REVIEW

Recent Advances in Assessing Environmental Effects of Marine Renewable Energy Around the World

AUTHORS

Andrea E. Copping
PNNL

M. Luisa Martínez
INECOL

Lenaïg G. Hemery
PNNL

Ian Hutchison
Aquatera

Kristin Jones
Marley Kaplan
PNNL

ABSTRACT

Marine renewable energy (MRE) is increasingly of interest to coastal nations as a source of renewable energy that can support climate change mitigation goals as well as provide secure locally-produced energy for coastal and island communities. MRE extracts power from tidal streams, waves, ocean currents, run of rivers, and gradients in the ocean, with specialized devices developed and tested for each energy resource. Alongside development of MRE technologies and systems, first in Europe and then in North America, Australia, Asia, and other regions, it has been universally recognized that there is also a need to examine potential effects on marine animals, habitats, ecosystem processes, local communities and other sea users, to ensure that the MRE industry can be developed in a responsible and sustainable manner. This paper looks at the status of assessment and monitoring for potential environmental effects associated with MRE projects around the world. Over 80 projects were identified worldwide as having been tested, demonstrated, or commercially deployed with associated environmental monitoring. Five of the projects that represent tidal stream, wave, and run of river projects are examined in more detail to determine the types of data and information collected for those projects, the outputs of the monitoring campaigns, and the actions taken as a result of the data collection and analysis. Recommendations are provided for standardization of the monitoring approaches, instruments, and analysis methods at MRE project sites worldwide.

Keywords: marine renewable energy, environmental effects, risk retirement, environmental monitoring, stressor-receptor interactions

Introduction

Human activities, particularly the burning of fossil fuels and deforestation, have led to an increase in greenhouse gas concentrations in the atmosphere, resulting in climate change. The decade from 2011–2020 was particularly significant, with global surface temperatures reaching 1.1°C above the pre-industrial levels of 1850–1900 (IPCC, 2023; Lynas et al., 2021). Effects of climate change are becoming more apparent each year, as manifested in the increases in severe weather, strengthening intensities of hurricanes and typhoons, and rising sea levels (Edwards et al., 2021; Wolf et al., 2020). At the same time, coastal and island communities face increasing pressures around the availability, security and affordability of energy supplies as well as recognizing the detrimental effects of fossil fuel use on public health and nearshore environments (SIDS Dock, 2021). These concerns are leading to accelerated adoption of sustainable renewable energy around the world. While land-based and offshore wind and solar photovoltaics (PV) have gained the most ground, many countries are taking an "all of the above" approach, diversifying their portfolios of renewable energy and energy storage systems to supply their specific needs. In addition to countries in Europe, North America, Asia, and Oceania, more and more coastal and islands nations around the world are examining the potential for adding marine renewable energy (MRE) to the mix, which includes energy supplied by tidal streams, waves, persistent ocean currents, the run of large rivers, as well as thermal and salinity gradients in seawater.

In 2016, the United Nations wrote the Sustainable Development Goals, an "urgent call for action by all countries - developed and developing - in a global partnership" (United Nations, 2024). Different actions are recognized within the 17 Sustainable Development Goals, which include ending poverty and hunger, reducing inequality, together with strategies to improve health and education, promoting economic growth, and tackling climate change and environmental degradation (especially forests and oceans). Specifically, Goals 7 (ensuring affordable, reliable, sustainable, and modern energy for all) and 13 (take urgent action to combat climate change and its impacts) are related to energy and the environment. The agenda to achieve the Sustainable Development goals by 2030 was unanimously adopted in 2018 by the 193 UN Member States. This adoption is one of several reasons that many countries are actively working toward using renewable energy supplies.

MRE resource characterization studies have been carried out in many parts of the ocean (nearshore and offshore) to better understand what resources are available in specific regions and locations. Energy generation technology developers and researchers are engineering technology and supporting infrastructure required to efficiently and sustainably extract the energy from tidal streams, waves, ocean currents, large rivers, and gradients of temperature and salinity from ocean waters. While the adoption of renewable energy generation technologies, including MRE, are of utmost importance for climate change mitigation, sustainability of MRE development must also ensure that the marine environment, the marine life and habitats supported by oceanographic processes, and the coastal communities who rely on the ocean for their livelihoods are not significantly negatively impacted in the process. It is also important that opportunities for biodiversity recovery and enhancement, as well as economic growth and social inclusion, are considered when planning and developing MRE projects in order to maximize long-term sustainability.

Potential environmental effects of MRE development will depend, among others, on the type of generation technology selected, and its subsystems, supporting infrastructure requirements, the geographic and bathymetric aspects of the deployment site, placement of the device on the seafloor or in the water column, the presence of specific marine animals and habitats, the number and size of energy generating devices, the duration of deployment, as well as a range of social and economic factors such as the size and character of nearby communities, and potential conflicts, synergies, and cumulative effects with other marine uses. It will also be driven by the particular energy market application being targeted by the developer, that is, whether it is a large, utility scale development, a small array designed to power an island micro-grid, or an installation designed to power ocean observation platforms or an offshore aquaculture site.

Researchers in many nations have examined potential interactions between stressors (those components of MRE systems that may cause stress, injury, death, or degradation of marine animals, habitats, or ecosystem processes) and receptors—the animals, habitats, and processes (Boehlert & Gill, 2010) for tidal stream and wave devices (Copping, Hemery et al., 2020) and additional investigations are underway for ocean thermal energy conversion (OTEC) effects. The greatest perceived risks are associated with the areas of greatest uncertainty, and are considered to be from: marine animals colliding with rotating turbines blades (relevant to tidal stream, run of river, and ocean current only); effects on marine animal navigation and communication from underwater noise from operating MRE devices; effects on sensitive marine species from electromagnetic fields (EMFs) from power export cables and/or operational devices; changes in benthic and pelagic habitats from the presence and operation of devices; entanglement of large marine animals in mooring lines and draped cables; changes in oceanographic systems from the presence and energy removal by arrays of devices; and displacement of marine animals because of the presence and operation of large arrays (Copping & Hemery, 2020; Hemery et al., 2024; Martínez et al., 2021). Some of the potential effects on species, ecosystems, and abiotic factors induced by MRE devices are: altered behavior of the fauna including bioenergetic effects; changes in predation or competition levels; changes in migratory routes; population failures; injuries or death of individuals; changes in biodiversity and food webs; arrival of invasive species; degradation of habitats; shoreline changes; and changes in ecosystem connectivity (Hemery et al., 2024; Martínez et al., 2021).

The degree to which different nations have examined potential environmental effects of MRE depends on how prolific the development of MRE projects is in the nation; the rigorous nature of the regulatory process and whether the process requires an examination of specific types of interactions between the MRE project and associated infrastructure, with marine animals, habitats, and ecological processes; the location of proposed and existing MRE projects in areas frequented by marine species of concern;

the number of researchers focused on environmental effects of MRE; maritime capabilities such as vessels and remote operating vehicles and the trained professionals to operate them; the presence of other maritime industries such as fishing and shipping that may cause communities to oppose MRE; and the availability of strategic and project level funding to carry out studies.

Prior to the planned deployment of an MRE device or array for demonstration, testing, or commercial deployment, project proponents will collect physical data that include measuring the energy resource of the area and associated hydrographic conditions, the bathymetry, seabed characteristics, and potential hazards. Other key information collected will usually include the existing use of the area by other sea users, distance to ports and harbors for installation and maintenance, and the distance to the planned off-taker such as a grid or microgrid connection for grid-connected projects (LiVecchi et al., 2019), and the social perception toward the deployment and functioning of renewable energy devices (Wojtarowski et al., 2021). In addition, gaining regulatory approval in most nations requires the collection of certain physical, biological, and (often) social and economic data. Potential environmental effects are evaluated for consenting/permitting (hereafter consenting) purposes through baseline assessment of the habitat, flora, and fauna in the region and their relationship to physical parameters including bathymetry, location with respect to coastlines and other bodies of water, coastal geometry, and presence of ongoing anthropogenic stressors (Cradden et al., 2016). Some jurisdictions may also require some data collection post-consenting but prior to deployment (as a requirement of a consent). Most jurisdictions require some post-installation monitoring of potential effects (Buenau et al., 2022), although this may depend on the outcomes of consenting processes and the associated environmental impact assessment, as well as national and local policies.

Ocean Energy Systems-Environmental (OES-Environmental) is a consortium of 16 nations, tasked under the International Energy Agency's OES to examine the environmental effects of MRE to assist with consenting of MRE projects, helping the industry to develop in a responsible and sustainable manner. OES-Environmental is led by the U.S. Department of Energy Water Power Technologies Office and implemented by Pacific Northwest National Laboratory. For more information see Tethys (2024a).

The work of OES-Environmental has focused on evaluating the risks from specific stressors from MRE devices and systems by applying existing research results and developing a risk retirement process. The risk retirement process stands on the idea that not every stressor-receptor interaction needs to be examined at each new project site, but rather data and information applied from already consented sites, analogous industries, or research studies can be used to support regulatory processes including consenting. This concept of risk retirement, and the methods to apply existing data are documented in Copping et al. (2018) and have been applied to the examination of MRE projects here (Copping, Freeman et al., 2020).

This paper seeks to assess the status of MRE development around the world for which environmental effects have been examined, as well as the general trends in discovery of information on stressor-receptor interactions associated with MRE, by country, and by type of MRE converter. A subset of projects were chosen for a deeper examination of the processes of data collection and monitoring.

Methods

The information gathered for this analysis was collected largely from the OES-Environmental collection of "OES-Environmental Metadata Forms" (Whiting et al., 2019). These forms document environmental effects assessments and data collection for past and present deployments of MRE devices and projects, for which information is available. This collection documents work at test sites, open water pilot and demonstration projects, and commercial developments. The information reflected in the OES-Environmental metadata forms has been collected since 2010 with assistance of MRE technology developers, researchers, project developers, and others, and is the most complete collection of such information. As of July 1st 2024, there are 145 metadata forms available online on Tethys, reflecting tidal stream, wave, ocean current, large run of rivers, OTEC, and salinity gradient deployments (Tethys, 2024b).

For this study, each metadata form representing a deployment of an MRE device or array was examined for variables that describe the stage of development, environmental assessment, and monitoring (Table 1). The resulting data were parsed by country and region, as well as advancement in understanding

TABLE 1

Information on MRE devices, as reflected on OES-Environmental metadata forms, for which environmental data have been collected.

	Variables			
	Technology Type	**Region/Country of Deployment**	**Phase of the Project**	**Environmental Stressor—Receptor Interactions Examined**
Options	Tidal stream	By continent and country	Planned	Collision risk
	Wave		Deployed	Underwater noise
	Ocean current		Operating	EMFs
	Run of river		Tested only	Changes in pelagic/ benthic habitat
	OTEC		Abandoned	Changes in oceanography
	Salinity gradient		Decommissioned	Displacement
				Other

the results of specific stressor-receptor interactions.

A framework for evaluating the quality and outcomes of environmental assessment data collection, analysis, and interpretation was developed for a subset of MRE projects for which sufficient data were available that represented a range of the most common stressor-receptor interactions that drive consenting (Table 2). The purpose of this examination was to gauge the effectiveness of the data collection and monitoring for subsequent regulatory and operational actions, by cataloging the outcomes of the data collection and monitoring in terms of reports and papers, and to evaluate the outcomes as steps in regulatory processes.

Table 2 provides the framework against which five case studies were evaluated: two tidal stream projects, two wave projects, and one run of river project. Within the framework, the "Level of monitoring" is designed to evaluate the extent of baseline and post-installation monitoring that has been carried out, as well as the duration of data collection and standardization of the methods. Baseline assessments include all activities up until an MRE device or array is deployed, while post-installation monitoring covers all data collection after the project is in the water. The "Output of monitoring" lists the reports, papers, datasets, and other media that have been produced and analyzed as part of the project, while the "Outcomes or use of the information" address what has been done with the data and information produced from environmental monitoring. The outcomes are intended to provide insight into how well the information furthered the MRE project, as well as adding to the overall knowledge base of environmental effects. The results criteria are adjustable based on the set of projects examined and could be as simple as a presence/absence or a quality/quantity rating.

TABLE 2

Framework for evaluating environmental data collection, analysis, and monitoring.

	Criteria	Results
Level of monitoring	Duration of monitoring	–/+
	Baseline monitoring performed	Yes/No
	Post-installation monitoring performed	Yes/No
	Accepted methods used	Yes/No
Output of monitoring	Research report	Citations
	Government report	Citations
	Peer-reviewed paper	Citations
	Conference paper	Citations
	Other products	Citations
Outcome or use of the information	Risk was retired	Yes/No
	Mitigation required	Yes/No
	Led to delays or cancellation of project	Yes/No
	Were the outcomes linked to monitoring outputs	Yes/No

Results

The OES-Environmental metadata forms were sorted by country and

TABLE 3

Environmental monitoring for potential MRE effects, by region and nation. Most deployments have been of short duration for testing, while others are in late stages of planning for commercial deployment.

				Environmental Monitoring						
Region	Country	Type of Technology	Phase of Development	Collison Risk	Underwater Noise	Electromagnetic Fields	Habitat Changes	Changes in Oceanography	Displacement	Other
Europe	France	4 tidal	3 tested and decommissioned 1 planned							
	Ireland	1 wave	1 tested and decommissioned							Baseline assessment of fauna
	Italy	1 tidal	1 tested and decommissioned							
	Netherlands	1 tidal	1 operational							Movement of fauna
	Norway	3 wave	1 operational 2 tested and decommissioned							
	Portugal	2 wave	1 operational 1 tested and decommissioned							Sediment transport
	Spain	3 wave	1 operational 1 tested and decommissioned 1 planned							
	Sweden	Multiple wave	Multiple tested and decommissioned							Sediment sampling
	Sweden	1 run of river	1 operational							
United Kingdom	United Kingdom	14 tidal	7 operational 3 tested and decommissioned 1 tested and never recovered 3 planned							
	United Kingdom	4 wave	3 tested and decommissioned 1 planned							
	United Kingdom	9 tidal	5 tested at EMEC and decommissioned 2 operational							Navigation, human dimension
	United Kingdom	8 wave	7 tested at EMEC and decommissioned 1 tested and never recovered							Atmospheric emissions, fisheries impacts, navigation, entanglement
	United Kingdom	1 ocean current	1 tested and decommissioned							Entanglement
Americas	Canada	8 tidal	5 tested and decommissioned 1 tested and never recovered 2 planned							Human dimrensions
	Canada	2 run of river	2 tested and decommissioned							
	Chile	1 wave	1 operational							Baseline assessment of fauna
	Mexico	1 ocean current	1 planned							
	United States	3 tidal	1 operational 2 tested and decommissioned							
	United States	4 wave	4 tested and decommissioned							
	United States	2 run of river	1 operational 1 tested and decommissioned							
Asia	China	1 wave	1 operational							
	Japan	1 tidal	1 tested and decommissioned							Fisheries interactions
Oceania	Australia	9 wave	7 tested and decommissioned 1 tested and never recovered 1 planned							Baseline assessment of fauna
	Australia	1 tidal	1 tested and decommissioned							Water quality, impacts on flora and fauna, vibration
Middle East	Israel	1 wave	1 operational							

technology type, and the environmental monitoring carried out at each site was organized by stressor-receptor interaction. This process helped to identify the MRE projects with the most complete monitoring information for examination, using the framework for evaluating the quality and outcomes of environmental monitoring.

Environmental Monitoring at MRE Sites Around the World

In nations where MRE projects have been deployed and where environmental data are collected and analyses are undertaken to determine potential ecological risks to marine animals, habitats, or processes, the information is organized by region (Table 3). As of July 2024, a total of 42 tidal stream, 37 wave, and five run of river projects were found to be in the final process of planning and/or have carried out environmental monitoring around MRE devices. No evidence of monitoring around OTEC or salinity gradients devices was found. The MRE projects have been categorized by the six most commonly recognized potential ecological risks from MRE project development (Copping & Hemery, 2020)—collision risk, underwater noise, EMFs, changes in habitats, changes in oceanographic systems, displacement of animals—with additional types of data collection and monitoring noted as well.

There are clear patterns among the various regions and countries where MRE projects have been planned and deployed, with the U.K. leading with 36 devices, followed collectively by the countries of Europe and the Americas with 16+ and 21 devices, respectively. As a nation, Australia has deployed 9 wave devices, while other countries and regions have fewer devices around which environmental data collection have been undertaken. Almost all of the device deployments and advanced planning for environmental monitoring have occurred at test sites or at pilot deployments, without the expectation that the projects would grow into commercial arrays, although many of the test and pilot projects have sent power to local or national grids. The number of projects in each nation is clearly influenced by the presence of test sites, with the European Marine Energy Center (EMEC) responsible for the largest number of tidal and wave deployments. Other test centers such as the Biscay Marine Energy Platform (BiMEP) in Spain and Wave Energy Test Site (WETS) in the U.S. have been responsible for other projects that have collected environmental data.

Operational projects should be considered as commercial endeavors if they address power needs of their end users, at the appropriate scale. Presently, these projects include: a) the tidal array project in Pentland Firth, Scotland, U.K.; b) the Nova Innovation tidal array in Bluemull Sound, Shetland, U.K.; c) the Oosterschelde Tidal Power turbines tidal turbines installed within the Eastern Scheldt storm surge barrier in the Netherlands; d) a river project in Sweden; e) the RivGen river current project in Igiugig, Alaska, USA; and the f) Eco Wave Power Station wave project in Jaffa, Israel.

All MRE projects examined had carried out some degree of baseline assessment in the project area prior to installation; many of these assessments relied heavily on data and information collected previously by government agencies or other stakeholders (e.g., Davison & Mallows, 2005; Minesto, 2016). All the jurisdictions that were examined specified the need to collect data post installation, for varying lengths of time.

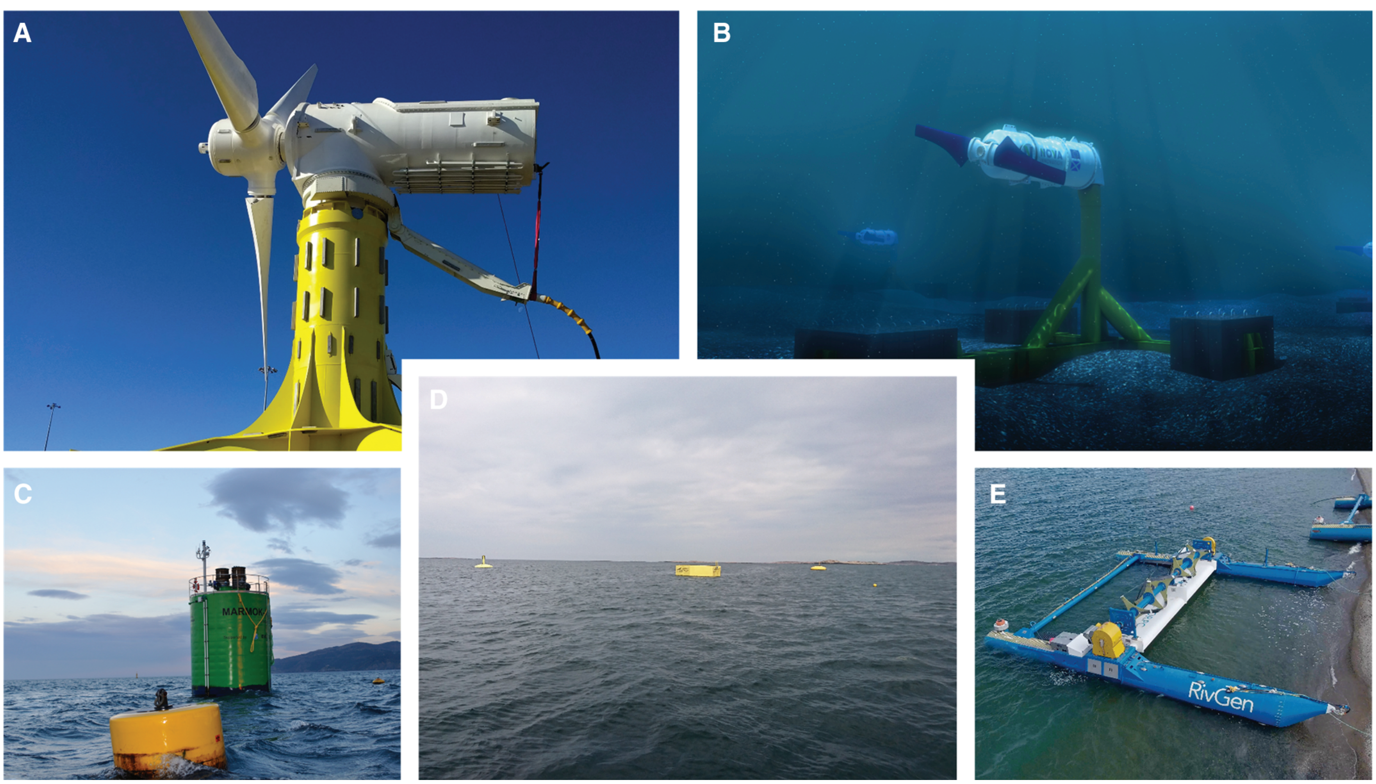
Applying the Framework

The framework developed to evaluate the type, level, and outcome of environmental monitoring undertaken around MRE projects was applied to five projects selected from Table 3; many of the listed projects were not mature or comprehensive enough to be included in this analysis. The framework enables an evaluation of the quality and outcomes of environmental assessment data collection, analysis, and interpretation at the selected projects, which include tidal stream, wave, and run of river energy. The stressor-receptor interactions covered by these selected projects are collision risk, underwater noise, EMFs, and changes in habitat. The projects chosen are those that have the most complete information available and have been deployed following a thorough regulatory process:

1. Tidal stream development at MeyGen in Scotland, U.K., with a focus on collision risk, underwater noise, and EMFs (Figure 1A).
2. Tidal stream development by Nova Innovation in the Shetland Islands, U.K., with a focus on collision risk (Figure 1B).
3. Wave energy development at the Spanish test site BiMEP, with a focus on underwater noise (Figure 1C).
4. Wave energy development at the Swedish test site Lysekil, with a

FIGURE 1

Tidal stream, wave, and run of river energy projects selected as case studies to apply the framework: (A) MeyGen in Scotland, courtesy of SAE Renewables; (B) Nova Innovation in Shetland, courtesy of Nova Innovation; (C) Marmok in Spain, courtesy of IDOM; (D) Lysekil in Sweden, courtesy of Division of Electricity, Uppsala University; and (E) RivGen in Alaska, courtesy of ORPC.



focus on underwater noise, and habitat changes (Figure 1D).

5. Run of river energy development near the village of Igiugig, Alaska, U.S., with a focus on collision risk (Figure 1E).

MeyGen Tidal Stream Energy Project

The first phase of the MeyGen tidal energy project by SAE Renewables (previously SIMEC Atlantic Energy Ltd) was installed in 2016 in Pentland Firth, Scotland, as a commercial project. The project has been consented for a total of 398 MW of power, divided into four phases. The first phase consists of four 1.5-MW turbines (6 MW power) and has been operational since 2018. The results of monitoring from phase 1 will be used to inform what monitoring is required going forward for future phases.

MeyGen carried out an extensive environmental impact assessment outlining potential risks and mitigation measures for a variety of environmental, socioeconomic, and ocean co-use impacts (MeyGen, 2012). While both baseline and post-installation monitoring include a wide range of stressors and receptors, the two major stressor-receptor interactions of concern were collision risk of marine mammals and diving seabirds with turbine blades, and electromagnetic effects on electrosensitive species from underwater cables.

EMF was determined to have no significant effects on fish when mitigation methods were employed, such as placing cables within natural crevices and cracks of the seabed to lower the cable below the surface of the seafloor, reducing the potential exposure to fish (Table 4). However, operational monitoring was still

TABLE 4

Application of framework for evaluating the quality and outcomes of environmental assessment data collection, analysis, and interpretation of data and monitoring results for MeyGen tidal project in Scotland. Notes are included at the bottom of the table to further explain values within the table. Based on the OES-Environmental metadata form (Tethys, 2024c).

	Criteria	Results
Level of monitoring	Duration of monitoring	++[1]
	Baseline monitoring performed	Yes[2]
	Post-installation monitoring performed	Yes[3]
	Accepted methods used	Yes[4]
Output of monitoring	Research reports	■ MeyGen, 2015 ■ Davies et al., 2019 ■ Palmer et al., 2019
	Government reports	■ MeyGen, 2012 ■ Band et al., 2016
	Peer-reviewed papers	■ De Dominicis et al., 2017 ■ Gillespie & Macaulay, 2019 ■ Onoufriou et al., 2019 ■ Gillespie et al., 2020 ■ Risch et al., 2020 ■ Gillespie et al., 2021 ■ Johnston et al., 2021 ■ Risch et al., 2023
	Conference papers	■ Fairley et al., 2015 ■ Williamson et al., 2018
	Other products	■ Thesis: Johnston, 2019 ■ Presentation: Marine Scotland, 2024
Outcome or use of the information	Risk was retired	Yes, retired for EMF but not for collision risk[5]
	Mitigation required	Yes[6]
	Led to delays or cancellation of project	No
	Were the outcomes linked to monitoring outputs	No

Notes:

[1]Baseline monitoring started in 2007 and continued until the turbines were installed.

[2]Data are presently being analyzed for long-term trends.

[3]Telemetry, passive acoustic monitoring, integrated platforms with multibeam sonar, multi-frequency echosounder, fluorometer, acoustic doppler velocimeter (ADV), ADCP.

[4]Seabed surveys, acoustic and visual survey detection of marine mammals, radar surveys for vessel traffic, visual surveys for seabirds, grab samples and photo surveys of benthic invertebrates, physical variables measured using ADCP, sonar, echo sounder, water quality samples, underwater photography and video.

[5]EMF risk was retired, but collision risk continues to be monitored. While marine mammals were found actively avoiding the operating turbine, some were observed passing close by.

[6]Mitigation of EMF required that when cables are not within boreholes, they must be laid where possible within natural crevices and cracks within the seabed, ensuring that the majority of the cable is below the seabed. When possible, use of soft start procedures to reduce noise were required.

TABLE 5

Application of framework for evaluating the quality and outcomes of environmental assessment data collection, analysis, and interpretation of data and monitoring results for Nova Innovation in Scotland. Notes are included at the bottom of the table to further explain values within the table. Based on the OES-Environmental metadata form (Tethys, 2024d).

	Criteria	Results
Level of monitoring	Duration of monitoring	++[1]
	Baseline monitoring performed	Yes[2]
	Post-installation monitoring performed	Yes
	Accepted methods used	Yes[3]
Output of monitoring	Research reports	■ McPherson, 2018 ■ Smith & Simpson, 2018 ■ Smith, 2021 ■ Smith et al., 2021 ■ Smith, 2022
	Government reports	
	Peer-reviewed papers	
	Conference papers	■ Love et al., 2023
	Other products	
Outcome or use of the information	Risk was retired	No
	Mitigation required	No
	Led to delays or cancellation of project	No
	Were the outcomes linked to monitoring outputs	Yes

Notes:
[1] Monitoring program ongoing since installation of first turbine in 2016.
[2] Vantage point surveys for marine mammals and seabirds since 2010, and seabed surveys using drop-down cameras prior to installation.
[3] Device-mounted underwater video cameras and vantage point surveys.

required for the risk of collision of marine mammals and diving seabirds with turbine blades to better understand collision, including avoidance and evasion behaviors, and inform potential future mitigation.

The monitoring program around the MeyGen array used a variety of established methods including harbor seal telemetry, passive acoustic monitoring, multibeam sonar, integrated instrument platforms, acoustic doppler current profiler (ADCP), blade strain gauge, and photo and video observation and was focused heavily around collision risk (MeyGen, 2016).

Nova Innovation Shetland Tidal Array

Nova Innovation's Shetland Tidal Array in Bluemull Sound, U.K., deployed its first three turbines in 2016 and 2017; three more turbines and an offshore hub were installed by 2023, with a total capacity of 600 kW. The project is grid-connected and delivers baseload power in Shetland.

Since the deployment of the first turbine, the company has developed an extensive environmental monitoring program focused on the risk of collision for marine mammals (especially harbor seals and porpoises) and diving seabirds (Table 5). While baseline data collection focused on marine mammals and seabirds (via vantage point surveys) and pre-installation seabed surveys using drop-down cameras, post-installation monitoring has involved both vantage point surveys and underwater video monitoring using device-mounted cameras.

The vantage point surveys were used to monitor the daytime presence and behavior of marine mammals and seabirds around the turbines. The underwater video cameras looked at the rotor-swept area from different angles and allowed monitoring nearfield interactions between animals and the turbines. Due to the extremely large size video datasets accumulated over the years, Nova Innovation started implementing automated detection approaches using machine learning (Love et al., 2023).

While collision risk has not been retired at the Shetland Tidal Array site, continuous underwater video monitoring has shown that no animals have ever collided with the turbine blades, and that animals moved away from the turbines when the blades were rotating (Smith, 2021).

MARMOK-A-5 Wave Energy Converter

The MARMOK-A-5 Wave Energy Converter (WEC) prototype designed by IDOM was installed in 2016 in Bilbao, Spain, at BiMEP. The project involved a single 30-kW floating WEC that was deployed twice, once from October 2016 to

June 2018 and again from October 2018 to June 2019. The outcomes and findings of the two deployments will be using by IDOM in future technological development.

IDOM monitored impacts to a variety of stressor-receptor interactions, including noise, EMFs, habitat change, and changes in flow. Any observed changes in flow and EMF impacts were found to be insignificant or to quickly dissipate away from the device. Noise and habitat change were considered to be the most important interactions (Table 6).

The effects of underwater noise from the devices were measured with three systems: A SoundTrap ST300 HF from Ocean Instruments was used to record 10 min each hour for 41 days; mobile surveys were carried out using passive acoustic measurements at 17 sampling stations for 5-min durations; and airborne measurements using equipment from Centro Tecnolgico Naval y Del Mar of Cartagena were carried out over the same timeframe and at the same location as the mobile surveys.

TABLE 6

Application of framework for evaluating the quality and outcomes of environmental assessment data collection, analysis, and interpretation of data and monitoring results for MARMOK-A-5 WEC. Notes are included at the bottom of the table to further explain values within the table. Based on the OES-Environmental metadata forms (Tethys, 2024e, 2024f).

	Criteria	Results
Level of monitoring	Duration of monitoring	++[1]
	Baseline monitoring performed	Yes[2]
	Post-installation monitoring performed	Yes
	Accepted methods used	Yes[3]
Output of monitoring	Research reports	■ Bald et al., 2021 ■ Felis, Madrid, Alvarez-Castellaros, Bald, Uriarte, & Cruz, 2021 ■ Fellis, Madrid & Bald, 2021
	Government reports	
	Peer-reviewed papers	
	Conference papers	■ Giry et al., 2018
	Other products	
Outcome or use of the information	Risk was retired	No[4]
	Mitigation required	No
	Led to delays or cancellation of project	No
	Were the outcomes linked to monitoring outputs	

Notes:
[1]Studies began in 2012 and continued throughout operation.
[2]Grab sampling and video imaging done to evaluate the physical environment and invertebrates present; measured sound background levels before and after cable installation.
[3]Remote operated vehicle imaging and sampling, passive acoustic sensor deployments, mobile acoustic surveys.
[4]Evidence of mooring chains clashing and turbine operations caused intermediate and low frequencies sound.

Lysekil Wave Energy Test and Deployment Site

The Lysekil Wave Energy Site was established 2 km off the west coast of Sweden in 2004 to avoid interference with shipping, as a place to test WECs and monitoring approaches. The first wave device was deployed in 2006, followed by several other devices.

The major environmental investigations around the test site were aimed at expected stressor-receptor interactions, especially changes in habitat, underwater noise, and displacement, and to develop new monitoring techniques. Post-installation monitoring was required to ensure no damage was being done to the site and surrounding habitats and was carried out in two phases: during the early years of the test site (2006–2008) and 12 years later (Bender et al., 2020).

The main concerns associated with the test site were around benthic infauna and biofouling organisms, as well as mobile fauna such as fish and crustaceans. Research studies focused on artificial reef effects and use of benthic habitats, including the cavities of foundations from wave devices (Table 7).

Igiugig Run of River Turbine Project

The native village of Igiugig, Alaska, partnered with Ocean Renewable Power Company (ORPC) to install low-profile, horizontal, cross-flow riverine RivGen® turbines in the Kvichak River to provide clean power for the village (Thomson et al., 2014). A first test RivGen device was installed in 2014 and re-deployed in 2015. The Kvichak River and nearby Bristol Bay tributaries sustains the largest sockeye salmon population on the

TABLE 7

Application of framework for evaluating the quality and outcomes of environmental assessment data collection, analysis, and interpretation of data and monitoring results for Lysekil Wave Energy Test and Deployment Site. Notes are included at the bottom of the table to further explain values within the table. Based on the OES-Environmental metadata form (Tethys, 2024g).

	Criteria	Results
Level of monitoring	Duration of monitoring	++[1]
	Baseline monitoring performed	Yes[2]
	Post-installation monitoring performed	Yes
	Accepted methods used	Yes[3]
Output of monitoring	Research reports	■ Langhamer, 2009a
	Government reports	
	Peer-reviewed papers	■ Leijon et al., 2008 ■ Langhamer et al., 2009a ■ Langhamer & Wilhelmsson, 2009 ■ Langhamer, 2010 ■ Langhamer et al., 2010 ■ Haikonen et al., 2013a ■ Langhamer, 2016 ■ Francisco & Sundberg, 2019 ■ Bender et al., 2020 ■ Bender et al., 2021 ■ Francisco et al., 2022
	Conference papers	■ Langhamer & Wilhelmsson, 2007 ■ Langhamer et al., 2009b ■ Lejerskog et al., 2011 ■ Haikonen et al., 2013b ■ Bender et al., 2017 ■ Bender & Sundberg, 2018 ■ Rémouit et al., 2018 ■ Bender & Sundberg, 2019
	Other products	■ Thesis: Langhamer, 2009b ■ Thesis: Francisco, 2016 ■ Thesis: Bender, 2022 ■ Book chapter: Wilhelmsson & Langhamer, 2014
Outcome or use of the information	Risk was retired	No[4]
	Mitigation required	No
	Led to delays or cancellation of project	No
	Were the outcomes linked to monitoring outputs	No[5]

Notes:
[1]Over 12 years of benthic habitat and artificial reef monitoring.
[2]Characterization of infauna using sediment cores.
[3]Using sediment cores, diver surveys, ROV surveys, cage studies, hydrophones, seabed-mounted sonar systems.
[4]Risk was not retired, but they cite "low effects/impacts by presence or operation of WECs" and "positive effects in terms of artificial reef effects, FAD's and no-take zone."
[5]However, changes in macroinvertebrate distribution and abundance, succession of artificial reef communities over 12 years, differences in impact vs. control sites for decapods and sea pens were noted.

North American continent, draining Illiamna lake into the Bering Sea. The RivGen is a crossflow turbine (Figure 1E) that is designed to provide power to the tribal village of Igiugig. The major concern for regulators and stakeholders was the possible collision of salmon adults and smolts with the rotating turbine blades. Underwater cameras were placed on the turbine structure and foundation to observe fish passage by the turbine.

The framework was applied (Table 8), demonstrating the baseline assessment and post installation outcomes, including the retirement of collision risk to adult salmon, and prompting additional monitoring of down-migrating salmon smolts past the turbine. The outcome of the monitoring allowed for the installation of a second RivGen turbine downstream from the first in 2023.

Discussion

This paper has documented over 80 MRE projects around the world for which environmental data have been collected that align with the stressor-receptor interactions of greatest concern for consenting processes. For the most part, these projects have used methods that are accepted by the research community as pertinent to answering the outstanding questions around interactions of MRE with the marine environment. The MRE devices for several projects listed in Table 3 have not yet been deployed but were included in this analysis as they have carried out extensive baseline or pre-installation data collection and have robust post-installation monitoring programs plans. Table 3 was organized by the most commonly accepted stressor-receptor interactions of importance (Copping, Hemery, et al., 2020).

TABLE 8

Application of framework for evaluating the quality and outcomes of environmental assessment data collection, analysis, and interpretation of data and monitoring results for Igiugig riverine MRE project. Notes are included at the bottom of the table to further explain values within the table. Based on the OES-Environmental metadata form (Tethys, 2024h).

	Criteria	Results
Level of monitoring	Duration of monitoring	++[1]
	Baseline monitoring performed	Yes[2]
	Post-installation monitoring performed	Yes[3]
	Accepted methods used	Yes[4]
Output of monitoring	Research reports	■ TerraSond, 2011 ■ Preist & Nemeth, 2015 ■ Matzner et al., 2017
	Government reports	■ FERC, 2019
	Peer-reviewed papers	■ Guerra & Thompson, 2019 ■ Courtney et al., 2022
	Conference papers	
	Other products	■ Dataset: ORPC, 2014
Outcome or use of the information	Risk was retired	Yes, for adult fish, smolts still to be investigated with later study
	Mitigation required	No
	Led to delays or cancellation of project	Some delay in getting second device in the water
	Were the outcomes linked to monitoring outputs	Yes, video of fish around first turbine led directly to ability to operate and then, with smolt collision risk planned, for second turbine.

Notes:
[1]Two seasons of monitoring.
[2]Fisheries counts of migrating sockeye salmon, from previous fisheries surveys; no pre-installation possible for collision risk.
[3]Monitoring with cameras in place around turbine for up-migrating adult salmon, later for down-migrating smolts.
[4]Cameras were installed at 5 points around the turbine. Closest to state of the art for fish monitoring.

However, by constraining the types of data collection and monitoring noted in Table 3, other approaches to providing information to support consenting may have been overlooked, including investigations into other potential stressors that have not proven to be of concern, such as potential for chemical contamination from MRE systems (Copping et al., 2015).

Each of the tidal stream and run of river projects collected data to inform collision risk (Table 3) as this remains the most significant concern for consenting of MRE devices with rotating turbine blades (Sparling et al., 2020). Measurements of underwater noise were the most commonly collected data for wave projects; without concerns about collisions, underwater noise disruption of marine mammals and fish are generally seen as the most likely risk from wave devices (Copping & Hemery, 2020; Cruz et al., 2015). Few projects collected data on EMF emissions; field measurements, supported by laboratory studies, have generally shown that EMF emissions from MRE export cables are low and unlikely to cause harm to marine life (Gill & Desender, 2020; Taormina et al., 2018). Data that describe changes in benthic habitats were collected at tidal and wave projects equally, although few monitoring programs address potential changes in pelagic habitats. A subset of the tidal and wave projects shown in Table 3 assessed changes in oceanographic conditions, either with field measurements that could not resolve any effects from MRE devices, or with numerical models that predict potential effects from very large arrays that are not reflective of the planned and deployed projects (Whiting, Garavelli, et al., 2023). Few projects attempted to monitor effects of displacement by MRE devices and small arrays (e.g., EMEC; see Long, 2017) as these effects are not expected until much larger arrays are deployed (Hemery et al., 2024).

There is a growing consensus in the research community that the six stressor-receptor interactions (collision risk, underwater noise, EMFs, changes in habitats, changes in oceanographic systems, and displacement of marine animals) continue to be most closely related to potential risks from MRE devices and systems, and that much of that potential risk could be addressed with additional data collection and monitoring around deployed devices (Copping et al., 2018; Eaves et al., 2022). Applying the risk retirement construct that

OES-Environmental has developed (Copping, Freeman, et al., 2020), many of the stressor-receptor risks could likely be retired for small numbers of devices, reinforced by additional data collection, where needed. As these uncertainties decrease, monitoring foci can be shifted to the more complex interactions, as well as toward potential effects of larger arrays.

The methods and instrumentation that were used by the MRE projects depicted in Table 3 are also becoming widely recognized as most appropriate for collecting accurate data and helping to decrease the uncertainty for the individual stressor-receptor interactions (Bender et al., 2017). This is best illustrated by the case studies that embrace these methodologies, for the most part. For example, collision risk of marine animals with operating turbines has been investigated using a combination of acoustic, underwater video, and/or vantage point observations in the MeyGen, Nova Innovation, and Igiugig case studies (Tables 4, 5, and 8). These methods reflect the understanding that more than one type of data may be needed to better understand the different factors associated with collision risk (i.e., encounter rate, avoidance and near field behavior, collision detection) for marine mammals, diving seabirds, or fish with rotating turbine blades (Hasselman et al., 2020; Chapman et al., 2024). Underwater noise from devices is increasingly being measured within the framework of the international specification, developed under the International Electrochemical Commission (Haxel et al., 2022; IEC TC114, 2024). The Marmok wave case study reflects these methods (Table 6). EMF measurement methods have not been standardized, but the myriad of magnetometers and electrical measurement devices created for other industries have been found fit for purpose (Gill & Desender, 2020; Grear et al., 2022). There are a number of techniques needed to measure the extent of changes in habitat and function from MRE installation and operation, based on the location, substrate type, as well as the species composition, abundance, and community structure (Bender et al., 2017; Hemery et al., 2022). Several of these techniques are reflected in the case study from Lysekil (Table 7). It is generally accepted by the research community that measuring changes in oceanography due to the operation of MRE devices is not reasonable based on the very limited amount of energy removed by small numbers of devices. However, once large arrays begin to harvest significant amounts of energy from channels for tidal or river turbines, or from the height of waves, standard oceanographic instruments and methods will be able to note changes (Whiting, Garavelli, et al., 2023). Observations of animal displacement will likely require the development of new techniques and instrument packages to measure changes to migratory animal routes or other movements from the presence of large numbers of MRE devices (Hemery et al., 2024; Isaksson et al., 2020).

The differential among MRE deployments and environmental studies from region to region and country to country is significant (Table 3). Early deployments were largely focused in the U.K. and Europe, as well as in Canada and the U.S., and the total number of devices around which environmental data collection and monitoring have been carried out reflects this pattern. Australia has moved rapidly to add wave projects, while other nations, including Japan, Mexico, and Israel, are beginning to increase their focus on testing and demonstration. The wealth of research studies is similarly clustered in these nations. The patterns of early adoption of MRE technologies follows two trends: test sites (or "clusters") and availability of resources. The presence of an established test site helps to motivate deployments, consenting processes, and additional research studies in environmental areas. The most obvious example of this is the operation of the EMEC in Scotland that was commissioned in 2004. Thirty-five MRE devices have been tested at EMEC from 22 different companies, which is more than any other site in the world (EMEC, 2024). In addition, established test sites in Portugal (Aguçadora), Spain (BiMEP), and the U.S. (WETS) have moved the science forward, while new test site in Wales (META) and the U.S. (PacWave) are attracting MRE developers and studies (META, 2024; PacWave 2024). Some countries such as Mexico are exploring the deployment of test devices while assessing environmental changes. It is clear that the wealthier nations have had more government funds available to directly support MRE device tests and deployments, as well as to support research studies (IEA-Ocean Energy Systems, 2024). These same nations tend to have more resources in terms of vessels and supply chains, as well as greater concentrations of marine research stations and researchers.

As additional MRE devices are deployed and potential environmental effects are examined, there is a recognition of the importance of sharing data and information, publishing analyses and interpretations of the data, and disseminating the results of studies. MRE device and project development companies are recognizing the need to work with academic and other institutional researchers and to share data and information on environmental effects, even while protecting valuable intellectual property and power performance data (Whiting, Ricardo, et al., 2023). Efforts to share results of environmental effects findings are reflected in the growing participation in conferences, webinars, and workshops around the world (Rose et al., 2023).

Conclusions and Recommendations

MRE deployments are increasing around the world, and more of these deployments are accompanied by environmental data collection and monitoring each year. While early deployments were centered in the U.K. and Europe, deployments in other locations are increasing. Project developers and companies testing and demonstrating technologies with deployments at sea are increasingly realizing the need to meet consenting requirements as well as the overall advantages of adding to the environmental effects evidence base to help this industry develop sustainably, to ensure that consenting processes are based on the best available data, and that the outcomes of those processes are commensurate to the potential risks.

The range of technologies, locations, and environmental data collection programs around the world is reflected in the collection of OES-Environmental metadata forms. Interactions among researchers at conferences, workshops, and through strategic initiatives such as OES-Environmental indicate that there is growing interest among tropical and southern hemisphere nations to explore MRE development as well. The resources available in these nations are likely to include OTEC, wave, and ocean current, rather than only tidal stream or large run of river resources that predominate in northern hemisphere countries.

While the active global MRE research community globally has reached some level of consensus on what stressor-receptor interactions should be prioritized for investigation during strategic and project planning processes, there is no agreed-upon approach to addressing the overall data collection and monitoring needs for each MRE project, to ensure that environmental effects are understood and mitigated where needed. Reaching a standardized set of monitoring approaches, instruments, and analysis methods will be needed eventually to ensure that data collected in different jurisdictions are comparable, and to streamline the pathway toward a sustainable MRE sector. Based on the evaluation of this set of MRE projects for which environmental data have been collected, we would like to recommend that the following steps be taken with new MRE projects:

- Establish a robust, suitable, and proportionate baseline of biological and physical features of a proposed project/deployment site, based on historical data, as well as any data collected as part of the project. In addition to the obvious need to understand the MRE resources available for generating power, the baseline is a necessary component against which to assess and, where necessary, measure any potential changes. Requirements will be determined by relevant policy, as well as the location, scale and type of the proposed development, the extent of available baseline data, and potential risks identified in relation to the proposals.
- Use available data and information from the established and growing evidence bases wherever possible during the consenting process.
- Determine the most likely risks from the proposed project that might affect marine animals, habitats, or ecosystem processes in or near the project area.
- Determine the likely level of concern for each of the identified stressor-receptor interactions, using existing datasets and findings from other MRE projects, analogous industries, or research studies that have similar features of MRE devices and receptors.
- Identify stressor-receptor interactions for which insufficient data are available and create pre-installation and/or post-installation monitoring plans to fill those data gaps. Where possible and appropriate, use strategic resources that have research priorities for the sector have been identified, such as OES-Environmental or the Offshore Renewables Joint Industry Programme (ORJIP) for Ocean Energy's "Forward Look" (ORJIP, 2024).
- Seek assistance from experts in the supply chain, as well as academic and other research institutions, in designing, reviewing, and carrying out monitoring programs.
- Execute monitoring plans using the best accepted methods available and ensure that the data collected are robust, quality controlled, and documented.

- Use those data to inform the consenting process (including any post-installation monitoring reporting requirements) and ensure that the data are placed on an open-data site where they will be publicly and sustainably hosted.
- Determine the values and needs of nearby communities, including the level of social acceptance or rejection of MRE projects.

Many of these recommendations can be supported in detail by work documented by OES-Environmental and other groups, and can be found on the Tethys website (Tethys 2024i).

Collaboration among MRE device and project developers, researchers, supply chain providers, regulators, and other interested stakeholders can provide the most efficient and effective path to creating a sustainable MRE industry that is committed to the mitigation of climate change as well as protecting precious and threatened marine resources.

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Corresponding Author:

Andrea Copping is a Senior Advisor and Researcher at Pacific Northwest National Laboratory in Seattle, WA, USA.
Email: andrea.copping@pnnl.gov

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