2.0

Progress in Understanding Environmental Effects of Marine Renewable Energy

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

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

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

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

2.1.
CONSIDERATIONS FOR DEPLOYMENT OF MRE DEVICES

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

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

2.2.
EVALUATING PROGRESS IN EXAMINING ENVIRONMENTAL EFFECTS OF MRE

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

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

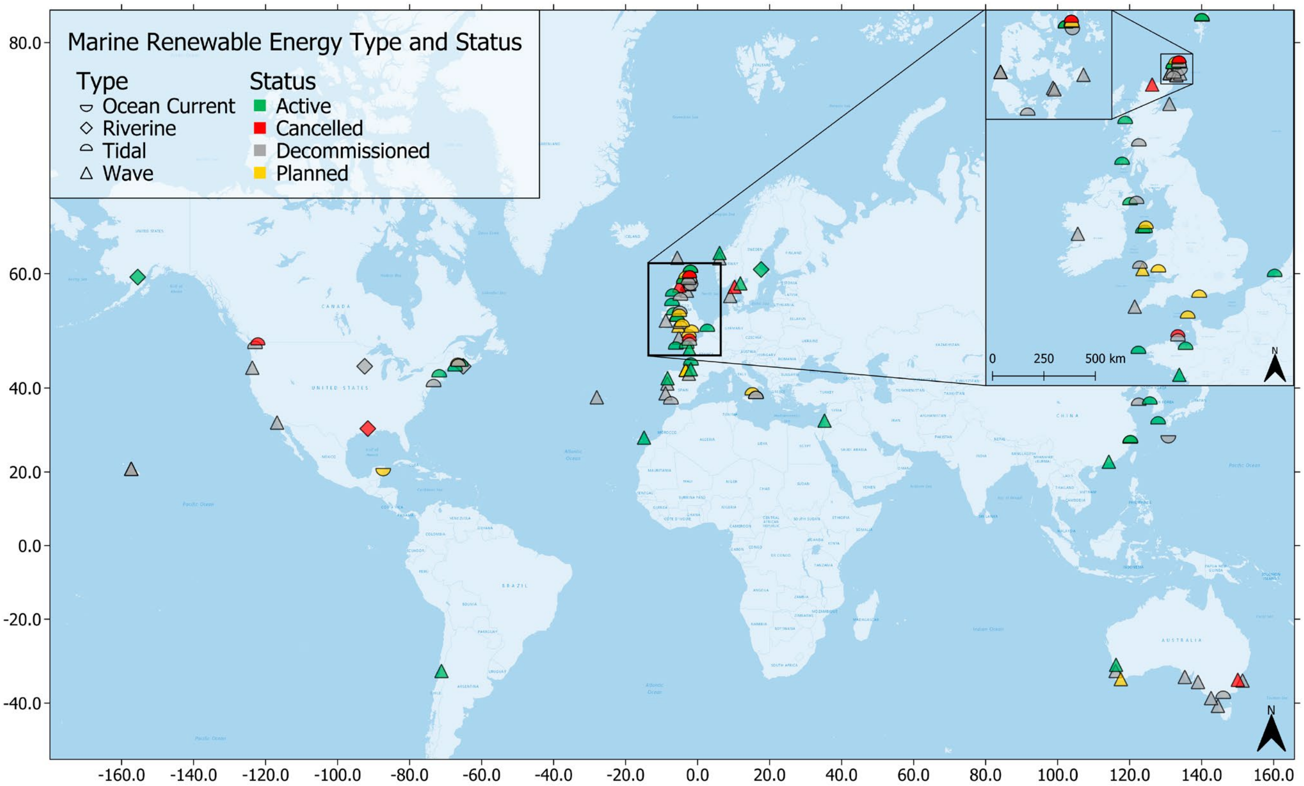


Figure 2.1. Marine renewable energy projects around the world with associated records of environmental monitoring, separated by type of technology and status of development.

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

2.3.
CASE STUDIES OF MRE PROJECTS

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

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

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

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

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

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

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

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

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

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

2.3.1.
MEYGEN TIDAL ENERGY PROJECT

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

The research team used an integrated instrument platform that collected passive and active acoustic data to monitor marine mammals and other mobile species (Gillespie et al. 2022; Gillespie et al. 2023). The platform was cabled to provide power and data transmission to shore. An array of hydrophones on the platform recorded harbor porpoise vocalizations, while high frequency multibeam sonars were used to investigate seal behavior around the operational turbine. The research team showed that marine mammals actively avoided the operating turbine, although some individuals swam close to the turbine (Gillespie et al. 2020, 2021; Palmer et al. 2021). Current work investigating seal behavior and quantifying their avoidance on a localized scale (10's of meters) is being undertaken by the same team. The regulators considered that EMF levels were too low to cause harm to marine animals and the risk was retired (see Chapter 3). However, it was decided to assure that marine animals would receive the minimum EMF exposure possible by keeping the cables below the seabed wherever possible, either by the cables passing through boreholes or laid within natural crevices and cracks within the seabed (MeyGen 2015). Underwater noise was measured during installation and operation of the MeyGen turbines with the hydrophone on an integrated platform (Risch et al. 2020, 2023) but was only considered to be a risk during installation from piling; regulators required a soft start for installation procedures to reduce noise when possible (MeyGen 2012). Modeling efforts for sediment transport demonstrated the needs of many more turbines than are consented at MeyGen to show significant changes (Karunarathna et al. 2015).

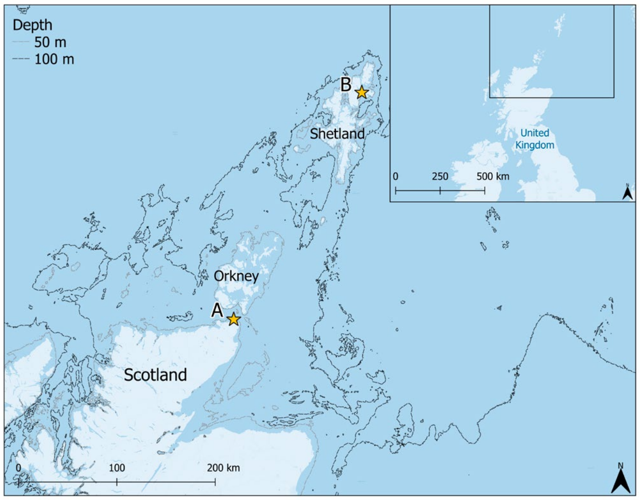


Figure 2.2. Locations of the MeyGen Tidal Energy Project (A) and the Nova Innovation Shetland Tidal Array (B) in Scotland, United Kingdom (yellow stars).

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

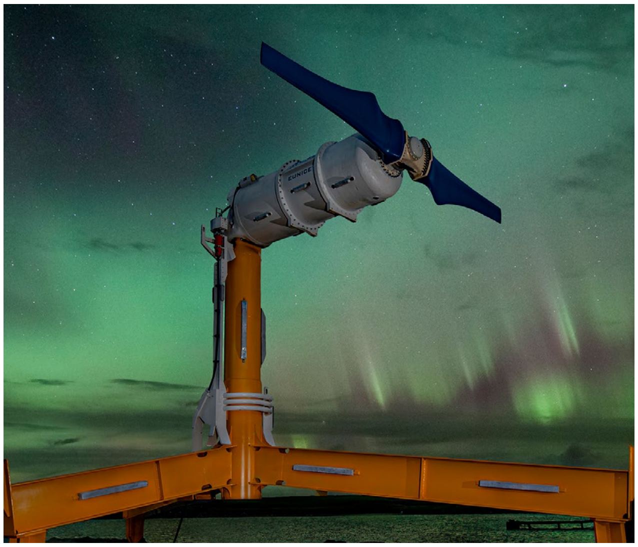
2.3.2.
NOVA INNOVATION SHETLAND TIDAL ARRAY

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

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

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

To date the method has captured underwater images of harbor seals, diving seabirds, and fish in close proximity to the turbines when they are not operating, as well as some of the animals moving away from the turbines when the blades begin rotating (Smith 2021). No animal has ever been observed interacting with any of the moving turbine blades. After consultation with Marine Scotland, Nova Innovation has transitioned to semi-automated underwater video processing (Smith 2024). Underwater noise generated by turbines in the Shetland Tidal Array was measured in 2023 using drifting hydrophones (Pierpoint et al. 2023). The results demonstrated that acoustic injury to marine mammals is highly unlikely, even after prolonged exposure in proximity to the turbines. Some minor behavioral disturbance may be possible at close range to turbines, reducing the risk of any collisions occurring, but unlikely to result in significant disturbance (Chapter 6).



2.3.3.
MARMOK-A-5 WAVE ENERGY CONVERTER

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

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

BOX 2.1.

AUTOMATED DETECTION OF ANIMALS IN PROXIMITY TO TURBINES USING MACHINE LEARNING

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

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

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

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

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

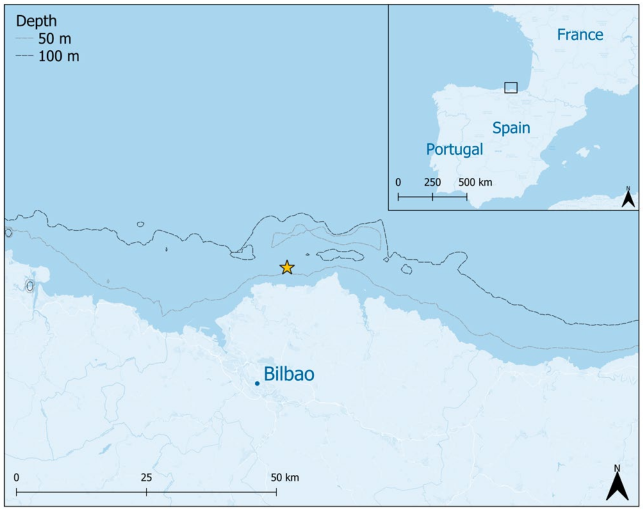


Figure 2.3. Location of IDOM's MARMOK-A-5 wave energy converter at the Biscay Marine Energy Platform in northern Spain (yellow star).

2.3.4.
LYSEKIL WAVE ENERGY TEST SITE

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

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

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

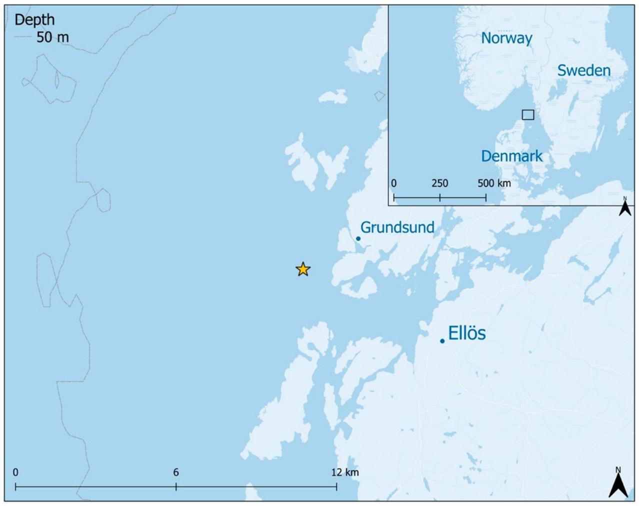


Figure 2.4. Location of the Lysekil Wave Energy Test Site off the west coast of Sweden (yellow star).

2.3.5.
IGIUGIG HYDROKINETIC PROJECT

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

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

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

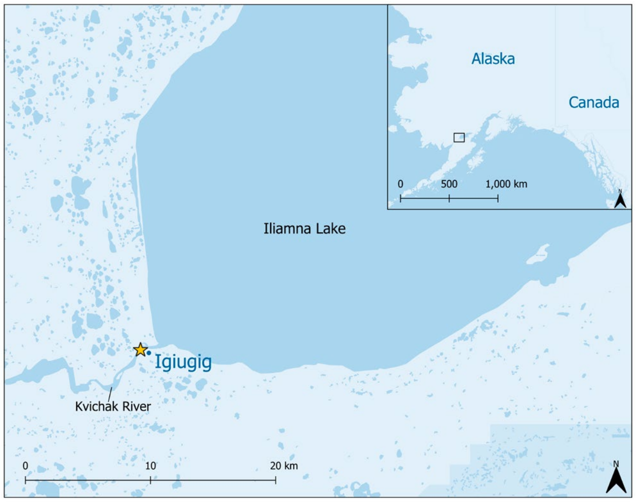


Figure 2.5. Location of ORPC's RivGen® Power System near the village of Igiugig, Alaska, United States (yellow star).

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

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

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

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

2.4.
PATTERNS OF ENVIRONMENTAL EFFECTS STUDIES

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

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

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

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

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

2.5.

OUTCOMES OF MRE ENVIRONMENTAL EFFECTS MONITORING

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

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

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

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

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

2.6.
RECOMMENDATIONS FOR ENVIRONMENTAL EFFECTS ASSESSMENT AND MONITORING

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

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

2.7.
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