD&D	research, development, and demonstration
RITE	Roosevelt Island Tidal Energy
rms	root mean square
RPM	rotations per minute
SAMS	Scottish Association for Marine Science
SEL	sound exposure level
SEL _{cum}	cumulative SEL
SEL _{ss}	single strike SEL
SBT	split-beam transducer
SMRU	Sea Mammal Research Unit
SNL	Sandia National Laboratories
SPL	sound pressure level
SPL _{peak}	peak SPL
SPL _{peak-peak}	peak to peak SPL
TGU	turbine generator unit
TPOD	Timing Porpoise Detector
TTS	temporary threshold shift
UK	United Kingdom
VAMS	Vessel-mounted Aimable Monitoring System
WEC	wave energy converter

Executive Summary

Annex IV is an international collaborative project to examine the environmental effects of marine energy devices among countries through the International Energy Agency's Ocean Energy Systems Initiative (OES). The U.S. Department of Energy (DOE) serves as the Operating Agent for the Annex, in partnership with the Bureau of Ocean Energy Management (BOEM; formerly the Minerals Management Service), the Federal Energy Regulatory Commission (FERC), and National Oceanographic and Atmospheric Administration (NOAA).

Numerous ocean energy technologies and devices are being developed around the world, and the few data that exist about the environmental effects of these technologies are dispersed among countries and developers. The purpose of Annex IV is to facilitate efficient government oversight of the development of ocean energy systems by compiling and disseminating information about the potential environmental effects of marine energy technologies and to identify methods of monitoring for these effects. Beginning in 2010, this three-year effort produced a publicly available searchable online database of environmental effects information (*Tethys*). It houses scientific literature pertaining to the environmental effects of marine energy systems, as well as metadata on international ocean energy projects and research studies. Two experts' workshops were held in Dublin, Ireland (September 2010 and October 2012) to engage with international researchers, developers, and regulators on the scope and outcomes of the Annex IV project. Metadata and information stored in the *Tethys* database and feedback obtained from the two experts' workshops were used as resources in the development of this report.

This Annex IV final report contains three case studies of specific interactions of marine energy devices with the marine environment that survey, compile, and analyze the best available information in one coherent location. These case studies address 1) the physical interactions between animals and tidal turbines; 2) the acoustic impact of marine energy devices on marine animals; and 3) the effects of energy removal on physical systems. Each case study contains a description of environmental monitoring efforts and research studies, lessons learned, and analysis of remaining information gaps. The information collected through the Annex IV effort and referenced in this report, can be accessed on the *Tethys* database at <http://tethys.pnnl.gov/>.

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01.

BACKGROUND FOR ANNEX IV

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

Under the OES Initiative, countries are brought together to advance RD&D of conversion technologies to harness energy from all forms of ocean renewable resources, such as tides, waves, currents, temperature gradient (ocean thermal energy conversion and submarine geothermal energy) and salinity gradient for electricity generation, as well as for other uses, such as desalination, through international cooperation and information exchange. The collaboration consists of 19 member countries (as of November 2011), each of which is represented by a Contracting Party that nominates representatives to the OES Executive Committee, which is responsible for the OES work program. Executive Committee participants are specialists from government departments, national energy agencies, research, or scientific bodies and academia.

The OES work program carried out by the Contracting Parties consists of RD&D, analysis, and information exchange related to ocean energy systems. Work is conducted on diverse research topics that are specified in “Annexes” to the Implementing Agreement. Each Annex is managed by an Operating Agent (usually the member who takes the initiative to propose and undertake a plan of activities).

Origins and Intent of the Annex

The concept for the formation of an annex focused on the potential environmental impacts of ocean renewable energy was initiated by the United States and Canada in 2006 and responds to a need for information about the environmental effects described in the summary of the IEA’s meeting on ocean energy systems held in Messina, Italy (the Messina report).³ After an experts’ meeting in late 2007, the United States developed a proposal for the formalization of Annex IV, which was submitted and approved by the OES Executive Committee in 2008. The proposal stated the need to compile and disseminate information about the environmental effects of ocean renewable energy and about

¹ See: <http://www.ocean-energy-systems.org>.

² See: <http://www.iea.org/>.

³ National Renewable Energy Laboratory (USA) and Natural Resources Canada (Canada). October 18, 2007. Potential Environmental Impacts of Ocean Energy Devices: Meeting Summary Report.

identifying methods of monitoring for such effects. Annex IV was proposed to focus primarily on ocean wave, tidal, and current energy development.

In 2009, six countries (Canada, Ireland, Spain, Norway, New Zealand, and the United States) that had an interest in participating in Annex IV, formalized commitments to the effort and developed a work plan and budget for the project. The work plan described a three-year effort to do the following:

- Compile information from monitoring and mitigation efforts around deployed renewable energy devices and analogous marine technologies.
- Develop and populate a publicly accessible database to house this information.
- Organize two experts' workshops to inform the effort and provide feedback about products.
- Develop this final report to characterize the environmental effects, identify successful monitoring and mitigation methods, and describe lessons learned and best practices derived from environmental monitoring and mitigation regimes.

The three-year work plan officially began at the beginning of calendar year 2010, when member nations appointed one of the U.S. Department of Energy's (DOE's) national laboratories, the Pacific Northwest National Laboratory (PNNL), to lead the process of database development, data gathering, and analysis to support the objectives of Annex IV. Through a competitive solicitation, PNNL later selected the Wave Energy Centre (Portugal) and the University of Plymouth (United Kingdom [UK]) as contractors to assist with data collection. PNNL also hired the Irish Marine Institute to organize and host the first experts' workshop under Annex IV, which included a discussion among 58 experts from 8 countries about the information needs for the Annex. A report from this workshop highlights the recommendations that were incorporated into the revised Annex IV work plan.⁴ The primary recommendations from the workshop were to do the following:

- Shift the focus from the collection of raw environmental monitoring data to metadata, identifying what research and monitoring is occurring around the world.
- Decrease the emphasis on the collection of environmental information from analogous marine technologies, which were seen to have limited benefits to increasing the understanding of the specific potential impacts of ocean renewable energy technologies.
- Avoid identification of best practices for environmental monitoring, given the early state of the industry and the limited number of deployed projects on which to base this assessment.

In 2011, PNNL developed the framework for the Annex IV database using the existing structure for a knowledge management system already under development in the United States (dubbed "*Tethys*"), which was designed to accumulate and organize environmental information for marine energy and offshore wind development. Details of the database and metadata collection efforts are provided below.

In 2012, Annex IV representatives gathered metadata information and submitted lists of researchers and developers who had environmental research or monitoring results. The metadata forms, in

⁴ See: <http://tethys.pnnl.gov/publications/oes-ia-annex-iv-environmental-effects-marine-and-hydrokinetic-devices>.

addition to other documents and reports in the database, were analyzed and used to develop three case studies, which provide a snapshot of the current research and understanding for three types of potential environmental impacts of particular concern for ocean renewable energy development.

Members of Annex IV

Current Annex IV member nations include the United States, Canada, Norway, Spain, Ireland, and New Zealand. The DOE serves as the Operating Agent for the annex in partnership with the Bureau of Ocean Energy Management (formerly Minerals Management Service), Federal Energy Regulatory Commission (FERC), and National Oceanographic and Atmospheric Administration (NOAA). The member nations and working partners have contributed financially to support the Annex IV work, and they have provided in-kind support by contributing metadata and research information about the environmental effects of marine energy projects, established contact with marine energy developers and researchers around the world, reviewed products, and provided advice on the scope of work.

02.

PRODUCTS OF ANNEX IV

Large numbers of ocean energy technologies and devices are being developed worldwide, but the few existing data on the environmental effects of these technologies are dispersed amongst different countries and developers. Annex IV aimed to facilitate efficient government oversight of the development of ocean energy systems by expanding the baseline knowledge of environmental effects and monitoring methods related to ocean wave, tidal, and current energy development. One of the primary goals of Annex IV was to ensure that existing information and data about environmental monitoring (and, to the extent possible, practices for environmental mitigation) are more widely accessible to those in the industry; national, state, and regional governments; and the public. With relatively few marine energy devices in the water, there are few examples of mitigation strategies for which data are available; this report refers to incidences where the application of mitigation strategies is clear, but in general, such analysis will be postponed until more information is available. The products of Annex IV will be made publicly available to facilitate knowledge and information transfer. The products that have been developed include an accessible and searchable database, two experts' workshops and associated reports, and this final report.

Database

Annex IV members collaborated on developing the requirements for a searchable database of research and monitoring information to be used to evaluate environmental effects. Both metadata with some results from monitoring and associated research studies investigating the potential effects of marine energy projects (wave and tidal) are included from this effort. The database is a readily accessible platform to identify information collected about the environmental effects of marine energy development, including monitoring techniques and mitigation strategies, where available. Collected information is also intended to be dynamic, evolving with ongoing updates as additions become available. The information collected to date represents the work of many contributors, and additional contributions, updates, and corrections are being actively sought.

STRUCTURE AND DEVELOPMENT OF THE DATABASE

Annex IV is housed in a database previously created by the DOE national laboratory PNNL to construct a Knowledge Management System that captures the environmental effects of marine energy development in the United States. This database, dubbed *Tethys* for the Greek titaness of the oceans, integrates the information collected by the Annex IV effort. The primary function of *Tethys* is to facilitate the creation, annotation, and exchange of information on the environmental effects of ocean energy technologies. The Annex IV data has become an integral part of the *Tethys* database, and is accessible from the *Tethys* home page (<http://tethys.pnnl.gov/>).

The *Tethys* database was developed using the Semantic MediaWiki software. All entries are tagged with key words and themes to assist search capabilities; for example: *Electromagnetic Fields (EMF) and Marine Mammals*. Semantic MediaWiki allows *Tethys* to organize and semantically search through individual files, documents, and data based on their associated tags. In doing so, the *Tethys* knowledge base supports access and organization of hundreds of journal articles, technical reports, and research studies about the environmental effects of marine energy developments.

PROCESS FOR DEVELOPING THE DATABASE

Tethys consists of a knowledge base of documents and links, and an interactive map that provides access to all geo-referenced sites and research studies contributed under Annex IV. The content of Annex IV was gathered using two metadata forms sent to marine energy developers, researchers, and other knowledgeable parties. The first metadata form (*project sites form*) was created to collect information about the environmental effects of ocean energy projects. A second form (*research studies form*) was subsequently created to capture research studies that address environmental effects that are not necessarily directly associated with marine energy project sites.

The Annex IV metadata forms were vetted by the member nations and beta tested with selected project developers and researchers. The metadata forms were widely distributed to the representatives of the member nations, members of the OES Executive Committee, marine energy developers, and researchers. PNNL, partnering with the Wave Energy Centre and the University of Plymouth Marine Institute actively sought input from developers in countries well beyond the Annex IV member nations, and contacted researchers around the world. Although direct input from developers was limited, researchers commonly found information through reports and studies associated with the project. Forms are available on the *Tethys* website and invitations to contribute to the database appear in several locations on the website.

The project site metadata forms and research study forms were integrated into the *Tethys* knowledge base and linked to the *Tethys* map (Figure 1). All project sites represented by metadata forms are shown as bubbles on the map. Research studies associated with project sites are added to the specific location of the site; other geo-referenced research studies are also shown. Research studies that are not tied specifically to a location do not appear on the map, but are listed in the *Tethys* knowledge base.

The project site forms and research studies forms are monitored and updated as new information becomes available and/or after a period of time has passed. PNNL staff communicates with the respective developers or researchers, seeking input to update metadata forms or to remove the forms in favor of published papers or reports. For example, as the results of research studies are published, the metadata forms are removed and replaced with a link to the associated paper or report.

USE OF THE DATABASE, EXAMPLES

Information about the Annex IV program, and links to key documents and websites (such as the first experts' workshop report, OES website, etc.), can be found on the right side of the *Tethys* home page (Figure 2), as well as through the About Annex IV page under the *Working with Tethys* dropdown menu (Figure 3).

The Map compiles all documents, U.S. permitting sites, and international Annex IV metadata forms that are associated with a geographic location. This view allows panning and zooming, while results can be narrowed by keyword searches and by selecting values in the boxes to the right. Clicking on a marker will open a bubble with more information that links to the document page.

[Link to Tethys Knowledge Base](#)

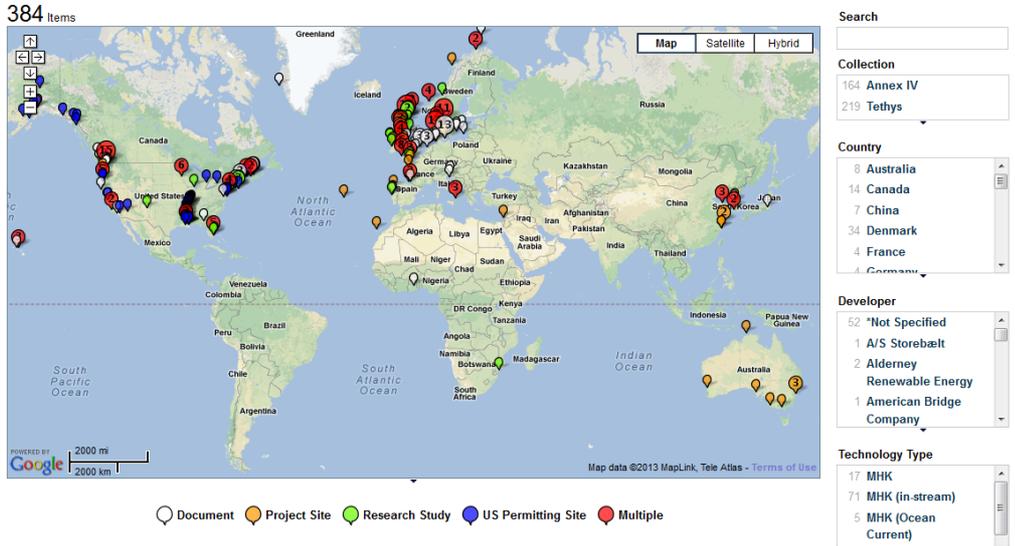


Figure 1. Tethys Map view

Marine and Hydrokinetic (MHK) Energy Development: MHK development is moving forward in U.S. and international waters, with projects that include the following devices:

- Tidal turbines placed in coastal and estuarine areas;
- Riverine turbines in fast-moving rivers;
- Wave energy converters in open coastal areas with significant waves;
- Current turbines in the Gulf Stream; and
- Ocean Thermal Energy Converters in deep tropical waters.

Please contact us if you would like to contribute any MHK information or research to Tethys.

Annex IV Research Studies Metadata Form
[Ocean Energy System - Annex IV Experts' Workshop: 1](#)
[DOE MHK Webinar Series](#)
[Tethys FY11 Annual Report](#)
[Tidal Energy Workshop Report](#)
[Wave Energy Workshop Report](#)
[West Coast Environmental Protocols Framework - Draft Report](#)

Offshore Wind Development: The first offshore wind farms are under development in U.S. waters, while significant generation of offshore wind already contributes to electricity needs in Europe and Asia. Nearshore offshore wind turbines are drilled into the seabed on monopoles; deeper waters require jacketed or floating wind turbines.

Please contact us if you would like to contribute any offshore wind information or research to Tethys.

Annex IV Collaborative Information Sharing: Under the auspices of the Ocean Energy Systems Implementing Agreement (OES-IA), Annex IV is a collaborative project to gather and share information on the environmental effects of ocean energy development (tidal, wave, and ocean current). The Annex IV effort will be used to improve the worldwide understanding of potential impacts of MHK development, develop effective monitoring programs, and collaboratively develop effective mitigation strategies. Annex IV information is currently being gathered from MHK project developers, utilities, and researchers from the OES-IA member nations and will be made available beginning in early 2013.

Figure 2. Tethys home page, showing the link to the About Annex IV page

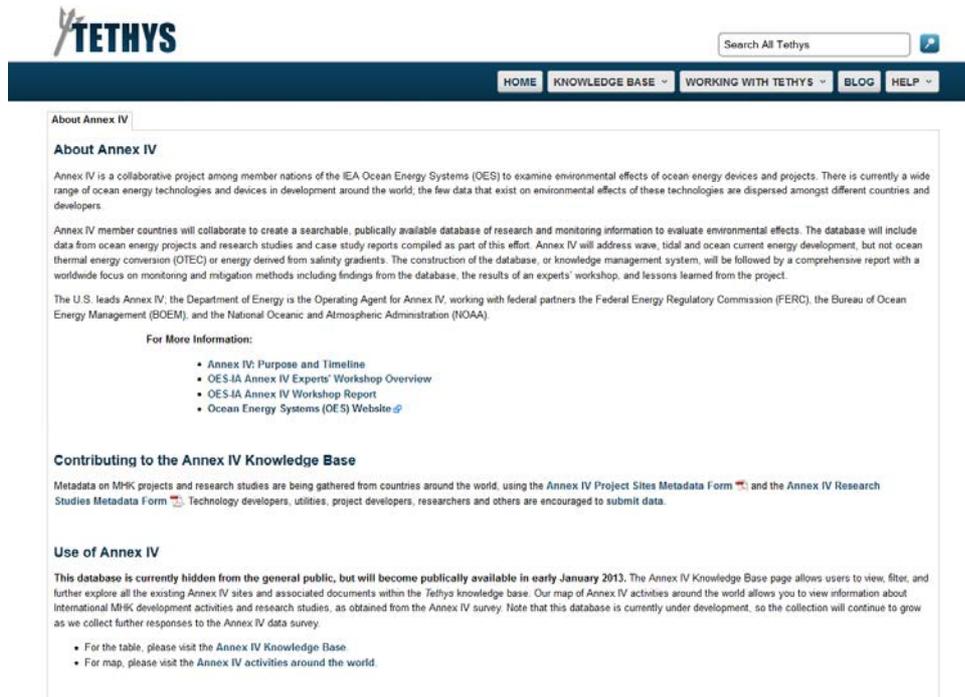


Figure 3. About Annex IV page, accessed under the *Working with Tethys* dropdown menu

Background information on Annex IV data is available on the About Annex IV page (Figure 3). Data may be accessed by selecting the Knowledge Base menu and then choosing either the map view (Figure 1), or the spreadsheet view (Figure 4). Once at the *Tethys* Map and Knowledge Base pages, both *Tethys* and Annex IV content can be filtered on and off via the Collection facet box on the right side of the screen.

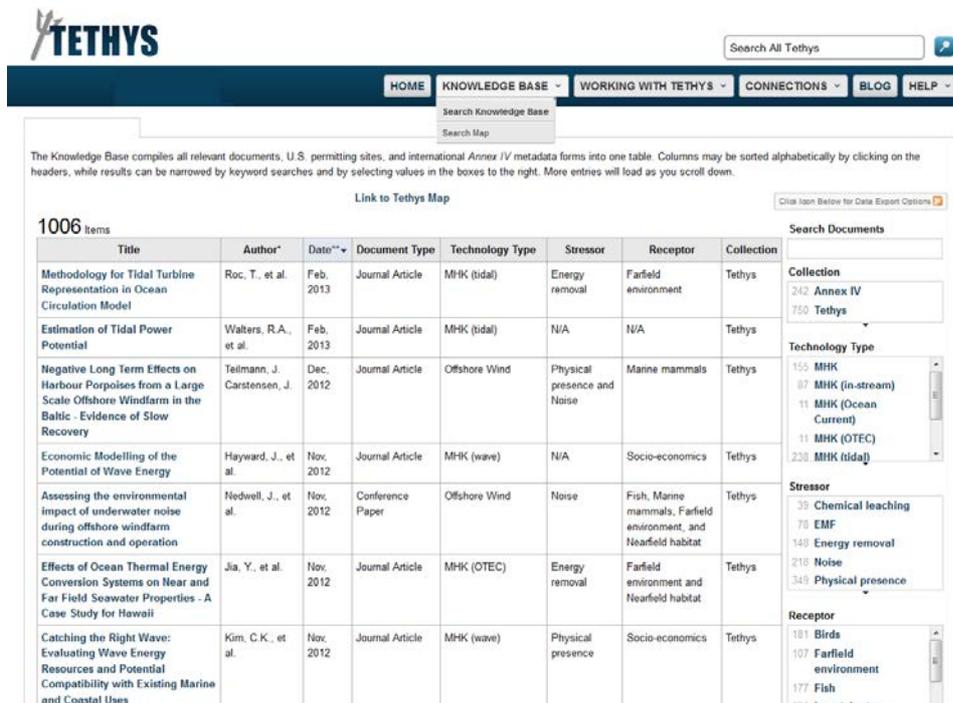


Figure 4. *Tethys* Knowledge Base view

The *Tethys* map view shows the location of all the geo-referenced projects for which metadata have been collected (Figure 1). The bubbles are coded for the location of metadata on project sites (orange), metadata on research studies (green), locations to which published documents refer (white), and locations where project site and research study metadata are available (red). An example of a project site is shown in Figure 5, with the dialogue box that allows the user to go to the project site page (Figure 6).

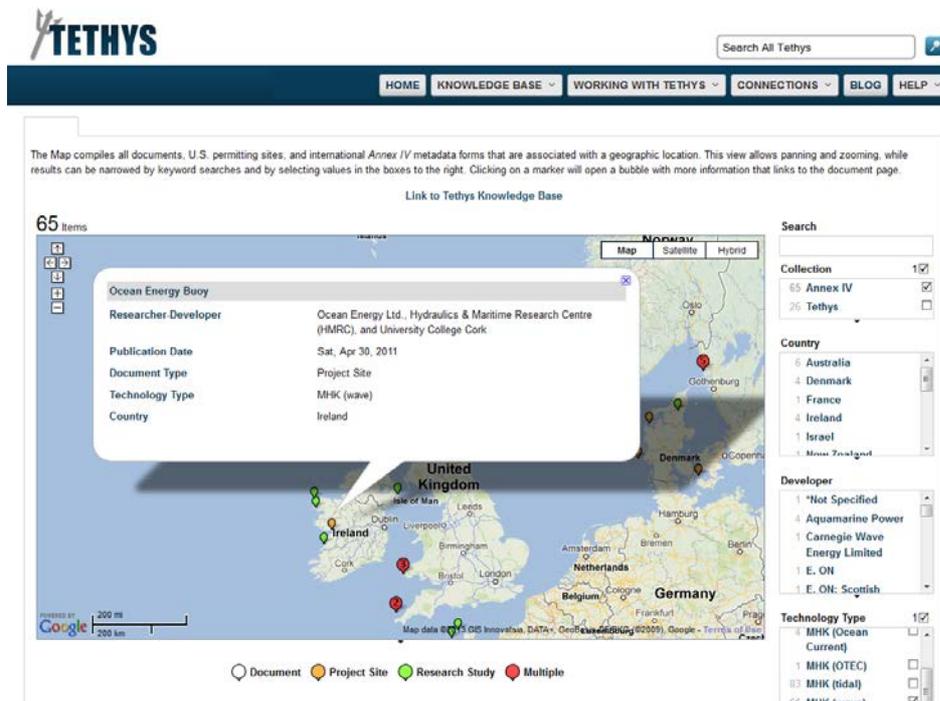


Figure 5. Image of *Tethys* Map view, centered over European project sites, with the Ocean Energy Buoy highlighted

Project Name
Ocean Energy Buoy OE 50

Description
Technology: Oscillating Water Column
Project Scale: Single device
Installed Capacity: Quarter scale
Additional Description: The OE Buoy is a floating, oscillating water column device. The water columns are held in rectangular tubes facing away from the incident waves. This device uses wave energy to compress air in a plenum chamber and pumping it through an air turbine system. The mouth of the OWC is facing away from the wave direction, this results in high-energy efficiencies at the operating point because of the motions of the float system relative to the waves. However in extreme waves, the efficiencies reduce.

Location
The site is located at Galway Bay, Ireland.

Process Status
The OE Buoy device was subjected to eight months of sea trials over 2007 and 2008 at the Manne Institute/SEI Wave Energy Test Site in Galway Bay. During the eight-month trial period, the device was subjected to a wide range of wave conditions including a severe storm with wave heights of 8.2 metres. It was found that the mooring system had no difficulty coping with these conditions, and the device as a whole did not suffer from any defects from the extreme waves. Currently a 1/4 scale model is being tested (Galway, Ireland).

Key Environmental Issues
Galway is rich in Fauna, an environmental survey was carried out, out of the species observed: 56 were polychaetes (segmented worms), 31 were crustaceans (crabs, shrimps, prawns), 18 were molluscs (mussels, cockles, snails etc.), 6 species were echinoderms (brittlestars, sea cucumbers), 2 species were ctenophores (sea anemones, corals), 2 species were sipunculids (peanut worms) and 1 species was a phoronid (horseshoe worm). Infauna such as Burrowing decapods, large epibenthic, *Goneplax rhomboides* and *Marthasterias glacialis* inhabit the site. Leatherback turtles (*Demochelys coriacea*) are regularly spotted around Galway and is considered a regular member of the Irish marine fauna.

GIS Resources
The project area has the following coordinates:



Project Site

Name: Ocean Energy Buoy OE 50
Developer: Ocean Energy and University College Cork
Website: <http://www.oceanenergy.ie/>
Launch Date: 2011/05/01
Country: Ireland
Attachment: Original Form
Technology Type: MHK (wave)



Ocean Energy Buoy

Figure 6. Project site page for Ocean Energy Buoy, linked from the *Tethys* Map Viewer

A rudimentary search of the Knowledge Base, using the facet boxes on the right side of the screen, yields a smaller list of pertinent documents and links (Figure 7); the same search could be conducted using search terms in the box at the top of the facet boxes.

The Knowledge Base compiles all relevant documents, U.S. permitting sites, and international Annex IV metadata forms into one table. Columns may be sorted alphabetically by clicking on the headers, while results can be narrowed by keyword searches and by selecting values in the boxes to the right. More entries will load as you scroll down.

Link to Tethys Map Click Icon Below for Data Export Options

14 Annex IV Research								Search Documents	
Title	Author*	Date**	Document Type	Technology Type	Stressor	Receptor	Collection	Collection	1
Pilot Marine Spatial Plan for the Pentland Firth and Orkney Waters	Tumbull, S.	Mar. 2012	Research Study	MHK (tidal) and MHK (wave)	EMF, Energy removal, Physical presence, and Noise	Birds, Invertebrates, Fish, and Marine mammals	Annex IV	14 Annex IV	<input checked="" type="checkbox"/>
Environmental Impact Assessment of the Danish Wave Energy Center	Margheritini, L. Azzellino, A.	Dec. 2011	Research Study	MHK (wave)	EMF, Energy removal, Physical presence, and Noise	Birds, Invertebrates, Fish, Marine mammals, and Reptiles	Annex IV	6 MHK 3 MHK (tidal) 7 MHK (wave) 2 Offshore Wind	<input checked="" type="checkbox"/>
Conference on Wind Energy and Wildlife Impacts	May, R. Blevanger, K.	Dec. 2010	Research Study	Offshore Wind	EMF, Physical presence, and Noise	Birds, Invertebrates, Fish, and Marine mammals	Annex IV	3 Chemical leaching 14 EMF 14 Energy removal 26 Noise 27 Physical presence	<input checked="" type="checkbox"/>
Coastal Elasmobranch Surveys	Kajjura, S.	Dec. 2010	Research Study	MHK	EMF	Fish	Annex IV		<input type="checkbox"/>
Atlantic Marine Energy Test Site Environmental Impact Statement	Kavanagh, P.	Dec. 2010	Research Study	MHK (wave) and MHK	Chemical leaching, EMF, Energy removal, Physical presence, and Noise	Birds, Invertebrates, Fish, and Marine mammals	Annex IV		<input type="checkbox"/>
Active Acoustic Monitoring	Dr. Peter J. Stein, Dr. Patrick Edson	Aug. 2010	Research Study	MHK	EMF, Physical presence, and Noise	Fish and Marine mammals	Annex IV	9 Birds 14 Fish 9 Invertebrates 10 Marine mammals 5 Reptiles	<input checked="" type="checkbox"/>
Bayesian Integration for Marine Spatial Planning and Renewable Energy Siting	Halsey, K. Goldfinger, C.	Aug. 2010	Research Study	MHK	EMF, Energy removal, Physical presence, and Noise	Birds, Invertebrates, Fish, Marine mammals, and Reptiles	Annex IV	2 Presentation 14 Research Study 1 Technical Report	<input checked="" type="checkbox"/>

Figure 7. *Tethys* Knowledge Base narrowed by the search terms Annex IV, EMF, Fish, and Research Study.

18

Expert's Workshops

EXPERTS' WORKSHOP 1 – SEPTEMBER 2010

The first experts' workshop was held in Dublin in September 2010. Fifty-eight experts, including marine researchers, ocean energy developers, regulators, and others from eight countries, participated in the two-day workshop. The purpose of the workshop was to bring additional expertise to bear on the identification and collection of appropriate data, to plan for the analysis of the data, and to scope appropriate case studies. The Irish Marine Institute assisted PNNL with organizing, hosting, facilitating, and documenting the workshop. Input from the first experts' workshop was used to modify the scope of the Annex, including shifting the focus of the effort to the collection of metadata rather than more detailed data sets, and broadly considering all existing marine energy projects as potential case studies, rather than choosing only a few. A draft workshop report was prepared, circulated to the member nations, and a final report was published. The report can be accessed at <http://tethys.pnnl.gov/publications/oes-ia-annex-iv-environmental-effects-marine-and-hydrokinetic-devices>.

EXPERTS' WORKSHOP 2 – OCTOBER 2012

The second experts' workshop was held in Dublin on October 15, 2012. Fifty-five experts from nine countries participated. The intent of the workshop was to review the Annex IV information presented via the *Tethys* database for content and functionality, review the draft final report with its associated case studies, and provide substantive comments on these Annex IV products prior to report revision and publication at the end of 2012. All materials were provided to workshop participants for review four weeks before the workshop. The workshop included two breakout sessions to discuss the Annex IV database and to review the draft final report. During the second breakout sessions, participants were also asked to provide guidance on future Annex IV activities and comment on whether the Annex IV project and its associated activities should to be extended. The comments and suggestions received during this workshop were used to ensure the Annex IV knowledge base accommodates the needs of the Annex IV community and provide guidance for future Annex IV activities. All comments and suggestions have been taken into consideration in developing this final report.

0.3

ANNEX IV FINAL REPORT AND CASE STUDIES

This report discusses some of the key pieces of information gathered through the Annex IV process; it provides analysis of monitoring efforts and mitigation strategies (where available) and guidance to international marine energy stakeholders, including policymakers, developers, regulators, agencies, academic institutions, and research organizations. Greater understanding of the environmental effects and monitoring methods related to marine energy will foster public acceptance and help to advance marine energy technology. Information in this report is presented and analyzed under three case studies focused on key interactions of marine energy devices with the environment. The report also summarizes the process for developing the Annex, including the involvement of over 70 experts from 9 nations brought together at 2 experts' workshops. As Annex IV draws to a close, a paucity of environmental information remains available, despite the ongoing deployment of more marine energy devices.

Intent of the Case Studies

Case studies were developed to evaluate specific interactions of marine energy devices with the marine environment in order to survey, compile, and analyze the best available information in one coherent location. Only information that is readily available in the public domain was used in the case studies; in many cases there are likely further data that will be available in the near future but they were not accessible at the time this report was published. The results of the case studies reported here do not include figures from the papers or reports used to support the analyses because copyright issues may be substantial; however, links to all of the cited papers, reports, and metadata forms are available in *Tethys*.

Although the original concept of the case studies was to focus on monitoring efforts related to specific marine energy projects, the slower than projected pace of development encouraged a re-examination of the most efficacious topics for case studies. The criteria used to select the three case studies presented in this report were as follows:

- The topic must be a common environmental concern or question among multiple nations.
- The topic must be raised as a significant issue in permitting (consenting) of marine energy sites in more than one nation.
- There must be sufficient information available to make an assessment.

Process for Developing the Case Studies

Information to support the case studies was gathered from all available sources and evaluated to provide an understanding of the state of the science for each topic. Scientific papers and technical reports form the majority of the material; where there are no published reports available, Annex IV metadata forms (collected on Annex IV project sites), research studies, and other unpublished sources were used. To the extent possible, each source was documented and appears in the Annex IV database.

Each case study begins by defining the problem addressed, presents available evidence from marine energy monitoring and/or research studies, and concludes with a discussion of the lessons learned and data gaps presented by the available information. All cited references are listed for each study and can be accessed through the Annex IV database.

Annex IV Case Studies, Goals, and Objectives

The three case studies and their respective goals and objectives are briefly described below.

CASE STUDY 1 – INTERACTION OF MARINE ANIMALS WITH TURBINE BLADES

The goal of this case study was to examine existing information about the interactions of marine animals with turbine blades from marine energy projects worldwide. Specific objectives included the following:

- Identify tidal and in-stream projects that have monitoring data about marine animal interactions with turbine blades.
- Collect ancillary information from laboratory flume and tank studies and numerical modeling studies that may inform the understanding of the interaction of marine animals with turbine blades.
- Evaluate the comparability and applicability of the information from different projects and ancillary studies to determine interactions between marine animals and turbine blades.
- Identify key gaps in data and studies that need to be filled to complete the understanding of these interactions.

CASE STUDY 2 – EFFECTS OF ACOUSTIC OUTPUT FROM TIDAL AND WAVE DEVICES ON MARINE ANIMALS

The goal of this case study was to examine existing information about the effects of acoustic output from tidal and wave devices on marine animals from marine energy projects worldwide. Specific objectives included the following:

- Identify tidal and wave projects that have monitoring data about the effects of acoustics on marine animals.

- Collect ancillary information from laboratory studies and numerical modeling simulations that may inform the understanding of the effects of acoustics from tidal and wave systems on marine animals.
- Evaluate the comparability and applicability of the information from different tidal and wave projects and ancillary studies to determine the effects of acoustics on marine animals.
- Identify key gaps in data and studies that need to be filled to complete the understanding of the effects of noise from marine energy projects on marine animals.

CASE STUDY 3 – THE ENVIRONMENTAL EFFECTS OF MARINE ENERGY DEVELOPMENT ON PHYSICAL SYSTEMS

The goal of this case study was to examine existing information about the effects of tidal and wave devices on water circulation, sediment transport, and the quality of the environment from marine energy projects worldwide. The monitoring information and modeling studies that focus on currently deployed devices represent marine energy projects that are too small to be expected to demonstrate changes in the physical system. The information in this case study attempted to anticipate the potential effects in larger-scale deployments. Specific objectives included the following:

- Identify tidal and wave projects that have monitoring data that can be used to determine physical changes in the environment.
- Collect ancillary information from laboratory studies and numerical modeling simulations that may inform the understanding of the potential effects of tidal and wave systems on the physical environment.
- Evaluate the comparability and applicability of the information from different tidal and wave projects and ancillary studies to determine the potential effects on the physical marine environment.
- Identify key gaps in data and studies that need to be filled to complete the understanding of the effects of marine energy projects on the physical environment.

0.4

CASE STUDY 1 – INTERACTION OF MARINE ANIMALS WITH TURBINE BLADES

Introduction

This case study was developed as part of the OES Annex IV. Annex IV sought to bring together information about the environmental effects of marine energy development from around the world and to assist OES member nations with environmentally responsible acceleration of the marine energy industry. As marine energy development begins to gain momentum internationally, Annex IV case study analyses focused on the early stages of development from single devices to multiple device arrays. Metadata—descriptive information about data—were collected from projects and research studies to form the basis of the input to this case study.

This case study focused on investigating the interactions of marine animals with tidal turbine blades.

GOAL AND OBJECTIVES OF THE CASE STUDY

The goal of this case study was to examine existing information about the interactions of marine animals with turbine blades from marine energy projects worldwide. Specific objectives included the following:

- Identify tidal and in-stream projects that have monitoring data about marine animal interactions with turbine blades.
- Collect ancillary information from laboratory flume and tank studies and numerical modeling studies that inform the understanding of the interaction of marine animals with turbine blades.
- Evaluate the comparability and applicability of the information from different projects and ancillary studies to determine interactions between marine animals and turbine blades.
- Identify key gaps in data and studies that need to be filled to complete the understanding of these interactions.

APPROACH

As will become clear in the ensuing sections, information about the interactions of marine animals with tidal turbine blades was brought together from a chosen set of readily accessible verifiable sources for analysis. Information from full-scale tidal device deployments was preferred, but, with limited tidal projects in the water, information about the interactions drawn from small-scale devices, laboratory flume and tank studies, and indications from numerical models were used to help inform our understanding of interactions. Each information source was examined to determine whether the outcome informed the case study. Information was compared among projects and research studies,

common responses of animals around blades were identified, and the likely outcomes of the increased presence of tidal blades in the water were evaluated. Gaps in information that hinder further analysis or interpretation were identified.

SOURCES OF CASE STUDY INFORMATION

The information collected for this case study was derived from metadata collected from several project site investigations worldwide and metadata collected from research studies. Where applicable, the underlying data sources and interpretations from reports and papers were sought for analysis. Certain information was collected from analogous industrial interactions with marine animals, including oil and gas exploration and rig operation, pile driving in nearshore applications, and offshore wind development. However, the use of these data to inform the understanding of the interaction of marine animals with tidal turbine blades was considered to be of limited use because of fundamental differences in technology and habitat. Analogous industry data may peripherally inform the interaction of animals with turbines; for instance, the rich body of literature describing the aggregation of fish and other marine animals around oil and gas drilling platforms (Fabi et al. 2004; Jørgensen et al. 2002). Other industries have significant differences in tidal and in-current devices, including conventional hydropower and ships' propulsion systems, making comparisons more difficult. In comparison to conventional hydropower turbines, tidal turbines turn much more slowly, without the presence of hydraulic pressure forcing water and fish through tidal turbines. Depending on the size and location of the system, conventional hydro turbines can rotate anywhere from 80 to 600 rotations per minute (RPM), while tidal turbines operate within the range of 5 to 30 RPM. Similarly, ship and boat propellers move much faster than tidal turbines (for example, 70 to 140 RPM for the average cargo vessel), shedding energy to the surrounding waters, while a tidal turbine slows the flow of water and removes energy. RPM corresponds linearly to blade tip speed for a horizontal turbine; however tip speed for a vertical axis turbine is much lower, based on the fundamental design.

USE OF THE CASE STUDY OUTCOMES

The information gathered and analyzed for this case study can help inform regulatory and research investigations of potential risks to marine animals from turbine blades, and can assist marine energy developers in developing engineering, siting, and monitoring options for tidal projects to minimize encounters with marine animals. Used in conjunction with site-specific knowledge, the case study outcomes may simplify and shorten the time to permit (consent) deployment of single and multiple device arrays. The information brought together for analysis in this case study represents readily available, reliable information about animal interactions with turbine blades; however, the analysis and conclusions drawn from this case study are not meant to take the place of site-specific analyses and studies, or to direct permitting (consenting) actions or siting considerations in specific locations.

Interactions of Marine Animals with Turbine Blades

Specific groups of marine animals are potentially at heightened risk for interaction with turbine blades because of the following factors:

- geographic co-location and position in the water column with sites where tidal energy is likely to be harvested

- specific behaviors and life stages of animals that may increase the chance of contact with turbines
- attraction of animals to the turbines because of the availability of shelter, daily animal movements or seasonal migrations, the creation of an artificial reef, and/or increased prey concentrated near the turbines.

Of particular concern are animals that are afforded special legal protection because of their decreased population sizes, the cumulative effects of other environmental factors that threaten their population viability, or their heightened importance as a commercial, recreational, or subsistence food source for humans. Examples of this special protection include the species listed in the *Endangered Species Act of 1973* and *Marine Mammal Protection Act of 1972* in the United States, the *Species at Risk Act* in Canada, or the Council Directive 92/43/EEC, as amended, on the conservation of natural habitats and of wild fauna and flora (Habitat Directive) in Europe.

ANIMALS AT RISK AND KEY SOURCES OF INFORMATION

Animal groups that may be at risk from interaction with turbine blades include marine mammals (e.g., mustelidae such as otters, pinnipeds such as seals and sea lions, and cetaceans such as whales and dolphins); sea turtles; fish (resident and migratory); and diving birds (Wilson et al. 2007; DOE 2009).

Direct measurements of animal interaction with tidal turbines are the most useful, particularly data that provide optical or acoustic “pictures” of interactions. Underwater photography and videography can potentially provide the clearest indication of interactions. Unfortunately, the fast-flowing water and turbid conditions around tidal turbines and the challenges of deploying and maintaining optical equipment can limit the number of installations where optical pictures (still photography or videography) can successfully be collected, but success at the European Marine Energy Center (EMEC, Orkney Islands, UK) has shown promise for optical images in clear shallow water. In addition, tidal turbines that are placed below the depth of light penetration and/or in turbid waters will require the use of artificial illumination in order to use underwater photography or videography; continuous or strobe lighting to illuminate the field of view may cause unnatural changes in behavior among marine animals, most commonly attraction to the source. Acoustic detectors ranging from passive hydrophones to single beam and multi-beam active acoustic imaging devices can also provide clear illuminations of animals close to turbines. Crittercams or acoustic tags also may be attached to animals to provide a better understanding of animal interactions with tidal turbines.

Acoustic detection, characterization, and ranging of animals at a scale that informs the understanding of interactions with turbines require sophisticated data processing and equipment integration. Although this is an area of active research and development, only a small number of acoustic monitoring packages are currently providing data on animal interactions with deployed turbines. There are likely to be very few captured images of the marine animals considered to be at risk in relation to the amount data recorded. This scarcity will necessitate the review of very large amounts of optical or acoustic data, and optical or acoustic cameras that are triggered by movement tuned to the animals of interest could focus the results more effectively. Examples of these data are examined in this case study.

All remote monitoring systems (optical and acoustic) must be validated using data collected on the ground or in the water when they are first introduced to ensure that the systems are providing accurate and usable results. Once a track record of data collection has been established, these systems will require only periodic calibration. Typical validation procedures require human observers and other

techniques to verify the operational accuracy and precision of the equipment, and to assist with detailed identification and classification of at-risk animals. For many early stage tidal turbine deployments, observers have played a key role, often supplying the bulk of available data.

Field and laboratory experiments have been designed to inform field studies and monitoring program results of animal interactions with turbines, and to better understand the associated near-field behaviors and consequences of such interactions. Experimentation that exposes marine animals to tidal turbines provides valuable information about the level of physical harm that an animal may experience in the vicinity of a hydrokinetic turbine, including the rate of survival of those that pass through the turbine. To date, all of these experiments have been carried out on fish. These laboratory experiments and field trials must be scrutinized to identify the limitations and departures from real tidal energy site conditions that may affect the applicability of the results. In general, only fish and certain invertebrates can be used for laboratory experiments, because regulatory prohibitions and public opinion prohibit the experimentation with higher life forms. Extrapolating the results of experiments of fish encounters in tanks or flumes to behaviors and encounters with tidal turbines, as well as extrapolating the results to other animals, remains challenging.

Hydrodynamic models of water movement near tidal turbines, the effect of water flow around the turbines, and models of animal movement can provide valuable insights into how the animals may encounter a turbine and the range of potential outcomes of the encounter. These models can be developed from relationships between physical and biological factors, such as water flow, temperature and salinity, tidal range, animal population size, and animal movements to create a virtual world of animals and tidal turbines. Numerical models allow for many trials, building a statistically robust set of probabilities of encounters, and they can be used to direct field data collection efforts at low cost. However, numerical models are only simulations of what may occur, based on physical and biological principles; validation of the models with data from field observations is critical to ensure that the model predictions are realistic. Collecting an adequate amount of data for the creation and calibration of these models can be very difficult and is often the limiting factor in creating an accurate model. In addition to the numerical models of interactions between marine mammals, sea turtles, and diving birds with tidal turbines, key behavior and population data measurements are needed to develop robust models for these animals.

OBSERVATIONS OF MARINE ANIMALS INTERACTING WITH TIDAL TURBINES

Direct observations of marine animals interacting with turbine blades are restricted to locations where deployments of tidal devices have occurred; to date these have consisted of small-scale devices and/or single devices, most often for relatively short periods of time, in comparison with commercial-scale development. By examining the results of visual or acoustic observations of fish (and in one case, birds) in the vicinity of these small and short-term deployments, researchers hope to expand the knowledge of how these devices may affect marine animals. These results will be used to inform and support planning of effective and efficient monitoring studies for larger and longer-term deployments in the future. Observations of marine mammals in the vicinity of a tidal turbine also provide valuable insights into the animals' behavior. Each of the following project summaries provides information about interactions of animals with turbine blades. Each project is briefly described to set the stage for interpreting the results; the key marine animals of concern are listed and results of direct observations of animals interacting with the turbines are presented. Citations for each project are provided to allow the reader to delve into additional details of the marine energy project design, monitoring activities, and where appropriate, mitigation strategies. Observations from these projects, coupled with experimental data from laboratory and flume studies, and outputs from predictive models, are used to

analyze the state of the knowledge of animal interactions with turbine blades, and to identify key gaps in information that, if filled, would enhance understanding of these key environmental interactions.

Evidence Pertaining to the Effects of Turbine Blades on Marine Mammals

The following sections describe tidal projects where the effects of the presence of and interaction between tidal turbine blades and marine mammals have been measured and/or observed. Laboratory studies and modeling efforts are discussed in later sections.

SEAGEN OBSERVATIONS OF MARINE MAMMALS IN STRANGFORD LOUGH, NORTHERN IRELAND

Marine Current Turbine's SeaGen is a tidal energy device consisting of two 16-m open-bladed rotors attached to a pile in the seabed in 26.2 m of water; its surface expression includes a turret supporting an observation platform. The rotor blades can be raised and lowered for maintenance and can be feathered to slow or stop rotation. The deployment site is in the center channel of the Narrows in Strangford Lough, Northern Ireland, where tidal currents reach up to 4.8 m/s. The presence of harbor seals (*Phoca vitulina*), grey seals (*Halichoerus grypus*), harbor porpoises (*Phocoena phocoena*), and otters, as well as the diverse array of habitats, has led to the designation of Strangford Lough as a conservation site under international, European Union (EU), and national legislation. In an effort to eliminate strike risk to seals during operation of the SeaGen turbine, the turbine was shut down during daylight hours when seals swam within 50 m of the turbine and after dark. The distances and protocols triggering shutdown changed over the life of the project. Initially, shutdown was triggered manually when the marine mammal observer located a seal within 200 m of the turbine. The role of the marine mammal observers was augmented and later replaced by a sonar unit mounted on the pile. Later iterations allowed seals to approach within 30 m before shutdown. Shutdown was always triggered manually whether initiated by a direct observation or alerted by a sonar unit. At the start of the project, the turbines were shut down on average three times per 24 hours of operation; later in the project shutdown occurred less than once per 24 hours of operation. Shutdowns occurred more frequently on the ebb tide than the flood tide. Detailed information about the methods and results of the SeaGen monitoring program are provided by Keenan et al. (2011).

The purpose of the SeaGen deployment in Strangford Lough was to test the efficiency and survivability of the gear and to determine its potential interactions with the environment.

Monitoring at the project site was led by Royal Haskoning and was designed to measure the following environmental effects caused by the presence of the tidal device:

- presence of harbor and grey seals near the tidal blades, based on observations made by marine mammal observers and sonar (active acoustics)
- blade strikes on marine mammals, based on post mortem evaluations of any stranded marine mammal carcasses

- a barrier effect and/or displacement of marine mammals (common/harbor seals, harbor porpoises, and grey seals) from Strangford Lough and seal haulout sites (locations out of the water where seals or other animals rest) from the tidal device, based on visual observations made by marine mammal observers, observations from boat surveys and aerial surveys, Timing Porpoise Detector (TPOD) acoustic monitoring for harbor porpoises, and tracking of tagged seals
- the effect of the noise from the tidal turbine on seal behavior, based on visual observations made by marine mammal observers and sonar (active acoustics), correlated with the acoustic output of the turbine measured by hydrophone (passive acoustics)
- changes in relative abundance of seals in Strangford Lough, based on visual observations made by marine mammal observers, observations from boat surveys and aerial surveys, TPOD acoustic monitoring, and tracking of tagged seals; overall population changes were measured by comparing historical data to aerial survey and seal telemetry data
- changes in the populations of seabirds in Strangford Lough, based on shore-based and boat-based seabird observations
- changes in the benthic community and habitats in the vicinity of the tidal turbines, from grab samples of the bottom habitat, and microscopic counts of benthos to determine species diversity and species abundance.

Baseline conditions and pre-installation environmental monitoring began approximately four years prior to turbine installation. After installation, three years of monitoring was carried out, including aerial and shore-based surveys of marine mammals and seabirds by marine mammal observers; aerial, satellite, and boat surveys to follow telemetry data from tags placed on selected individual seals; passive acoustic monitoring for harbor porpoise clicks using TPODs deployed in the Lough; and monitoring of underwater turbine noise from a device mounted on the pile holding the turbine. The presence and movement of marine mammals when the turbine was operating and when it was still were correlated with the rotational speed and acoustic output of the turbine to determine the effect of the turbine operation on the animals.

The turbine shutdown procedures did not allow for observations of direct interactions of the animals with turbine blades, and post mortem evaluation of all recorded marine mammal carcasses did not reveal any evidence of fatal strike to a marine mammal by the SeaGen device. However, the monitoring program was also designed to document effects outside the immediate vicinity of the blades, and it showed no major impacts on marine mammals, birds, or benthic habitat from the tidal turbine. Harbor seals and porpoises were seen to swim freely in and out of the Lough while the turbine was operating and they were not excluded from the waterbody, a phenomenon commonly known as the barrier effect. Similarly, no significant displacement of seals or porpoises was observed, although the marine mammals appeared to avoid the center of the channel when the turbine was operating. Harbor porpoises were temporarily displaced from the Narrows during construction, but other areas around the project site maintained baseline abundance, and porpoises returned to normal baseline in the Narrows once construction was complete. SeaGen did not cause a significant change in the use of harbor seal haulout sites. Harbor seals exhibited some redistribution on a small scale (a few hundred meters) during turbine operation. Seal telemetry data showed that seals transited farther away from the center of the Narrows after SeaGen installation. Seabirds were also seen to avoid the immediate vicinity of the turbine, but no changes in overall bird populations occurred, nor did the device displace foraging birds from important feeding areas.

Information about the SeaGen project can be found in the *Tethys* database at <http://tethys.pnnl.gov/publications/seagen-environmental-monitoring-programme>.

OBSERVATIONS OF FISH AROUND A TIDAL TURBINE IN COBSCOOK BAY, MAINE, USA

Ocean Renewable Power Company's (ORPC) Cobscook Bay Tidal Energy Project (CBTEP) is planned as a commercial installation of three cross-axis turbine generator units (TGUs) in 26 m of water in Cobscook Bay in coastal Maine, USA. Average current speeds at the test site are around 1.0 m/s; maximum current speeds reach 2.0 m/s. Phase I of the CBTEP, a single TGU, began commercial operation in September 2012. Two years prior to installation, a demonstration TGU was fixed on a barge (17 x 7 m) that allowed the turbine to be lowered into the water for testing. Eight species of fish, sea turtles, and marine mammals (two fish, two reptiles, and four mammals) that are known to frequent the bay are protected under the federal *Endangered Species Act of 1973*.

The purpose of operating the barge-mounted turbine in Cobscook Bay was to test the turbine and to acquire environmental data that would help guide the permitting process and future modifications of the turbine. A team, led by the University of Maine, conducted monitoring to classify fish behaviors in reaction to the turbine in a natural environment, quantify the observed behaviors, and assess the effects of time of day (day or night), fish size, and turbine movement (still or rotating) on fish behavior. Two acoustic (Dual-Frequency Identification Sonar [DIDSON]) cameras were mounted fore and aft of the turbine, angled to observe a cross section of the device and support structure, and data were collected over a 24-hour period. Fish behavior was classified into categories for analysis. Reaction distance—the distance between the fish and the turbine at which fish were seen to actively alter course to avoid the turbine—was recorded for all fish that exhibited avoidance behavior. Researchers analyzed the effect of time of day (day/night), fish size, and current speed on the proportion of fish interacting with the turbine and the type of interaction observed (Viehman 2012).

Researchers also established the baseline abundance and distribution of fish species in the bay and documented changes in benthic habitat and benthic communities in the vicinity of the turbine. Because there are few population estimates of fish species in the bay, the researchers surveyed fish using a series of trawls, nets, and traps to establish a baseline against which future changes following commercial tidal turbine deployment might be measured. The methods used in the study were not designed to detect the direct interaction of fish with the turbine, including blade strike. Fish captures and sizes obtained in this study indicate that those in the DIDSON footage that were classified as “small” were likely to be stickleback and juvenile herring, and “medium” and “large” fish were likely to be older herring and mackerel.

It was clear from the acoustic camera data that fish did not entirely avoid the area occupied by the turbine and barge; they regularly approached it closely. Results from the study showed that a higher proportion of fish interacted with the turbine when it was still than when it was rotating and that during these interactions the predominant behavior was fish entering the turbine. The study was not able to discover the disposition of the fish that passed through the turbine, although there were no incidences of dead or dying fish recorded after passage through the operating turbine. Visibility may be an important factor in determining fish behavior around the turbine: at night, the reaction distance of fish was shorter, more medium- and large-sized fish interacted with the turbine, and the behavior of small- and medium-sized fish shifted from avoiding to entering the turbine.

Most of the fish detected by the cameras were already located above or below the turbine when they entered the field of view, which may indicate that they were able to detect the turbine prior to the

distance 2.5 m upstream of the turbine captured by the DIDSON cameras. Large fish (older herring, mackerel) appeared to have a greater ability to avoid the turbine than small- and medium-sized fish (sticklebacks and juvenile herring). Interestingly, schooling fish also appeared to be better able to detect and avoid the turbine than individual fish. Observed fish were almost always present in the wake of the turbine when the current was strong enough to generate a wake (regardless of the turbine rotating or still), with greater numbers observed in the wake than observed entering the turbine. This may indicate a preference for lower-energy regions of the water column, such as those caused by the presence of the turbine. Large fish appeared to have a greater ability to avoid the turbine than small- and medium-sized fish (sticklebacks and juvenile herring). Interestingly, schooling fish also appeared to be better able to detect and avoid the turbine than individual fish.

In August 2012, the ORPC deployed an environmental monitoring system mounted on an underwater tower. The system is composed of a Simrad EK60 split-beam transducer to monitor environmental interaction near the TGU. The marine life interaction system provides three-dimensional (3D) position monitoring of acoustic targets (representative of fish or other marine life) that can be tracked using a differential global positioning system and heading, pitch, and roll (HPR) sensors as they approach the TGU. The advantages of the proposed tower-mounted monitoring system include the potential for uninterrupted data collection, automated analysis of the data, the ability to view a large sample area, and the use of a hard-wired system that does not use batteries or require retrieval of data-loggers.

The ORPC started recording marine life interactions with the operating turbine in early September 2012. Processed fish tracks and schools will be geo-located to position the fish and their direction of movement relative to the TGU. Data are collected as fish (or other marine life as evidenced by large acoustic targets) enter and exit the turbine zone, depending on the tidal cycle. Fish tracks and schools will be analyzed to provide the percentage of fish moving through, over, under, and beside the TGU sorted by TGU operation state, tidal and diel cycles. The data can also be separated by estimated target strength (roughly equivalent to fish size) and seasonal trends. While no available technology has been proven for in situ application to sample the direct interaction of fish and other marine life, analysis of the acoustic sonar data over time should demonstrate whether fish (and other marine life) are avoiding the TGU by moving around it or through it (based on the position and trajectory of the target) and should demonstrate the swimming behavior of fish on the downstream side of the TGU.

Many of the results and conclusions from this project are supported by the scientific literature on fish behavior under different conditions and during interactions with various structures. It was not possible in this project to determine whether fish that entered the turbine were struck by the blades. However, the researchers suggested that it would be useful to combine field results such as these with laboratory studies investigating strike injuries and mortalities to gain a better understanding of the outcomes of fish interactions with turbines, particularly at high current speeds that can make field observations difficult.

Information about the Cobscook Bay project can be found in the *Tethys* database at <http://tethys.pnnl.gov/annex-iv-sites/cobscook-bay-tidal-energy-project>.

FISH PASSAGE THROUGH A HYDROKINETIC RIVER TURBINE ON THE MISSISSIPPI RIVER, USA

In 2008, the City of Hastings, Minnesota, USA, installed a test Hydro Green Energy (HGE) turbine on a barge in the tailrace of an existing hydroelectric dam on the Mississippi River. The purpose of the

deployment was to test the gear and to determine the potential effects that the turbine might have on fish. Many species of fish have been documented in the section of the river below the dam, including walleye (*Sander vitreus*), sauger (*Sander Canadensis*), smallmouth (*Micropterus dolomieu*) and white bass (*Morone chrysops*), bluegill (*Lepomis macrochirus*), crappie (*Pomoxis anularis*), northern pike (*Esox lucius*), and catfish (*Ictalurus punctatus*). Based on entrainment of fish in the hydropower turbines, studies were undertaken to determine the survival rates of fish passing through the HGE turbine. Fish that survived the turbine passage were also evaluated for visible injuries, loss of equilibrium, and scale loss. Detailed information about the methods and results of the HGE monitoring program are reported by Normandeau Associates (2009).

Normandeau and Associates (2009) introduced surrogate freshwater fish of two sizes directly into the turbine and retrieved them downstream after they passed through the turbine. The test fish included yellow perch (*Perca flavescens*), bluegill, catfish, smallmouth buffalo (*Ictiobus bubalus*), and bigmouth buffalo (*Ictiobus niger*). The fish were outfitted with radio-frequency tags and balloon tags that inflated after passage through the turbine, allowing the researchers to net the fish at the surface. The fish were assessed for mortality and injury immediately after retrieval, held, and re-examined after 48 hours. Survival for the small (115–235 mm length) and large (388–710 mm length) fish was greater than 99% after 48 hours. Of the test fish, only one yellow perch was observed to sustain injury, possibly because the balloon tag caused the fish to be dragged into the chain drive of the turbine.

Information about the HGE project can be found in the *Tethys* database at <http://tethys.pnnl.gov/publications/estimation-survival-and-injury-fish-passed-through-hydro-green-energy-hydrokinetic>.

VIDEO OBSERVATIONS OF FISH AROUND A TIDAL TURBINE AT THE EUROPEAN MARINE ENERGY CENTER, SCOTLAND

OpenHydro has deployed a series of 6-m open-center tidal turbines sequentially on a research frame and grid connected at the EMEC since 2006. The water depth at the EMEC tidal test site in Fall of Warness (Orkney) is less than 20 m. A second non grid-connected turbine was placed on the seabed nearby with a video camera trained on the surface of the turbine. More information about the OpenHydro deployment at the EMEC is provided by Polagye et al. (2011).

The purpose of the OpenHydro deployments at the EMEC was to test the gear for efficiency and survivability, provide detailed feedback to improve engineering design for each subsequent turbine, and gain understanding of the potential environmental effects of the turbine's presence and operation. Investigations of marine animals interacting with the tidal turbines has been focused on video footage taken at the face of the pile-mounted turbine, supplemented by observations of marine mammals and seabirds from land-based observers using binoculars and spotter scopes. The shallow depth of deployment of the pile-mounted turbine and the clear water of the EMEC tidal test site allow for video observation of animal interaction with the turbine using surface light, avoiding the use of artificial light that can affect animal behavior. No video was collected at night. Many hundreds of hours of video footage have been collected at the face of the OpenHydro turbines. Researchers have viewed well over 100 hours of footage (S. Barr personal communication 2009). Based on the video that has been sampled, no marine mammals have been observed interacting with the turbines, but seals, porpoises, and small whales are frequently observed transiting through the region around the turbine. Fish, primarily pollock, began to visit the lee side of the turbine after the first year to graze on vegetation attached to the structure while the blades were not moving. As tidal currents picked up and the

turbine began to rotate, the fish appeared to leave the area. In the video analysis to date, no fish have been observed swimming through the turbine while the turbine is rotating and no fish strike mortality has been observed.

Information about the OpenHydro project can be found in the *Tethys* database at <http://tethys.pnnl.gov/annex-iv-sites/openhydro-emec-project>.

ACOUSTIC MEASUREMENTS OF FISH AND BIRDS AROUND TIDAL TURBINES, NEW YORK, USA

Verdant Power deployed six tidal turbines in 10 m of water in the East River of New York as a demonstration for the Roosevelt Island Tidal Energy (RITE) project. The Verdant turbines are three-bladed unducted turbines mounted on the seabed. More information about the RITE island deployment can be found at <http://www.theriteproject.com/Documents.html>.

The purpose of the Verdant deployment was to test the tidal devices and foundations and to determine the potential effects of the turbine presence and operation on migratory fish, including endangered sturgeon and the commercially important striped bass (*Morone saxatilis*), and seabirds. Verdant used many methods to determine the presence, abundance, and behavior of fish and other animals (e.g., birds, marine mammals) in the project area, including a stationary array of 24 acoustic cameras (split-beam transducers [SBTs]), mobile SBT transect surveys, DIDSON systems, and vessel- and shore-based observations of bird activity. Beginning in 2005, baseline information was collected prior to deployment to inform a pre- and post-installation comparison designed to determine the effects of turbine presence on fish activity in the project area. In the course of the demonstration project, Verdant developed a useful method for making direct observations of fish around an operating turbine by combining two acoustic cameras, dubbed a Vessel-mounted Aimable Monitoring System (VAMS). The VAMS was deployed during three 15–17 hour periods in the fall of 2008 and used both a downward-looking SBT and a DIDSON system oriented towards a turbine to observe fish movement and behavior.

Results showed that resident and migratory fish avoided the areas in which the turbines were located and tended to prefer inshore, slower moving waters; the data indicated that fish behavior appeared to be primarily influenced by the natural tidal currents and secondarily by the presence of the operating turbines. Fish were not present while turbines were operating, when the flow velocity increased to greater than 0.8 m/s, compared to typical turbine cut-in velocities of 0.7 to 1.0 m/s. However, limited observations showed fish passing by the rotating turbines following the hydrodynamics of the system. These data indicated that fish were able to detect and successfully pass around the operating turbines. Observers did not see a change in bird abundance or behavior around the project area.

Information about the Verdant RITE project can be found in the *Tethys* database at <http://tethys.pnnl.gov/annex-iv-sites/roosevelt-island-tidal-energy-project>.

Laboratory Experiments

To supplement monitoring of aquatic animals around turbines, laboratory and flume experiments have been devised to develop an understanding of the interaction of aquatic animals in a controlled situation. The Electrical Power Research Institute (EPRI) worked in cooperation with researchers at

Alden Laboratories and the U.S. Geological Survey Conte Laboratory to develop a series of experiments to examine the interaction of fish with turbine blades.

The Alden Laboratory experiments were performed in a flume at approach velocities (or the mean flow velocities) of 1.5 and 2.1 m/s, introducing freshwater rainbow trout (*Oncorhynchus mykiss*) and largemouth bass (*Micropterus salmoides*) juveniles directly in front of an operating turbine to determine injury and survival rates from direct interaction with the turbine and to observe the behavior of fish in the presence of a turbine. Two size classes of experimental fish were used in the experiments: 100–150 mm and 225–275 mm. The fish were introduced within 25 cm of the turbines. Survival and injury were assessed visually and behavior was assessed using video cameras recording the fish under water. Two different turbine designs were used—the Lucid spherical turbine, which is a Darrius-type turbine (four-bladed cross-flow turbine; 45 in. in diameter), and the Welka UPG axial-flow turbine (ducted horizontal-axis turbine; 60 in. in diameter).

The Conte Laboratory used a flow-through river flume with current velocities of up to 3 m/s. These experiments used introduced native Atlantic salmon (*Salmo salar*) smolts and American shad (*Alosa sapidissima*) adults into a vertical axis Encurrent turbine, and examined the fish for survival rate and behavior around the turbine. Survival rate was assessed visually and behavior was assessed using telemetry from tags in the fish and using underwater video.

In the Alden experiments, only small numbers of fish passed through the turbine-swept area, while most fish swam upstream and/or were swept around the turbine. Control fish were introduced into the flume without the turbine to normalize the results. Survival rates for fish passing through the turbines were greater than 98% for all trials (range: 98.4 ± 1.10 to 102.9 ± 2.94) and were generally similar between the experimental and control groups. Few injuries were seen in the experimental fish and most of them were attributed to handling rather than to passage through the turbine-swept area. The video monitoring was not very successful in clearly capturing the active behavior of the fish around the turbines because of the presence of entrained air bubbles and other technical difficulties.

The Conte results showed no injuries were seen and there were no significant differences between survival and control mortality in both the salmon smolt and shad trials.⁵ The telemetry results showed that salmon smolts appeared to be somewhat attracted to the turbine although the results were not conclusive. The researchers were not able to determine whether the American shad were attracted to or avoided the turbine. Similar challenges with the use of underwater video hampered results of behavioral analysis, further exacerbated by turbid water in the river flume.

A theoretical model was adapted from predicting strike probability and mortality of fish passing through conventional hydropower turbines, in coordination with the laboratory studies. The model predicted mortality based on the rotational speed of the turbine and fish length; fish behavior associated with avoiding or being attracted to the turbine was not accounted for in the model. Observations of fish in the flume indicate that the fish had some ability to avoid the turbine. Without accounting for this behavioral response, the model output overestimates the direct interactions of the fish with the turbine, leading to an overestimate of the potential effects of fish interaction with the turbine. In particular, the model estimates of fish passing through the Lucid turbine overestimated mortality compared with the experimental results, because fish actively avoided the turbine.

⁵ Because of sample size, the experiment did not have the ability to detect differences in mortality smaller than 5%.

Information about the EPRI studies can be found in the *Tethys* database at <http://tethys.pnnl.gov/publications/evaluation-fish-injury-and-mortality-associated-hydrokinetic-turbines> and in the report by Amaral et al. (2011), available at <http://tethys.pnnl.gov/publications/evaluation-fish-injury-and-mortality-associated-hydrokinetic-turbines>.

Modeling Encounters Between Animals and Hydrokinetic Turbines

Few data available from field or laboratory observations can be used to inform the understanding of risk to animals from encounters with tidal turbines, because there have been few deployments where fish have been observed and laboratory experiments to observe fish interactions have not been successful. In the absence of such data, the risk to animals from encounters with turbines may be estimated through modeling exercises. Most common numerical models are used to determine the probability aspect of risk; models that explore the probability of encounters between animals and hydrokinetic turbines can be informed by models of collision of fish with hydropower turbines and by predator-prey encounter models. Alternatively, the consequence aspect of risk can be informed by modeling the severity of encounters of animals with turbine blades. Conceptual models of encounters that are parameterized as individual-based models are most common; physics-based models are less common. Several examples have been developed for encounters of fish and marine mammals, but few of the models have been validated with laboratory or field data to date.

MODELING STRIKE AND ITS CONSEQUENCES

As hydrokinetic turbines are placed in rivers and estuaries, there is an increasing possibility for fish and other aquatic organisms to encounter the machines, requiring that we understand the strike potential and consequences of these interactions. Researchers at Oak Ridge National Laboratory (ORNL, USA) have developed a geometric-area model to explain the encounter rates and consequences of interactions for fish and other organisms, based on empirical measurements of the cross sections of rivers and estuaries where hydrokinetic turbine placement is proposed (from the FERC database of preliminary permits) and the likely spatial distribution of fish and invertebrate species in those waters. The model estimates the probability and consequence of fish and other organisms encountering hydrokinetic turbines and does not account for the ability of fish to avoid turbines.

Preliminary model results suggest that the probability and severity of strike are dependent on the placement of the turbines in the water column; the specific structure and swept area of the device and associated installation structures, including the number of blades on the turbine; operational parameters of the turbine including RPM; the flow velocity of the river; and the turbidity that may impair visual avoidance capabilities of the organisms. The specific fish and invertebrate species at risk will vary by location and waterbody, as well as by the placement and operational features of the turbine.

The model has not been validated with experimental or field data, although the researchers hope to carry out laboratory experiments over the next year.

More information about the ORNL modeling project is provided by Schweizer et al. (2011), available at <http://tethys.pnnl.gov/publications/estimation-risks-collision-or-strike-freshwater-aquatic-organisms-resulting-operation>.

FISH AND HARBOR PORPOISE ENCOUNTER MODEL

Models for marine organism encounters with tidal turbines can be developed using the premise that drives predator-prey encounter models. Researchers at the Scottish Association for Marine Science (SAMS) developed a model of collision risk for fish, diving birds, and harbor porpoises, based on a classic 3D ecological predator-prey encounter model, as adapted for encounters that result in predation by a medusa on small fish. The model is dependent on variables that include the swept area of the turbine, the velocity of the blades and the animals' swimming speeds, and the density of animals. The model was developed to estimate encounters between both herring and harbor porpoise and a hypothetical array of 100 tidal turbines off the coast of Scotland. More information about the SAMS modeling project is provided by Wilson et al. (2007).

The SAMS researchers recognized that the model made assumptions that are unlikely to be valid in the oceans; i.e., herring and harbor porpoise being evenly distributed throughout their range, the animals could not engage in evasive behavior, and the particular turbine design and depth of deployment will not affect the outcome.

The model predicted that, for the 100-turbine array, 2% of Scotland's herring population would encounter a turbine each year, and that 13 harbor porpoises would encounter each turbine every year (or 1300 encounters per year), which represents more than 10% of the harbor porpoise population. The higher turbine encounter rates for porpoise over herring are considered to be related to the animals' faster swimming speeds.

The encounter model is likely to produce an overestimate of the risk to the animals. The SAMS researchers stress the need to validate the model with field data, and that encounters with a turbine do not necessarily indicate that the animals will be struck by a rotating blade.

Information about the SAMS modeling project can be found in the *Tethys* database at <http://tethys.pnnl.gov/publications/collision-risk-between-marine-renewable-energy-devices-and-mammals-fish-and-diving>.

ESTIMATING THE CONSEQUENCES OF AN ENCOUNTER WITH A TIDAL TURBINE

Models that estimate encounters between animals and turbines generally assume that if an encounter takes place, the consequences will be severe, resulting in injury or death of the animal. In response to a specific concern about the potential severity of encounters between an endangered small whale and a tidal turbine in Puget Sound, Washington, USA, researchers at PNNL and Sandia National Laboratories (SNL) undertook an analysis of the severity of strike on the head region of a Southern Resident Killer Whale (*Orcinus orca*) by an open-center OpenHydro turbine. The researchers evaluated the most severe scenario of a large adult whale swimming towards the turbine and placing its head between the turbine blades. SNL researchers modeled the forces (stress and strain) that would be exerted on the head region of the whale, based on the technical specifications from OpenHydro, and PNNL researchers estimated the consequence of those forces on the skin and underlying tissues of whale, using surrogate materials for the whale tissue. More information about the PNNL/SNL analysis is provided by Carlson et al. (2012).

The PNNL and SNL researchers stressed that the analysis neither accounted for many aspects of the whale's behavior, nor provided detailed information about the strengths of specific whale tissues. This analysis may not be generally applicable to encounters between other species of animals and other turbine designs. Follow-on work is being done to refine the analysis and to examine interactions of other marine mammals with other turbine designs.

The outcome of the analysis showed that the encounter would almost certainly not be fatal, immediately or over time. The study assumed that scenarios for more severe injury such as damaging the jawbone of the whale and breaking the skin were unlikely and were not included in the analysis.

Information about the PNNL/SNL analysis can be found in the *Tethys* database at <http://tethys.pnnl.gov/publications/assessment-strike-adult-killer-whales-openhydro-tidal-turbine-blade>.

Discussion and Identification of Data Gaps

As tidal turbines are introduced into marine waters, the first concern often raised by stakeholders and regulators is the risk of encounters of marine animals with rotating tidal blades; there are few analogues that inform the interaction of marine mammals, sea turtles, diving birds, and fish with rotating turbine blades. Conclusive information about the risks will only be gained from many years of data collection and observations of species around operating turbines. As that body of monitoring evidence is built, indications of potential strike, entrainment, and changes in behavior may be gleaned from the available in situ studies, laboratory experiments, modeling outputs, and the opinions of experts in the field of marine animal behavior.

As initial studies provide insight into animal interactions with turbine blades, the next steps will be to understand how these interactions may change with the deployment of multi-device arrays, as well as the interactive influences of multiple arrays in a waterbody.

DIRECT INTERACTIONS WITH TURBINES

At the time of this analysis, the limited information available provided no evidence that direct interaction of marine mammals, birds, or fish with tidal turbine blades was causing harm to the animals. The information collected and analyzed for this case study takes an important first step in better understanding the interactions between marine animals and turbine blade strike; however considerably more information is needed to determine that the risk is negligibly small. Five small, short-term current deployments have provided information from project development sites: SeaGen in Strangford Lough (Northern Ireland); ORPC's TGU demonstration deployment in Cobscook Bay (USA); Verdant turbines in New York (USA); the HGE turbine in Minnesota (USA); and the OpenHydro turbine at the EMEC (Scotland).

The SeaGen project provides limited information about the direct effects of marine mammal encounters with turbine blades because the turbines were initially shut down when seals were detected within 200 m of the devices. Although the shutdown distance has been reduced to 30 m and this particular mitigation has been successful in protecting the species under special conservation, the animals never had the opportunity to interact with the turbines while they were operating, thereby

implying that it is unclear whether they were at risk. The ORPC tidal demonstration project provides important information about fish interactions with horizontal turbines; over the short periods of observation, no fish strike was observed. The Verdant RITE project detected no direct interactions with fish or diving birds, but the short deployment time and limited scope of the acoustic measurements cannot definitively rule out the occurrence of direct interactions. Interaction experiments around the HGE turbine indicated that sizable fish passing through the turbine were not harmed. Video footage of fish interacting with the face of the OpenHydro turbine at the EMEC provides no indication that there will be deleterious effects on the fish because they were seen to move away from the turbine when the cut-in speed of the tidal current was reached. There is little reason for fish or other animals to remain in high-speed tidal currents because the bioenergetics cost of maintaining their position is high (Forward et al. 1999; Arnold et al. 1994; Webb 1994; McCleave and Kleckner 1982). However, it is important to note that fish commonly use tidal currents to assist with transiting an area; the very high-energy tidal races where energy production is preferred present a bioenergetics challenge that will not encourage fish or other animals to remain in these areas unless they have a specific reason to do so. This natural aversion to being in the vicinity of operating turbines may act as a natural deterrent to being harmed.

Laboratory data from the EPRI/Alden/Conte Laboratory studies support the HGE outcome; almost no mortality or significant injury to fish was introduced in the immediate vicinity of a turbine. Modeling studies are inconclusive: the SAMS study looking at herring and harbor porpoise over a large (100-turbine) array indicates the potential for significant encounters, but the severity of these encounters is not known. The ORNL model provides an estimate of risk to fish from turbines but does not consider the ability of the fish to change course to avoid the machines. For each of these models, the assumptions used to develop the models are likely to result in overly conservative estimations of potential encounters, including most notably that the animals are evenly distributed over space and that the animals will engage in little or no evasive behavior in the presence of the turbines. Very few fish-encounter models have been validated with field data including direct observations of animals in close proximity to tidal turbines. Until these models are validated with the appropriate data, their predictive power is limited.

INDIRECT INTERACTIONS WITH TURBINES

Indirect interactions between marine animals and turbines may include attraction to or avoidance of the turbines; these interactions are unlikely to prove acutely lethal but may have greater long-term effects on populations and ecosystems. Attraction of animals to turbines could result in increased risk of direct effects (strike, entrainment) or could sufficiently change the behavior of animals such that they may be less successful in feeding, mating, and reproducing. It is also possible that the noise generated by the turbines may keep marine mammals at a greater distance unless their curiosity overcomes their caution. The SeaGen experience in Strangford Lough indicates that marine mammals (seals and porpoises) tend to avoid the area where strong tidal currents allow the device to operate. Anecdotally, there are also concerns that attraction to a device might expose members of a depleted population to increased risk of predation. Avoidance of turbines could create a barrier to or displacement from important feeding, resting, migrating, mating, and rearing grounds, or it could change migratory patterns sufficiently that animals may be unable to survive long migrations to vital foraging, mating, and rearing grounds (DOE 2009).

Evidence from project monitoring, laboratory studies, and modeling provides some clues about the behavior of marine animals around limited numbers of tidal devices, but data on whether these patterns persist with larger installations has not been gathered to date. In Strangford Lough, the

presence of one tidal device was not shown to create a barrier to either harbor porpoise or seal passage; these groups readily passed through the Strangford Narrows at all tidal states when the turbine was operating. Similarly, fish were not prevented from passing by the Verdant turbines in the East River of New York. Fish also passed by the ORPC TGU test turbine in Cobscook Bay, and were not seen to move away from the Open Hydro turbine at the EMEC. Evidence of attraction of marine animals to these turbines is also limited: video evidence shows fish preferentially gathering on the lee side of the OpenHydro turbine at the EMEC, and there are indications that fish swam among the rows of turbines in the Verdant RITE project. The seals and harbor porpoises, however, avoided the SeaGen turbine when the blades were moving, preferring to pass through the Strangford Narrows closer to each shore.

To date, the most comprehensive field study in a natural environment of animal behavior in the presence of an operating tidal turbine comes from the acoustic fish studies around the ORPC TGU test unit in Cobscook Bay, Maine. The acoustic cameras clearly show evidence of fish approaching the turbine and a certain proportion turning away from the turbine to swim back towards their origin or to pass above or below the turbine on their original track; few fish (most notably smaller fish) pass through the turbine-swept area. Fish were almost always present in the wake of the device, when it was present. No fish were seen to be struck or suffer damage from passing through the turbine, but the windows of observation were relatively short in comparison to the life of an operating turbine. In addition, the researchers were not able to observe the fish after they left the vicinity of the turbine or to assess any long-term effects of passing through the turbine.

The EPRI/Alden laboratory studies provide some support for the patterns seen in Cobscook Bay: a proportion of the fish sent into the turbine in the Alden Laboratories' flume turned away from the turbine, retreating back upstream or passing by the turbine. It is important to note that the fish in the EPRI/Alden experiment were introduced in close proximity to the turbine, allowing them very limited ability to take evasive action or room to pass around the sides of the turbine. The fish introduced into the turbine for the HGE experiment had virtually no ability to take evasive action.

BEHAVIORAL INTERACTIONS WITH UNDERSEA OBJECTS

Observations of marine animal behaviors in natural habitats and habitats altered by human activities indicate that many species of fish are strongly attracted to objects in the environment and will reef or shoal to gain shelter, food resources, and to find conspecifics and mates (Pickering et al. 1998; Pelc and Fujita 2002; Langhamer et al. 2009). Marine mammals are known to be highly curious and may investigate new objects in their environment (Jefferson et al. 1991). However, marine mammals are also known to be highly intelligent and able to evade danger, unless that danger is more mobile (such as high-speed boat propellers or predators such as other marine mammals or sharks) (Cummings and Thompson 1971; Deecke 2006; Wirsing et al. 2008). Diving birds may be attracted to underwater features that present foraging potential (Grecian et al. 2010). Sea turtles are known to reef around objects in the marine environment (Chaloupka and Limpus 2001).

The sum of behavioral research that is pertinent to interactions between marine animals and tidal turbines allows some extrapolation from the limited monitoring around deployed turbines and supporting laboratory and modeling data.

Fish would appear to be most at risk from tidal turbine blades because many species may preferentially stay in the vicinity of turbines. However, the OpenHydro data support the theory that the bioenergetics of swimming for prolonged periods in strong tidal flows are not advantageous to most

marine animals, even though fish and other marine animals are known to use tidal currents as a means of moving through an area (Polagye et al. 2011; Forward et al. 1999; Arnold et al. 1994; McCleave and Kleckner 1982). The risk to marine mammals from turbines could be somewhat increased by their natural curiosity, but this interaction could be mitigated by their intelligence and the habituation that is likely to take place as more devices are deployed. There is little evidence to determine the risk to diving birds; a recent study in Pentland Firth (Scotland) indicated that some sea birds preferentially forage for fish in fast-moving tidal streams (Pingree et al. 1978; B. Scott personal communication 2012). Until the risk of fish strike from turbines is determined, it is not clear whether birds will be attracted to fish that have been stunned or damaged by tidal turbines, in turn presenting a strike danger to the birds. No information is readily available to determine whether sea turtles are likely to be at risk from tidal turbines, but several species of sea turtle have been known to use fast currents and eddies for transportation and feeding purposes (Luschi et al. 2003) and are known to reef around structures in the ocean (Chaloupka and Limpus 2001).

As additional observations of animals in the vicinity of tidal turbines are documented, behavioral aspects of animal groups may help to interpret and add predictive power to these studies results.

SCALING FROM SMALL DEPLOYMENTS TO COMMERCIAL SCALE

The data on encounters between marine animals and tidal turbines have been collected from deployments of single or small numbers of devices that have been in the water for relatively short periods of time (months to a year or so). While these limited deployments provide insight into animal encounters, the leap to understanding potential interactions of marine animals with large numbers of turbines, operating over years to decades, will require additional effort and investigation. Just as researchers are modeling and measuring physical parameters that define the potential wake interactions and flow changes within an array of tidal turbines, it is essential to model and estimate the risk of encounter of animals and multiple devices within arrays.

Direct measurements of animals and tidal arrays are available from the acoustic data collected around the six-machine Verdant RITE deployment. These measurements indicate that the indigenous fish perceived the array as a collection of separate objects, aligning themselves between the turbines. The short duration of deployment and the small number of turbines suggests, but does not confirm, that at least some fish species are likely to interact at fairly close range with the turbines. Modeling of encounters within arrays is limited to work by SAMS researchers on herring and harbor porpoise, showing the potential for significant encounters over periods of months and years with large tidal arrays. However, the SAMS researchers caution that their model overestimates encounters because it does not allow for avoidance behavior or consider that each encounter may not be injurious or lethal.

Considerations for modeling and estimating encounter rates of marine animals with arrays must take into account the interactions of animals with single devices added to a number of other factors, such as the following:

- potential confusion from the physical presence and acoustic output of multiple devices that may lead to increased risk of strike or entrainment
- possible barrier effects or displacement of animals due to lines or groupings of devices across established migratory or transit routes

- potential for increased predation as prey animals are attracted to individual and multiple devices (reef effect)
- increased noise in the marine environment from multiple devices that may affect marine mammal communication and navigation in critical migratory and feeding areas
- potential additive effects of tidal arrays in areas where anthropogenic factors already stress marine animals.

Until there are arrays of multiple tidal devices deployed with substantial monitoring programs in place, information about the encounters of animals with arrays will depend on modeling efforts.

SIGNIFICANT GAPS IN DATA

Significant gaps in data limit the conclusions that can be reached about the behavior of marine animals in turbulent waters and their interaction with tidal turbine blades. In particular, the lack of observations and measurements of animal movement around tidal turbines of varying designs that are deployed in multiple waterbodies limits the evidence needed to understand and predict how devices might affect animals in new project locations. Each waterbody where tidal energy might be exploited supports a wide variety of animals, including marine mammals, sea turtles, diving birds, and fish; however, lessons can be learned without comprehensive studies being carried out in each location. That being said, until more tidal turbines are deployed around the world, in single deployments and arrays, this body of evidence will not be conclusive.

Specific experiments and deployments will help to move the state of understanding forward. A well-defined program of deployments and data collection that parse the major differences in specific stressors found among commercial tidal turbines, deployed in waters with marine receptors and animal groups that are considered to be at risk and/or commercially and recreationally important, could move the state of knowledge forward. For example, key information could be gleaned by focused observation, using visual and acoustic methods, of the risk afforded by the following:

- open-bladed and ducted tidal turbines
- size of tidal turbine versus deployment depth
- rotational speed of the turbine
- solidity of the turbine
- foundation or anchor structural design and materials
- acoustic signature of the device (as a potential acoustic deterrent)
- associated deterrents such as pingers or noisemakers.

Additional laboratory and flume experiments are needed that place fish in a position to interact with operating turbines, while allowing greater choice of movement and avoidance of the turbine to study their behavior. Experiments with species that are expected to be found in the vicinity of tidal turbines are needed, including marine fish that are known to reef or shoal, thereby elevating their risk by being in the vicinity of an operating turbine.

More complex modeling efforts that explicitly simulate the physics and biological interactions are needed to provide predictive power and insight into the design of laboratory and field experiments,

with a special emphasis on incorporating the behavioral responses of animals near turbines. Validation of these models with laboratory and field data is essential to improve confidence in the predictions.

Multi-turbine arrays coupled with robust monitoring programs need to be deployed to gather information about encounters with animals in order to understand the cumulative and additive effects of commercial-scale tidal energy development.

In conclusion, the limited information available to estimate the effects of interactions between tidal turbine blades and marine animals from single device and short-term deployments does not suggest that major effects should be expected as devices are deployed in coastal waters around the world. However, more evidence must be gathered from a large number and size of projects in geographically diverse locations to define the risk to the range of marine animals likely to be found in the waterbodies in which tidal energy generation is practical. Once the risks are known and appropriate monitoring and mitigation are determined, the extrapolation to multiple device arrays and multiple arrays in a region will continue to require scrutiny.

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CASE STUDY 2 – EFFECTS OF ACOUSTIC OUTPUT FROM TIDAL AND WAVE DEVICES ON MARINE ANIMALS

Introduction

This case study was developed as part of the OES Annex IV. Annex IV seeks to bring together information about the environmental effects of marine energy development from around the world and to assist OES member nations with environmentally responsible acceleration of the marine energy industry. As marine energy development begins to gain momentum internationally, Annex IV case study analyses focused on the early stages of development from single devices to multiple device arrays. Metadata—descriptive information about data—were collected from projects and research studies to form the basis of the input to this case study.

This case study focused on investigating the effect that noise from marine energy devices may have on marine animals. Note the terminology (harmed, threatened, etc.) contained in this case study is used in its ordinary sense, and not in reference to the regulatory definitions used in the *Endangered Species Act of 1973* or *Marine Mammal Protection Act of 1972*.

GOAL AND OBJECTIVES OF THE CASE STUDY

The goal of this case study was to examine existing information about the effects of acoustic output from tidal and wave devices on marine animals from marine energy projects worldwide. Specific objectives included the following:

- Identify tidal and wave projects that have monitoring data on effects of acoustics on marine animals.
- Collect ancillary information from laboratory studies and numerical modeling simulations that inform the understanding of the effects of acoustics from tidal and wave systems on marine animals.
- Evaluate the comparability and applicability of the information from different tidal and wave projects and ancillary studies to determine the effects of acoustics on marine animals.
- Identify key gaps in data and studies that need to be filled to complete the understanding of the effects of noise from marine energy projects on marine animals.

APPROACH

As will become clear in the ensuing sections, information about the noise levels from tidal and wave devices deployed in the marine environment on animals that may be in proximity to the installations was brought together from readily accessible verifiable sources for analysis. Information from

full-scale tidal and wave device deployments was preferred; however, with a limited number of marine energy projects in the water, information about the interactions drawn from small-scale devices, laboratory studies, and indications from numerical models were used to help inform our understanding of potential effects. Each information source was examined to determine how the outcome informs the case study. Information about the acoustic output levels was compared among projects and research studies, common responses of animals to those levels of noise were identified, and likely outcomes of the increased presence of underwater noise from tidal and wave installations were evaluated. Gaps in information that hinder further analysis or interpretation were identified.

SOURCES OF CASE STUDY INFORMATION

The information collected for this case study was derived from metadata collected from project site investigations worldwide and from metadata collected from research studies; these data were entered into the *Tethys* database found at [http://tethys.pnnl.gov/knowledge-base?f\[0\]=field_project%3A3](http://tethys.pnnl.gov/knowledge-base?f[0]=field_project%3A3). Where applicable, the underlying data sources and interpretations from reports and papers were sought for analysis. Certain information was collected from analogous industrial interactions with marine animals, including the sound levels and responses associated with pile driving and with ship propulsion systems.

The use of analogue data to inform the understanding of the effects of noise from tidal and wave installations on marine animals was of somewhat limited use. Percussive sounds from pile driving, such as those associated with installing monopile or jacketed offshore wind turbines, last only throughout the installation stage. However, these sound sources and received levels of sound can be extremely loud and may affect marine mammals, fish, and other marine animals (Deecke 2006; Halvorsen et al. 2012; Madsen et al. 2006; Wang et al. 2007). Although pile driving may be required for the installation of certain tidal devices and anchors for wave energy converters (WECs), in general, installing wider-diameter piles such as those used in the offshore wind and oil and gas industries involves higher source levels than installing the smaller-diameter piles more likely to be associated with wave or tidal devices. For instance, installing a 4-m-diameter pile, such as those used in the offshore wind industry, at 750 m from the pile has an approximate single strike sound exposure level (SEL_{ss}) of 177 dB re $1 \mu Pa^2 \cdot s$, while a 1-m pin-pile for a marine and hydrokinetic (MHK) device may have a SEL_{ss} of 159 dB re $1 \mu Pa^2 \cdot s$ (Matuschek and Betke 2009). The SEL is a measure of acoustic energy and is used to assess the potential for physical damage to animals. The difference in SELs relative to pile diameter is further compounded by differences in installation methods; certain pile-driving methods may emit less sound than others.

Acoustic output from ships and boats varies with the type of vessel, speed of transit, and other factors, including draft of the vessel, and weather conditions. The amplitude of shipping sound is continuous and generally occurs within a particular frequency range. Tidal turbine sound is continuous during high flows although the frequency may vary. Sound from WECs will vary in amplitude and frequency with the characteristics of the waves. The source levels of vessel traffic can vary from 150 dB for smaller vessels such as small commercial fishing boats to 195 dB re $1 \mu Pa$ for larger container ships and tankers (Bassett 2010; Bassett et al. 2010; Scrimger et al. 1990). While the frequency of these sources may vary from <50 kHz to several kilohertz, the frequencies with the highest peak amplitude typically occur below 1000 Hz depending on the vessel type. Vessel size and load influence the acoustic output; different types of ships, including tankers, cargo ships, and passenger ships emit somewhat different sound levels; container ships (and tankers up to 188 dB re $1 \mu Pa @ 1m$) emit the loudest sounds, while bulk carriers and passenger vessels are somewhat quieter (up to 177 dB

re 1 μ Pa@1m). The frequency distribution of broadband noise from commercial shipping is generally within the range of 40 Hz to 100 Hz (McKenna et al. 2012).

USE OF THE CASE STUDY OUTCOMES

The information gathered and analyzed for this case study can help inform regulatory and research investigations of the potential risks to marine animals from the acoustic output of tidal and wave installations. This information may also assist marine energy developers in developing engineering, siting, and operational strategies for tidal and wave projects to minimize the amplitude and/or change the frequency of sound from their devices to mitigate effects on marine animals. Used in conjunction with site-specific knowledge, the case study outcomes may simplify and shorten the time to permit (consent) deployment of single and multiple device arrays. The information brought together for analysis in this case study represents readily available, reliable information about the acoustic output of tidal and wave devices and reactions of marine animals to those sound levels; however, the analysis and conclusions drawn from this case study are not meant to take the place of site-specific analyses and studies, or to direct permitting (consenting) actions or siting considerations in specific locations.

Effects of Underwater Noise on Marine Animals

Specific groups of marine animals are most likely to be affected by acoustic output from tidal and wave devices because of their susceptibility to sound and their potential proximity to marine energy devices (Pelc and Fujita 2002; Cummings and Thompson 1971). Factors that will determine these risks include the following:

- Additional underwater sounds may mask marine animals' hearing and thus their ability to engage in social interaction, locate prey, avoid predators, and navigate hazards because they use underwater sound for scene analysis, (knowledge of their surroundings).
- A tendency for animals to assemble in the vicinity of underwater objects ("reef effect") may place animals at greater risk of exposure to sound from tidal and wave devices and may expose them to the sound over longer periods of time.

Of particular concern are animals that are afforded special legal protection because of their decreased population sizes, the cumulative effects of other environmental factors that threaten population viability, or their heightened importance as a commercial, recreational, or subsistence food source for humans (Polagye et al. 2011b). Examples of this special protection include the *Endangered Species Act of 1973* and *Marine Mammal Protection Act of 1972* in the United States, the *Species at Risk Act* in Canada, or the EU Habitat Directive in Europe.

Distinct steps in measuring and understanding the effects of operational noise from marine energy devices on animals should be followed:

- Accurately measure the underwater noise generated by a tidal turbine or WEC under water close to and at distances moving away from the turbine, taking into account changes in noise generation from turbines and WECs over time, and the level of those sounds above ambient noise.

- Using the information gained from monitoring single energy units (tidal and wave) as inputs into models of multiple marine energy units to determine the potential additive noise levels and to determine propagation losses at the specific site.
- Measure and evaluate the direct and indirect effects that the sound spectra may have on the marine animals of interest.

Each of these classes of measurement is difficult to carry out; there are no purpose-built instruments to measure the sounds from tidal and wave devices and their effects on marine animals, so existing measurement systems must be adapted and engineered. The interpretation of the results (sound levels and their effects on animals) is in the very early stages of development. The properties of underwater sound and systems for measurement around marine energy devices were examined, as were methods for measuring effects on marine animals.

MEASURING UNDERWATER SOUND

Sound waves travel in seawater almost five times as fast as in air, at approximately 1500 m/s. The speed will increase as the temperature or depth of the ocean increases, but these changes are small. Sound intensity decreases in water due to spreading and scattering of the sound waves, and absorption by particles in the water, eventually dissipating at a distance from the sound source. The absorption of sound is proportional to the square of the frequency, so that higher frequencies are absorbed more rapidly than lower frequency sounds. Sound travels (or propagates) much more efficiently through water than does light, explaining why many marine animals use sound rather than light to “see” in the ocean (Garrison 2010).

Sound waves have two components: pressure and particle motion. In the farfield, these two components are related and reported as a constant (Lurton 2010). Marine mammals detect the pressure component of sound waves, while pinnipeds apparently detect particle motion and vibration with their facial vibrissae, in addition to detecting pressure with their ears (Riedman 1989). Depending on the fish species, fish can detect particle motion, pressure, or both components. Understanding the various sensory systems of marine animals and physics of underwater sound guides the reporting and measurement of the appropriate components of sound and ways to protect marine animals.

Measuring underwater sound is a well-developed science, dating back over a century (Rayleigh 1887), with significant investments in the development of instruments and applications by sovereign navies and oceanographic institutes. However, these measurements are seldom made in areas of high flow or significant wave activity. Tidal turbines and wave energy devices are purposely placed in high-energy areas where natural ocean sounds (waves, wind, friction, and movement of bottom sediments, and “pseudo noise” caused by turbulence) are overwhelming. Sorting out the acoustic output of a tidal or wave device from this background, further complicated by noise from shipping and other activities, requires new measurement techniques and the use of more sophisticated sound measurement equipment.

The potential exposure of animals to underwater sound is evaluated using various measurements, always in reference to a specific pressure level, in micropascals (μPa). These measurements include the following:

1. Sound Pressure Level (SPL) is a measure of the effective sound pressure, converted to decibels, expressed in dB re 1 μPa for underwater sound.

2. Root mean squared (rms) is the average amplitude of a wave over a set time duration.
3. Peak SPL (SPL_{peak}) is the maximum amplitude of a sound wave.
4. Peak to Peak SPL ($SPL_{peak-peak}$) is the range from the maximum positive peak to the maximum negative peak.
5. Sound Exposure Level (SEL) is a mathematical calculation used to represent acoustic energy and is a useful measure to assess the potential for physical damage to animals. SEL takes into account both the intensity and the duration of a noise event, and is stated in dB re $1 \mu Pa^2$ -s, for underwater sound.
6. Cumulative SEL (SEL_{cum}) is the total sum of energy over a number of individual impulsive events.
7. Single strike SEL (SEL_{ss}) is the energy in a single impulsive event.

The underwater sound from tidal and wave devices are periodically in sync with the times that the devices are generating power. In general, the sound from these devices is of fairly low amplitude that fluctuates with the tidal state, resulting in a few hours each day during which noise levels could be of higher amplitude. However, most of the time the sound generated will be at a lower level, ranging from 116 to 170 dB SPL at 1 m from the source (Bassett 2011; Polagye et al. 2011a), with most of the energy below 1 kHz. While this range of source levels falls below the Level A Injury Threshold for marine mammals (180 dB re $1 \mu Pa$ rms for cetaceans and 190 dB rms for pinnipeds) set forth by NOAA, it may exceed Level B Disturbance Thresholds for marine mammals (120 dB rms for continuous sounds and 160 dB rms for impulsive sounds). Whereas for fish, NOAA set forth dual regulatory criteria for pile driving signals, which include a SPL_{peak} of 206 dB for a single strike and SEL_{cum} value for fish >2 g of 187 dB re $1 \mu Pa^2$ -s. Hawkins and Popper (2012) suggest that there is no consensus for fish behavioral responses to sound. To determine whether these criteria are met or exceeded for fish, more information about each sound type (turbine noise and pile driving) would be needed.

ANIMALS AT RISK

Many marine animals detect and emit sound to communicate, orient themselves, seek prey, and evade predators—all over a wide range of frequencies and amplitudes depending on the organism. For example, fish can detect infrasonic and low-frequency sounds ranging from 15 Hz to 1 kHz and some can emit sounds below 1 kHz at an amplitude of 120 dB re $1 \mu Pa$ rms (Halvorsen et al. 2011; Gotz et al. 2009). Conversely, marine mammals can hear higher frequency sounds ranging from below 100 Hz up to 180 kHz and emit sounds up to 200 kHz with amplitudes reaching 235 dB re $1 \mu Pa$ rms (Gotz et al. 2009). The diverse auditory capabilities of marine animals make them susceptible to anthropogenic noise, manifesting in a range of physiological and behavioral effects. Animal groups that may be most at risk from underwater noise include marine mammals (particularly cetaceans or whales and dolphins; as well as pinnipeds or seals and sea lions); fish (resident and migratory); diving birds; and potentially sea turtles and certain invertebrates (Wilson et al. 2007; DOE 2009).

As sound propagates through seawater, the energy of sound waves can cause rapid changes in pressure, which can cause a range of effects on marine animals, depending on the amplitude and frequency of the sound. Common effects include diminished animal hearing (either temporarily or permanently), damage to non-auditory tissues such as swim bladders, irregular formation of gas bubbles in fish and marine mammal tissues, and neurotrama (Gotz et al. 2009; Oestman et al. 2009; Halvorsen et al. 2011). Anthropogenic sounds such as those emitted from tidal and wave devices may also cause changes in marine animal behavior, resulting in the animals avoiding the sound source, or in some cases, being attracted to the sound. It is not always apparent why animals react to

underwater sound as they do; behaviorists speculate that the sound can interfere with the animals' sense of predator avoidance, prey detection, and their ability to seek refuge or to find mates. Masking is another source of behavior change, occurring when sound source levels interfere with the detection of biologically relevant signals such as those used for communication, navigation, and locating prey (Clark et al. 2009; Gotz et al. 2009). Changes in attraction or avoidance around turbines and wave devices can best be documented by human observers, by optical or acoustic recording methods such as video or still photography, or by passive and active acoustic (sonar) imaging.

Measurements that are commonly used to describe the physiological effects of sound on aquatic animals are a shift in the threshold at which animals hear sound, either temporary or permanent (the temporary hearing shift being analogous to the after effects of listening to a loud rock music concert); injury from impact of sound waves on tissues and organs; or death. Measuring these effects around operating turbines and wave energy devices is very difficult; these effects are generally measured in the laboratory using specialized equipment.

KEY SOURCES OF INFORMATION ABOUT ACOUSTIC EFFECTS

Direct measurement of the acoustic output of turbines and wave energy devices and the effects the output may have on marine animals are restricted to locations where deployments of devices have occurred; to date deployments have consisted of small-scale devices and/or single devices, most often for relatively short periods of time, in comparison with commercial-scale development.

Data collected from active marine energy sites to evaluate the effects of noise on marine organisms rely on human observers, optical, or acoustic measurements. Observer data are very useful but limited; most marine animals are only visible when they are on the surface, disappearing as they dive. Underwater photography and videography can potentially provide a clear indication of behavior change due to the effects of noise; unfortunately, the fast-flowing water and turbid conditions around tidal turbines and in high wave climates, and the challenges of deploying and maintaining optical equipment in seawater severely limit the number of installations where optical pictures (still photography or videography) can successfully be collected. It is also possible that the noise from devices may keep animals at sufficient distance that their images will not be captured by underwater photos and video equipment. Acoustic detectors, ranging from passive hydrophones to single-beam and multi-beam active acoustic imaging devices, can also provide clear illustrations of animals, although subtle behavioral changes may be hard to detect. This is an area of active research and development, but few acoustic monitoring packages have been deployed to date and the available data are limited. Active acoustic monitoring must be applied with care because some frequencies of particular use for imaging marine animals fall within the hearing range of marine mammals and could change their behavior or cause them harm. For many marine animals, particularly marine mammals and rare species, there are likely to be very few observations of close encounters with tidal turbines or wave devices, which necessitates the review of very large amounts of optical or acoustic data to look for potentially small changes in behavior. Researchers are exploring the possibility of deploying optical or acoustic cameras that are triggered by movement, so that fewer more targeted data might be collected. Examples of these data were examined within this case study. All remote monitoring systems (optical and acoustic) must be validated using data collected on the ground or in the water when they are first introduced to ensure that results are providing accurate and usable results. Once a track record of data collection has been established, these systems will require only periodic calibration. Typical validation procedures require human observers and other techniques to verify the operational accuracy and precision of the equipment, and to assist with detailed identification and

classification of species. For many early stage tidal and wave turbine deployments, observers have played a key role, often supplying the bulk of available data.

There are limited data available from tags and probes adhered to marine animals to gather information about diving rates and depths, acceleration and swimming speeds, and other behavioral information. As these tools are used more broadly, they may prove to be useful in estimating the potential behavioral and physiological effects of noise from marine energy devices on marine animals.

Controlled experiments carried out in the field and/or laboratory have been designed to augment monitoring programs to provide interpretation for the effects of underwater noise on marine animals. Exposure of marine animals to playback of turbine or WEC noise in the laboratory can help determine the effects the sound might have in a real world situation. To date all laboratory acoustic exposure experiments associated with tidal or wave devices have been carried out on fish. The experiments must be scrutinized to identify the limitations and departures from real tidal energy site conditions that may affect the applicability of the results. Extrapolating the physiological or behavioral response of fish exposed to a particular sound level in the laboratory to the effects of the sound from turbine and wave energy device noise in the field must take into account the interaction with moving water and with other species. Interpreting these results is extremely challenging.

Measurements of sound emitted from tidal turbines and wave devices can be modeled to determine the 3D propagating sound field and the time and distance over which sound from a source will be attenuated. Numerical models take into account the bathymetry of the marine energy deployment site, the geomorphology and sediment type (to determine the degree to which sound will be reflected or absorbed), the density the water, and other oceanographic features. Modeling sound fields around tidal turbines and wave energy devices and providing data to validate the models is made challenging by the same features (fast-moving water, high concentrations of particles or bubbles, pseudo-sound from turbulence, etc.) that complicate measurement of the sound in the field. Sound profiles in seawater have been combined with models that simulate the movement of animals that may be at risk, notably for sound originating from pile driving and shipping; to date these models have not been applied to the soundscape around tidal turbines or wave energy devices.

Evidence Pertaining to the Effects of Noise on Marine Animals

The following sections describe tidal and wave projects where underwater noise has been measured and/or the effects of noise from the devices have appeared to affect marine animals. Laboratory studies and modeling efforts follow in later sections.

SEAGEN MEASUREMENT OF ACOUSTIC EFFECTS ON MARINE ANIMALS IN STRANGFORD LOUGH, NORTHERN IRELAND

Marine Current Turbine's SeaGen is a tidal energy device consisting of two 16-m open-bladed rotors, attached to a pile in the seabed in 26.2 m of water; its surface expression includes a turret supporting an observation platform. The pin-pile was drilled into the seabed using standard piling methods. The rotor blades can be raised and lowered for maintenance and can be feathered to slow or stop rotation. The deployment site is in the center channel of the Narrows in Strangford Lough, Northern Ireland,

where tidal currents reach up to 4.8 m/s. Strangford Lough is a conservation area for harbor and grey seals. In an effort to eliminate strike risk to harbor seals during operation of the SeaGen turbine, the turbine was shut down during daylight hours when seals swam within 50 m of the turbine and after dark.

Detailed information about the methods and results of the SeaGen monitoring program is provided by Keenan et al. (2011, available at <http://tethys.pnnl.gov/publications/seagen-environmental-monitoring-programme>).

The purpose of the SeaGen deployment in Strangford Lough was to test the efficiency and survivability of the gear and to determine its potential interactions with the environment. Monitoring at the project site was led by Royal Haskoning and was designed to measure the effect of underwater noise from the turbine on marine mammals. The Sea Mammal Research Unit (SMRU) observed the presence of marine mammals throughout the duration of the project.

Baseline conditions at the project site were established prior to turbine installation. After installation, three years of monitoring were carried out, including aerial and shore-based surveys of marine mammals and seabirds by marine mammal observers; aerial, satellite, and boat surveys to follow telemetry data from tags placed on selected individual seals; passive acoustic monitoring for harbor porpoise clicks using TPODs deployed in the Lough; and monitoring of underwater turbine noise from a device mounted on the pile holding the turbine. The presence and movement of marine mammals were correlated with the rotational speed and acoustic output of the turbine when the turbine was operating and when it was still to determine the effect of the turbine operation on the animals. The turbine shutdown procedures did not allow for observations of direct interactions of the animals approaching the turbine blades at maximum rotation and sound output.

Environmental effects caused by acoustic output from the device were examined, as described below.

Ambient Noise

Understanding the effect of noise from the tidal turbine on marine animals required that the ambient noise of the Lough be determined, from both natural sounds and those from human activities including boating. Using hydrophones placed around Strangford Lough, the research team determined that the SPLs in the Lough, including the region around the turbine, are typical for shallow coastal waters with an average level of 120 dB re 1 μ Pa (range of 115 to 125 dB re 1 μ Pa); information on the frequency range is not available. Elevated noise signatures at higher frequencies (200 Hz to 70 kHz) in Strangford Narrows were measured and have come to be recognized as the sound of tidal flows (Keenan et al. 2011). These levels of sound, particularly the high frequencies measured in the Narrows, are within the hearing range of harbor porpoises, exposing them to levels of sound that have been known to cause behavior changes in some cetaceans (Southall et al. 2007).

Construction Noise

During installation of the pin-piles, sound was measured over a one-day period using underwater hydrophones at 10-m depths from a drifting boat. The boat was allowed to drift away from the drilling operations in order to measure sound from 23 to 2130 m; other sources of sound such as ship engines and electrical equipment were turned off in order to isolate the sound of the pile-driving operation. The results of acoustic measurements during construction ranged from SPLs of 136 dB re 1 μ Pa at 28 m from the pile-driving site to 110 dB re 1 μ Pa at 2130 m; the drilling noise fell to

background noise levels at a distance of 464 m. The drilling operation produced low-frequency sounds (20 to 100 Hz); these levels are comparable to sounds produced by small vessels including tugs and maintenance vessels. Harbor porpoises were temporarily displaced from the Narrows during construction; the cause of the displacement was not known. Other areas around the project site maintained baseline abundance and porpoises returned to the normal baseline in the Narrows once construction was complete.

Operational Noise

Once the turbine was operational, the effect of the turbine noise added to the ambient noise. Seal behavior was measured based on visual observations made by marine mammal observers and by a 300- and 670-kHz Compressed High Intensity Radar Pulse sonar (active acoustics) mounted on a drifting boat, and the sound correlated with the acoustic output of the turbine measured by hydrophones (passive acoustics) also mounted on the drifting vessel. The presence of a barrier effect and/or displacement of marine mammals (common/harbor seals, harbor porpoises, and grey seals) from Strangford Lough and seal haulout sites due to sound from the tidal device was evaluated based on visual observations made by marine mammal observers, observations from boat surveys and aerial surveys; TPOD acoustic monitoring for harbor porpoises; and tracking of tagged seals. Researchers also examined the effects of sound on key commercial fish species, including herring, cod, and dab. Changes in the relative abundance of seals in Strangford Lough were evaluated based on visual observations made by marine mammal observers, from boat surveys and from aerial surveys; TPOD acoustic monitoring; and tracking of tagged seals. Overall changes in seal and harbor porpoise populations were measured by comparing historical data using aerial survey and seal telemetry data. Harbor seals and porpoises were seen to swim freely in and out of the Lough while the turbine was operating and were not excluded from the waterbody. Similarly, no significant displacement of seals or porpoises was observed, although the marine mammals appeared to avoid the center of the channel when the turbine was operating. SeaGen did not cause a significant change in the use of harbor seal haulout sites. Harbor seals exhibited some redistribution on a small scale (250 m) during turbine operation. Seal telemetry data showed that seals transited farther away from the center of the Narrows after SeaGen was installed.

Noise Perceived by Marine Animals

Using a frequency-weighted scale— dB_{ht} (*Species*) suggested by Nedwell et al. (2007)—a perceived anthropogenic noise is weighted (i.e., filtered) with the hearing sensitivity range of a species of interest. A measurement of the noise perceived by a species under water was calculated to estimate the level of sound from the turbine experienced by animals around the SeaGen turbine (Keenan et al. 2011; Nedwell et al. 2007), based on the noise levels measured with hydrophones from the drifting vessel.

During construction, harbor seals were calculated to perceive noise from $59 \text{ dB}_{\text{ht}}$ at 28 m and $30 \text{ dB}_{\text{ht}}$ at 2130 m, from the drilling source. Calculations indicate that the harbor porpoise would cease to perceive the noise from drilling at 300 m from the source. Herring were calculated to perceive the drilling noise as $62 \text{ dB}_{\text{ht}}$ at 28 m and $25 \text{ dB}_{\text{ht}}$ at 2130 m from the source. These perceived levels of sound from pin-pile drilling are generally lower than ambient levels of sound in the Narrows, although the drilling noise may peak above ambient levels periodically. Dab and trout species were calculated to perceive the drilling noise at the higher energy levels while commercially important herring and cod species were likely to perceive the drilling sound levels across the entire range of the sound emitted. Harbor seals were thought to be likely to perceive the higher sound energies from drilling. Some

marine mammal researchers consider a perceived level of 90 dB_{ht} to be an appropriate threshold for strong avoidance behavior due to noise, for the species considered (Nedwell et al. 2007).

Calculations of the perceived noise level for the marine mammals and fish of interest in Strangford Lough indicated that the animals are unlikely to be disturbed at distances more than 115 m from the drilling operation.

Drifting boat-based hydrophones were used to measure the sounds from the operating turbines and to validate underwater sound propagation models to predict how the noise levels would vary with distance from the turbines when the turbines were operating or stationary. The model outputs were compared to data on marine mammal hearing ranges to estimate the zone of auditory influence around the tidal turbine and to predict potential auditory injury, masking of sounds important for marine mammal communication and navigation, and behavioral responses.

Information about the SeaGen project can be found in the *Tethys* database at <http://tethys.pnnl.gov/annex-iv-sites/strangford-lough-mct>.

ACOUSTIC MONITORING AROUND A TIDAL TURBINE IN COBSCOOK BAY, MAINE, USA

Ocean Renewable Power Company's CBTEP is planned as a commercial installation of three cross-axis TGUs in 26 m of water in Cobscook Bay in coastal Maine, USA. Phase I, a single TGU, began commercial operation in September 2012. Two years prior to installation, a demonstration TGU was fixed on a barge that allowed the turbine to be lowered into the water for testing. Eight federally listed threatened or endangered marine species (two fish, two reptiles, and four mammals) may occur in the general project vicinity.

Detailed information about the methods and results of the Cobscook Bay monitoring program can be found at <http://www.orpc.co/content.aspx?p=h3jCHHn6gcg%3d>.

Measuring Sound from a Pilot Turbine Deployment

The purpose of operating the barge-mounted turbine in Cobscook Bay was to test the turbine and acquire environmental data that would help guide the permitting process and future modifications of the turbine. Monitoring carried out by Scientific Solutions, Inc. was performed to demonstrate the measurement of noise in a strong tidal current using drifting hydrophones, establish ambient noise levels in Cobscook Bay prior to turbine deployment, and measure the radiated noise from the barge-mounted TGU, as a measurement of the noise expected from the commercial array of bottom-mounted turbines.

A buoy system was used to suspend two hydrophones to measure underwater sound. A series of experiments were carried out under varying tidal current speeds and a range of operating conditions for the turbine. The buoy was released by a research vessel and recovered some distance downstream in the area where the barge-mounted turbine was normally operated to measure ambient noise. Similarly, the buoy was released upstream once the barge-mounted turbine was in place, and recovered downstream to measure the noise of the turbine. All other sources of noise were suspended in the vicinity of the experiment while the hydrophones were collecting data. Instrumentation mounted on the turbine allowed for correlation of the measured sound with the operating speed of the turbine.

The researchers found that sound from the barge-mounted turbine was less than 100 dB re $\mu\text{Pa}^2/\text{Hz}$ at 10 m from the turbine; at 200 to 500 m, the turbine sound was undetectable above ambient sounds within the bay.

Sound from Pile Driving to Install Turbines

Installation of the Phase 1 TGU in the spring of 2012 in Cobscook Bay required driving pin-piles for the foundation. Acoustic monitoring and mitigation measurements were conducted in accordance with two key drivers: 1) NOAA criteria for peak SPL of 206 dB and 187 dB SEL for potential damage to endangered Atlantic salmon smolt, and 2) an Incidental Harassment Authorization (IHA) issued by NOAA for marine mammal Level A and B harassment. In addition, ORPC conducted in-air acoustic monitoring to provide information at potential bald eagle nesting sites and seal haulout locations.

ORPC's monitoring team measured SPLs and SELs from the installation barge at a distance of 10 m and from a drifting vessel at various distances to determine source level harassment ranges.

The results of hydroacoustic monitoring for impact pile driving and by default, conservatively for vibratory hammer activities indicated SPLs and SELs below NOAA impulsive threshold criteria for Atlantic salmon smolt. For marine mammals, measured Level A and B isopleths ranges were significantly shorter than the conservative calculated ranges included in the IHA. Although birds and harbor seals were sighted in the vicinity of the project area both before and after pile driving, their responses to pile-driving noise were minimal. This included harbor seals, or possibly a single individual harbor seal, that returned to the project site (outside the Level A exclusion zone) on multiple days of pile driving.

Mitigation measures used during pile driving were successful in maintaining acoustic source levels within acceptable ranges and minimizing impacts on the environment. These measures included wood sound-absorption devices installed in the head of the impact hammer and a "soft start" that initiated pile driving at less than 100% energy for both hammer types. In addition, modifications made by the contractor to the physical connection between the pile and the follower alleviated initial acoustic spikes.

Protected Species Observers were successful in recording marine mammal sightings, determining sighting locations and the animal's behavior. However, marine mammals were not observed within or approaching the Level A exclusion zone (initially estimated to be 500 ft). Shutdown or delay procedures, therefore, were not initiated during pile-driving activities.

Information about the Cobscook Bay project can be found in the *Tethys* database at <http://tethys.pnnl.gov/annex-iv-sites/cobscook-bay-tidal-energy-project>.

MEASURING SOUND AROUND TIDAL TURBINES, NEW YORK, USA

Verdant Power deployed six tidal turbines in 10 m of water in the East River of New York as a demonstration for the RITE project. The Verdant turbines are three-bladed unducted turbines mounted on the seabed. The purpose of the Verdant deployment was to test the tidal devices and foundations and to determine potential effects of the turbine presence and operation on migratory fish, including endangered sturgeon and the commercially important striped bass, and seabirds with the turbines. More information about the RITE island deployment can be found at <http://www.theriteproject.com/Documents.html>.

The Verdant team set out to establish the ambient underwater sound signature for the East River and for the array of tidal turbines. At the time the turbine acoustic measurements were made, blades on one of the six turbines were broken and another turbine was failing, resulting in more noise generation than would be expected in normal operating mode. Using underwater hydrophones, transects were made parallel to shore, surrounding the turbine array footprint, before and after the array was deployed, to gather data on the ambient and turbine noise.

Noise from the subway travelling under the East River dominates the ambient noise signature, and is comparable to the sound of the Verdant array (up to 145 dB re 1 μ Pa) measured at a distance of 1 m from the array. Verdant scientists compared the turbine noise to the hearing thresholds of 14 fish species known to be in the area (four species with narrow hearing ranges and 10 species that hear across a broadband range). The fish species hearing thresholds ranged from 20 to 100 dB. For 13 of the fish species, the sound measured from the damaged turbine array did not reach levels known to cause injury in fish.

Information about the Verdant RITE project can be found in the *Tethys* database at <http://tethys.pnnl.gov/annex-iv-sites/roosevelt-island-tidal-energy-project>.

MEASURING SOUND AROUND A 1/7TH-SCALE WAVE ENERGY CONVERTER IN PUGET SOUND, USA

Columbia Power Technologies (CPT) tested its SeaRay 1/7th-scale wave buoy in West Point, Puget Sound near Seattle, Washington, for 14 months, from March 2011 through April 2012. The purpose of the deployment was to test the survivability, tuning, and power potential of the device in a sheltered environment with small waves before progressing to a full-scale deployment in the open ocean. More information about the CPT trials can be found on the company website at <http://www.columbiapwr.com>.

To characterize the acoustic signature of the SeaRay and compare it to the ambient acoustic environment in Puget Sound, researchers from the University of Washington Northwest National Marine Renewable Energy Center (NNMREC) measured the sound signature of the wave device and the surrounding waters. NNMREC researchers conducted a series of experiments using a cabled drifting array of hydrophones at two depths (5 and 15 m) and one autonomous drifter at a 1-m depth, in the vicinity of the wave device. Ships in the area were identified using the Automatic Identification System that records the presence of vessels from an onboard transmitter required for all large commercial shipping in U.S. waters and the ships' acoustic signatures identified from the hydrophone data.

The NNMREC researchers measured ambient levels to be approximately 116 dB, peaking at 132 dB in a frequency band of 20 Hz to 20 kHz when ship traffic was close to the SeaRay deployment site. They were able to acoustically identify the wave device within 500 m when there was no ship traffic in the area; when ships were present, the high ambient noise levels appear to have masked the wave device sound. SPLs for the SeaRay were measured to be 126 dB, which is the equivalent of a tugboat passing at a range of 1.25 km. In addition, the sound from the SeaRay was closely correlated with the wave period.

Information about the 1/7th-scale WEC in Puget Sound can be found in the *Tethys* database at <http://tethys.pnnl.gov/publications/underwater-noise-measurements-1-7-scale-wave-energy-converter>.

MEASURING AND EVALUATING THE ACOUSTIC ENVIRONMENT IN A TIDAL DEPLOYMENT AREA, ADMIRALTY INLET, USA

A major utility in the Puget Sound region is planning to deploy two 6-m OpenHydro tidal turbines in 55 m of water in Admiralty Inlet in 2013. Information being collected prior to deployment includes significant site characterization that will be used to support the permitting (consenting) process. Many species of marine mammals and fish are sensitive to noise that occur in the inlet, including a highly endangered population of orcas (Southern Resident Killer Whales), an endangered diving bird, and several stocks of Pacific salmon. These animals are afforded special protection under U.S. law, leading to the need for extensive evidence that the turbines will not cause the animals harm. More information about the Admiralty Inlet project can be found on the Snohomish Public Utility District website at <http://www.snopud.com/powersupply/tidal.ashx?p=1155>.

University of Washington NNMREC researchers characterized the acoustic environment of Admiralty Inlet and evaluated the potential addition of the noise of two turbines to the location. SMRU researchers evaluated the level of predicted noise from the turbines on marine mammals in the area. An associated laboratory project by PNNL that examines potential effects of the turbine noise on fish is described in the Laboratory Studies section of this case study.

NNMREC researchers used bottom-mounted Acoustic Doppler Current Profilers and hydrophones to determine the tidal current movement and noise at the proposed turbine deployment location. Vessel traffic (commercial ships and a passenger ferry) in the region was tracked using the Automatic Identification System and traffic noise was recorded by hydrophone.

The researchers found that the low-frequency ambient noise (<1000 Hz) in Admiralty Inlet is dominated by vessel traffic and by bedload transport at high frequencies (>1000 Hz), particularly during periods of strong tidal currents. Breaking waves and rain on the surface of the water also contribute to the ambient high-frequency noise, but do not significantly contribute to the ambient noise budget at this location.

To estimate the sound that the turbines are likely to contribute to the environment in Admiralty Inlet, NNMREC researchers used measurements from a 6-m OpenHydro turbine deployed at the EMEC; the results were re-analyzed to estimate the acoustic output in Admiralty Inlet. Using this technique, the maximum noise level from the two turbines in Admiralty Inlet was estimated to be 172 dB re 1 μ Pa at 1 m from the turbine, at a tidal current level of 3.6 m/s. This maximum acoustic output is expected to occur less than 0.01% of the time that the turbine is operating. Using established hearing threshold values, SMRU researchers examined the potential effects of the turbine sound on four species of fish and marine mammals, and compared them to the six frequency bands of the turbine's sound spectrum. The sound levels are expected to always be below the threshold of injury (180 dB re 1 μ Pa SPL rms) for marine mammals and below criteria for fish (206 dB re 1 μ Pa). Also, relying on the acoustic model, the probability that marine mammals (cetaceans and pinnipeds) in the region will detect the noise of the turbine is likely to fall below 25% within a kilometer of the site.

Information about the Admiralty Inlet project can be found in the *Tethys* database at <http://tethys.pnnl.gov/annex-iv-sites/admiralty-inlet-pilot-tidal-project>.

Laboratory Experiments

To supplement measurement of the acoustic output of turbines and wave devices, and the effects that sound may have on marine animals, laboratory and flume experiments have been devised to develop an understanding of the sound generation and effects in a controlled situation.

MEASURING TIDAL TURBINE NOISE IN A FLUME

Researchers at the University of Newcastle upon Tyne, UK, examined the sound produced by tidal turbine blades, including estimates of the acoustic signature of the device, with the addition of acoustic energy shed from blade tip vortices as a result of cavitation. Working with a 1/50th-scale, three-bladed turbine in a marine propeller test flume (Emerson Cavitation Tunnel), researchers measured the ambient noise in the flume as well as the sound pressure levels from the scale turbine under three stream speeds: pre-stall, stall, and post-stall of the turbine. Using these three conditions, the researchers were able to determine the speed of the tidal stream at which cavitation will occur. The turbine noise was measured at two (simulated) depths in the flume: 11 m and 20 m below the surface. Scaling the turbine noise up to a full sized tidal turbine, the SPL measured at 20 m was lower than that measured from a fisheries research vessel at sea.

The estimated SPL was highest at the 11-m depth post-stall mode; it reached 150 dB. In the pre-stall and stall modes, the acoustic output was estimated to exceed that of the fisheries research vessel at some lower frequencies. The SPLs from the 20-m depth simulation are lower than for the shallower depth. The simulation and analysis of the turbine noise in the flume follow protocols intended for marine propeller blades and have not been verified against tidal turbines in the field. Using these protocols, it is clear that cavitation of the blades contributes to the acoustic output of the turbine.

Information about this project can be found in the *Tethys* database at

<http://tethys.pnnl.gov/publications/investigation-cavitation-noise-and-slipstream-characteristics-ocean-stream-turbines>.

EXAMINING THE EFFECTS OF FISH EXPOSED TO TURBINE NOISE, USA

Researchers at PNNL investigated the physiological response of fish to simulated turbine noise to determine the extent of hearing shift and injury that might occur in the immediate vicinity of a tidal turbine. More information about the acoustic effect on fish experiments is provided by Halvorsen et al. (2011, available at <http://tethys.pnnl.gov/publications/effects-tidal-turbine-noise-fish-hearing-and-tissues>).

Juvenile Pacific (Chinook) salmon were used as the experimental animal because they are ecologically important throughout the North Pacific, protected in most countries where they occur, and their hearing range coincides with the range of noise generated by tidal turbines. Fish were held in the laboratory and exposed to a recording of a 6-m OpenHydro turbine from the EMEC, ranging from 155.4 to 162.6 dB re 1 μ Pa; this sound level simulates the level an animal might receive at a distance of 1 m from the turbine over a prolonged exposure (up to 24 hours). This exposure is greater than that which fish might be exposed to during 24 hours of tidal turbine operation because the turbine will generate peak sound while operating at peak tidal current speed. The fish were assessed for hearing shift, using a technique called Auditory Evoked Potential, and for injury at necropsy, by examination using a scale known as the Fish Index of Trauma. Fish were held for several days after exposure to determine delayed effects, before being sacrificed.

The noise from the turbine was not found to significantly alter the hearing of the fish. However, some minor injuries (the equivalent of bruising) were found at a significant level, upon necropsy. While these injuries were deemed not to be life threatening, the effects and likelihood of more frequent sound exposure still need to be evaluated.

Information about the project investigating the acoustic effects on fish can be found in the *Tethys* database at <http://tethys.pnnl.gov/annex-iv-sites/lock-and-dam-no-2-hydroelectric-project>.

Modeling the Effects of Noise from Tidal Turbines and Wave Energy Converters

There are few acoustic data available from field or laboratory observations that can be used to inform the understanding of the effects on marine animals, because there have been few tidal and wave deployments where sound has been measured and the behavior of marine animals observed or tested. In the absence of these data, the effect of sound from tidal and wave devices can be estimated using modeling exercises. Most commonly, these models estimate an acoustic signature from a device and model the potential physiological and/or behavioral response of the animals of concern. In some cases sound data have been acquired from operating tidal turbines or WECs and used to validate the acoustic portion of the model. The animal behavior portion of the models is generally guided by using the known hearing thresholds of animals and/or laboratory testing of effects of sound on animals. No behavioral models to date have been validated with laboratory or field data.

MODELING THE ACOUSTIC SIGNATURE OF WAVE ENERGY CONVERTERS, PORTUGAL

Researchers at the Wave Energy Center and other institutions in Portugal modeled the propagation of sound produced by several WECs and examined the sounds in the context of potential effects on species in the area. More information about the study is provided by Patricio et al. (2009).

The researchers used the acoustic output from a group of three Pelamis wave devices, surface attenuators that ride the top of the waves, perpendicular to the wave crests, flexing at joints between sections to drive hydraulic turbines. One set of trials simulated operation of only one of the WEC generators, and a second set of trials simulated all three generators operating. They modeled the transmission loss out to 10 km and applied the noise input from the WEC generators to determine the broadband SPL, allowing for a calculation of acoustic influence zones for species of concern. The zones of acoustic influence included the following:

- an audibility zone where the SPL was >20 dB over the hearing range of a harbor porpoise
- a disturbance zone where the SPL was >120 dB
- a temporary auditory injury zone, where SPL was >60 dB over the hearing range of the porpoise.

For the single operational generator, the model results show that a harbor porpoise might hear the WEC at a distance of 5 km, might be disturbed at 3 km, and might suffer temporary auditory injury at 1 km. With all three generators, the zones of auditory influence, disturbance, and temporary injury expand to 6, 4, and 2 km, respectively. The researchers noted that the animals are unlikely to stay in the areas of disturbance or injury but have the option of moving away.

Information about the acoustic modeling from WECs can be found in the *Tethys* database at <http://tethys.pnnl.gov/publications/noise-modelling-wave-energy-devices>.

MODELING THE EFFECTS OF ACOUSTICS FROM ARRAYS OF TIDAL AND WAVE DEVICES, SCOTLAND

Researchers from Scotland estimated the noise produced by arrays of tidal and wave devices with increasing numbers of devices (3, 9, 51) in different array configurations (linear and square) with all devices spaced 10-m apart. Using available estimates of acoustic information from single devices and analogues, the researchers modeled the acoustic output of the arrays, making the assumption that the first (or central) device in an array is responsible for the greatest acoustic output, while each subsequent device contributes a smaller amount to the noise signal. This less-than-additive assumption yielded results indicating that the noise from a 9-device array will increase the sound levels by 3 dB over a single device, and by 5 dB for a 51-device array. The researchers suggest that real world arrays are likely to be spaced more than 10 m apart, thereby reducing the additive sound even more.

Based on the model output, the researchers estimated the effects that the sound from tidal and wave arrays might have on fish, marine mammals, and submerged human beings (divers). The baseline they used was a scaled array of 1-MW output, with assessments for permanent threshold shifts (PTSs) and temporary threshold shifts (TTSs) in hearing, for specific exposure conditions.

For tidal devices, the PTS was calculated for 30-minute exposures, while the TTS was calculated for 8-hour exposures. In both cases, the researchers depended on audiograms indicating the hearing range of fish, toothed whales, seals, manatees, and human divers. The results indicate that sensitive species might suffer PTSs from 30-minute exposures at 16 m from the devices, while TTSs might occur after 8 hours of exposure within 934 m of the device.

For the wave device, the calculations led the researchers to conclude that WECs will not cause PTSs, while an animal would need to spend 8 hours within 6 m of the array to suffer a TTS.

The researchers noted that animals are unlikely to spend large amounts of time in close proximity to devices emitting noise, so the risk of hearing damage would likely be reduced.

Information about the acoustic modeling of arrays is provided by Richards et al. (2007), the Scottish Executive (2007), and in the *Tethys* database at <http://tethys.pnnl.gov/publications/scottish-marine-renewables-strategic-environmental-assessment>.

IDENTIFYING THE NOISE FROM A PELAMIS WAVE DEVICE, SCOTLAND

Researchers with QinetiQ set out to model the noise generated from a Pelamis WEC, using technical specifications and radiated noise models. They concluded that they could not accurately model the device noise but were able identify the components of the system most likely to produce audible sounds under water, which included hydraulic power generators, hydraulic rams, and wave noise during heavy seas.

By simulating the WEC with a steel-hulled vessel, the QinetiQ researchers summed the possible noise sources and concluded that the likely underwater noise generated by the Pelamis system ranged from 175 to 350 Hz, at 127 to 141 dB re 1 μ Pa, at a distance of 1 m from the device.

Information about the Pelamis acoustic estimation can be found in the *Tethys* database at <http://tethys.pnnl.gov/publications/scottish-marine-renewables-strategic-environmental-assessment> and the report by Richards et al. (2007).

DEVELOPING AN ACOUSTIC SIGNATURE FOR A HYDROKINETIC TURBINE, USA

Researchers at SNL and Pennsylvania State University's Advanced Research Laboratory have modeled the acoustic output of a generic hydrokinetic turbine to develop predictions of the output of specific turbines, in order to advise on methods to lower the noise through the design and manufacturing processes. The researchers modeled a 5-m-diameter operating turbine with hollow (water filled) and solid fiberglass blades.

Simulating measurements 1 m from the turbine, the researchers found that the hollow and solid blades produced sounds of 128 and 123 dB re 1 μ Pa, respectively.

Information about the modeling project can be found in the *Tethys* database at <http://tethys.pnnl.gov/publications/influence-blade-solidity-marine-hydrokinetic-turbines>.

FIELD CALIBRATION OF ACOUSTIC MODELS FOR NOISE PREDICTION, PORTUGAL

Researchers at the University of Algarve in Portugal conducted a field experiment to calibrate an acoustic propagation model at a proposed future wave energy development site on the continental shelf off the southern coast of Portugal. The field site was approximately 100 m deep and had smooth even bathymetry. The researchers towed an acoustic source and recorded temperature and depth, travelling at 4 knots, while two free drifting Acoustic Oceanographic Buoys with multiple hydrophones recorded the sound from distances of 2 km and greater.

The field data helped to calibrate existing sound propagation models, highlighting small but significant overestimates in transmission losses from the models.

More information about the project is provided by Martins et al. (2011 available at www.siplab.fct.uaalg.pt/pubs/nmartins1.11.pdf). Information about the field calibration can be found in the *Tethys* database at <http://tethys.pnnl.gov/publications/acoustic-field-calibration-noise-prediction-calcom-10-data-set>.

MODELING ACOUSTIC DETERRENCE TO DEVELOP MITIGATION FOR MARINE MAMMALS, USA

Researchers from Oregon State University and Pacific Energy Ventures tested the effectiveness of an acoustic deterrent to keep gray whales (*Eschrichtius robustus*) from interacting with wave energy devices off the coast of Oregon. The objective was to achieve a 500-m zone of influence, or 500-m area around the device, in which whales would exhibit an avoidance response. Using a level of sound that is within the whales' hearing range (1–3 kHz), sound propagation models were run for the area to determine the source level required to achieve this 500-m zone of influence. Sound speed profiles for December and March yielded similar results, suggesting that a source level of 170 dB re 1 μ Pa at 1 m would be appropriate. The acoustic device was moored on the seafloor off Yaquina Head, Oregon, from January to mid-April 2012, during the southbound and northbound-A (non-calf) phases of the gray whale migration. Concurrent shore-based theodolite observations were conducted from Yaquina Head to determine whether whale distribution differed during times when the acoustic device was transmitting and when it was off (control period). The loss of the mooring's surface expression (buoy)

during a storm and again when it was run over by a vessel prohibited the regularly scheduled maintenance and battery changes of the device. In addition, few whales traveled through the small zone of influence even during control periods. These factors combined to prevent the collection of a large enough sample size to determine whether the deterrent was effective; however, the limited data collected suggest that the deterrence device may not have been effective. The researchers suggest that increasing the zone of influence by increasing the sound source level will allow for the collection of larger sample sizes in future testing and ultimately help determine whether such a deterrent would be an effective mitigation tool.

Discussion and Identification of Data Gaps

As tidal turbines and WECs are introduced into marine waters, concerns that sound from the devices might harm marine animals are being raised by stakeholders and regulators. Other industries, mostly notably pile-driving and shipping, provide information about the level of sound presently introduced to the marine environment. A number of studies worldwide have raised concerns that these sounds may be deleterious to marine mammals, fish, and other organisms, by changing the animals' behaviors, causing injury and death (NRC 1994; Garrison 2010). So few tidal and wave devices are deployed that measurements of the amplitude and frequency of sound likely to be contributed to the marine environment are sparse, as are measurements of animal response. Conclusive information about the risks of sound from marine energy devices will only be gained from many years of data and observations around operating turbines and WECs. As that body of monitoring evidence is being built, indications of the effects on animals may be gleaned from in situ studies, laboratory experiments, modeling outputs, and the opinions of experts in the field of marine animal behavior.

Operational noise from individual devices or small arrays of MHK devices is unlikely to have large-scale effects on organism behavior or survival. Most concerns regarding noise stem from the uncertainty of additive noise from large numbers of devices and from the more intense sounds associated with some types of construction and site assessment activities. As initial studies provide insight into the effects of the additive noise from marine energy devices on the marine environment and the effect it may have on animals, it is essential to consider the enhanced frequency and amplitude that may be delivered by large tidal or wave arrays, and the cumulative effect of the sound of multiple arrays within a waterbody.

THE CHALLENGE OF MEASURING THE EFFECTS OF MARINE ENERGY ACOUSTICS

Understanding the effect of acoustics requires three separate research areas in which data should be collected:

- characterization of the acoustic environment into which the devices will be deployed in order to understand the patterns of sound propagation from new sources of underwater sound and to understand the context into which the sound from a marine energy device will be propagated
- accurate measurement of the amplitude (dB) and frequency spectrum (Hz to kHz) of the new sound source, as well as the variation in the sound source over time and the directionality of the source

- observation of the response of marine animals to the sound source in order to determine potential harm to individuals and populations.

A fourth area of research helps span some of the data deficiencies, focusing on the comparison of acoustic signatures of devices with auditory ranges of species of interest. For some species, significant research into the effects of noise has been done, generally for purposes such as the potential effects of pile driving; data derived from these efforts can help inform researchers of the possible effects and distances over which acoustic effects of marine energy devices might be felt. In particular, there is a the lack of audiograms for low-frequency cetaceans or diving seabirds, and a lack of laboratory experiments describing the behavioral responses of marine mammals to tones and specific sounds rather than broadband sound levels. Measurements of the effects of acoustics on marine animals have been developed, with varying degrees of completeness and applicability, to help bridge the gap between real world observations, laboratory findings, and indirect evidence of behavioral change in animals (Ellison et al. 2011; Tollit et al. 2011; Wright et al. 2007; Clark et al. 2009).

Each research area presents specific challenges. Measuring the acoustic environment is the best-developed methodology; experience has been gained by sub-bottom profiling for oil and gas exploration (Hazelwood 1975), naval operations (Brüel & Kjær 2009), and other oceanographic investigations (Garrison 2010). Few of these investigations have been carried out for purposes of marine energy siting; two of the few examples are presented here (e.g., south coast of Portugal and Admiralty Inlet USA).

Measurement of the sound spectra from marine energy devices is not a well-established methodology, and few appropriate systems of instrumentation exist for collecting these data. The high-energy environments into which marine energy devices are deployed provide unique challenges to separating the sound of the turbine or WEC from the pseudo-noise of turbulence and ambient contributions from shipping and other anthropogenic activities. Drifting hydrophones are showing promise as a method to overcome these challenges (Wilson et al. 2007; Keenan et al. 2011; Snohomish Public Utility District website: <http://www.snopud.com/powersupply/tidal.ashx?p=1155>). Several research efforts are presented here as evidence (e.g., tidal turbines in Cobscook Bay and the East River of New York and WECs in Puget Sound).

The least developed methods and technologies for understanding the effects of marine energy acoustics are associated with observations and interpretations of animal behavior in and around the devices, and the ability to scale from behavioral reactions of a small number of animals to potential effects on population health and survival. Other industries and activities that introduce sound into the ocean are faced with similar limitations. The lines of evidence presented in this case study represent most of the efforts to increase understanding of the effects of noise from marine energy devices (e.g., SeaGen in Strangford Lough).

EXISTING EVIDENCE FOR UNDERSTANDING THE EFFECTS OF MARINE ENERGY ACOUSTICS ON ANIMALS

The chains of evidence that make up this case study inform one or more of the necessary research efforts to understand the effect of acoustics, but none definitively answers all the questions associated

with the effects of single devices or larger arrays. The projects and research studies presented in this case study were examined as they inform the following topics:

- acoustic measurements and effects on marine animals
- interpretation of laboratory studies
- modeling of acoustic signatures
- determination of the acoustic environment for marine energy deployments.

ACOUSTIC MEASUREMENTS AND THE EFFECT OF NOISE ON MARINE ANIMALS

The most comprehensive monitoring efforts to date for the acoustic output and links to animal behavior have been made around the SeaGen tidal turbines in Northern Ireland. The SeaGen project assessed the ambient soundscape in Strangford Lough and the Narrows using drifting and fixed hydrophones; the researchers did not carry out a more in-depth experiment to determine sound propagation in the waterbody but felt they understood the acoustic profile sufficiently to interpret the addition of turbine noise to the stresses facing marine mammals and fish in the waterbody. The deployment of drifting acoustic measurement technology in the Lough provided an important addition to the toolset for measuring turbine noise. Land- and boat-based observers, aerial surveys, tracking of tagged seals, historic abundance and distribution data for seal haulout sites, and the use of sonar (active acoustics) to observe the distributions and movement of marine mammals and fish around the turbines provided an excellent first-order look at the reaction of the animals to the turbines. However, it was not possible to determine what part of the turbine avoidance by marine mammals is due to the noise emanating from the generator and turbine blades, versus avoidance because of disturbance of the water flow from the presence and operation of the device. Intuitively, marine mammal experts believe that the sound of the device will warn animals to avoid the hazard, but there is no clear evidence of this around tidal or wave devices to date (Wilson et al. 2007).

The SeaGen project team applied a metric for the hearing threshold of species for underwater sound: dB_{ht} (*Species*) (Nedwell and Howell 2004). This metric has been used to evaluate the acoustic effects of offshore wind and marine energy in the UK but has not been applied extensively elsewhere. Based on the findings of the SeaGen studies, it appears that the construction noise from drilling pin-piles for the device had limited effect on the marine mammals and fish in the Lough because the operation was of short duration and the auditory range of the drilling sound was limited. More drastic effects such as injury and death from the sound of drilling activities for installation of SeaGen appear even less likely. Similarly, it appears that the sound from the operating turbines in the immediate vicinity of the device is below the level at which effects on the animals' hearing is expected; and the sound levels where changes in the behavior of seals and harbor porpoises might be expected are reached within a few hundred meters of the installation. In addition, observers noted that the marine mammals spent little time in close proximity to the installation when the turbines were turning, further limiting their exposure to hearing shift. Alternately, observers saw seals and harbor porpoises routinely within the region where behavior changes such as avoidance might be expected.

Measuring Noise and Estimating the Effects on Animals

Several U.S. marine energy projects highlighted in this case study have measured the acoustic output from tidal turbines and WECs, and used those levels to estimate the effect the sound might have on marine animals of interest. One of the greatest lessons learned from these investigations is the extreme challenge of measuring sound from a marine energy device in a high-energy environment.

Most researchers are pursuing forms of floating hydrophones, pioneered by researchers at the SAMS working at the EMEC, to isolate the sound of the device in noisy high-energy environments.

Researchers in Cobscook Bay further developed a system of floating hydrophones to measure the acoustic output from the barge-mounted TGU in a very noisy tidal energy environment to determine the noise level that might be anticipated for the commercial-scale TGUs. The research plan called for acquiring acoustics data from the same location with and without the barge-mounted TGU in place, carefully controlling for other sources of noise, thereby effectively isolating the sound of the TGU. The researchers conservatively estimated the noise output from the 5-TGU commercial unit (each of the units has two generators) to be 10 times that of the single barge-mounted unit. The resulting noise met regulatory standards for fish hearing shift and allowed the regulators to lift a restriction on pile driving during periods when Atlantic salmon smolt may migrate through Cobscook Bay (April 10 to November 7).

The need to pin-pile the TGU base for commercial installation in Cobscook Bay provided an additional opportunity to refine the drifting hydrophone technology to acquire an acoustics signature and define the SPL and SEL at 10 m from the pile-driving location. The resulting noise met regulatory standards for fish hearing shift and allowed the regulators to lift a moratorium on pile driving during the months when Atlantic salmon migrate through coastal Maine (April through November).

The Verdant RITE project took a different approach to measuring tidal turbine noise, using towed hydrophones in transects parallel to the shoreline. The East River of New York is a relatively narrow waterbody, creating a challenge for the drifting hydrophone systems used elsewhere. Measurement in close proximity to the turbines was also challenging because of shallow water. Although the measurements made at the turbines were compromised by the condition of several turbines and turbine blades, the noise measurements were consistently lower than levels at which harm to fish and diving birds is expected. In addition, the urban nature of the site, including the movement of subway trains in a tunnel under the river, created a noisy acoustic environment in which the Verdant turbines would likely be unnoticed by fish.

Further refinements of a floating hydrophone system allowed university researchers to measure the sound from an anchored wave device in Puget Sound, and to compare the sounds to those of commercial shipping in a deep waterbody with commercial shipping. Although the CPT WEC was subscale (1/7th of expected commercial size), the researchers were able to document the characteristic sound signature of the two moving parts and generator against the ambient soundscape when ships were not present out to 500 m. However when ships ranging from tugs to container ships were in the vicinity, the noise of the WEC was masked. The acoustic levels generated by the WEC were below levels at which hearing shift or injury might be expected for fish or marine mammals.

Interpreting the Results of Laboratory Studies

Until there are sufficient opportunities for gathering acoustic data from deployed tidal turbines and wave energy devices, data from laboratory studies can provide insight into certain aspects of the effects question. Interpreting those results is not simple: the ability to scale the results of laboratory and flume studies to the size and energy levels of tidal flows and ocean waves is challenging. Further complications arise from interpreting the effect of the edges of a test tank on animals or on water movement (a combination of reflections of sound off the walls and the artificial boundaries placed on

experimental animals within a tank), assessing the condition of the experimental animals, and interpreting data from sensors not designed to measure realistic marine energy flow conditions or animals' reactions to those conditions.

Measurements of the acoustic output of a three-bladed turbine in a tunnel in the UK provided an important first step in a controlled environment. The researchers applied techniques and calculations designed for testing ship propellers as the closest analogue to a tidal turbine. The researchers learned valuable lessons about the importance of designing and tuning turbine blades to reduce the sound signature, and they raised questions about the rates of energy production and water flow that may cause turbine blades to cavitate and produce increased sound levels, although it should be noted that most engineering designs work to minimize cavitation because of its detrimental impacts on the device itself.

Laboratory experiments in the United States introduced fish to sounds from a tidal turbine at a level consistent with the animal being in close proximity to the device, and found relatively low levels of harm (the equivalent of tissue bruising) are likely from the exposure. This dosage of sound from an open-center shrouded turbine could be considered the "worst case" scenario; it is expected that fish (particularly migratory fish) are unlikely to spend considerable time in close proximity to the turbine, unless they are attracted to the noise of the device, which is currently unknown (Dempster and Kingsford 2003). At least for this turbine design and juvenile migratory salmon, the direct effect of sound output appears to be of little environmental concern. Challenges remain, including scaling from the sound of a single turbine to many turbines in a commercial array, estimating the effect of sound signatures from other turbine designs on marine animals, testing the response of other marine fish with differing physiologies and lifestyles than salmon, and extrapolating from effects on fish to other marine animals such as mammals for which experimentation is not possible.

Modeling Acoustic Signatures

Efforts to understand the sound propagation from marine energy devices have encouraged modeling efforts to define sound levels from tidal or wave energy devices, simulate the propagation of sound in proposed marine energy locations, and, in some cases, compare the model results to estimates of hearing ranges and sound levels at which animals might be affected.

Researchers in Portugal examined the sound output from a small array of wave devices, focusing on the differential sounds produced by a single generator versus multiple generators. By comparing the modeled sound levels from the devices to the hearing range and sound levels at which animals (harbor porpoise) are thought to be affected, the researchers defined the distance from devices at which animals might be affected, including a non-linear expansion of the potential risk zone as one moves from a single device to multiple devices.

Researchers in Scotland took an additional step forward in modeling the acoustic output of arrays of tidal devices, scaling from measured sound output from single devices to small arrays (3 and 9 devices), up to large arrays of more than 50 devices. By comparing the modeled acoustic field to levels at which animals are believed to suffer temporary or permanent hearing damage, the researchers were able to estimate the distance and exposure levels at which concerns for specific animal groups might be notable.

Measurements and associated modeling efforts in Admiralty Inlet in the United States for tidal turbines also compared the values for the presumed tidal turbine acoustic profile with levels at which animals

are expected to be affected. The study concluded that fish and marine mammals are unlikely to be harmed by the two proposed turbines and would detect the acoustic signals only a relatively short distance from the source.

Modelers in Scotland, the United States, and Portugal concurred with researchers measuring sound from marine energy devices and gathering observations of animal behavior: marine animals are likely to be deterred by noise from marine energy devices and to move out of the immediate area of the devices. Direct observations from the SeaGen project tend to refute this claim, however; there were multiple observations of harbor porpoises and seals swimming, apparently unconcerned, within the zone where acoustic deterrence might be expected. This ambiguity points to the need for further examination of the sound levels at which harm or deterrence of animals are thought to occur, as well as controlled field experiments that examine the behavior of animals around marine energy devices.

Modeling efforts that simulate the acoustic output from devices have also honed in on specific aspects of wave and tidal devices, providing important information about the potential for noise disturbance in animals. Estimates of the possible sound from a Pelamis wave device in Portugal pointed to specific parts of the technology that may be responsible for much of the sound output. Similarly, U.S. researchers modeled the sound output from tidal turbines to understand the difference in acoustic output from different blade designs. Information from these and similar models can assist in the future redesign of the components and/or changes in how the devices are operated, in order to lower the potential for acoustic harm to marine animals.

Determining the Acoustic Environment for Marine Energy Deployments

The first step in evaluating the effect that noise from wave and tidal devices may have on animals is an accurate evaluation of the ambient acoustic environment where animals and devices may interact; this can only be done prior to device deployment. Two examples of projects that have very effectively examined the sound fields around proposed marine energy projects include the assessment of the potential for sound propagation of wave energy devices off the south coast of Portugal, and the assessment of the ambient sound and propagation potential for tidal turbines in Admiralty Inlet, in Puget Sound in the United States. Both studies took into account the oceanographic and bathymetric features of the sites that determine the propagation of sound in the area. The Portuguese researchers were able to measure the propagation of sound from a simulated wave device sound source, while the U.S. researchers focused on understanding the make-up and propagation of existing sound near the proposed tidal turbine deployment site. Both pieces of information are important to accurately evaluating the sound of single marine energy devices, as well as larger arrays; these studies must be undertaken after the marine energy systems are deployed and operating. Only with these sets of measurements can observations of animal behavior around the devices be interpreted to understand the risk posed by the acoustic output and to form the basis of effective mitigation measures.

SCALING FROM SMALL DEPLOYMENTS TO COMMERCIAL SCALE

The data on the effects of noise from marine energy devices have been collected from deployments of single or small numbers of devices that have been in the water for relatively short periods of time (months to a year or so). While these limited deployments provide insight, the leap to understanding the effects of noise from large numbers of tidal turbines or WECs, operating over years to decades, will require additional effort and investigation to determine whether large arrays of devices may present an increased risk to animals. To date the sound signatures from single or small numbers of operating tidal devices and WECs do not appear to be causing harm to animals. The complex

propagation of sound through seawater makes it very difficult to predict possible additive or synergistic sound effects that might be generated from marine energy arrays.

No reliable data on acoustic output around arrays are available; the Verdant RITE project sought to measure such effects but the malfunction of several turbines limited the value of these data. Some modeling efforts have addressed the issue of noise output from arrays, notably the Portuguese examination of multiple wave generators and the Scottish modeling of small and large arrays. Validation of these models with field data would greatly assist in understanding potential effects.

As future measurements of acoustic outputs and marine animal behavior are collected around arrays of devices, it will be important to consider factors such as the following:

- potential confusion of animals because of the physical presence and acoustic output of multiple devices that may lead to increased risk of strike or entrainment
- potential barrier effects or displacement of animals because of a broad noise field from multiple devices, particularly in established migratory or transit routes
- potential for increased predation as prey animals change their behaviors to avoid the devices or as they are attracted to individual and multiple devices (reef effect)
- potential additive effects of acoustic disruption around marine energy arrays in areas where anthropogenic factors already provide stress to marine animals.

Until arrays of multiple tidal devices are deployed with substantial monitoring programs in place, information about the effects of acoustics on marine animals with arrays will continue to depend on laboratory experiments and modeling efforts.

SIGNIFICANT GAPS IN DATA

At this time, there are perhaps more questions raised than answers provided concerning the effect of noise from marine energy devices on marine animals. Among the small number of tidal and wave deployments worldwide, most of relatively short duration, only one (SeaGen) has supplied insight into the full suite of measurements from ambient noise fields, the acoustic output of the device, and observing animal behavior. Interpretation of the SeaGen data is hampered by a lack of information about the sound propagation potential within Strangford Lough, as well as uncertainty related to the effect of the sound propagation levels from the turbines on marine animals. Reconciling the observations of animals in proximity to the turbines with sound levels expected to deter the animals, and the continued need for validation of the decibel hearing threshold for marine species metric, do not allow researchers to definitively determine the effect of turbine acoustics on fish and marine mammals.

Other strands of evidence presented in this case study provide valuable additions to the measurement toolset and understanding of the issue; however, to date no single project, experiment, or modeling effort has supplied substantial data or proof necessary to classify and evaluate the effect of marine energy devices on animals.

The uncertainty associated with the effects of noise from tidal and wave devices will moderate as more devices are deployed and environmental investigations progress. However, to advance our collective understanding of the risk posed to marine animals, key lines of evidence are needed, including the following:

- Field deployments must follow the full suite of needed studies, including measuring the ambient sound field and propagation potential of the waterbody prior to deployment of the marine energy device, accurately measuring the sound of the operational device, and observing animals around the device using multiple tools such as observers, active acoustics, and satellite tags and aerial surveys for appropriate animals.
- Dose/response relationships are needed to understand the amplitude and frequencies of sounds that elicit reactions in animals of concern; these studies need to be done in the laboratory for fish and invertebrates, with extrapolation to marine mammals and sea turtles.
- As arrays of devices are deployed, assumptions about the additive or multiplicative effects of acoustic outputs over single devices must be validated with field data.
- Investigations of acoustic output and its effects are needed for a range of tidal and wave energy devices that represent the major technologies under development, because each device, and probably each anchoring, mooring, and foundation system, will have a unique acoustic signature.

In conclusion, the limited information available about the effects of acoustics on marine animals from marine energy devices suggests that animals are unlikely to be killed or seriously injured by the operational or pin-piled installations sounds associated with devices designed to date. Evidence to date suggests that both wave and tidal energy converters will have time-varying sound signatures that will require a probabilistic description of sound to determine the potential risk to marine mammals. The evidence of hearing shifts, behavioral, or migratory effects is less certain and will require continued data gathering and analysis as additional devices go in the water. It appears likely that examinations of acoustic effects will continue to play a significant role in the understanding of environmental effects of marine energy development into the future.

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CASE STUDY 3 – THE ENVIRONMENTAL EFFECTS OF MARINE ENERGY DEVELOPMENT ON PHYSICAL SYSTEMS

Introduction

This case study was developed as part of the OES Annex IV. Annex IV seeks to bring together information about the environmental effects of marine energy development from around the world and to assist OES member nations with environmentally responsible acceleration of the marine energy industry. As marine energy development begins to gain momentum internationally, Annex IV case study analyses focused on the early stages of development from single devices to multiple device arrays. Metadata—descriptive information about data—were collected from projects and research studies to form the basis of the input to the case studies.

This case study focused on investigating the effects that the presence and operation of marine energy devices may have on the physical aspects of the marine environment, including the quality of the water and sedimentation.

GOAL AND OBJECTIVES OF THE CASE STUDY

The goal of this case study was to examine existing information from marine energy projects worldwide about how tidal and wave devices may affect water circulation, sediment transport, and environmental quality. Specific objectives included the following:

- Identify tidal and wave projects that have monitoring data that determine physical changes in the environment.
- Collect ancillary information from laboratory studies and numerical modeling simulations that may inform the understanding of the potential effects of tidal and wave systems on the physical environment.
- Evaluate the comparability and applicability of the information from different tidal and wave projects and ancillary studies to determine the potential effects on the physical marine environment.
- Identify key gaps in data and studies that need to be filled to complete the understanding of the effects of marine energy projects on the physical environment.

APPROACH

Measuring or simulating changes in water circulation from the presence and operation of marine energy devices requires a solid understanding of the movement of water and sediment in the natural systems in which the devices are deployed. This understanding presents a significant challenge

because, despite many decades of oceanographic measurement of tides, waves, and the parameters that define water circulation throughout the coastal and estuarine areas of the oceans, researchers seldom deploy instruments or mount field campaigns in ocean areas where extremely high energy persists. These high-energy areas are precisely where wave and tidal devices are planned for deployment to take advantage of the power resources. Changes in the physical environment around tidal and wave devices are only just now being measured and modeled.

Information for this case study was gathered from all available sources and sorted to provide an understanding of the state of the science for identifying the power resources present in key areas for tidal and wave energy development, and an understanding of the effects that the energy removal will have on the physical environment. As reflected in the following sections, each information source was examined to determine how the outcome informs the case study; information about changes in the physical environment was compared among projects and research studies; and gaps in information that hinder further analysis or interpretation were identified.

SOURCES OF CASE STUDY INFORMATION

The information used in this case study was derived from metadata collected from project site investigations worldwide and from research studies; these data are entered into the *Tethys* database found at http://tethys.pnnl.gov/knowledge-base?ff0=field_project%3A3. Where applicable, the underlying data sources and interpretations from reports and papers were sought for analysis. There are no *truly* analogous industrial applications that remove energy; however, modeling studies are often informed by changes in water flow around objects placed in the water column; where applicable, these analogous data were included in the case study.

USE OF THE CASE STUDY OUTCOMES

The information gathered and analyzed for this case study can help inform regulatory and research investigations of the potential risks to the marine environment from the presence and operation of tidal and wave installations. Future efforts may be informed by which monitoring studies were found to be worthwhile. This information may also assist marine energy developers in developing engineering, siting, and operational strategies for tidal and wave projects to minimize the effects on the waterbodies in which they plan to deploy their systems. Used in conjunction with site-specific knowledge, the case study outcome may simplify and shorten the time to permit (consent) deployment of single and multiple device arrays. The information brought together for analysis in this case study represents readily available, reliable information about changes in water circulation, sediment transport, and the potential effects on marine habitats; however, the analysis and conclusions drawn from this case study are not meant to take the place of site-specific analyses and studies, or to direct permitting (consenting) actions or siting considerations in specific locations.

Effects of Changes in Water Flow and Energy Removal

The natural circulation of water in the ocean is affected by the bathymetry and geometry of the waterbody (for example, the constrictions of a tidal basin, or the sloping bottom in a wave energy area), forcing by the tides or ocean currents, input of freshwater into seawater, heat exchange at the air-sea interface (creating and sustaining the estuarine mechanism in estuaries, or stratification in coastal areas), and by winds driving surface waters. Sediment is swept from river mouths, or

resuspended from the sea bottom, and carried throughout coastal waters and estuaries by the movement of the overlying water. The movement of water in local and regional areas forms and transports the sediments that form benthic habitats and defines the open water pelagic habitats (Garrison 2010). Placing marine energy devices in the water may have two, linked but separate forcing effects: 1) the physical presence of the surface and subsurface devices will change the natural flow of water, potentially creating scour around anchors and foundations, and changing the flow of the mid water column and the bottom water layer; and 2) the removal of energy that was responsible for ecosystem functions, now transmitted along power cables as electricity (Polagye et al. 2011). Tangible environmental concerns that could be caused by changes in water flow and removal of energy include alterations in the sediment transport and deposition patterns that nourish and replenish benthic habitats, changes in rates of flushing with oxygenated seawater in enclosed waterbodies that will mitigate low concentrations of dissolved oxygen or other deleterious substances affecting water quality, changes in water movement that decrease the distribution of planktonic larvae of marine animals and/or seeds and propagules of marine plants, and changes in mixing and stratification in the water column that can affect marine ecosystem processes, such as primary production, although many of these potential effects would only result after the extraction of very large amounts of energy from a system (Pelc and Fujita 2002; Wilson et al. 2007; Venugopal and Smith 2007; DOE 2009). Determining the potential effects of the presence and operation of tidal and wave devices on the physical environment entails understanding which of the mechanisms of water circulation and sediment transport will be affected and the magnitude of the effect.

Placing tidal or wave devices in the water will affect the circulation of seawater at some level, both from changes in flow and energy removal; however, these changes are expected to be immeasurably small for single or small numbers of devices (Polagye et al. 2011). Concerns about the potential to affect water quality, sediment transport, the quality of marine habitats, and ultimately the marine food web must be considered as large arrays of devices are set for deployment in coastal and estuarine waters. However, even at the scale of large arrays, sorting out the signal of marine energy device effects from the natural variability of oceanographic processes may prove to be very difficult. Numerical (computer) models can be used effectively to simulate the presence and operation of tidal and wave devices in marine waters, allowing the researcher to add many more devices to a waterbody than might be practical, in order to understand the limits of development that may trigger environmental effects and the limits beyond which energy production diminishes (Polagye et al. 2011). Modeling results can also be immensely helpful in designing the most cost-effective and useful monitoring programs with which to measure potential effects.

From a regulatory (consenting) perspective, changes in the physical system that support essential marine ecosystem functions must be evaluated. Key regulatory drivers include the EU Habitat Directive in Europe, the *Fisheries Act* in Canada, and the *Clean Water Act of 1977* in the United States.

MEASURING WATER CIRCULATION AND SEDIMENT TRANSPORT

Typically, the movement of water is expressed as a speed and a direction (velocity vector), measured by instruments that record the water movement either directly as movement over an impellor mounted on a recording instrument known as a current meter, or indirectly by acoustic (Acoustic Doppler Current Profiler [ADCP]; Acoustic Doppler Velocimeter [ADV]) or electromagnetic (Electromagnetic Velocity Meter [EMV]) visualization of the particles found in seawater. Waves are measured using a range of instruments mounted on buoys at sea (accelerometer, wave gauge, X-band radar, ADCP) or from satellites (synthetic aperture radar, altimeter). To gauge the energy potential at the site, marine

energy developers routinely measure water velocity for tidal energy development and wave heights and periods for wave energy development. At a finer scale, turbulence in water must be measured to determine whether strong gusts may cause harm to marine energy equipment, generally using ADCP/ADV instruments. The linear scale at which turbulence occurs is smaller than most turbines or WECs and can have significant effects on the functioning of the marine energy device, and it can be used to determine the effect that the machine may have on the nearfield (and ultimately the farfield) environment.

Each of the oceanographic instruments that measures movement of water uses a different principle; ADCPs provide a velocity profile using a diverging acoustic beam pattern emitted from one point, and typically sample a large spatial volume. ADVs are acoustic point measurement systems, using convergent acoustic beams patterns emitted from more than one point, and they sample a much smaller volume of water than ADCPs. ADCPs and ADVs provide high-resolution 3D measurements of velocity that can resolve very rapid shifts and changes. They are typically bottom-mounted and look upward through the water column to measure the movement of water, or they are mounted near the seabed and look downward to measure the water movement responsible for sediment transport. These instruments can also be mounted on a ship, looking downward, to survey a larger area covered by the ship trajectory. While most commonly associated with the measurement of tidal and river flows, ADCPs are also used to measure the orbital velocities of waves beneath the surface, to judge the power potential of the waves. Although used less commonly, EMVs can also be used to measure water flow, relying on the conductive properties of seawater to generate an electrical signal proportional to the speed of the water.

Numerical models allow researchers to understand the movement of water throughout an area, and provide powerful predictive tools for estimating the potential effects of marine energy devices on the marine physical system. Parameters that are routinely measured to support calculations of water movement include temperature, salinity (or conductivity), and water depth, using electronic sensors deployed vertically throughout the water column known as CTD (conductivity-temperature-depth) sensors. The data points derived from CTD casts are used to calibrate numerical models and to allow for extrapolation beyond the spatial or temporal region of the measurements. Direct measurements of currents using current meters are also used to calibrate numerical models. Numerical simulations of the effect of marine energy devices (sometimes known as marine energy modules) can be developed and embedded in the models, allowing for a realistic estimate of the effect of disrupting flow and removing energy from the ocean water. To understand how realistic these simulated effects might be and to validate the models' estimates of water movement, further oceanographic measurements are needed after wave and tidal devices have been deployed and operating. The changes in water circulation and the consequent effects on sediment transport and water quality are expected to be very small, even for large arrays, and may not be easily measurable until the array has been operating over long periods of time. The necessary model validation measurements are not available today, and may not be for years to come until large commercial arrays of wave and tidal devices have been in the marine environment for extended periods of time.

HYDRODYNAMIC MODELING

The ability to accurately and rapidly model waterbodies allows researchers to examine oceanographic phenomena and examine future scenarios of change in those waterbodies with a high degree of precision. Current computing capabilities support very detailed spatial and temporal analyses of changes in water flow and the processes dependent on water flow, including transport of sediment, changes in water-quality parameters, and growth of marine organisms; this capability also supports

analysis of the changes in flow and energy removal associated with marine energy devices. All this detail does not ensure accurate results, but requires proper calibration with high-resolution grid and bathymetry detail to emulate a complex system.

Researchers may develop models with varying degrees of complexity to address particular questions; more complex models are likely to yield more realistic and complete simulations, but require specialized expertise and increasingly large computational resources. The simplest physical models of water flow are one-dimensional (1D) models that describe the water flow in one direction; two-dimensional (2D) models define the water mass as the dimensions of the surface (length and breadth), while 3D models take into account the movement of water over all three spatial directions. All three types have been used to define the water flow and potential changes in waterbodies from marine energy removal.

Examining the potential effects of marine energy removal requires that a modeler develop and calibrate a model of the waterbody of interest to determine a realistic baseline condition (i.e., with no marine energy device). This development requires the researcher to define the boundaries of the waterbody and lay out a grid of points joined to define shapes on the surfaces of the waterbody (simple surface grid for 1D, a vertically layered grid taking the shorelines and sea bottom into account for 2D, and a complex grid showing interactions between vertical layers bounded by the shorelines and seabed for 3D). Measurements or predictions of physical parameters for water (for example, tidal elevation and currents or waves) at the boundaries of the waterbody are used to “force” the water into the area of interest, while other forcing functions ensure that the water moves properly. For tidal basins, the forcing functions are the tides (measured very accurately at many points in the coastal ocean), atmospheric pressure/winds, heat flux, and freshwater flow into the basin. For wave areas, the spectrum of waves (wave height, period, and direction) that hit the boundaries is propagated through the waterbody, forced by the wind. The models then create the circulation within the model domain through equations governed by physical principles, including gravity that affects the density of the water and the bathymetry that guides the flow. The addition of a module that simulates marine energy devices will indicate changes in water flow, compared to the baseline (without marine energy devices) condition. For tidal flows, the semi-enclosed nature of most tidal basins will show changes in circulation far from the devices (farfield) with the addition of tidal devices, potentially manifesting as poor water quality, low dissolved oxygen, changes in sedimentation patterns in deep and shallow water, and small changes in the tidal prism and the intertidal zone. Changes in wave energy from harvesting large amounts of marine energy will directly affect the nearshore wave climate that is responsible for forming beaches and other soft-bottom shore forms.

Key Sources of Information

Marine energy developers and researchers commonly measure water movement at tidal and wave energy sites, but very few such measurements have been made before and after deployment of devices. In two examples presented below researchers attempted to measure changes in water flow after the installation of tidal devices; to date no such data are available around WECs. Numerical models of tidal velocities and wave resources in the vicinity of proposed deployments are becoming common, but only a small number account for changes in flow and energy removal due to power production. To date, none of these models has been validated around operating arrays, although a small number of modelers have used laboratory data or synthetic data sets to validate their models.

Measurement of Changes in Water Circulation Around Tidal Devices

The following synopses represent key examples of work undertaken by tidal project developers and researchers to determine changes in water velocity near their projects, before and after the installation of devices. Modeling studies and calibration efforts follow in later sections.

WATER VELOCITY MEASUREMENTS AROUND THE SEAGEN TURBINE IN STRANGFORD LOUGH, NORTHERN IRELAND

Marine Current Turbine's SeaGen is a tidal energy device consisting of two 16-m open-bladed rotors attached to a pile in the seabed in 26.2 m of water; the surface expression includes a turret supporting an observation platform. The pin-pile was drilled into the seabed using standard piling methods. The rotor blades can be raised and lowered for maintenance and feathered to slow or stop rotation. The deployment site is in the center channel of the Narrows in Strangford Lough, Northern Ireland, where tidal currents reach up to 4.8 m/s.

Detailed information about the methods and results of the SeaGen monitoring program are provided by Keenan et al. (2011), available at <http://tethys.pnnl.gov/publications/seagen-environmental-monitoring-programme>.

The purpose of the SeaGen deployment in Strangford Lough was to test the efficiency and survivability of the gear and determine potential interactions with the environment. Descriptions of the monitoring activities associated with understanding potential interactions with, and effects on, marine animals and birds are described in the first two case studies. Researchers also investigated the potential effects of the turbine on the water flow regime within Strangford Narrows. The primary question of interest to regulators was whether the placement and operation of the turbine would disturb the benthic community in the Narrows; investigations into potential effects on long-term water quality or sediment transport throughout the Lough were not addressed.

Researchers measured water velocity near the seabed and near the water surface, directly downstream of the turbines, and at the scale of the Lough and nearby waters, using a vessel-mounted ADCP. The ADCP was operated to survey the water column from seafloor to surface. The researchers took velocity measurements prior to and after turbine deployment under several turbine-operating conditions: at slack tides, at neap ebb tides, and at spring flood tides. They examined the nearfield effects (within a few meters of the turbine) and as far away as 2 km from the turbine (farfield effects). Measurements of water flow taken before turbine deployment and after the turbine was installed and operating showed little change in the water velocity outside the immediate wake of the operating turbine; the greatest changes in instantaneous velocity were seen at neap ebb tides when the flow change was as high as 15%. Velocity measurements made near the seabed showed little change, although the surface wake from the turbine was measurable up to 300 m downstream, largely due to the footprint of the tower; the change in flow velocity near the seabed was considered insufficient to disturb benthic communities, even in close proximity to the turbine tower. The average direction of the current in the Narrows changed by less than 4 degrees between pre-and post-deployment. The researchers concluded that the operating turbine did not modify the flow dynamics, scour patterns, or turbulence characteristics of the Strangford Narrows such that it affected the benthic community structure; benthic monitoring studies show that changes observed in the benthos are within the natural seasonal variability for abundance, species competition, and succession of the benthos.

Information about the SeaGen project can be found in the *Tethys* database at <http://tethys.pnnl.gov/annex-iv-sites/strangford-lough-mct>.

MEASURING WATER VELOCITY AROUND TIDAL TURBINES, NEW YORK, USA

Verdant Power deployed six tidal turbines in the East River of New York in 10 m of water as a demonstration for the RITE project. The Verdant turbines are three-bladed unducted turbines mounted on the seabed. The purpose of the Verdant deployment was to test the tidal devices and foundations and to determine their potential environmental effects. Descriptions of the monitoring activities associated with understanding potential interactions with, and effects on, marine animals and birds are described in the first two Annex IV case studies. More information about the RITE island deployment can be found at <http://www.theriteproject.com/Documents.html>.

The Verdant team collected information about water velocity using a stationery ADCP and a vessel-mounted ADCP to determine the flow structure in the channel before and after turbine installation, in response to regulatory concerns about the effects of energy removal from the river. Specifically, the Verdant team addressed concerns that the turbines might increase turbulence at the scale of the turbine blades, creating water column changes in the nearfield that could affect fish and birds and their food supply; the team also addressed concerns about changes in the flow field farther from the turbines. Using tidal information from the NOAA, the Verdant team also modeled the river channel to examine the potential effects of turbulence; the modeling results are covered in the next section. The results of the ADCP measurements were used to support the modeling findings. The team concluded that the small size of the turbines in the fast-flowing channel was unlikely to cause measurable changes in water flow or other associated physical changes with the exception of wake and elevated turbulent kinetic energy due to mixing.

Information about the Verdant RITE project can be found in the *Tethys* database at <http://tethys.pnnl.gov/annex-iv-sites/roosevelt-island-tidal-energy-project>.

Modeling Studies

Modeling studies that inform the understanding of the potential effects of placing and operating marine energy devices in the water are described first for wave energy areas then for tidal areas. For each modeling effort, the waterbody in which the device deployment is planned is simulated by the model, and the model's accuracy is validated using field data for the boundary conditions. For the modeling efforts, the presence of wave or tidal devices (singly or in arrays) is simulated with a series of equations in the model; the changes in the circulation of the waterbody and often other changes such as transport of sediment are created by the model. In a very few select cases, the realism of the marine energy module within the model has been validated with field or laboratory data.

MODELS THAT CALCULATE THE EFFECTS OF WAVE ENERGY DEVELOPMENT

The investigations conducted to understand changes to the physical system induced by wave arrays as described in this case study were conducted in the waters of Portugal, the UK, and Sweden.

Wave Energy Models Developed in European Waters

Several research groups have examined the potential effects of wave energy installations off the UK and Portuguese coasts (for example, Millar and Reeve 2007; Norgaard and Poulsen 2010; Palha et al. 2010; Reeve et al. 2011). In each case, researchers examined the potential impacts that multiple planned wave farms might have on nearshore waves and on coastal shore forms including beaches. The wave arrays were simulated using different modeling techniques; most commonly the modeling studies focused on the deployment and operation of arrays of Pelamis devices.

For the Portuguese study (Palha et al. 2010), the well-established REFDIF model was used to simulate the propagation of sinusoidal waves of different amplitudes, periods, and directions with and without wave farms. Observed wave data were used as boundary conditions for the model. Different wave array configurations were tested to understand the potential impacts during three different seasonal wave regimes (winter, summer, and autumn). The researchers found that the presence of the wave farms decreased the significant wave height by less than 30 cm and changed the direction of incident waves by less than half a degree; these changes fall within the margin of error for prediction of the model. Depending on the number of farms modeled off the coast, the length of shoreline over which the effects may be felt ranged from 15 to 26 km; smaller numbers of offshore arrays affected less shoreline. Detailed information about the methods and results of the modeling study is provided by in Palha et al. (2010), available at <http://tethys.pnnl.gov/publications/impact-wave-energy-farms-shoreline-wave-climate-portuguese-pilot-zone-case-study>.

Investigators at the University of Plymouth in the UK modeled the effects of a wave array on the incident waves and the impact on the shoreline, under present and future climate change scenarios, off the coast of Cornwall, UK (Reeve et al. 2011). The model predicts that available wave power will increase in the area with climate change by 1–3%, depending on the specific Intergovernmental Panel on Climate Change climate scenario modeled. This change will affect the rate and power of the waves reaching the shoreline, as modified by the wave farm. Detailed information about the methods and results of the modeling study is provided by Reeve et al. (2011), available at <http://tethys.pnnl.gov/publications/investigation-impacts-climate-change-wave-energy-generation>.

The potential effects of other types of WECs have been examined as well. Off the Pembroke coast of the UK, Wave Dragon Wales has proposed to deploy an overtopping WEC that will generate 4 to 7 MW of energy. Field sample collection of sediment samples and an assessment of the shoreline supported modeling efforts to examine the effects on the physical and biological environment, including waves, currents, and sediment distribution. The output of the model indicated that there are likely to be moderate impacts on the waves close to the devices and perhaps some localized effects on the currents and beach processes in the immediate vicinity of the device. Farther from the device, the researchers predicted no measurable effects of the device on the waves, shoreline, or the biological processes they support.

Detailed information about the methods and results of the modeling study are provided by PMSS Ltd (2007), available at <http://tethys.pnnl.gov/publications/wave-dragon-pre-commercial-wave-energy-device-environmental-statement>.

Studies of WECs off Sweden, drawn from modeling hypotheses, link changes in sediment transport caused by arrays to changes in benthic organisms and habitats (Langhamer et al. 2009; Langhamer 2010). The addition of hard substrates in soft-bottom habitats (such as anchors from wave arrays) can have indirect effects on benthic organisms by changing local currents, nutrient abundance,

sediment coarseness, and accumulation of organic material and marine growth. These effects may change the abundance of macrofauna near the introduced substrate, or may attract predators that further change the benthos. Additional information about this work can be found in the *Tethys* database at <http://tethys.pnnl.gov/publications/artificial-reef-effect-and-fouling-impacts-offshore-wave-power-foundations-and-buoys> and <http://tethys.pnnl.gov/publications/effects-wave-energy-converters-surrounding-soft-bottom-macrofauna>, respectively.

Wave Energy Models Developed in North American Waters

Researchers with CPT and Oregon State University in the United States developed a model to examine the effects that a wave array will have on the nearshore wave climate. Using laboratory (wave tank) data to calibrate and check the model, the researchers found that the WEC array is likely to have an effect on the wave field on both the offshore and lee side of the array.

Modelers at SNL examined the effects of wave arrays on the nearshore wave field in a bay off the coast of Hawaii (Kaneohe Bay); they also modeled the effects on the nearshore waves, currents, and sediment transport off the coast of California (Monterey Bay). For modeling both wave climates, the researchers used a widely used wave model (SWAN); for the California case, they embedded the wave model into a circulation model (SNL-EFDC). It was assumed that 100% of the incident wave energy was absorbed by each array. The baseline (i.e., no WECs) wave model off California was validated with offshore and nearshore wave buoy data, and the circulation model was validated with nearshore ADCP measurements. Both a small array (10 WECs) and a large array (200 WECs) were introduced in a honeycomb shape. The researchers found that wave, circulation, and sediment transport properties were significantly altered in response to the simulated California large WEC array. The 200-WEC installation allowed for more deposition of fine sediments than the smaller array. For the simulated 3 WEC array off Hawaii, the model was validated using wave buoy data. More information about the modeling studies is provided by Roberts et al. (2012) for California, Roberts et al. (2011) for Hawaii, and in the *Tethys* database at <http://tethys.pnnl.gov/publications/wec-farm-effects-wave-current-and-sediment-circulation>.

MODELS THAT CALCULATE THE EFFECTS OF TIDAL ENERGY DEVELOPMENT

Modeling efforts to predict the removal of energy and interruption of water flow from tidal energy development are more common than those for predicting the effects of WEC operation, largely because the physics of developing a realistic model of a turbine and its effects are better known. Efforts in Europe to determine the effects of tidal development on the physical system have been underway for several years, and there have been attempts to test the models with the collection of field data. To date there have not been sufficient devices in the water anywhere in the world to sufficiently calibrate these models.

TIDAL ENERGY MODELS DEVELOPED IN EUROPEAN WATERS

As a part of the MAREN project, researchers at Cardiff University in the UK examined the potential effects of an array of tidal turbines with 10-m-diameter blades in the Severn Estuary and Bristol Channel using a widely used 2D hydraulic model (DIVAST), considering the shape and density of arrays on water flow, water level, and sediment transport. After calibrating the flow model with existing tidal velocity data, the researchers found that spacing turbines allows for additional energy generation (up to 50% more electricity) than closely packed arrays. They were not able to detect any change in the water level (i.e., tidal prism) from any of the array configurations examined, including an array of 2000 turbines packed in a 7.2-km² area, but every array configuration slowed the flow immediately

upstream and downstream of the arrays, while flow speeds increased around the sides of the array. Changes were also seen in the rate of sediment transport around the arrays, which may affect the transport of contaminants such as fecal coliform bacteria. More information about the modeling study is provided by Ahmadian et al. (2012) and Kadiri et al. (2012), available at <http://tethys.pnnl.gov/publications/far-field-modelling-hydro-environmental-impact-tidal-stream-turbines> and <http://tethys.pnnl.gov/publications/review-potential-water-quality-impacts-tidal-renewable-energy-systems>.

Researchers at the University of Plymouth examined alterations in the circulation patterns of the sea shelf caused by the development of a tidal turbine farm. The modeling work focused on a theoretical stretch of coastline and a theoretical array of 12-km-diameter turbines placed in varying turbine densities that was similar to the eastern Celtic Sea, including the Bristol Channel. Of particular interest to the modelers was determining how extracting energy using tidal turbines might change the total amount of energy that could continue to be extracted, and how these changes might be determined within the waterbody. The researchers used a 3D ocean circulation model, validated against existing flow data in UK waters, adding modules that simulated three different densities of turbine arrays. They validated the marine energy module using a synthetic data set that simulated data collected from drifting instruments around the arrays. They also found that densely packed turbines reduced the amount of extractable energy, while more widely spaced farms had little effect. The researchers were able to calculate changes in the ocean circulation at distances of 100 km or more from the arrays, particularly from densely packed arrays placed in the open sea; the effects of arrays placed in a channel were felt locally but had less farfield effect. The overall conclusions reached are that the size, shape, geometry, and siting of tidal arrays may have distinct effects on nearfield and farfield water movement. More information about the project can be learned from Shapiro (2010) and the *Tethys* database at <http://tethys.pnnl.gov/publications/effect-tidal-stream-power-generation-region-wide-circulation-shallow-sea>.

Tidal Energy Models Developed in North American Waters

In addition to measuring tidal current speed in the East River of New York, the Verdant Power team created numerical models to examine the effect of energy removal and flow change around the tidal turbines on water level elevation and flow in the tidal river channel. They defined the potential areas of effect as 1) microscale: closest to the turbine, at a scale of the turbine blades, where interactions can be modeled using computational fluid dynamics (CFD) models; 2) mesoscale: areas within two turbine diameters of the turbines, where the wake behavior of the turbines can be modeled using expanded CFD models; and 3) macroscale: the farfield areas farther from the turbines, where potential changes that might happen in the river because of the placement of the Verdant turbines can be modeled with a 1D hydrodynamic model. The CFD models were not calibrated; the results of field measurements were used to check the output of the 1D macroscale model. The model results predicted that, due to the presence and operation of the turbine, the water levels in the channel would change by less than 0.08% and the water velocity would change by about 3%; closer to the turbines, the overall water depth would increase slightly (by about 12 mm) and the flow velocity would decrease slightly (by about -0.07 m/s). More information about the RITE island deployment can be found at <http://www.theriteproject.com/Documents.html> and in the *Tethys* database at <http://tethys.pnnl.gov/annex-iv-sites/roosevelt-island-tidal-energy-project>.

Researchers at the Bay of Fundy, Canada, examined the effects of tidal energy extraction on the available energy, near the sea bottom and over the entire water column in Minas Passage, using a

3D ocean circulation model (Princeton Ocean Model) of the Bay of Fundy and the Gulf of Maine. The circulation model was well validated with existing data; the researchers checked the effects of introducing tidal turbines into the model with a series of numerical experiments creating synthetic data sets. They found that, if the theoretically extractable energy were all extracted from Minas Passage, the tidal elevation and current would increase throughout the Gulf of Maine, while being reduced in the upper Bay of Fundy, especially in Minas Basin. However, the model also showed that extraction of energy from the lower water column had less effect on tidal elevations and current speed in the Bay of Fundy and Gulf of Maine than would the same amount of tidal energy extraction spread throughout the water column. More information about the study is provided by Hasegawa et al. (2011), available at <http://tethys.pnnl.gov/publications/far-field-effects-tidal-energy-extraction-minas-passage-tidal-circulation>.

Researchers at PNNL developed modeling tools to examine the effect of tidal turbines placed in a channel leading to an estuary, like that of Puget Sound, in Washington State. Using a coastal ocean circulation model (Finite Volume Coastal Ocean Model or FVCOM), the researchers created a realistic model of Puget Sound validated with measurements from CTD casts. The researchers created a tidal turbine module and calculated the maximum amount of energy that could be removed (or number of turbines that could be deployed) before measurable decreases in water circulation and increases in water-quality problems would arise. Researchers modeled both very large arrays (>1000 turbines) and more realistic sized arrays (~100 turbines). Under scenarios with hundreds of turbines, researchers determined that although the resulting ~10% slowing of water circulation might be acceptable; the flushing time of the estuary would increase to the point that water-quality problems would be expected. Using a more realistic number of turbines, detailed changes in vertical water column structure and flushing suggested less deleterious outcomes. The work also showed that using 3D models for determining the effects of energy extraction provides more realistic outcomes than 2D models. More information about this research is provided by Yang et al. (2012) and in the *Tethys* database at <http://tethys.pnnl.gov/publications/modeling-tidal-stream-energy-extraction>.

Researchers at the University of Washington modeled four different types of tidal channels to predict the farfield effects that arrays of tidal turbines might have on the water circulation of the channels. Tidal areas that resembled those examined were Massett Sound, Canada; Roosevelt Island, East River of New York; Minas Passage, Bay of Fundy, Canada; and Puget Sound, Washington State. Using a 1D model, the researchers modeled the tides, water transport, power dissipated by friction, and power density in channels that mimicked the complexity of the natural waterbodies. The model helped the researchers conclude that energy removal by tidal turbines is unlikely to be measurable until large numbers of devices are deployed, each channel or site in which turbines are deployed will have unique features that will determine potential effects, and the geometry and siting of multiple turbines in a channel will largely determine the potential effects on the farfield water flow and associated environmental changes.

More information about this research is provided by Polagye and Malte (2010) and in the *Tethys* database at <http://tethys.pnnl.gov/publications/far-field-dynamics-tidal-energy-extraction-channel-networks>.

Researchers at SNL modeled the interaction of tidal turbines in a river channel (Mississippi River, Louisiana) and in two tidal channels (Cobscook Bay, Maine, and San Francisco Bay, California) using a 3D hydrodynamic model (SNL-EFDC) modified to include sediment transport and MHK modules; they examined the effects of array size and geometry on water flow, water elevation, flushing, and sediment transport. SNL-EFDC enhancements were validated against flume experiments of sediment

transport and turbine operation. The researchers used the models to examine the relationship between array size and geometry on power output and environmental effects to support array optimization. In all systems, the researchers found that the operation of small numbers of turbines (30 or fewer turbines) had a negligible effect on farfield hydrodynamics and flushing. Near the devices, water flow was significantly decreased in the device wake (recovering to 90% after about 15–20 m) causing water flow to increase around and over/under each device and the array as a whole. They found that for bottom-mounted devices the velocity deficit behind the turbine could lead to excess deposition in the wake region, but that flow increases below and around the turbine arrays could lead to erosion of the banks and scour in the vicinity of the turbine foundation. For the Mississippi river channel, a modeled scenario with turbines bottom-mounted on 4, 23, and 112 pilings with a total of 12, 124, and 534 turbines, respectively, did not pose a significant flooding hazard; maximum water elevation gains were between 2 cm and 5 cm during above-average flow conditions. For the Cobscook Bay tidal array, the researchers modeled 5 ORPC TidGen cross-flow turbines each ~30 m long and ~4.5 m tall. The resulting decrease in the tidal range due to the presence of the turbines was less than 1 mm and flushing was increased by less than 0.25%; both represent essentially no change. For San Francisco Bay, the researchers modeled 30, 150, and 300 tidal turbines that had 20-m diameters. Maximum tidal range decreases were 0.2 cm, 2 cm, and 4 cm, whereas flushing was increased by less than 0.1%, 1%, and 3% for the operation of 30, 150, and 300 turbines, respectively. More information about this research is by Barco et al. (2012) for Louisiana, Roberts and James (2012a) for California, and in the *Tethys* database at <http://tethys.pnnl.gov/publications/snl-efdc-model-application-cobscook-bay-me> and <http://tethys.pnnl.gov/publications/snl-efdc-model-application-scotlandville-bend-mississippi-river>.

Discussion and Identification of Data Gaps

As tidal turbines and WECs are introduced into marine waters, the most common environmental concerns raised by regulators and stakeholders are the safety of marine animals and habitats. However, the long-term integrity of the marine ecosystem requires that inquiries also be made into the potential effects of placing devices in the moving waters and the ecosystem effects of withdrawing energy from those systems.

Tidal and wave energy developers are keenly interested in measuring the movement of tidal streams and wave heights/periods, respectively, to estimate the availability of power for harvest. As marine energy moves towards commercial arrays, developers also require measurements of energy and flow to optimize array configurations, limit wake effects, and gauge the number of devices that can be supported in a given area. In response to the concerns of regulators and stakeholders, developers may also measure the physical system (water flow, sediment transport, effects on nutrient and contaminant dispersal, and effects on the marine food web) to determine the potential deleterious effects from marine energy devices and arrays.

As the marine energy industry moves forward, single devices or very small arrays are being deployed. The small footprint of these devices, entering into large bodies of swiftly moving water, ensures that there is little possibility of measurable changes to the physical environment. Until commercial-scale arrays are deployed, particularly in close quarters with other arrays, there is little likelihood that disruptions of water flow, sediment transport, or other effects will be distinguishable from the natural variability of these high-energy waterbodies. Similarly, the potential effects of marine energy devices may not be seen for years or decades of operation because the very small effects on each tidal cycle or wave train must accumulate over time before effects will become measurable. Data on the movement of water in marine energy areas will be collected by developers to support calculations of energy potential and assist with the siting of devices, and it is likely that regulators will continue to request measurements of the potential effects on the physical environment. However, results from high-fidelity numerical models may have a greater capacity to provide useful predictions of future effects than will direct water measurements at commercial-scale deployment.

CHALLENGES FOR PREDICTING THE EFFECTS OF MARINE ENERGY ON THE PHYSICAL ENVIRONMENT

The large temporal and spatial scales of potential marine energy effects on the physical environment present a considerable measurement challenge. The following five additional challenges are likely to benefit from focused research that will improve the accuracy of predictions:

- **Model Validation** – The most critical element for accurately predicting future effects on the physical environment is the validation of numerical models using field data collected around operating marine energy devices. Researchers validate oceanographic models using tidal, wind, incoming wave, and bathymetric data; these models require measurements that are symptomatic of changes in flow around wave and tidal devices, changes in sedimentation patterns, and sediment transport rates. Energy balances can be routinely evaluated once these measurements are made to prevent ambiguities in the level of power generation modeled. Because of the variability in the environment and the complexity of the system, some discretion must be taken when using model outputs.
- **Turbulence** – Measuring turbulence in high-energy tidal or wave generation areas is difficult because ocean conditions are not conducive to the deployment, operation, and recovery of instruments. Although ADCPs, ADVs, and EMVs are routinely used by oceanographers to measure turbulence, their application to the small scale of a tidal turbine or WEC requires significant improvements in instrumentation and software for data processing and analyses. Without accurate measurements of turbulence, results from numerical models may magnify effects that are nonexistent or may overlook other important effects.
- **Effects from specific marine energy devices** – Results of research studies that couple marine energy modules with established oceanographic models are appearing in the scientific literature; however, the results related to the specific mechanisms of energy removal and flow disruption for energy devices are generalized. The plethora of marine energy device designs, particularly WECs, makes it difficult to judge the applicability of these generalized model results to specific devices deployed in specific waterbodies. Computer code for energy removal must be written so that model parameters more accurately represent particular devices; additional studies of the interactions between device design and the marine environment are needed to simulate the many types of devices.

- Coupling the nearfield with the farfield – Modeling efforts to date have focused on the nearfield (immediately around the device) or the farfield (generally at a distance from the device and/or encompassing a significant portion of a waterbody). Coupling these two types of models and creating a coherent understanding of the linkages between what is happening around the device and within a waterbody is a necessary step to understanding the effects on the physical system at the local and system-wide scale.
- Cumulative effects – The ability to extrapolate measurements of water flow and sediment transport in marine energy sites, coupled with the development of effective numerical models, can help predict the potential effects of the first hundred or so marine energy devices deployed in coastal waters. However, the baseline calibration for a model may not remain static with high levels of energy removal, so there is also a need to look ahead to potential cumulative effects once multiple marine energy installations are built within a region. Interactions between and among arrays, as well as intra-array interactions and possible additive or multiplicative effects, will require more complex models and enhanced field validation data.

EXISTING EVIDENCE FOR UNDERSTANDING THE EFFECTS ON PHYSICAL SYSTEMS – MEASUREMENTS

Few marine energy projects have reported measurements of the physical environment with the express purpose of understanding the potential effects of deployment and operation of the devices. Two prominent examples of these measurements are the Verdant RITE project in the United States and the SeaGen Strangford Lough project in Northern Ireland.

Verdant measurements in the East River were not able to detect changes in flow patterns in the immediate vicinity of the tidal turbines (microscale), in the area adjacent to the turbines (mesoscale), or farther away in the river channel (macroscale). The researchers concluded that the six relatively small Verdant turbines neither disrupted the river flow nor removed sufficient energy to be measured against the natural variability. The measurements made in the river channel were used to verify the 1D modeling results.

SeaGen researchers in Northern Ireland measured flows at greater distances from the turbine, but were also not able to detect changes before and after turbine installation.

The inability of these two project investigations to measure changes in the physical system with the presence of tidal turbines, using the most sensitive instruments commercially available, leads to the conclusion that the signal must be extremely small against the background noise of tidal flow. At a minimum, larger array deployments are needed before there is any chance of detecting change. Although neither of these projects attempted to measure turbulence at the turbine blade scale, there is no indication that the disruption caused by turbulence will cause damage except perhaps to the turbine blades and mechanical parts. The experience in the East River and Strangford Lough can assist other projects in determining the efficacy of relying on velocity measurements to gauge potential effects on the physical environment, and underscores the need to apply these measurements to modeling efforts to predict effects over a variety of spatial and temporal scales.

EXISTING EVIDENCE FOR UNDERSTANDING THE EFFECTS ON PHYSICAL SYSTEMS – WAVE MODELING

There are challenges to modeling the potential effects of WECs on the physical environment. Oceanographers have considerable experience modeling waves, but the locations of initial WEC

deployment (within a few miles of shore in high-energy areas) are not preferred research venues. The complexity of WEC designs has complicated the process of placing the necessary code in models to simulate flow disruptions and energy loss. The potential secondary effects of wave energy removal (such as changes in longshore currents and sediment transport) are also not well documented in the high-energy areas where marine energy development is preferred.

Wave modeling studies from Europe and North America have addressed a variety of questions related to the effects of WEC operation on the physical environment. The most common outcome of the models is to underscore that the effects of WECs are highly dependent on many factors: the type of device (Palha et al. 2010; Wave Dragon), the seasonal wave height and period (Palha et al. 2010), the temperature and climate condition of the ocean (Reeve et al. 2011), water depth and the distance from shore (Palha et al. 2010; CPT), and the number of WECs in an array (Palha et al. 2010; Roberts et al. 2012). Most of the numerical models that have considered the issue use theoretical energy dissipation to simulate the removal of energy from WECs; only a few (CPT; Roberts et al. 2012) have developed computer code that specifically simulates the elements of a WEC that affect the wave propagation flow of water and that act as energy dissipation sinks (energy removal sites).

EXISTING EVIDENCE FOR UNDERSTANDING THE EFFECTS ON PHYSICAL SYSTEMS – TIDAL MODELING

Oceanographers have focused more closely on models of ocean circulation than on wave models; hence, the development of models that simulate removal of energy and flow changes from tidal turbines have proliferated. The physics of an enclosed tidal basin or race are not simple but are better understood than the open boundary conditions that delineate wave models. Modelers are assisted in the development of tidal energy removal modules by experience modeling related to terrestrial wind and conventional hydro turbines.

Modelers in Europe and North America have focused on several end points to describe the potential effects on the physical environment: changes in tidal elevation (Ahmadian et al. 2012; Kadiri et al. 2012; Polagye and Malte 2009; Verdant Power 2003; Hasegawa et al. 2011), changes in flow rates (Ahmadian et al. 2012; Kadiri et al. 2012; Polagye and Malte 2009; Yang et al. 2012; Roberts and James 2012b), sediment transport and scour (Barrett 2012; Ahmadian et al. 2012; Roberts and James 2012a), and flushing time (Yang et al. 2012). In each case, the oceanographic models have been validated to ensure that the operation is realistic and produces reproducible results; however, tidal energy modules still need validation.

LESSONS LEARNED, DATA GAPS FOR MEASURING THE EFFECTS ON PHYSICAL ENVIRONMENT

Numerical models present the best opportunity to predict the potential effects of large-scale buildout of marine energy farms in coastal and estuarine waters. Present-day computing power and a strong academic discipline of oceanographic model creation provide a powerful platform for developing accurate and useful numerical models for gauging potential effects. It is clear from the modeling results to date that nearfield changes in water flow in high-energy tidal and wave sites are unlikely to be measurable at individual turbines and WECs; strong evidence also supports the likelihood that measurable farfield changes in water flow or sediment patterns will only occur with buildout of large numbers of marine energy devices. There is, however, significant uncertainty about the number of turbines or WECs that might be needed to observe farfield changes in the environment. Typically, researchers measure the potential endpoint of such a buildout by placing sufficient devices to capture a significant portion of the available ocean energy. In most cases, these buildout scenarios entail

model deployment of hundreds or even thousands of devices—far more than could ever be permitted in a region because of interactions with marine animals and habitats. The great unknown for predicting changes in the physical environment is whether it is possible to predict a tipping point where farfield changes might occur at device numbers well below the point where significant available power is harvested, or whether in fact such a tipping point is even plausible. Additional model development and validation will bring researchers closer to answering these questions.

Although oceanographic instrumentation is well developed and improvements continue as researchers examine the deep oceans and world navies explore the far corners of the Earth, specialized instrumentation is needed to better measure turbulence at the scale of single turbine or WEC components, and in the high-energy waters where they are deployed. However, the push for improved instrumentation must address the measurement of power resources and water movement that may be detrimental to marine energy devices and capture changes that may affect the overall physical marine environment. Opportunities to collect quantities of physical data abound with siting and planning for tidal and wave deployments and array buildouts; it is critical that environmental data needs be considered at the same time, and that marginal additions to assessments and monitoring programs be made to continue to explore the potential for effects on the physical environment through improved model validation.

Finally, the basics of oceanographic processes are well known, particularly the movement of water and sediment. The chemical and biological processes that depend on these physical processes are not well elucidated; however it is expected that changes in water flow will result in biological changes to individuals, populations, and communities. The energetic nature of marine energy sites presents challenges that may require new conceptual models and methods of measurement. Collaborations among scientists from biological, physical, and biogeochemical fields focused on marine energy may provide the best opportunity to improve model predictions and bring better understanding of the potential for harm to the physical environment.

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DISCUSSION

The initial phase of Annex IV is completed with the distribution of this report. Progress has been made in developing and populating the database of information about the environmental effects of marine energy development from participating nations, and three case studies have been written to explore the state of knowledge from existing wave and tidal demonstration and small-scale pilot projects and from research studies. Future activities that expand on the initial Annex IV process will build on the information collected in the database, learn from the material examined for the case studies, and be informed by the involvement and critical thought of the participants in the two experts' workshop as well as those who contributed to the metadata and advice on the process.

Lessons Learned from the Case Studies

The three case studies provide lessons related to the purpose of each, as well as several common themes. Overall the greatest lesson from the case studies (and the Annex IV process in general) is that there continues to be a dearth of quantitative environmental information from tidal and wave devices that have been deployed in coastal waters. In addition, there are inadequate research and modeling data to adequately characterize the potential effects of marine energy devices, particularly at the large commercial scale.

Following the principles of adaptive management, many regulators have acknowledged the need to allow pre-installation data collection efforts to help inform the design and implementation of post-installation monitoring activities on an iterative basis. Some device and project developers have agreed to create and implement adaptive management plans for monitoring around devices as a way to "learn by doing". Adaptive management plans can be used to identify the perceived risk level for each targeted marine resource, and link that risk to the appropriate level of monitoring effort. Researchers are actively engaged in designing field experiments that can build upon the results of previous studies, and that will allow future data collection efforts to maximize the information gained.

The most significant findings of case study 1 of the interaction of marine animals and turbine blades are as follows:

- There is no direct evidence of adverse interactions between marine animals and rotating tidal turbine blades from installed devices that have been monitored to date. However, the very small number of deployments and monitoring results, generally over short periods of time, do not provide a robust record of interactions and additional monitoring results and field experiments are needed to assess the potential risk to animals from blade strike. The potential effect of turbine blades is likely to continue to be raised by regulators and stakeholders for considerable time; even as additional, larger, and longer-term deployments occur, the conundrum of trying to prove that animals do not interact with the blades adversely will remain challenging, because scientists must

prove the negative to succeed. Alternative means to understand and estimate the potential interactions of animals and blades may prove to be necessary to ease concerns about risk.

- Changes in the behavior of animals in the vicinity of turbine blades, including attraction to or avoidance of the devices, is likely to require ongoing monitoring, once more devices are in the water, to determine whether these changes in behavior have population-wide adverse effects such as confusing behaviors needed for survival (e.g., hunting, avoiding predators, and/or reproductive or developmental success). Population-wide effects caused by behavioral changes are unlikely at the pilot scale.
- Significant gaps in information that will help to inform the risk from animals interacting with turbine blades include the need to examine encounters of a range of animals with a range of designs of turbines that represent the developing tidal device market.

The most significant findings of case study 2 of the effects of noise from tidal and wave devices are as follows:

- Accurate measurements are needed of the ambient noise in the waters in which marine energy devices are deployed and the noise created by the devices themselves. The details of temporal and spatial propagation of the sound from the devices are complex, and they require integration of the sound levels (dB) as well as the frequency range (broadband, Hz, kHz) in order to understand the noise environment to which marine animals will be subjected.
- Measurements of operational sound from the small number of deployed pilot-scale devices have been relatively small compared with other overall sound budgets of the environments in which the devices are placed. For most device types, the potential for large-scale effects from operational noise is an issue most relevant to commercial-scale, rather than pilot-scale projects.
- The very limited number of projects that have examined the effects of construction and operational noise have found no long-term changes in animal movement or behavior patterns, although one project showed short-term displacement of harbor porpoises during construction activities. However, evidence of displacement and disturbance of marine animals due to underwater noise from other marine industries suggests that investigations of potential effects will be needed as large marine energy arrays are deployed and operated in coastal waters.
- Understanding the effects that specific noise signatures from tidal and wave devices will have on marine animal hearing, behavior, and other potential injury, is essential to predicting how these devices may affect marine populations, and to designing appropriate mitigation, if needed. Marine animal behavioral changes in response to noise may manifest as attraction to or avoidance of devices and potential hearing threshold shifts. These changes may cause displacement from important habitats for feeding, mating, rearing, migrating, and resting. Until sufficient measurements of sound around operating devices and observations of animals in the vicinity of devices can be obtained, this issue will likely continue to be raised by regulators and stakeholders. However, by direct measurements and observations around large arrays over periods of time, it should be possible to directly correlate any potential effects with acoustic output of the devices.
- Key data gaps include the need to develop and deploy improved instrumentation for measuring the acoustic output of the devices, observing animals' behavior around devices, and correlating the two.

The most significant findings of case study 3 of the effects of energy removal by wave and tidal devices on the oceanographic systems in which they are deployed as follows:

- To date, deployments of tidal and wave devices are far too few and far between to measure their potential effects with accuracy. As large commercial-scale arrays are deployed, with multiple arrays in close proximity, measurements of changes caused by changes in water flow and energy removal might be measureable.
- Numerical models that can realistically load tidal and wave energy areas with many devices present the best opportunity to predict potential effects. Models to date tend to over-emphasize the number of turbines or WECs that might be deployed in order to show effects; models that engage realistic numbers of devices are likely to be used in future to try to understand the likelihood of changes at the ecosystem level in water quality, sediment transport, and the marine food web.
- The greatest data needs in this area are data sets that can be used to validate the numerical models. These models must continue to become more realistic and to describe the interactions of marine energy devices with the environment using modeling code that is specific to devices found in the emerging marine energy market.

Path Forward for Annex IV

As the three-year Annex IV project draws to a close, it is clear that future activities could further support the understanding of the environmental effects of marine energy development and continue to meet the goals initially identified under the Annex IV work plan. The amount of environmental monitoring data collected to date has been limited in both scope and scale, as the marine energy industry progresses through the early stages of development. Key environmental questions remain unanswered that future activities could help to inform. The Annex IV Operating Agent (the United States) has agreed to commit resources to maintaining the *Tethys* database and continuing to collect information from around the world for input into the database. However, continued commitment from other nations would greatly augment the ability to identify and aggregate information about environmental monitoring from marine energy development and research projects around the world. As was noted repeatedly at the second Annex IV experts' workshop (held October 15, 2012, in Dublin, Ireland), unless the *Tethys* database is adequately maintained and perceived to contain sufficient quantities of up-to-date information, it will not be used by the marine energy community. At the time of this report's publication, the United States has engaged the OES member countries to discuss the possibility of extending the Annex IV effort for an additional period, or initiating a new Annex sometime during calendar year 2013. Activities under an extended or new Annex would likely be focused on continued metadata collection and analysis by member nations, formal periodic reviews of the database, and expanded database functionalities as identified during the second Expert's workshop. Other potential activities may include partnering with other organizations to host international scientific conferences or workshops, and future publications to provide updates on new environmental monitoring or research activities. The most important goal is to ensure that the work completed thus far under Annex IV forms the foundation for future efforts that further development of a thriving, environmentally sustainable marine energy community around the world.