3.0

Marine Renewable Energy: Stressor–Receptor Interactions

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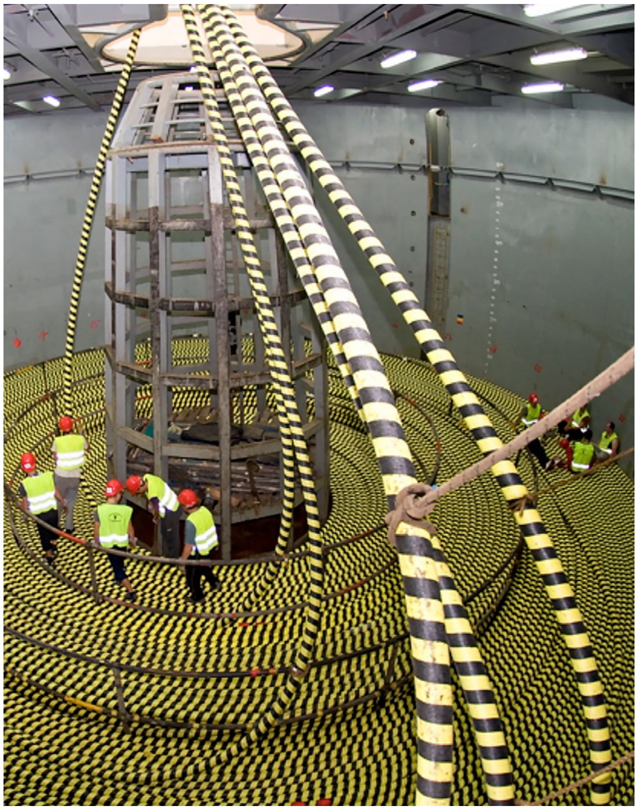
Determining the potential effects of marine renewable energy (MRE) development on the ocean requires consideration of how each component of a tidal, wave, riverine, or other MRE system might affect marine animals, habitats that support marine communities, or processes that make up essential oceanographic and ecological systems.

Researchers around the world have been assessing the potential effects of MRE deployments and operations using a variety of instruments, models, analytical methods, and approaches. The most common approach, and the one followed throughout this report, is the framework of stressor–receptor interactions (Boehlert & Gill 2010), where stressors are the components of an MRE device and associated system that may cause stress, injury, or death to a marine animal, habitat, or ecosystem. The receptors are the species, their habitats, and the oceanographic and ecological processes that support them.



At present, only a small number of MRE devices have been deployed, and while commercial development of MRE arrays may present additional stressor-receptor interactions in the future, seven interactions have been recognized as key to understanding the potential effects of MRE development. These stressor-receptor interactions are:

- Risk of collision of marine animals with moving parts of MRE devices, generally associated with tidal, riverine, or ocean current turbines;
- Effects of underwater noise from operational MRE devices on marine animal behavior and essential sensory capabilities;
- Effects of electromagnetic fields (EMFs) from power cables and other portions of energized MRE devices on sensitive marine animals;
- Changes in benthic and pelagic habitats that support marine species;
- Entanglement of large marine animals in mooring lines or draped cables associated with MRE devices;
- Changes in oceanographic systems due to changes in ocean circulation, wave height, energy removal, or sediment transport; and
- Displacement of marine animals from their normal movements or migratory patterns due to the presence of MRE devices.

This chapter provides a succinct background on the state of knowledge of each of these stressor-receptor interactions, as documented in the *2020 State of the Science* report (Copping & Hemery 2020), followed by updates in research, monitoring, and further insights into the stressor-receptor interactions that have been documented since 2020.[1] Most of the existing information on these interactions pertains to tidal or river turbines and wave energy converters (WECs), as these technologies are the most common types of MRE that have been developed and deployed at the moment. Although devices designed to harvest energy from persistent ocean currents at the western sides of ocean basins are being developed, few have been tested in open water and little is known about their potential environmental effects. In addition, early development of systems to harvest energy from thermal and salinity gradients in the ocean is under consideration. Ocean thermal energy conversion (OTEC)—the generation of power from the temperature differential between warm surface ocean water in the tropics and cold deep ocean water—is a technology that has been investigated longer than other MRE technology, yet has not gained commercial traction; it is currently under revived consideration in tropical islands and remote areas. Where applicable, the stressor-receptor interactions associated with OTEC will be discussed. Salinity gradient power is generated from the osmotic pressure differential of freshwater meeting ocean water at river mouths, and is in the early stages of testing, but little is known about potential effects.

3.1.
COLLISION RISK FOR MARINE ANIMALS AROUND TURBINES

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Uncertainty around the likelihood of an animal coming into contact with a turbine blade and the consequences of such an event on the individual and the population remains a key barrier to consenting new tidal or riverine energy projects (Figure 3.1.1). Concerns around collision risk have resulted in significant time delays for projects, with some being abandoned (Copping & Hemery 2020). As such, uncertainty around this issue continues to have a significant impact on the sustainable development of the tidal and riverine energy sector. Reducing uncertainty around all aspects of collision risk for key receptor groups (including marine mammals, fish, and diving seabirds), is a priority for strategic environmental research programs and project-level post-consent monitoring.

Several terms are used to describe the potential interactions of marine animals with MRE turbines such as encounter, avoidance, evasion, and collision (Box 3.1.1). The assignment of each term depends on the spatial scale at which an animal interacts with a turbine (Figure 3.1.2). One of the challenges in reducing uncertainty around the potential risk of collision between marine animals and turbines is related to the ability to gather useful data about each type of interaction.

Observations using sensors (e.g., video cameras) around turbines are technically challenging, within the

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[1] Displacement was not reported in the *2020 State of the Science* report; the assessment of this stressor-receptor interaction in this chapter covers all available information on that topic.

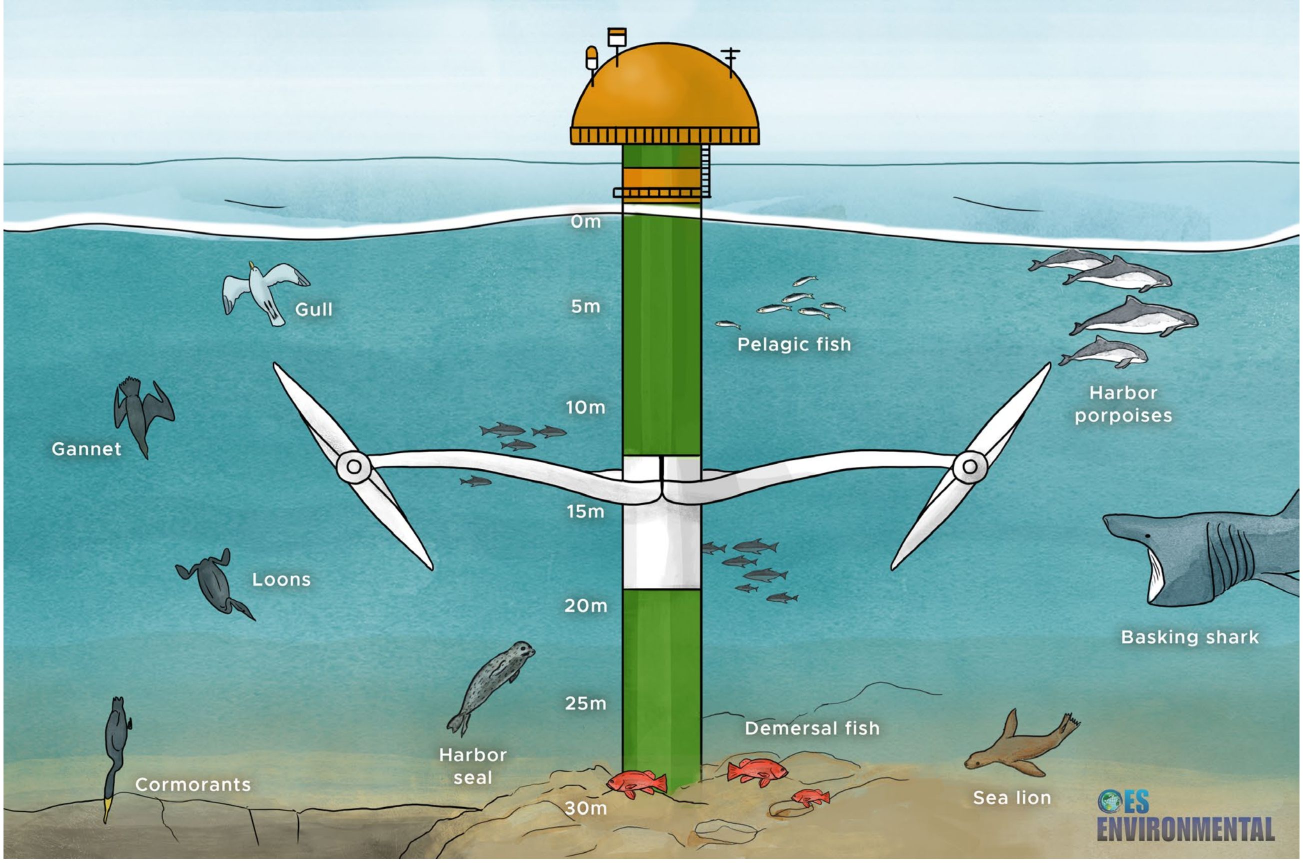

Figure 3.1.1. Schematic of marine animals (seabirds, fish, marine mammals) that can interact with a turbine. (Illustration by Stephanie King)

high-energy, often turbid waters where turbines are typically deployed. Individual animal behavior, sensory capabilities, and learning abilities vary greatly across species and locations of deployment, which, combined with a lack of understanding of the natural behavior of these animals in these environments, result in further uncertainty around the understanding of potential responses to the presence of MRE turbines. There are no appropriate analogs that can represent the interaction of marine animals and turbines (Sparling et al. 2020a), requiring that observations and assessments rely on real-world deployments of turbines at sea or in riverine environments that are accompanied by comprehensive monitoring programs.

BOX 3.1.1.

DEFINITIONS OF TERMS RELATED TO COLLISION RISK

The different ways that animals interact with marine renewable energy turbines are also illustrated in the Marine Energy Adventure: Collision Risk game (see Chapter 7).

- Encounter: when an animal is in proximity of a tidal turbine (= nearfield), at about 1-5 turbine diameters.
- Avoidance: behavior of an animal responding to and moving away from a turbine at a distance greater than 5 turbine diameters.
- Evasion: when an animal changes its behavior to escape contact with a turbine within 5 turbine diameters.
- Collision: when an animal contacts the moving parts (often a blade) of a turbine.

In the *2020 State of the Science* report (see Sparling et al. 2020a), general recommendations to better understand collision risk for marine mammals, fish, and seabirds included:

- improving technologies for monitoring and assessing collision risk;
- collecting species-specific data on behavior and presence across seasons and at different sites;
- investigating sublethal injuries after collision events and how these injuries might result in death to the animal;
- understanding how individual losses could be scaled up to population effects; and
- creating array-scale collision risk models (including variability and uncertainty in risk modeling).

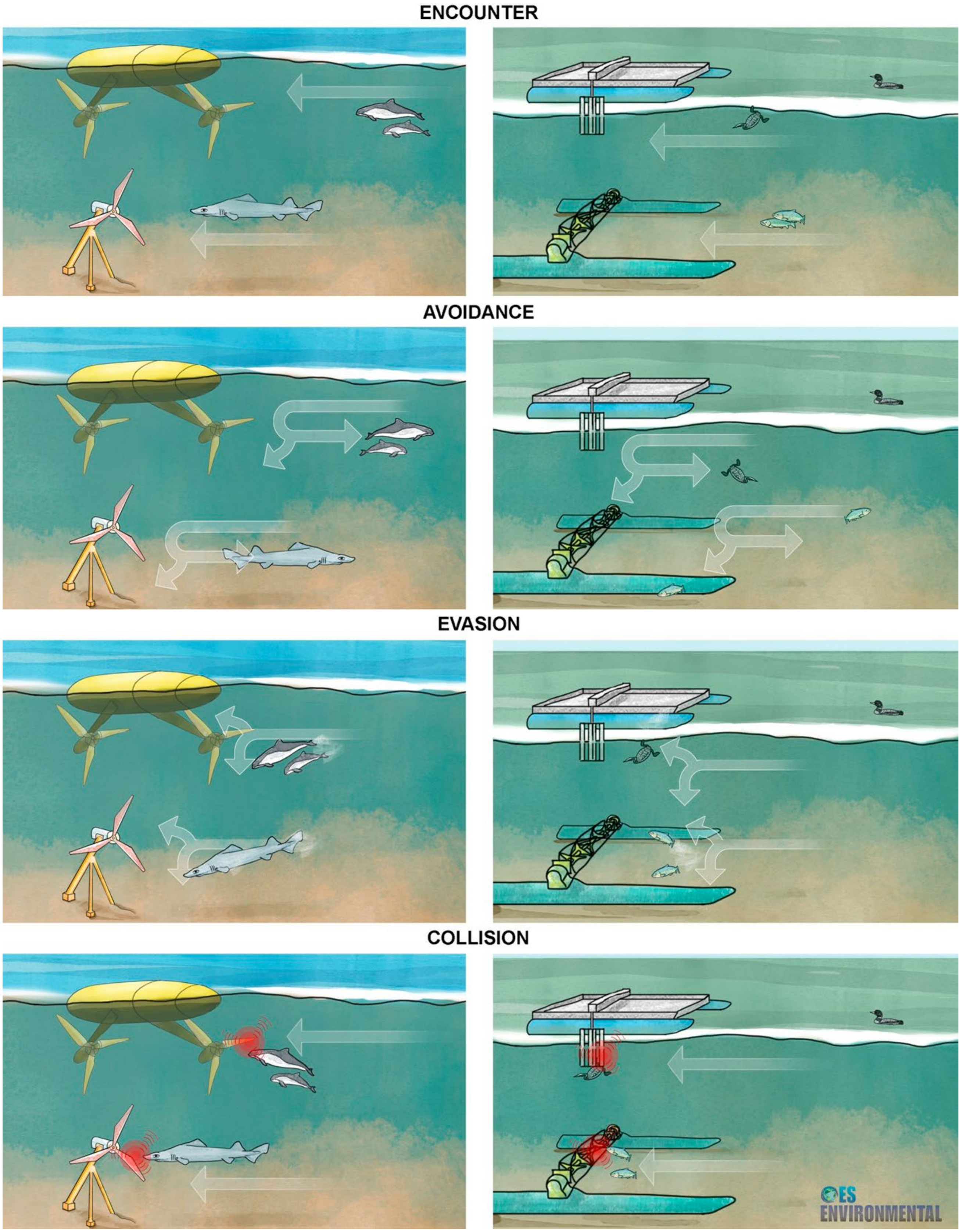

Figure 3.1.2. Interactions between animals and turbines related to collision risk (encounter, avoidance, evasion, collision) at sea (left) and in the river (right). (Illustration by Stephanie King)

3.1.1.
ADDITIONAL KNOWLEDGE GAINED SINCE 2020

The current knowledge around collision risk comes from both empirical and modeling studies that examine animal behavior in the vicinity of turbines, such as avoidance and evasion that enable them to avoid harm from collision with turbine blades (Figure 3.1.2). The evidence to date has been from single turbine deployments or small arrays (up to six turbines). Research in recent years has also focused on the probability of animals colliding with turbine blades, using numerical models and probabilistic approaches.

AVOIDANCE AND EVASION

For fish, avoidance behavior is noticed when turbines are operating, and less avoidance behavior is usually observed when the turbine is not operating (Bender et al. 2023; Grippo et al. 2020). In Cobscook Bay, Maine, United States (US), a decrease in fish numbers was observed starting 140 m from the Ocean Renewable Power Company (ORPC) TidGen® tidal turbine (Grippo et al. 2020). Unlike avoidance behavior, evasion behavior of fish at close range to the turbine is challenging to observe due to the technical limitations of monitoring technologies. Evidence of close encounters and evasion by fish around turbine blades has been documented in both laboratory and field settings (Smith 2021; Yoshida et al. 2020, 2022). As part of the environmental monitoring for the Shetland Tidal Array, Bluemull Sound, Shetland, Scotland, United Kingdom, subsea video cameras were deployed on each tidal turbine and 4,049 hours of video footage collected up to March 2020 were analyzed (Smith 2021; see Table 3.1.1). Saithe (*Pollachius virens*; also known as pollock in the US) were frequently observed around the rotating turbines, aggregating in small to large groups. During turbines operations, saithe were never observed to pass through the swept area of the blades and some individuals exhibited evasive behavior when approaching the moving blades. In laboratory conditions, 71% of fish (ray-finned fish *Gnathopogon elongatus*) exhibited evasion behavior near a rotating turbine and fish with slower swimming speeds and those swimming near the bottom of the flume had fewer interactions with the turbine (Yoshida et al. 2022). Müller et al. (2023) observed evasion behavior of fish (juvenile rainbow trout *Oncorhynchus mykiss*) only when the turbine was rotating.

The operation of tidal turbines was also shown to influence the avoidance behavior of marine mammals at several deployments in Scotland. Harbor seals (*Phoca vitulina*) have been observed avoiding a tidal array (four turbines) during turbine operations with the abundance of animals decreasing up to 2 km from the array (Onoufriou et al. 2021). Recent monitoring around four MeyGen tidal turbines shows that harbor porpoises (*Phocoena phocoena*) moved away from the turbines when they were operating, passing to the sides of the device within 10 m, as well as swimming below the rotor swept area (Gillespie et al. 2021; Palmer et al. 2021). At least one harbor porpoise passed through the rotor swept area when the turbine was not operating, but none were seen to pass through the rotor when the turbine blades were rotating (Gillespie et al. 2021). During the environmental monitoring of the Shetland Tidal Array, only 10 individual harbor seals were observed (representing 0.014% of the analyzed footage when considering multiple consecutive occurrences by the same animal), and only at low tidal speeds when the turbine was not operating (Smith 2021).

Seabirds have been observed in video footage collected up to March 2020 from the Shetland Tidal Array environmental monitoring (Smith 2021). Twelve individual European shags (*Phalacrocorax aristotelis*) and five individual black guillemots (*Cepphus grylle*) were observed, when the turbines were not operating, and no physical contact with the blade was observed. The spatial distribution of the seabirds overlapped with the turbines during slack water or current speeds less than 0.8 m/s. Seabird habitat use in tidal development areas has also been assessed through telemetry or observations, with the results used to predict potential interactions with a tidal turbine (Costagliola-Ray et al. 2022; Couto et al. 2022; Isaksson et al. 2021; Johnston et al. 2021. See 3.4.).

COLLISION

Several recent collision risk monitoring studies for fish have focused on detecting direct contact with turbine blades, using different technologies. In Alaska, salmon smolts are of particular concern during their downstream migration. An acoustic camera was used to attempt to detect Pacific salmon (*Oncorhynchus* spp.) smolts and other fishes around the New Energy EnCurrent turbine in the Tanana River Test Site near Nenana, Alaska, US (Staines et al. 2022). The distinction between fish and debris was not possible because fish movement could not be detected. Also in Alaska, potential interactions between Sockeye salmon (*Oncorhynchus nerka*) and the ORPC RivGen® river turbine were assessed with video cameras positioned on the turbine in the Kvichak River (Courtney et al. 2022). Of the 2,374 fish identified in the images, 382 (16%) fish were observed to swim in a disoriented manner. This disoriented behavior was related to the turbulence and flow associated with the presence of the turbine and was rarely observed (2%) when the turbine was not operating. Direct contact between fish and the turbine was observed 36 times (1.5%), at production speed, and the outcomes of collision were unknown because of limited field-of-view. During laboratory experiments, direct contact between fish and turbine blades was observed, only when the turbine was operating, and no injuries were observed (Müller et al. 2023; Yoshida et al. 2020). As of 2024, no collisions between marine fish and tidal turbines have been observed.

So far, field studies assessing the interactions between marine mammals and tidal turbines have not detected any instances of direct contact. The sensory capabilities of marine mammals suggest that collisions with turbine blades will be rare events (Onoufriou et al. 2021). For seabirds, the occurrence of collision with moving structures has never been observed and is likely dependent on their spatial overlap with a turbine in horizontal and vertical dimensions, temporal overlap, and the absence of evasion behavior (Isaksson et al. 2020). Collision risk is expected to be minimal if seabird distribution does not overlap with tidal areas.

NUMERICAL MODELS

The use of numerical models for assessing collision risk is mainly driven by the need to estimate the probabilities of encounter or collision between marine animals and a turbine, to be used to inform regulatory decisions during the consenting process and in post-construction monitoring and management. The purpose of such models is to estimate the likelihood of an encounter or contact (collision) between an animal and a device. The rates of encounter and/or collision depend on several parameters such as the size and location of the device, as well as the animal's behavior. The outcomes are the probabilities of encounter and/or collision. If the survival rate of the animal after a collision is included in the model, the potential effects on the population can be assessed. At the individual scale, two types of models can be used to estimate the interactions between animals and devices: encounter rate models and collision risk models. At the population scale, exposure time (amount of time an animal spends at the depth and in the nearfield of a device) population models can be used (Buenau et al. 2022; see Box 3.1.2).

Models developed to assess collision risk use a large range of parameters as inputs (i.e., data on the technology as well as on the ecology and biology of the animals) and depend strongly on the availability of input data. For fish, field acoustic telemetry detections have been used in a species distribution model (boosted regression tree analysis) to predict the likelihood of animal presence in tidal areas and assess the potential for encounter (Bangley et al. 2022). An alternative analytical approach using acoustic telemetry data estimated the probability of encounter with a tidal device from an ensemble averaged estimate of acoustic detection efficiency (Sanderson et al. 2023a).

Because existing collision risk models do not consider fish behavior, the influence of vertical swimming behavior (direction, speed) on collision rate for silver eels (*Ariosoma mellissii*) was assessed using a coupling between a hydrodynamic model and an agent-based model (Rossington & Benson 2020). The highest collision rate was predicted without vertical migration in the model, highlighting the need to consider realistic animal behavior when modeling collision risk. To estimate probabilities of encounter and the subsequent potential interactions between fish and a turbine, Peraza & Horne (2023) incorporated empirical data of fish distribution and avoidance scenarios in a probability model. Probabilities of encounter and interactions with turbines (i.e., impact) were lowest when avoidance behavior was included. To estimate the probability of collision between marine animals and a turbine, spatial simulations can also be used. A four-dimensional (three dimensions and time) simulation-based approach was developed by Horne et al. (2021) and included flexible parameters for the device and the animal movement. Such a model has been used to estimate the collision probability between a tidal kite and a seal, considering the angle of approach of the animal toward the device, its speed, and its size. The variation of input parameters influenced the collision probability. A similar approach was used to estimate mortality after a collision with a turbine depending on the speed and location of the collision (Horne et al. 2022).

Since 2020, no models have been developed to estimate the collision probabilities of seabirds with a turbine.

PROBABILISTIC APPROACH

Given the challenges associated with collecting data around the likelihood and consequence of collision events and the limitations of numerical models, Copping et al. (2023) developed a framework for organizing data to move toward quantifying the likelihood of sequential events that must take place for a marine animal to approach an operating tidal turbine, collide with a rotating turbine blade, and be harmed. This framework relies on stressor-receptor interactions for tidal turbine blades and the marine animals most likely to encounter them, and outlines a stepwise probabilistic methodology that applies existing knowledge. The framework is based on a "bullseye" approach with concentric circles of probabilities of occurrence, with the "worst-case" outcome (serious injury or death of a marine animal) as the middle circle (Figure 3.1.3).

The probability that a marine animal will suffer a significant injury or death from a collision with a tidal turbine blade is represented by the center red dot (Figure 3.1.3). However, for this outcome to occur, each of the previous steps must result in a positive probability of occurrence, starting with the outer ring of the bullseye (probability of *being present in the water column* and the *vicinity of the turbine*). The probability of a marine animal suffering a deleterious outcome (step 6 – animal collides with rotating turbine blade and step 7 – animal injured or killed), will result only if the animal "successfully" meets the probability of each one of the steps in sequence. For example, a marine mammal, fish, or diving seabird must:

- Be present in the vicinity of the turbine (step1);
- Be at the depth of the turbine (step 2);
- Be present when the turbine is rotating (step 3);
- Not avoid or evade the turbine blades (step 4); and
- Not be small enough to be deflected away from the face of the turbine due to the hydrodynamic forces (step 5).

If every one of these circumstances is satisfied, the animal may enter the rotor swept area, but must encounter a turbine blade that is rotating through the area (step 6), and that collision must occur at sufficient speed on a vulnerable part of the animal's body (likely the head or abdomen) to cause death or an injury from which the animal will not recover (step 7). If any of the steps in the framework presents a near zero probability of occurrence, the overall probability, and therefore the risk of collision, must be considered near zero as well. However, if any step in the process is shown to present a more substantial risk, there is a need to delve into that step in more detail. This framework can also help pinpoint the steps at which a greater risk of collision might be derived, allowing for the direction and amplification of resources to reduce the uncertainty of that step, and potentially apply mitigation.

At this time, it is not possible to quantitatively measure what the probability will be of a marine animal meeting the requirements at each step of the framework; additionally, the probabilities will be dependent

BOX 3.1.2.
DESCRIPTION OF MODELS CURRENTLY USED IN COLLISION RISK STUDIES

Encounter rate model: Analytical model with a similar structure to that of a predator-prey model, with the predator being the blade of a turbine and the prey being the animal (Wilson et al. 2007). Parameters included in an encounter rate model are the volume of water swept by the blades, the size of the prey, the prey density, and the relative swimming speeds of both predator and prey. In an encounter rate model, the turbine blade, viewed from the side, sweeps a certain volume of water in a unit of time that an animal has some probability of occupying. The outcome is the likelihood of encounter between the animal and the turbine blade.

Collision risk model: Based on the Band (2012) model developed to assess the collision risk of birds with wind turbines. The analytical approach of a collision risk model integrates the area covered by the turbine rotor, the size of the animal, its transit time across the plane of the rotor, and the animal behavior and density. Analytical collision risk models are sensitive to assumptions about avoidance rate; however, studies rarely include avoidance or evasion behavior within a model. Spatial simulations are another approach to assess collision risk with the representation of an animal and a device in 3D over time (Rossington & Benson, 2020). Spatial simulations integrate the shape and movement of a device, the animal's behavior, and size.

Exposure time population model: Approaches collision risk from the perspective of populations. This model was developed by Grant et al. (2014) for assessing the collision of diving birds with tidal turbines, but can be applied to other species. It integrates two models: a population model and an exposure time model. The population model estimates the amount of additional mortality caused by collisions that would not decrease the population growth rate. The exposure time model estimates a collision probability from the amount of time animals spend at the depth of the device and the proportion of that depth occupied by the device. The combination of both models estimates the collision risk per unit of time based on existing data for the population size and the individual exposure time. All the collision events are assumed to be fatal, and the animal's behavior is not included.

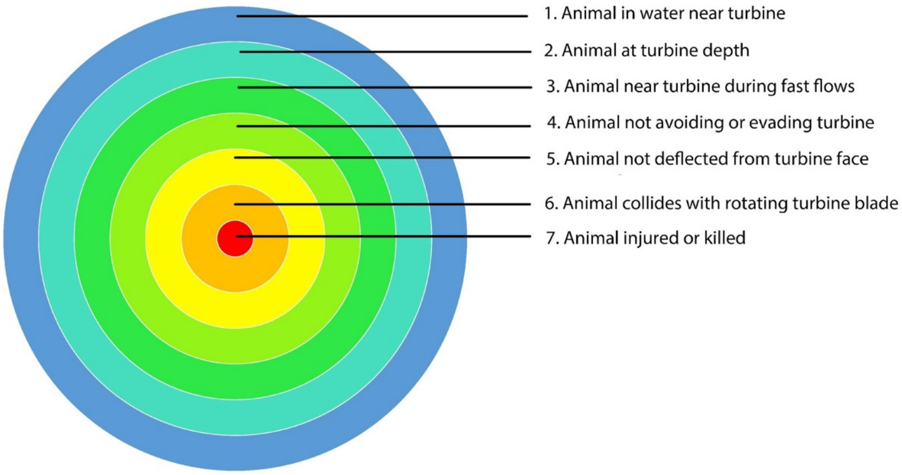

Figure 3.1.3. A conceptual probabilistic framework for organizing data to move toward quantifying the likelihood of collision risk for marine animals and operational tidal energy turbines. The framework outlines a series of sequential steps that must take place, each with an associated probability, for a marine animal to approach an operational turbine, be struck by a turbine blade, and be harmed (i.e., suffer a critical injury or mortality). (Figure from Copping et al. 2023)

on: 1) species characteristics including its behavior and anatomical attributes; and 2) the geometry, size, and rotational speed of the turbine. Although the risk of collision will be specific to each project, location, and health of local species, the likelihood of a serious injury or death to an animal can be estimated using the framework developed by Copping et al. (2023).

3.1.2.
STATUS OF RISK RETIREMENT

Although animal movements around and within the vicinity of turbines have been monitored at several tidal and riverine turbine sites over the last decade, there have been no observations of marine mammals or diving seabirds coming into direct contact with turbine blades. Overall, estimating collision risk is challenging due to the difficulty of observing marine animals in the vicinity of a tidal or riverine turbine. Environmental conditions (fast currents, high turbidity), low light, and the low probability of a collision event decrease the opportunity to collect useful nearfield data and subsequently use those data to inform collision risk assessments. Even for small MRE developments, uncertainty around the potential effects of collision risk remains and both research and project-level studies are still needed to increase the understanding of the various parameters that inform collision risk assessments, and the potential consequences on individuals and populations of concern. Numerical models have been used to predict collision rates and estimates of mortality, but the outputs of such models are dependent on the assumptions made about the animals' behavior (e.g., the ability to detect or avoid a turbine) and the potential consequences of animals colliding with turbines.

One step toward better understanding collision risk is the increasing availability of monitoring data around single devices and small arrays (ORJIP Ocean Energy, 2022a; Smith 2021). Increased monitoring data will help inform the probabilistic framework of Copping et al. (2023) and other methods of estimating collision risk, including numerical models. A key element of the potential to increase informed monitoring outcomes has become part of certain environmental consenting requirements and research studies, including collecting large amounts of video data recorded around several deployed devices. These datasets can be leveraged for scientific research around collision risk, before designing expensive field campaigns to collect new videos and other data. Some of these video datasets have been provided by developers for researchers to review and assess risks of collision for fish, marine mammals, or seabirds. The current list of identified video datasets is provided in Table 3.1.1. These datasets are often large and require intensive labor to be analyzed, which is time consuming and costly. Automated processing is therefore needed to analyze these large volumes of datasets, identify marine animals present in the images, and potentially characterize their behavior around a turbine. Love et al. (2023) developed a machine learning algorithm to analyze the underwater video footage obtained around the Shetland Tidal Array (Smith 2024; Table 3.1.1; see Chapter 2). The algorithm accuracy to classify marine animals was 80%, differentiating the animals from

Table 3.1.1. List of existing video datasets recorded during post-installation monitoring of tidal turbines.

Developer	Device	Location	Year	Link to metadata or publication	Animals observed in the datasets
Voith Hydro	HyTide	Fall of Warness, Scotland, United Kingdom	2014	https://tethys.pnnl.gov/project-sites/voith-hytide-emec	Fish, seabird
Nova Innovation	M100, M100-D	Bluemull Sound, Shetland, Scotland	2015-2020; ongoing	https://tethys.pnnl.gov/project-sites/nova-innovation-shetland-tidal-array	Fish, harbor seal, seabird
Simec Atlantis (now SAE Renewables)[2]	Andritz Hydro Hammerfest	Pentland Firth, Scotland	2017	https://tethys.pnnl.gov/project-sites/meygen-tidal-energy-project-phase-i	
Sabella	D10	Fromveur Passage, France	2018, 2019	https://tethys.pnnl.gov/project-sites/sabella-d10-tidal-turbine-ushant-island	Fish
SME Canada	PLAT-I	Grand Passage, Canada	2019	https://tethys.pnnl.gov/project-sites/plat-i-463-tidal-energy	Fish, jellyfish
Ocean Renewable Power Company	RivGen®	Kvichak River, Alaska, United States	2021	https://tethys.pnnl.gov/publications/characterizing-sockeye-salmon-smolt-interactions-hydrokinetic-turbine-kvichak-river	Fish

background or detritus. Such analysis of large video datasets could also be useful for the assessment of nearfield effects such as evasion behavior and collision risk. The use of video cameras for data collection is however only suitable at certain sites and has limitations due to environmental factors (e.g., high turbidity, low light). Other types of data, such as from telemetry, acoustic imaging, and (for vocalizing species) passive acoustic monitoring, can also be leveraged for collision risk research. Several recent studies have collected acoustic data to assess the behavior of fish (Bangley et al. 2022; Bender et al. 2023; Grippo et al. 2020) and marine mammals (Gillespie et al. 2021, 2023; Palmer et al. 2021) around deployed turbines.

Although recent field studies have focused on assessing animals' interactions around turbines (Figure 3.1.4), the low number of deployments, the challenges of collecting nearfield data, and the rarity of nearfield encounters limit our understanding of collision risk. There is a need for additional data collection and research studies before collision risk can be considered for retirement (also see Chapter 6). To move forward on risk retirement for collision, Ocean Energy Systems (OES)-Environmental has developed a Collision Risk Evidence Base listing the key research papers and monitoring reports that define what we understand about the risk of collision and a Collision Risk Guidance Document to evaluate collision risk effects within a general regulatory context.

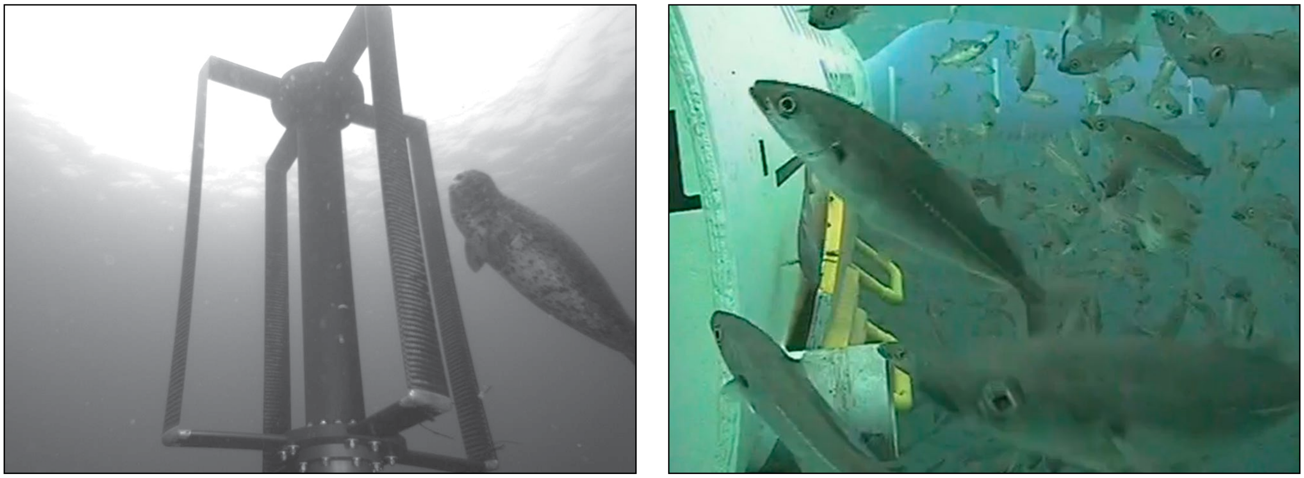

Figure 3.1.4. Photo of a harbor seal (*Phoca vitulina*) swimming around a turbine with stationary rotor at slack tide. Photo courtesy of Marine-Situ and Applied Physics Laboratory, University of Washington (left). Photo of a school of saithe/pollock (*Pollachius virens*) swimming around a stationary turbine at the Shetland Tidal Array, Bluemull Sound, Shetland, Scotland, United Kingdom (Smith 2021) (right).

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[2] No animals were visible on the videos from Simec Atlantis.

3.1.3.
RECOMMENDATIONS

Based on existing evidence, there appears to be a very low likelihood of collision events occurring but the potential consequences of even rare events for the animals (e.g., injury or death of an animal) and associated populations remain uncertain. To move forward on resolving these uncertainties and improve our understanding of collision risk, the MRE community (i.e., developers, researchers, regulators, funding agencies, and other stakeholders) needs to agree on high-priority research needs:

- Provide sustainable funding support for targeted research and dissemination of the results;
- Encourage developers through incentives to provide access to their turbines for monitoring, and make public their non-proprietary datasets and metadata on device monitoring studies;
- Focus research efforts on priorities identified by strategic programs; and
- Apply reasonable regulatory frameworks to allow the deployment of new projects in suitable areas to facilitate monitoring and research.

With adequate funding, results from studies on collision risk could be disseminated through direct engagement with regulators, advisors, and stakeholders. A consultative process should also be used to encourage researchers, regulators, and developers to formulate and prioritize important applied research questions that would advance the understanding of collision risk over the next few years.

In the absence of field observations of collision and other forms of measurable data, the use of frameworks for organizing and evaluating the completeness of datasets (Copping et al. 2023) and other methods of setting priorities can play a role in prioritizing information gathering and analysis for consenting. Numerical models are also a key element in interpreting and planning data collection and validation campaigns. Models that inform collision risk require specific input data types that are not necessarily available for all species of concern; collecting these data should become a strategic priority (Wood et al. 2022). Targeted research studies should be developed to fill the data gaps between parameters needed for models and data that are available from empirical studies. The use of integrated instrument platforms including acoustic sensors and cameras is advised to achieve successful monitoring of marine animals and collect relevant data for collision risk. Combining the use of video cameras with active acoustics or echosounders would also be beneficial for species identification. For protected species, the development and use of technologies to determine their presence and assess their behavior in the nearfield is recommended. In many cases, management bodies at the regional, national, or international level will already have assessments of these species that can be leveraged. For example, for managed fish species, it is recommended that MRE researchers work with fisheries agencies to access stock assessments that use repeated protocols for data collection (Xoubanova & Lawrence 2022). These data can then be used to validate models that inform the potential effects of collision risk on populations.

Recommendations for reducing uncertainty around collision risk for marine mammals, fish, and diving seabirds take similar forms; however significant differences in animal behavior, swimming speed, body dimensions, and presence in the water column require different approaches. Recommendations that are common for marine mammals, fish, and seabirds include:

- examining and processing (using artificial intelligence or deep learning methods) all existing video data collected around turbines that have marine mammals, fish, or other animals present, to understand and disseminate the true extent of our current knowledge;
- designing research projects that are geared toward collecting appropriate data for parameterizing and validating numerical models, and informing robust collision risk assessments, thus supporting decision-making processes;
- understanding the different parameters of a turbine that most influence collision risk to encourage the development of lower risk technologies;
- assuring that monitoring is focused on reducing uncertainty around collision risk, is carried out around existing and future turbine deployments, and is designed to answer the important questions for collision risk of fish, marine mammals, and diving seabirds (as appropriately defined by the relevant regulators for key species);
- documenting and disseminating information on the most appropriate set of instruments and methods that will provide accurate observations of collision

risk, suited to a range of site conditions and species of concern (e.g., Cotter & Staines 2023);

- continuing to update the MRE community on the state of the science on collision risk and encouraging developers to participate in data collection that will lead to robust model development; and
- developing a mitigation and monitoring planning framework for project developers, considering the scale and type of deployment.

In addition, collision risk estimates for marine mammals must consider that relatively few individuals are likely to be present at any time around a tidal turbine. This will necessitate the use of video cameras, as well as high-frequency acoustic cameras and echosounders, to capture images of the rare interactions that may occur or to confirm with greater confidence that encounters are not occurring. Estimates of the population size of marine mammal species known to frequent the areas before tidal energy development occurs are needed to establish a baseline against which to understand how rare encounters might be. This could also help gauge whether tidal turbines are likely to have any impact on animal behavior and local populations. Encounter risk and collision risk models can be useful but the ability to parameterize them, based on low population numbers and sightings (as compared to fish) may be challenging in many areas. Mitigating collision risk for marine mammals might be achieved by scheduling operations based on times when animals are less likely to be present.

Collision risk estimates for fish are more amenable to the collection of data that will drive encounter risk and collision risk models, particularly as many species are likely to aggregate around the structure and associated equipment of a tidal or riverine turbine (Copping et al. 2021a). Understanding the population dynamics and migration timing of large fish populations will help gauge the likelihood of encounter and collision at specific times and seasons. Monitoring fish around turbines will require video cameras, acoustic cameras, and echosounders. With larger populations and a greater likelihood of visualizing fish (compared to marine mammals), shorter monitoring periods will likely suffice to gain sufficient data, provided that seasonal fluctuations in species presence (for migratory fishes) are represented. Similarly, experiments with acoustic telemetry on captive fish released close to a research turbine could help resolve questions on encounter and collision as well as avoidance and evasion behavior. To mitigate collision risk for fish, the depth at which fish are distributed should be considered when placing the turbine and MRE systems should be adapted to minimize moving parts.

Finally, for seabirds, the risk of collision is expected to change with the type of device, the species of concern, their behavior (e.g., diving depth), and habitat use in the targeted area (ORJIP Ocean Energy, 2022b). The knowledge on collision risk for seabirds is poor and more information is needed to better understand the potential effects of multiple devices. Compared to fish and marine mammals that are always present underwater, seabirds primarily feed within the water column. To mitigate the collision risk of seabirds, minimizing the deployment of a turbine in their feeding habitat should be considered.

3.2.

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

Author: Deborah J. Rose

Contributors: Joseph Haxel, Brian Polagye, Chris Bassett

Marine animals use sound underwater for communication, social interaction, orientation and navigation, foraging, and predation avoidance. Ambient underwater sound environments include natural and biotic contributions from animal vocalizations, breaking waves, sediment movement, and wind or rain at the sea surface. In addition to these natural sounds, marine animals are subject to many sources of anthropogenic noise in the ocean from shipping, construction, surveys, and other marine industries (Duarte et al. 2021). As more MRE device development and installations occur, it is critical to understand how the introduction of these new sources of noise in the marine environment may affect surrounding organisms.

When considering the risks to marine animals that result from the noise produced by any anthropogenic activity, the amplitude, frequency, and directionality of the noise source, as well as propagation losses, prevailing ambient noise, hearing thresholds, and possible behavioral responses need to be considered. Operating MRE devices are generally expected to generate relatively low frequency noise (up to 1000 Hz), though higher frequency noise has been reported more recently for wave and tidal energy converters (Risch et al. 2023). Other anthropogenic noises may cover a much wider range of frequencies (Figure 3.2.1).

There are a range of potential effects of anthropogenic sound on marine animals, either due to the hearing capability of an animal or to other physiological effects (Popper & Hawkins 2019), as shown in Table 3.2.1.

The main receptors considered for understanding the effects of underwater noise are marine mammals, sea turtles, and some fish and invertebrates that have sensory capabilities for detecting changes in the acoustic environment. The effects of underwater noise may be unique to species and individuals within a population (Harding et al. 2019). This can be due to intrinsic characteristics, such as physical attributes, or extrinsic factors, such as previous exposure or the specific habitat in which the sound is produced.

Marine mammals, in particular cetaceans such as whales and harbor porpoises, and pinnipeds such as seals, have traditionally received the most attention and research, in part due to their size, legal protections, cultural value, and public perceptions as charismatic megafauna. In the US, noise thresholds for marine mammals have been set by the National Oceanic and Atmospheric Administration (NOAA) Fisheries (2018) to provide guidance on

Table 3.2.1. Potential effects of anthropogenic sound on marine animals in order of severity (adapted from Popper & Hawkins (2019) and Popper et al. (2023)).

Effect	Description
No obvious responses	Even if an animal detects a sound, it may show no response. This may occur in the presence of a low-level sound. Alternatively, animals may show habituation to repeated sounds.
Behavioral responses	Changes in normal behaviors that could be anything from a small movement (e.g., minor startle response), to movement away from feeding or breeding sites, to changes in migration routes (see Displacement subsection for more information).
Masking	Added sound can reduce the ability of the animal to detect biologically relevant sounds, such as those from potential mates or other conspecifics, predators, or prey.
Hearing threshold shift	Temporary decreased hearing sensitivity leading to decreased detection of biologically relevant sounds such as from oncoming predators or potential mates. **This has not been observed for MRE.**
Physiological changes	Physiological changes, such as changes in hormone levels, may result in increased stress or other effects leading to reduced fitness. **This has not been observed for MRE.**
Physical injury	Physical injury externally or internally, such as a ruptured swim bladder or internal bleeding, that produces immediate or delayed death. **This has not been observed for MRE.**
Death	Instantaneous or delayed mortality. **This has not been observed for MRE.**

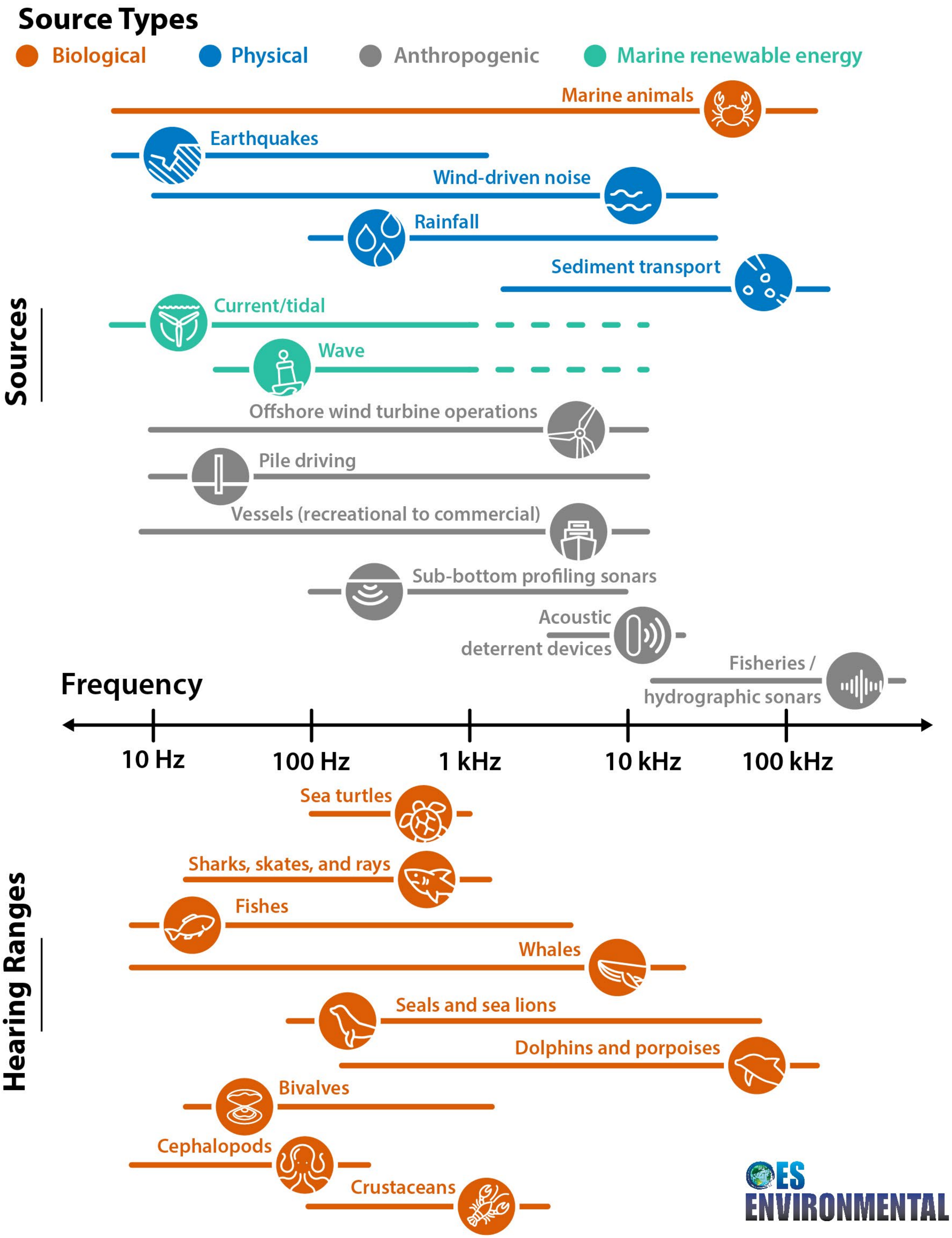

Figure 3.2.1. Sources of sound and their frequencies in the marine environment. Adapted and updated from Polagye & Bassett (2020). (Illustration by Stephanie King)

what levels of underwater noise affect marine mammals temporarily and permanently, as well as on what levels constitute harassment and injury. Several fish species have also been studied extensively (Popper & Hawkins 2019), and interim sound exposure guidelines have been developed for fish (Popper et al. 2014). These guidelines have been used in the US and Europe as representing the best available science (Hawkins et al. 2020). The European Union published its first-ever limits for underwater noise in 2022 under the Marine Strategy Framework Directive (Merchant et al. 2022), adding the requirement that no more than 20% of a specific marine area can be exposed to continuous underwater noise over the course of a year (Borsani et al. 2023). In principle, noise measurements (i.e., operational noise profiles that characterize a device) provided by device developers can be compared to these noise thresholds to evaluate their potential effects on species present at a planned project site, though specific profiles may be considered proprietary and not widely shared.

As of 2020, most studies investigating the underwater noise effects of MRE deployments assessed received sound levels at various distances from operational wave or tidal devices and compared these levels to ambient noise and/or animal hearing sensitivity as a proxy for potential behavioral responses (e.g., Lossent et al. (2018); Risch et al. (2020); Schmitt et al. (2018); Walsh et al. (2017)). Studies have also used "playbacks" of MRE device noise to directly observe animals' behavioral responses (e.g., Hastie et al. (2018, 2021); Robertson et al. (2018); Schramm et al. (2017)). The 2020 State of the Science report (Polagye & Bassett 2020) provides recommendations, including:

- Expanding the evidence base of rigorous, comparable acoustic measurements across a broad range of MRE devices and settings; and
- Establishing a framework for studying animal behavioral consequences of radiated noise from MRE devices.

These recommendations reflected multiple relevant and inter-related themes that inform the general uncertainties around the effects of radiated noise from devices. Technology convergence has not yet occurred among wave or current/tidal devices. When coupled with the differences in underwater noise measurement methodologies, this combination of factors makes direct comparisons between noise emissions from specific devices difficult, complicating a general understanding of the potential effects. However, it is important to emphasize that, even with these measurement challenges, there have been no indications that any effects more serious than behavioral changes in marine animals are likely due to the noise from operational MRE devices.

3.2.1.

ADDITIONAL KNOWLEDGE GAINED SINCE 2020

Since the release of the 2020 State of the Science report, many new noise measurement studies have been published, both specific to MRE and on the effects of underwater noise more generally. Several studies have measured sound output and/or potential effects on marine animals at MRE project sites. The findings from each study are available in Table 3.2.2.

Table 3.2.2. Research studies on underwater noise at marine renewable energy project sites since 2020 for wave energy devices, current/tidal energy devices, and ocean thermal energy conversion technologies[3].

WAVE ENERGY		
Reference	**Project / Site**	**Findings**
Buscaino et al. (2019)	Inertial Sea Wave Energy Converter (Pantelleria Island, Italy)	Characterization of ambient underwater noise prior to installation, and characterization of underwater noise produced by devices during installation and operation using a hydrophone deployed at a range of 40 m. Levels of noise measured were higher after installation, especially at frequencies up to 4 kHz and increased with wave heights. Median broadband sound pressure levels at 63 Hz for specific wave heights were 73 dB re 1µPa before, 106 dB re 1 µPa during installation, and 126 dB re 1µPa after.
Bald et al. (2022); Felis et al. (2020, 2021); Madrid et al. (2023)	Wave Energy in Southern Europe (WESE) Project: IDOM-Oceantec MARMOK-A-5 (Biscay Marine Energy Platform [BiMEP] and Mutriku Wave Power Plant, Spain)	Noise was recorded at the MARMOK A-5 device installed at BiMEP and the Mutriku Power Plant. In general, the contribution of the device to the surrounding environment was not significant, producing measurable sound from 40-120 Hz that exceeded ambient noise by up to 14 dB at 100 m, though this declined to 6 dB as significant wave height increased. Noise propagation from a hypothetical array of 80 devices was modeled using a geometric loss model, resulting in a maximum difference of 50 dB re 1 µPa when compared to a single device, and an area of disturbance in a 0.28 km radius around each device.
Raghukumar et al. (2022, 2023)	CalWave (California, United States [US])	The NoiseSpotter® was developed by Integral Consulting, Inc. and used to characterize the CalWave xWave™ WEC. The NoiseSpotter® was deployed at various distances, measuring acoustic pressure as well as particle velocity from 50 Hz to 3 kHz. During operation, sound levels around 95 dB re 1µPa were measured and linked to mechanical operations. In the context of the ambient soundscape, the noise from the wave energy converter was found to be insignificant.
Harding et al. (2023)	PacWave South (Oregon, US)	The effect of noise from a hypothetical wave farm (28 devices) was modeled for the PacWave South test site using ParAcousti, an open-source hydroacoustic propagation modeling tool. A metric—effective signal level—was developed to capture sound propagation, ambient noise, and hearing thresholds for marine species. The model results show many combinations where the hypothetical underwater noise generated by the wave farm was detectable in the study area, though with significant variation based on each set of model inputs, including some unlikely scenarios. The tool can be used to predict potential effects of anthropogenic noise on marine mammals across a variety of settings.

CURRENT/TIDAL ENERGY

Reference	Project / Site	Findings
Rosli et al. (2020)	HydroSpinna (Newcastle University, United Kingdom [UK])	Radiated noise levels from a scale Hydro-Spinna current turbine were measured in a lab test at Newcastle University. The results were extrapolated using models for several sizes of full scale devices and compared to fish reaction levels to noise from the International Council for the Exploration of the Sea (ICES, 1995). For the optimal designs, the turbine noise was found to be lower than the fish reaction threshold, indicating that emitted noise would only exceed the threshold if the device was operating incorrectly.
Haxel et al. (2022)	University of New Hampshire (UNH) Tidal Deployment Platform (New Hampshire, US)	Hydrophones were used to characterize the sound produced by a tidal turbine installed at the UNH Living Bridge. Noise produced by the turbine was not detectable relative to the ambient noise, which was high due to the urban environment and nearly continuous vessel traffic in the area.
Risch et al. (2023)	MeyGen (Scotland, UK)	This study measured noise levels from two tidal turbines deployed at the MeyGen site in the Pentland Firth, a 1.5 MW Atlantis AR1500 and a 1.5MW Andritz AHH1500, using drifting hydrophones and a three-dimensional COMSOL Multiphysics model to derive the source levels. The highest noise levels were between 50 Hz and 1 kHz, with the Andritz turbine generating lower amplitude sound. The current array with four turbines is likely detectable by harbor seals across a 0.2 km2 radius, and scenarios modeling noise propagation for a 30-turbine array of each turbine type suggest a 0.8 km2 radius for the Atlantis turbine and a 0.3 km2 radius for the Andritz turbine.

OCEAN THERMAL ENERGY CONVERSION (OTEC)[3]

Reference	Project / Site	Findings
Auvray et al. (2015)	Planned OTEC power plant on Martinique Island (France)	A model was used to estimate the noise radiated from the proposed OTEC device, propagating the noise from the pumps and turbines to the cold-water pipe. The sound pressure levels were compared to the Sound Exposure Levels for marine mammals (Southall et al. 2007) present at the project site and the nearby Agoa Sanctuary, but the findings were not reported.
Devault and Péné-Annette (2017)	Planned OTEC power plant on Martinique Island (France)	Operational noise was included as a potential effect for the proposed project. Noise levels generated by floating OTEC would be similar to the noise of a slow cargo ship (45-89 Hz), which could be audible to marine mammals but not above injury levels, though construction noise would likely be higher. Effects on dolphins in the close vicinity of the plant would need to be further investigated.
Rahman et al. (2022)	N/A	Multiple renewable energy devices were reviewed to compare their environmental impact. Underwater noise from OTEC was rated a level 3 out of 5 (moderate) for intensity of impact for both installation and operation, though no additional studies or direct measurements were done.

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[3] Note that a few documents for OTEC are included from prior to 2020 as these were not explicitly considered in the *2020 State of the Science* report.

MEASURING AND MODELING UNDERWATER NOISE

In addition to project studies, several reviews of the state of knowledge for measuring and modeling underwater noise have been published.

Popper et al. (2023) reviewed the acoustic effects of MRE devices on fish and aquatic invertebrates. They find that MRE devices most frequently produce low amplitude, discrete-frequency tonal sounds with harmonics. They also assert that as the MRE industry advances and designs begin to converge, sound radiated from operational devices will become more predictable and easier to characterize, lowering regulator concerns about uncertainty. Also, as the industry progresses, more devices will be deployed, tested, and acoustically characterized, providing additional data to inform decision making. However, they note that substrate vibration from MRE devices that are well coupled to the seafloor (e.g., piles or devices with a large seabed footprint) or devices that emit substantial low-frequency vibrational energy near the seabed could be unpredictable due to variations in substrate composition (e.g., Hawkins et al. 2021).

The existing regulatory frameworks for evaluating acoustic effects of MRE on marine animals rely heavily on sound pressure measurements, prioritizing hydrophones as the critical technology path for characterizing underwater noise. However, in addition to understanding the effects of sound pressure from MRE on marine mammals, new research characterizing the acoustic particle motion component of MRE sounds may also help inform potential effects of underwater noise (Nedelec et al. 2016) for fish and invertebrates that are not sensitive to sound pressure (Popper & Hawkins 2018) (Figure 3.2.2). It is critical to note that in situ

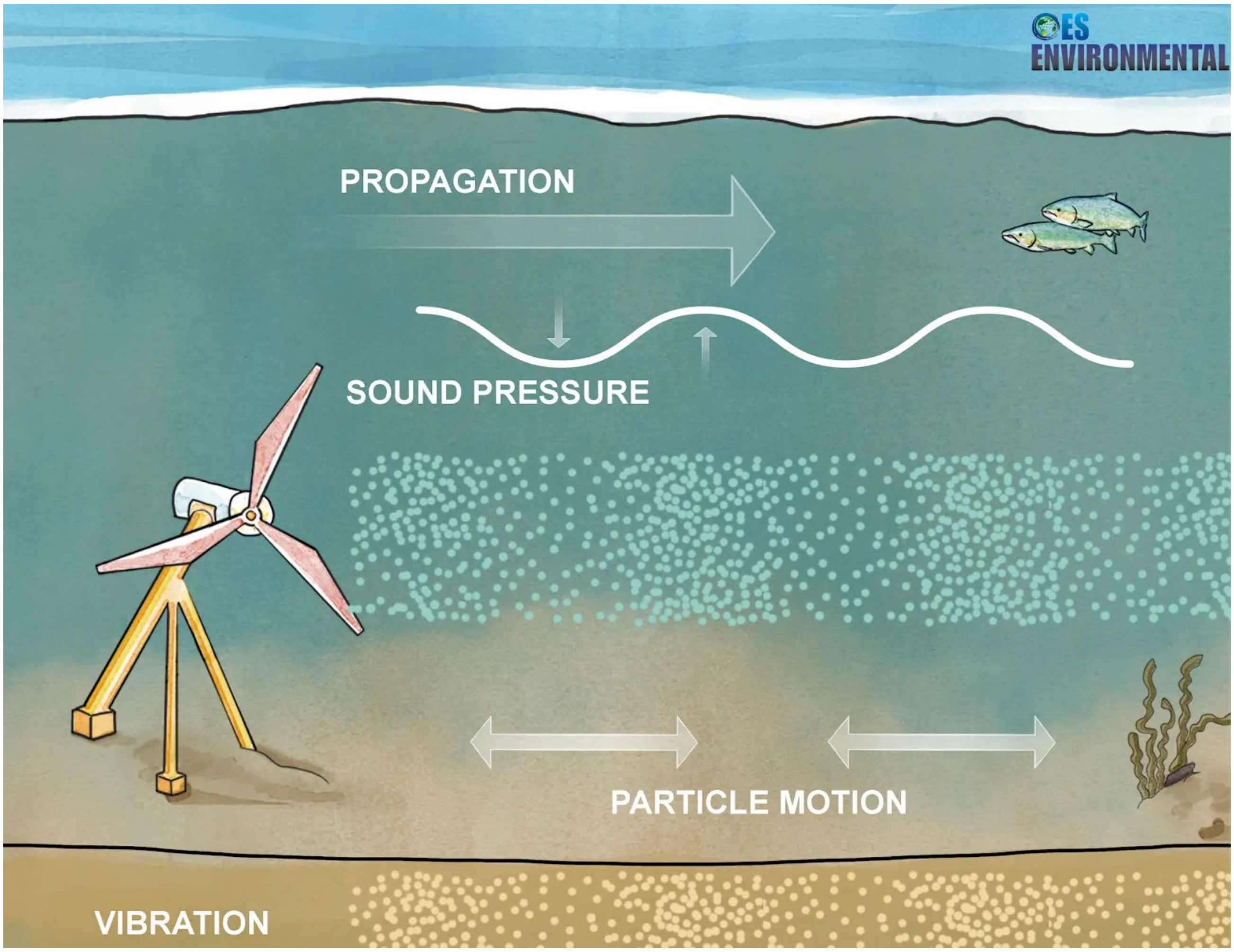

Figure 3.2.2. Underwater noise, particle motion, and vibration as potential stressors, adapted from Hawkins (2022) and Svendsen et al. (2022). A marine renewable energy (MRE) converter can radiate sound energy into the water and vibrations into the seabed. The particle motion component of the sound energy oscillates particles in the seawater back and forth as acoustic pressure propagates away from the device. Similarly, substrate vibration from the MRE converter propagates along and through the seabed away from the device. (Illustration by Stephanie King)

vector measurements of particle motion are more complex than scalar sound pressure measurements and require sophisticated instrumentation that are rarer than simple omni-directional hydrophones. In addition, unlike hydrophones, there is limited understanding of specific considerations required to collect useful data from vector sensors in energetic waves and currents. Therefore, it may be more effective to calculate acoustic particle velocities from sound pressure levels measured by hydrophones where bathymetric complexity allows. Nedelec et al. (2021) provide a best practice guide for measurement of acoustic particle motion, including equipment options and how to determine if particle motion measurements are recommended for biological applications or if it can be calculated from sound pressure. Effects of acoustic particle motion disturbance on fish and invertebrates are poorly understood and require significantly more research.

Buenau et al. (2022) reviewed modeling approaches for underwater noise. Underwater noise modeling is a well-established field, though only a few models are MRE-specific. They found no studies that modeled nearfield noise (10s of meters) from specific devices, or that allowed for environmental complexity (e.g., sea surface or seabed roughness). They also note that modeling effects of underwater noise on marine animals depends on key assumptions about impacts on behavior or vital signs and requires significant baseline data inputs.

van Geel et al. (2022) reviewed existing methods, metrics, and standards for monitoring underwater noise, focused on long-term monitoring for baseline studies and site characterization. They note that choices of metrics and analysis depend on specific research questions, and that full bandwidth of the source noise and, at minimum, the main frequency content of the signal across various relevant time periods, should be captured when possible.

The Helsinki Commission (2021) developed guidelines for monitoring continuous noise for the Baltic Sea, recommending sampling procedures and equipment to ensure consistent measurements, in particular for low-frequency anthropogenic noise (10 Hz to 20 kHz). They suggest selecting a frequency bandwidth between 20 Hz and 20 kHz and a sampling rate at least 2.5 times higher than the bandwidth of interest, as well as providing additional information on device setup, calibration, data processing, and reporting. These guidelines may be required in certain jurisdictions, while the existing international specifications may be most appropriate internationally.

NEW FRAMEWORKS

New frameworks have been developed that may be relevant to underwater noise effects for MRE, although none were prepared for, nor specific to, MRE.

Verling et al. (2021) developed a risk-based approach to assessment and monitoring aligned with the Marine Strategy Framework Directive’s goal of achieving Good Environmental Status in European Waters. They applied the approach to the risks associated with continuous underwater noise from shipping on cetaceans. The risk-based approach is demonstrated at different spatial scales and for different levels of data availability.

Ruppel et al. (2022) developed a tiered framework to categorize active underwater acoustics for regulatory purposes in the US, focusing on marine mammals. The framework includes assessment of several key factors, including audibility of the frequency for marine animals, received sound pressure levels less than 160 dB re 1µPa, the sound power level (radiated power), and degree of exposure. While not explicitly discussed, operation of MRE devices that radiate noise would fall under Tier 4 along with other oceanographic research devices, which are considered de minimus sources and are unlikely to harm marine mammals. They recommend that Tier 4 sources be exempt from most formal regulatory review and that a survey-by-survey review is unnecessary for single or multiple sources.

Southall et al. (2023) proposed a framework for assessing effects of anthropogenic noise on marine mammals to include population vulnerability and an exposure index in an ecological, risk-based framework, replacing the use of simple sound thresholds. The examples used in the paper are primarily for pile-driving installation of offshore wind farms, but the framework itself is intended to be used for various operational scenarios that include MRE.

TAXA-SPECIFIC STUDIES

The knowledge base on underwater noise effects from MRE would benefit from studies that do not explicitly include measurements around MRE devices, but instead focus on better understanding the effects of underwater noise, in general, on receptors of concern. This section summarizes a few studies that may be helpful for MRE.

Mickle & Higgs (2022) conducted a review of hearing ability of elasmobranchs, including their attraction and avoidance responses to underwater noise. Elasmobranchs do not have a swim bladder and specialized hearing structures, and as such only detect particle motion. The known hearing abilities of sharks, rays, and skates studied to date range from 25 to 1500 Hz. Sharks seem attracted to irregularly and rapidly pulsed sounds along broad-band frequencies that lacked a sudden increase in intensity, but tend to respond by avoidance to sudden increases in sound levels. (See Chapter 10)

Xoubanova & Lawrence (2022) conducted a literature review and consulted stakeholders to develop an evidence map for strategic fish and fisheries research. Their review includes a section on underwater noise evidence gaps, noting that there remains uncertainty in understanding behavioral responses of fish, effects of particle motion, and technological approaches to mitigation.

Solé et al. (2023) reviewed the knowledge on effects of underwater noise on a wide variety of marine invertebrates (protozoans, cnidarians, ctenophores, flat worms, annelids, mollusks, arrow worms, tunicates, and crustaceans) including study techniques, receptor systems of various invertebrates, acoustic sensitivities, and sound generation on both adults and early life stages at the individual and population levels. They found that biological mechanisms of sound reception and generation are not well described for many invertebrate species, and that adaptation to long-term noise exposure is unlikely due to short life spans for many species. Characterization of existing ambient noise is needed to distinguish the effects of a particular sound, and the interactions between multiple stressors need to be considered when assessing the effects of noise.

Olivier et al. (2023) developed a laboratory tank system to measure the effects of underwater noise on larval stages of marine invertebrates. The device primarily simulates pile-driving and drilling, which produce much higher levels of noise, and as such is less applicable for studying the effects of operational MRE devices.

Zang et al. (2023) reviewed underwater sound assessments for fish to identify knowledge gaps, and utilized a case study of traffic sounds from a floating bridge on tidal waters on migrating steelhead smolts in Washington, US, as an example of best practices for noise assessments. Using the case study, they suggested that even when sound pressure and particle motion levels were below the NOAA Fisheries thresholds identified through lab studies (National Marine Fisheries Service, 2018), there was potential for behavioral changes that could negatively affect migrating fish species in the marine environment. They suggest that this case study has implications for MRE devices due to the similar water depth, complex bathymetry, and confined areas in which MRE devices are likely to be installed.

3.2.2.
STATUS OF RISK RETIREMENT

OES-Environmental has developed an Underwater Noise Evidence Base listing the key research papers and monitoring reports that define what we understand about the risks from operational underwater noise from MRE devices and an Underwater Noise Guidance Document to evaluate the risk within a regulatory context.

The evidence base to date suggests that the effects of underwater noise from small-scale MRE developments are limited. Underwater noise measurements from operational MRE devices show that noise levels generally fall below those likely to cause injury or harm to marine mammals and fish, and that observed behavioral changes are unlikely to be attributed solely to noise from MRE devices. Overall, the scientific community has reached a general consensus that underwater noise from operational devices within small-scale MRE developments does not pose a risk to marine animals and can be retired for small numbers of devices (one to six devices) (Copping et al. 2019; Copping et al. 2020; ORJIP Ocean Energy 2022b; Polagye & Bassett 2020). However, this does not suggest that research on this topic has been discontinued or is no longer necessary, as evidenced by the studies

described in the previous section. The International Electrotechnical Commission Technical Committee (IEC TC) 114 published an international consensus Technical Specification (62600-40) for characterizing radiated noise near MRE devices, which provides protocols for sound measurements to enable consistent data collection and allow for comparison across MRE developments. This specification is now in the process of being updated based on feedback from its use to date. Updates are likely to be relatively minor and emphasize adjustments to deployment strategies. In the US, guidance thresholds for underwater noise exist for marine mammals (National Marine Fisheries Service, 2018) and fish (Popper et al. 2014). Research studies internationally are ongoing to assess the potential effects on new species of concern and various underwater soundscapes (e.g., Triton, Safe-Wave). Despite the growing consensus in the scientific community, regulators remain concerned about the potential effects of underwater noise radiated by MRE devices, and efforts to establish key research priorities for aspects that are not well understood are ongoing (e.g., NOAA's Ocean Noise Strategy, Jomopans (Kinneging 2023), Joint Action Underwater Noise in the Marine Environment).

3.2.3.
RECOMMENDATIONS

While progress has been made toward the recommendations from the *2020 State of the Science* report through the characterization of operational MRE devices and efforts to understand effects on animal behavior, significant knowledge gaps still exist. In fact, the recommendations of Polagye & Bassett (2020) remain top priorities. The following additional recommendations will help advance the state of knowledge around underwater noise and enable forward progress of the MRE industry:

- Each new MRE device design should be characterized, ideally using methodology consistent with the IEC TC 114 Technical Specification (62600-40). Measurements to establish the radiated noise signature of each device under different operating conditions are needed. While not part of the Technical Specification, comparisons of noise measurements to thresholds for key species can inform regulatory approaches for specific devices.
- Noise monitoring of operational devices can provide additional benefits, even if not required for consenting. Monitoring noise produced by MRE devices may provide an alternative method for assessing the engineering health of systems, with damaged or malfunctioning systems producing unanticipated sounds (Polagye et al. 2017; Walsh et al. 2015, 2017).

In addition to these recommendations, several research needs have been identified related to underwater noise. Resolution of these knowledge gaps is not likely needed for consenting processes to move forward for MRE, but rather to inform research directions for the broader research community, to address potential aggregated effects of offshore renewables as larger buildouts occur. A better understanding of the links between underwater noise exposure (including sound pressure, particle motion, and substrate vibration) and effects on fish and invertebrates is needed (Popper et al. 2023). Little is known about particle motion and substrate vibration effects on fishes and even less for invertebrates. Studies are also needed on sensory capabilities, including those related to particle motion and substrate vibration that help progress toward a better understanding of meaningful thresholds for disturbance (from the animal's perspective, e.g., masking) with respect to behavioral and physiological responses. Building on existing research (Nedelec et al. 2021), there is a need to characterize and describe conditions where sound pressure measurements are sufficient to calculate particle motion and infer effects on sensitive species. Measurements or calculations to characterize particle motion from MRE devices at project sites should be considered a value-added proposition of lesser importance than sound pressure measurements with hydrophones. More research is needed on effects of operational underwater noise from MRE for sea turtles. This may be an emerging area of research as interest increases in siting MRE projects in subtropical and tropical areas frequented by sea turtles.

3.3.
ELECTROMAGNETIC FIELD EFFECTS FROM POWER CABLES AND MARINE RENEWABLE ENERGY DEVICES

Author: Hayley Farr

As the MRE industry expands around the world, the prevalence of EMFs emitted by subsea power cables and other project infrastructure in the oceans will increase. Based on the knowledge to date, MRE-related EMF effects on marine animals are likely weak for single devices or small arrays; however, substantial uncertainties remain and research is ongoing as more MRE projects are planned and deployed.

EMFs occur naturally in the environment and consist of electric fields (E-fields), measured in volts per meter (V/m), and magnetic fields (B-fields[4]), measured in Tesla (T). The primary source of B-fields is the geomagnetic field, which varies between ~25 µT at the equator to ~65 µT at the poles[5]. In the marine environment, the movement of water or animals through the geomagnetic field creates motion-induced electric fields (iE-fields). Marine animals also produce very low-frequency bioelectric fields that some species can detect. Natural E- and B-fields provide important cues to electro-receptive and magneto-receptive species and the addition of anthropogenic fields may mask or modify these existing fields (Gill et al. 2014).

The primary sources of anthropogenic EMFs associated with MRE systems are the subsea power cables used to transmit the electricity produced to shore, which are either high voltage alternating current (AC) or direct current (DC). Within a cable, the B-field propagates perpendicular to the flow of electrical current along the cable axis, dissipating with distance, while the E-field is fully contained by shielding and grounding (Figure 3.3.1). The characteristics and

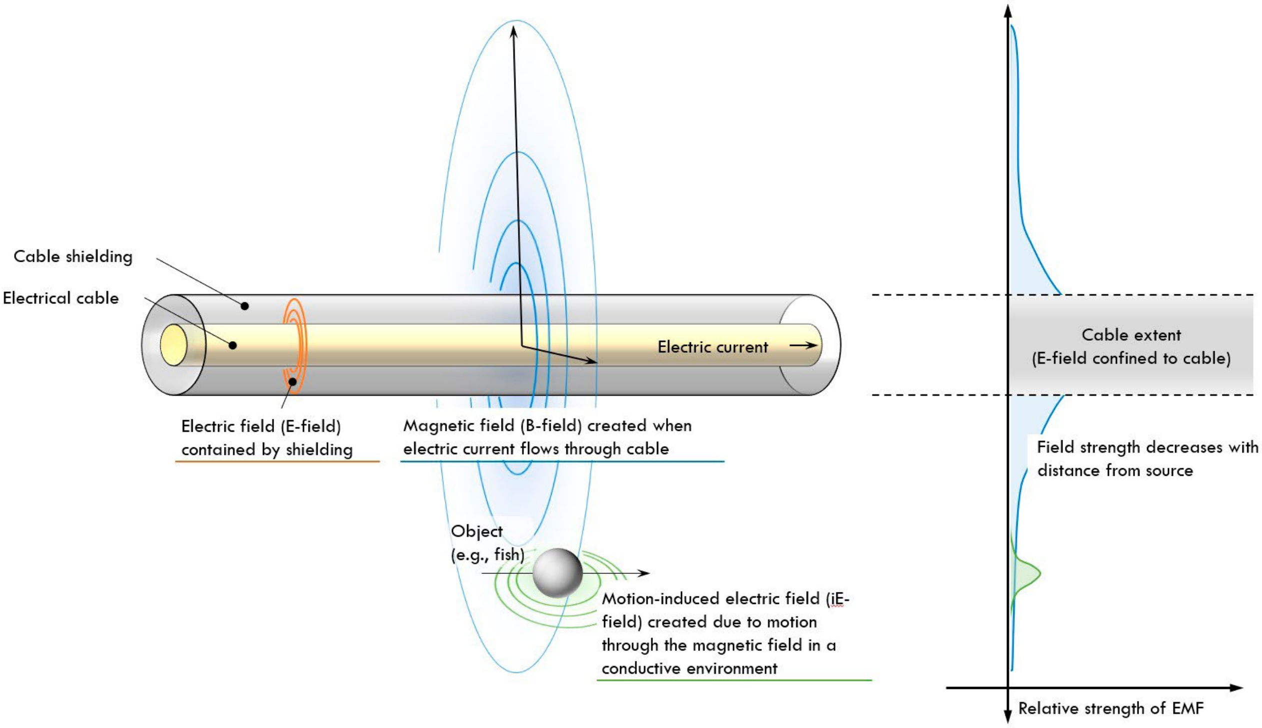

Figure 3.3.1. Depiction of an electromagnetic field (EMF) from an industry standard electrical cable (left) and relative field strength (right) from a snapshot in time. The electric field (orange) is contained by the cable shielding. The magnetic field (blue) is produced by both alternating current (AC) and direct current (DC) cables. A motionally-induced electric field (green) is created as an object or water moves through the geomagnetic field or the magnetic field from a subsea cable. The figure does not show an induced electric field that would be created around an AC cable due to the rotating magnetic field. (Courtesy of Mark Severy)

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[4] B-field is the accepted nomenclature for the magnetic field. It is technically termed the magnetic flux density. The B-field is easily measured (in Tesla) and considers the permeability of the medium.

[5] *https://www.ncei.noaa.gov/products/geomagnetic-data*

strength of EMFs emitted from these cables depend on the cable design, number of cables, type of current (AC or DC), power transmitted, local fields, and other environmental factors.

DC cables generate static B-fields, while AC cables, which have been used more commonly in MRE and offshore wind developments to date, generate B-fields that vary over time. The movement of water or animals through these B-fields generates secondary iE-fields in the environment outside of the cable (Figure 3.3.1); AC cables also produce iE-fields due to the rotating nature of their B-fields (not shown).

In general, the stronger the electrical current, the stronger the emitted B- and iE-fields. The strength of B-fields associated with MRE subsea cables can range from 10s of nT to a few mT, while E-fields can range from 1 to 100 µV/cm, which is similar to the bioelectric fields emitted by prey species (Taormina et al. 2018; Gill & Desender 2020). Cable burial can create additional distance between the strongest field intensities at the cable's surface and most marine animals living on or near the seafloor, but B- and iE-fields in the water column will be present and may be detected by marine species.

Other sources of EMFs include the MRE devices themselves, offshore substations and transformers, and the dynamic inter-array cables that connect devices to one another and to a substation. As more floating MRE projects are deployed, more pelagic species may be exposed to EMFs of varying intensities in the water column. Each cable connecting a device to the seafloor will carry less energy than the export cable running along the seabed to shore. However, there is little research on EMFs from cables in the water column.

Many marine species from diverse taxonomic groups can sense and respond to E- and/or B-fields and may encounter EMFs from MRE developments (Figure 3.3.2). The groups that are the focus of most EMF effects research include certain species of bony fish (teleosts and chondrosteans), crustaceans (crabs, lobsters, and prawns), elasmobranchs (sharks, skates, and rays), mollusks (snails, bivalves, cephalopods), cetaceans (whales and dolphins), and sea turtles. The sensory capabilities, biological relevance, and effects

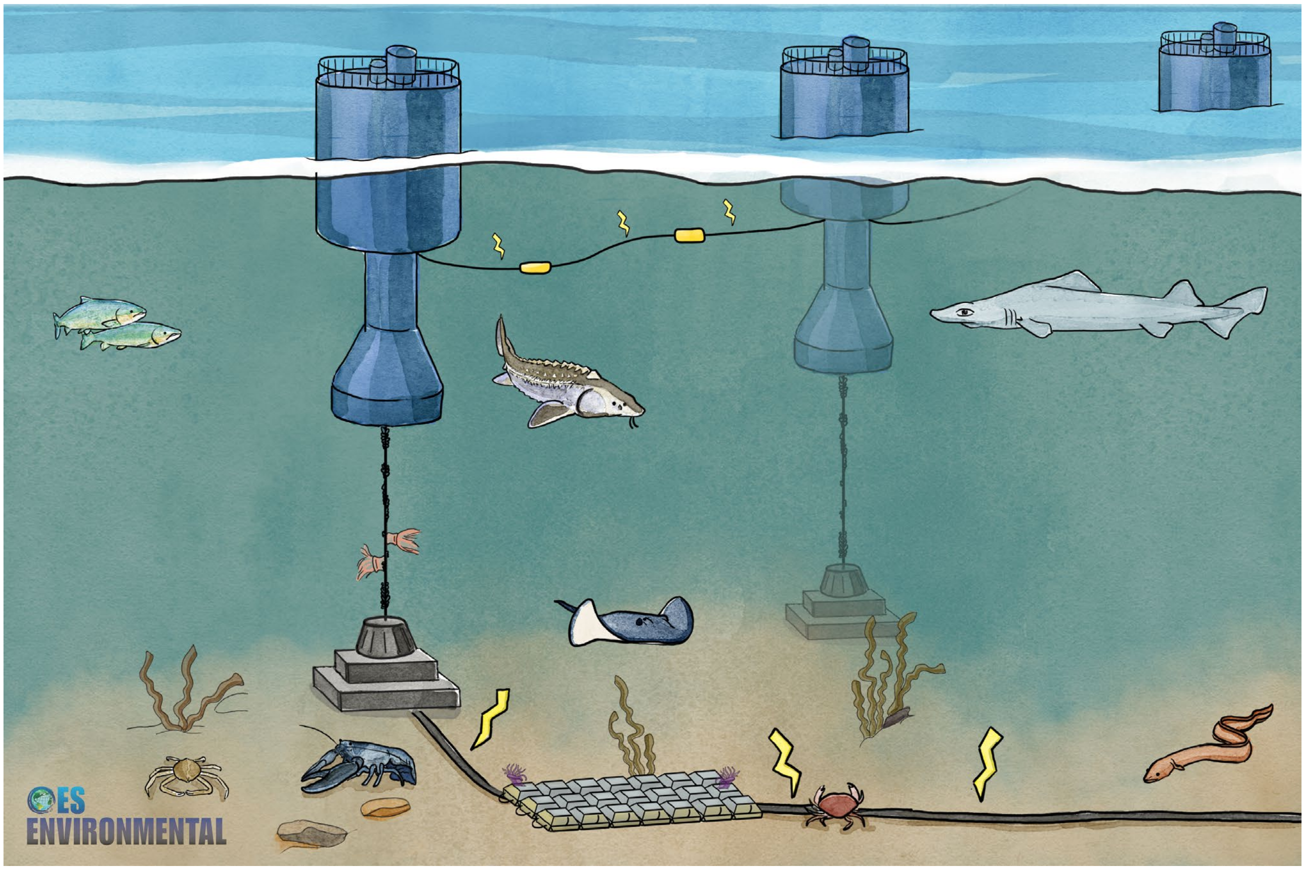
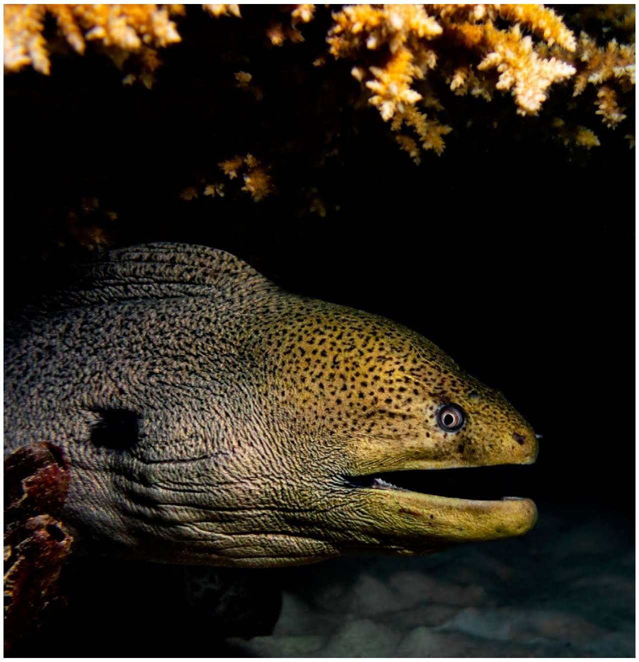


Figure 3.3.2. Illustration of some of the marine species likely to encounter electromagnetic fields emitted by subsea power cables associated with marine renewable energy devices. (Illustration by Stephanie King)



of EMFs vary across species and over different life stages (Nyqvist et al. 2020).

The *2020 State of the Science* report (Copping & Hemery 2020) focused on whether an effect or response recorded in a study can be considered an impact. Research has shown measurable behavioral, physiological, developmental, and genetic effects and responses to relatively high levels of E- and/or B-fields on a small number of individual species, but these effects are not evident at the EMF intensities associated with current small-scale MRE (Gill & Desender 2020).

To fill the remaining knowledge gaps around MRE and EMFs, the *2020 State of the Science* report (Gill & Desender 2020) recommended further efforts toward:

- Developing affordable methods and equipment to simultaneously measure E- and B-fields with the necessary sensitivity and precision for comparability;
- Validating existing models with EMF measurements from deployed MRE devices and power transmission cables;
- Conducting laboratory studies of species response to EMFs at different intensities and durations to determine the thresholds for species-specific and life stage-specific dose responses;
- Increasing understanding of the interaction of pelagic species (e.g., sharks, marine mammals, fish) with dynamic cables (i.e., cables in the water column); and
- Carrying out long-term, in situ studies to address the question of the effects of chronic EMF exposure on egg development, hatching success, and larval fitness.

3.3.1.
ADDITIONAL KNOWLEDGE GAINED SINCE 2020

Interest in EMFs has continued to grow in the four years since the publication of the *2020 State of the Science* report, and several studies have sought to improve understanding of the interactions between anthropogenic EMFs and marine species, with a strong focus on fish and invertebrates. Research has primarily involved controlled laboratory-based studies of anthropogenic B-fields (e.g., using Helmholtz coil devices), field-based surveys of EMF-emitting subsea cables, and a few numerical modeling studies.

It is important to note that several recent laboratory studies use much higher-intensity EMF levels than those expected from the subsea cables associated with current small-scale MRE developments, so their conclusions should be approached with caution. Very little research has been conducted on the effects at a scale relevant to MRE, and there is a need to assure realism about both the intensities and exposure timeframes used in experiments. Moreover, B-fields from anthropogenic sources are three-dimensional, but the experimental setups used in many laboratory studies only allow for the study of effects in two dimensions, so this and other study limitations should be considered.

Within the academic literature, several key reviews have also been published about the effects of EMFs on resource species (Hutchison et al. 2020) and early developmental stages of fish (Formicki et al. 2021), as well as the potential biological consequences of MRE deployments on marine species in general (Hemery et al. 2021a), modeling approaches for understanding environmental effects of MRE (Buenau et al. 2022), scaling up understanding of effects from single MRE devices to arrays (Hasselman et al. 2023), and marine animal displacement from EMFs generated from MRE devices (Hemery et al. 2024).

An expert workshop was held to advance understanding of EMFs from subsea power cables, with a particular focus on offshore wind, which developed several key outputs and recommendations (Gill et al. 2023). For example, the experts recommended that modeling of anthropogenic EMFs should also consider the local

geomagnetic field and prevailing water movement to determine the total EMF environment that an animal may encounter, and set out an agreed and standardized approach to determining the total EMF environment. The workshop also highlighted the importance of understanding the likelihood of animals encountering the total EMF environment when assessing potential impacts. Since this will depend on the presence and distribution of animals (spatially and temporally) and their use of the water column in relation to where the power cable (EMF source) is located, the experts suggested that a risk-based approach be explored (Gill et al. 2023).

Hermans et al. (2024) used an ecological risk assessment approach to determine the risk for behavioral effects of EMFs from offshore wind power cables on benthic elasmobranchs on the Dutch continental shelf. The study estimated exposure levels by comparing modeled B-fields to reported elasmobranch sensory ranges and effect levels, and found that potential risk levels differ depending on the biology and ecology of different species groups (e.g., rays, sharks, skates).

LABORATORY STUDIES ON FISH

Focusing first on the larval stage, Cresci et al. (2022a) exposed lesser sandeel (*Ammodytes marinus*) larvae to an artificial DC B-field gradient (50–150 µT) in a raceway tank to examine potential effects on their dispersal. Neither swimming speed nor distribution were affected, suggesting that lesser sandeel larvae will not be attracted to or repelled from subsea cables associated with MRE.

In a similar study, Cresci et al. (2022b) found that short-term exposure to an artificial DC B-field gradient (50–150 µT) also did not affect the spatial distribution of Atlantic haddock (*Melanogrammus aeglefinus*) larvae. However, the haddock larvae's median swimming speed and acceleration were significantly reduced, highlighting that B-field effects are species-dependent and individual-specific.

Building on these results, Cresci et al. (2023) exposed additional Atlantic haddock and Atlantic cod (*Gadus morhu*a) larvae to artificial DC B-fields (22–156 µT) to assess effects on their dispersal. Short-term exposure did not affect the spatial distribution of either Atlantic haddock or cod larvae, but it reduced their swimming activity, suggesting that both species are sensitive to weak intensity B-fields.

Using a similar experimental setup but slightly higher intensities, Durif et al. (2023) tested whether short-term exposure to an artificial DC B-field (230 µT) affected juvenile lumpfish (*Cyclopterus lumpus*) behavior. While swimming speed was reduced (by 16%), swimming activity and distance traveled were unaffected, suggesting that lumpfish migration and homing would not be significantly affected.

In the first study to expose an elasmobranch to uniform AC and DC B-fields (450 µT), Albert et al. (2022a) observed the short-term behavioral responses of juvenile thornback rays (*Raja clavata*) in controlled conditions. Rays exposed to B-fields during the midday experimental period exhibited an increase in active behaviors, but those exposed during the morning period did not. Results highlight the challenges of studying species that display long periods of inactivity and high inter-individual variability, particularly with small sample sizes, and the need for further long-term studies.

Finally, Jakubowska et al. (2021) found that rainbow trout (*Oncorhynchus mykiss*) larvae reared in either AC (1 mT) or DC B-fields (10 mT) did not show direct avoidance after being re-exposed to their respective B-fields. Rather, the results highlight that early-life stages of rainbow trout can detect and are attracted to artificial B-fields, with no visible signs of stress (i.e., increased oxygen consumption).

LABORATORY STUDIES ON INVERTEBRATES

Beginning with behavioral effects, Albert et al. (2023) explored the potential behavioral effects on the commercially important velvet crab (*Necora puber*) from short-term exposure (30-min) to artificial AC and DC B-field gradients (72–304 µT). Results from three experimental setups suggested that these B-fields intensities do not induce attraction or repulsion, or affect the velvet crab's exploratory, foraging, and shelter-seeking behaviors.

In one of the first EMF studies on the filtration activity of suspension-feeding bivalves, Albert et al. (2022b) demonstrated that short-term exposure (6 h) to artificial DC B-fields (300 µT) had no observable effects on the filtering activity and filtration rate of the blue mussel (*Mytilus edulis*), a widespread ecosystem engineer and keystone species.

Chapman et al. (2023) found no significant differences in physiological stress responses in the common periwinkle (*Littorina littorea*), common starfish (*Asterias rubens*), European edible sea urchin (*Echinus esculentus*), and velvet crab after a 24-hour exposure to an artificial DC B-field (500 µT). The study also investigated exposure to the coastal invertebrates' righting reflex, which is an important measure of anti-predation, and found no significant behavioral effects.

Scott et al. (2021) investigated the behavioral and physiological effects of exposure to varying B-field strengths on the commercially important edible crab (*Cancer pagurus*). While exposure to 250 µT had limited influence, exposure to higher intensities (500 and 1000 µT) increased stress-related parameters; crabs exhibited an attraction to EMF exposed shelters and spent significantly less time roaming, once again highlighting the importance of understanding strength-dependent effects.

Moving to even higher intensities, Harsanyi et al. (2022) exposed ovigerous female European lobster (*Homarus gammarus*) and edible crab to DC B-fields (2.8 mT) throughout embryonic development. Although exposure did not alter embryonic development time, larval release time, or vertical swimming speed for either species, chronic exposure led to significantly smaller larval size in both species, a higher occurrence of larval deformities, and lower swimming test success rates amongst lobster larvae.

Jakubowska-Lehrmann et al. (2022) assessed the effects of high-intensity AC and DC B-fields (6.4 mT) on the bioenergetics and physiological processes of a common bivalve, the cockle (*Cerastoderma glaucum*). The filter feeder maintained a positive energy balance after exposure to both experimental conditions, but significant changes in filtration rate and other physiological effects were observed, revealing the potential for oxidative damage and neurotoxicity in invertebrates exposed to high-intensity B-fields.

Finally, using a combination of biochemical, metabolism, and transcriptome studies, Fei et al. (2023) found that prolonged exposure to an extremely high-intensity DC B-field (1.1 T) increased oxidative stress, blood glucose, and lipid levels, and decreased immunity and physiological conditions in a benthic sea slug (*Elysia leucolegnote*). However, these B-field intensities are, once again, much higher than those expected from any existing or planned MRE developments.

FIELD MEASUREMENTS AND MODELING

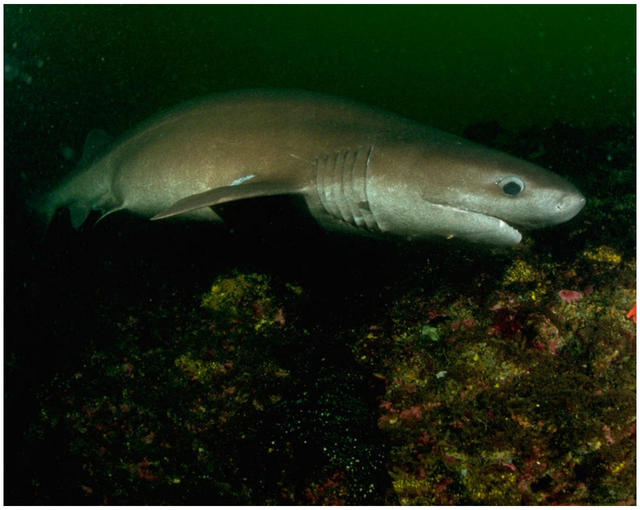
Since 2020, few studies have focused on quantifying the extent of natural and anthropogenic EMFs using field measurements and modeling, let alone the potential effects of EMF from MRE. Numerical modeling has been used to complement field and laboratory measurements, but the data needed for model validation are still lacking. EMFs can typically be modeled using analytical equations or numerical simulations, but applications have been constrained to simplified settings so far. A recent review of modeling approaches for understanding the environmental effects of MRE found no examples of realistic spatial variability or interacting fields, and no models of marine species' physiological or behavioral responses to EMFs (Buenau et al. 2022).

Building on the findings of Love et al. (2017), Williams et al. (2023) used experimental cages to study the response of red rock crabs (*Cancer productus*) to a 34.5 kV AC subsea transmission cable associated with an offshore oil and gas rig in the Santa Barabara Channel. Divers measured local B-fields near the cable, which peaked at ~1.2 µT along an exposed section and decayed to ambient levels 0.9 m away from the cable. The study found that red rock crab movement was not influenced by B-fields of similar intensity to those associated with existing MRE developments and was one of the first to measure the temporal variability of B-fields produced by a subsea transmission cable in situ.

Similarly advancing on previous work (Hutchison et al. 2018), Hutchison et al. (2021a) used the SEMLA sensor system to characterize the EMF emissions from an existing high voltage DC transmission cable and also conducted a tagging study to determine the potential encounter and responses of migratory American eels (*Anguilla rostrata*). Using high-resolution 2D and 3D telemetry data and modeling, the study found that while the eels moved faster when exposed to the DC B-field (-18 to 87 nT), the cable did not present a barrier to movement or migration.

In 2016, France Énergies Marines launched the SPECIES (Submarine PowEr Cables Interactions with Environment & associated Surveys) project to improve knowledge of the potential interactions between subsea cables and benthic organisms (Taormina et al. 2021). As part of the effort, the team conducted dynamic and static measurements of EMFs emitted by various subsea power cables using the PASSEM and STATEM tools (©MAPPEM). The PASSEM tool is towed by a surface vessel and can measure EMFs quickly over a wide area, but only at a single point in time and the movement creates noise in the data. Conversely, the STATEM tool is a stationary device that can measure EMFs over time and assess variations near signal sources.

Grear et al. (2022) tested two commercial-off-the-shelf instruments for measuring background B-fields at MRE sites, as well as a third sensor for improving the certainty of location measurements. Results from field testing at Pacific Northwest National Laboratory's Marine and Coastal Research Laboratory in Sequim, Washington suggested that background variability and anomalies in the B-field (on the orders of 10-100 nT) may make it difficult to measure distortions in the local field from relatively low power cables. Lessons learned and recommendations for measuring background B-fields at potential MRE sites are highlighted.



Based on the open-source Arduino platform, Luna et al. (2023) developed a low-cost device capable of detecting B-fields generated by a subsea cable. Results from laboratory and field tests confirmed that the device could take and store measurements at depths of up to 150 m, with about 10 µT accuracy.

As part of the Wave Energy in Southern Europe (WESE) project, Chainho & Bald (2020) conducted EMF surveys around the cable serving IDOM's MARMOK-A-5 wave energy device at the Biscay Marine Energy Platform (BiMEP) test site in Spain. However, no EMF signals could be identified as originating from the cable, likely due to the low power output of the device at the time.

Chainho & Bald (2021) also developed an open-source EMF modeling tool based on Python code and Finite Element Method Magnetics software to estimate EMF strength around the cables serving the MARMOK-A-5 device at BiMEP and the Waveroller device at the Peniche test site in Portugal. In both cases, the EMFs were small, decayed exponentially with distance, and reduced by at least one order of magnitude at 1 m from the cable. Lacking quality data from the deployments to validate their modeling, the team compared their results to a previous study (Slater et al. 2010) and found good correlation.

Hutchison et al. (2021b) used computational and interpretive models to explore the influence of cable properties and burial depth on the DC magnetic field produced by a bundled high voltage DC transmission cable. The study demonstrated the need to consider cable properties and burial when determining the strength and

extent of B-fields emitted and encountered by receptive species. Cables are unlikely to be buried at the same depth along the length of the cable, so the EMF will vary along the cable route.

3.3.2.
STATUS OF RISK RETIREMENT

Based on existing evidence, there is consensus among the scientific community that EMFs from small-scale MRE developments (one to six devices) are not harmful and do not pose a risk to marine animals, and therefore should not inhibit the installation of devices or require extensive monitoring (Copping et al. 2020a, Copping et al. 2020b, Gill & Desender 2020). The risk of EMFs for new MRE projects with small numbers of devices can be retired. Recent investigations have improved understanding of the interactions between EMFs and some fish and invertebrate species, but their conclusions should be approached with caution given the unrealistically high intensities used in some study designs.

OES-Environmental has developed an EMF Evidence Base listing the key research papers and monitoring reports that define what we understand about EMF effects, and an EMF Guidance Document to evaluate EMF effects within a general regulatory context.

3.3.3.
RECOMMENDATIONS

While some progress has been made to address the research and monitoring needs identified in the 2020 *State of the Science* report (Gill & Desender 2020), several gaps remain. Additional research and monitoring are needed to:

- validate existing models with field measurements from deployed MRE device cables;
- increase understanding of responses to EMFs at more realistic intensities and temporal patterns of power transmission by MRE devices;
- determine the total EMF environment, which will involve modeling and measurement of cable (or other source) EMFs, local geomagnetic fields, and prevailing water movement interactions;
- determine thresholds for species-specific and life stage-specific dose responses; and
- increase the understanding of the interaction of pelagic species (e.g., sharks, marine mammals, fish) with dynamic cables.

Additionally, EMF models for MRE are still in early stages and require further development for complex layouts, field validation, and incorporation of species-response data from controlled laboratory studies to assess potential long-term effects (Buenau et al. 2020). MRE developers and the cable industry should make cable properties and energy transmission data available to improve modeling and enable realistic environmental assessments. The development of environmental standards or guidelines for subsea cable deployment and the measurement of EMFs would also assure that data are transferable and can inform future developments. Finally, as larger MRE projects are planned alongside additional offshore energy development, the cumulative EMFs from multiple subsea cables and substations must be measured and these levels evaluated relative to what is known about marine animal sensitivities.

3.4.
CHANGES IN BENTHIC AND PELAGIC HABITATS CAUSED BY MARINE RENEWABLE ENERGY DEVICES

Author: Lenaïg G. Hemery

Benthic (seafloor) and pelagic (water column) habitats provide the biological and physical resources that marine animals rely on to live, including food and shelter. Like any artificial structure added to the marine environment, MRE devices and associated infrastructure may alter benthic and/or pelagic habitats and affect marine organisms (Figure 3.4.1). Bottom-mounted MRE devices are often attached to the seafloor by gravity foundations or pin piles, while floating devices are secured in place with anchors and mooring lines. Power is typically exported to shore by cables buried in the sediment, running along the seafloor, or draped in the water column between devices in a floating array. Usually, the environmental impact assessment stage identifies fragile, unique, or important habitats, which helps in siting projects away from those areas, and mitigating (i.e., avoid, reduce, or compensate for) any severe habitat changes. Nonetheless, the installation, presence, operation, and removal of MRE devices inevitably lead to some changes in marine habitats that may differ from natural variability. The nature of such changes may be neutral, negative, or possibly positive, for the environment.

The range of potential changes in benthic and pelagic habitats related to the various phases of MRE development (Hemery 2020; Hemery et al. 2021b; Martínez et al. 2021) is listed below and shown in Table 3.4.1:

- Loss of some habitat during installation immediately under device foundations, anchors, and cable protections; of colonized infrastructure upon removal; and of benthic and pelagic habitats and habitat connectivity due to the presence of operating devices and associated structures;
- Disturbance and potential removal of sediment during installation and removal of cables and devices, as well as scour of fine sediment around bottom structures;
- Increased turbulence and changes in flow velocity around the base of devices, affecting less resilient benthic organisms;

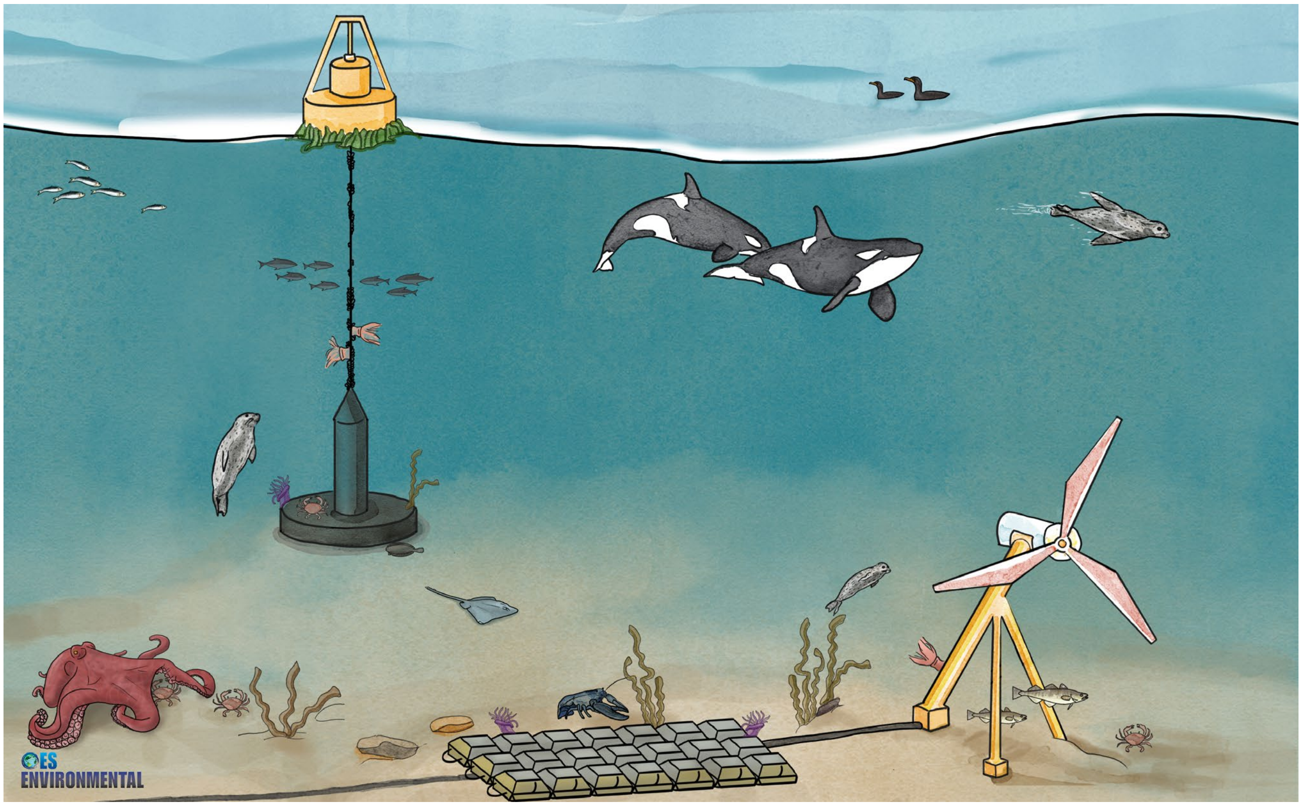


Figure 3.4.1. Representation of a temperate ecosystem with benthic and pelagic habitats influenced by a wave energy converter, a tidal turbine, and an export cable protected by a concrete mattress. (Modified from Hemery et al. 2021a)

- Colonization of new hard structures by biofouling organisms, possibly non-native invasive species, impacting local biodiversity;
- Attraction of mobile organisms to the devices and associated infrastructure acting as artificial reefs and shelters, increasing local biodiversity and prey availability;
- Local increase of biomass inside a project area, potentially acting as a marine reserve; and
- Enrichment of the surrounding seafloor with organic matter and nutrients due to increased biomass on and around the devices, with cascading effects on biogeochemical processes and benthic diversity.

Any animal species within a marine ecosystem may be affected by changes in benthic and pelagic habitats related to MRE development. For instance, individual sessile organisms may be lost during the installation phase, because they are unable to relocate, but the population may gain new habitat by colonizing the devices; mobile benthic and demersal animals may find new habitats on and around the foundations, anchors, and cable protections; non-native species, potentially invasive, may establish themselves on the new substrates; small pelagic fish may benefit from the food and protection provided by devices and mooring systems in the water column; and marine predators may take advantage of greater prey availability in the vicinity of MRE devices (Copping et al. 2021b; Hemery et al. 2021b; Martinez et al. 2021).

Table 3.4.1. Potential changes in benthic and pelagic habitats related to marine renewable energy (MRE) devices. Unless specified, the references provided in the descriptions of the potential changes are from an MRE context. References from surrogate industries were used when necessary.

Potential Changes	Description	Development Phase	Benthic or Pelagic
Loss of habitat	Inaccessibility of seafloor habitat directly underneath device foundations, anchors, and cable protections; proper siting will identify fragile habitats and avoid critical habitat loss (Hemery 2020) Presence of operating devices and associated structures may prevent access to certain habitats and limit connectivity (Miller et al. 2013) Habitat of colonized structures will be lost upon device removal (Miller et al. 2013)	Installation, operation, decommissioning	Benthic, pelagic
Sediment disturbance	Disturbance of soft/unconsolidated sediment habitats because of • Trenching or digging to install cables (Taormina et al. 2018), • Resuspension of fine sediments upon installation and removal of bottom structures (Taormina et al. 2018), • Scouring of sediment around structures due to localized turbulence (e.g., Davis et al. 1982, in the general context of man-made structures), and/or • Sweeping of seafloor areas by catenary mooring chains around anchors (e.g., Morrisey et al. 2018, in the context of boat moorings)	Installation, operation, decommissioning	Benthic
Footprint effect	Increased turbulence and changes in flow velocity around bottom structures can affect epibenthic organisms (O'Carroll et al. 2017a)	Operation	Benthic
Biofouling	Colonization of devices and associated components by sessile organisms or life-history stages, potentially non-native species (Macleod et al. 2016)	Operation	Benthic, pelagic
Artificial reef effect	Attraction of mobile animals to the devices and associated components for food and/or shelter (Langhamer, 2012)	Operation	Benthic, pelagic
Reserve effect	Local populations boost because of cessation or modification of fishing and other human activities in the project area (Alexander et al. 2016)	Operation	Benthic, pelagic
Seafloor enrichment	Accumulation of organic matter and decaying shells on/in the seafloor around devices due to increased litter falls from biofouling organisms and animals attracted to the artificial reef (Wilding 2014)	Operation	Benthic

As of 2020, most MRE studies investigating changes in benthic and pelagic habitats focused on the effects associated with the installation and presence of cables (e.g., Sheehan et al. 2020; Taormina et al. 2018); the footprint effect around tidal turbine foundations (e.g., O'Carroll et al. 2017a, 2017b); biofouling and the colonization by non-native species (e.g., Loxton et al. 2017; Macleod et al. 2016; Taormina, 2019; Want et al. 2017); the artificial reef effect of both MRE devices and their cables (e.g., Bicknell et al. 2019; Langhamer 2016; Sheehan et al. 2020; Taormina et al. 2018); and the reserve effect through modeling (Alexander et al. 2016).

Priority recommendations listed in the *2020 State of the Science* report (Hemery 2020) included:

- improving the understanding of marine animals' spatial and temporal distribution and habitat use in areas targeted for MRE development;
- conducting studies to clarify biofouling and artificial reef assemblage compositions and succession stages; and
- increasing the use of numerical models to assess habitat changes.

3.4.1.
ADDITIONAL KNOWLEDGE GAINED SINCE 2020

Since the publication of the *2020 State of the Science* report, many new MRE-specific studies have been released in alignment with the recommendations noted above, as well as increased focus on the development of monitoring technologies.

UNDERSTANDING ANIMALS' DISTRIBUTION AND HABITAT USE IN MRE AREAS

Most studies related to changes in habitats published since 2020 have been observational in nature and focused on animal distribution and use of tidal habitats. Receptors included marine mammals (mainly seals and harbor porpoises), fish, diving seabirds, and seafloor assemblages (i.e., benthos). These studies can be used as baseline information for future investigations of potential effects.

Marine mammals

To better characterize the risk of harbor seals colliding with tidal turbines, Onoufriou et al. (2021) equipped the animals with telemetry tags to quantify changes in distribution between pre- and post-installation and operation of the MeyGen tidal turbine array (Scotland, UK). Seals were shown to use the area closer to shore during the ebb tide and to be more dispersed offshore during the flood tide. There were no significant differences in seal distribution between pre- and post-installation survey periods. However, most seals remained about 2 km away from the array area when the turbines were operational.

Palmer et al. (2021) used acoustic surveys to assess the presence of harbor porpoises in close proximity to one of the operating MeyGen tidal turbines in the context of collision risk. In addition, they used the data to characterize their temporal habitat use of the tidal channel. They recorded intra-annual and diurnal variations in animal presence, across tidal states. Harbor porpoises were more abundant during winter, at night, and during the peak of flood tide, and less abundant when the tidal turbine was operating.

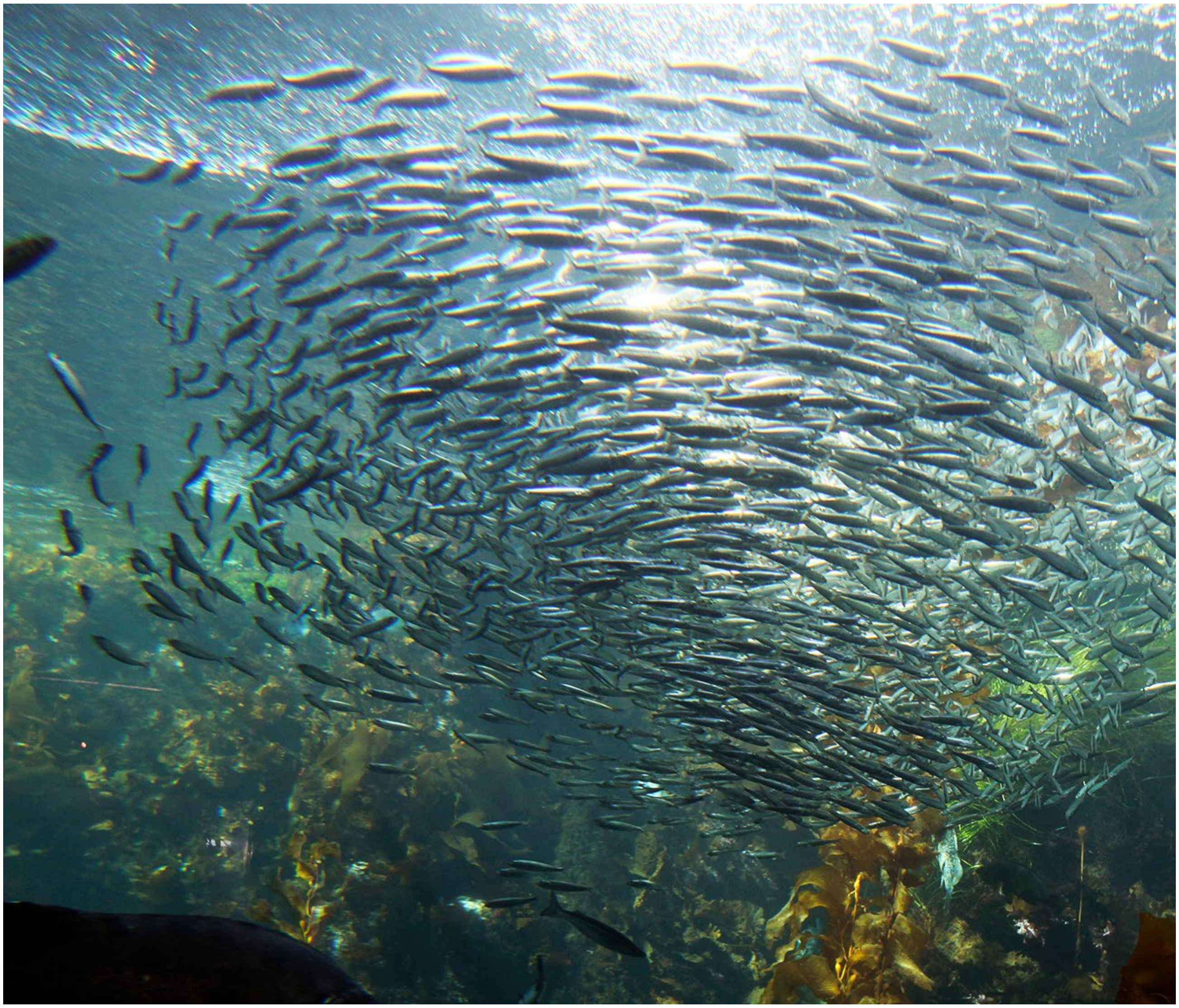
Land-based visual surveys by human observers and turbine-mounted video cameras were used over several years to assess the presence of animals around the Nova Innovation's Shetland tidal array on Bluemull Sound (Scotland) (Smith, 2021; Smith et al., 2021). In nine years of surveys (2010-2019), marine mammals were recorded infrequently in this tidal channel, with harbor seals recorded in 12% of surveys and harbor porpoises in 6% of surveys. In addition, harbor seals were seen on the video footage around the turbines on nine individual days, but no occurrences of harbor porpoise were ever recorded on video.

Marine fish

As part of a baseline characterization survey of a potential tidal energy site in the Banks Strait (Australia), Scherelis et al. (2020a) estimated small-scale cyclical changes in fish density distributions using sonars during a two-week campaign. Results showed that fish densities were significantly highest at night, at high current speed (1.75 to 2.0 m/s), in the 20 to 40 m depth range, close to the seafloor, especially in areas 15 to 40 m deep. Water temperature and seafloor habitat type did not explain fish density distributions. In a related baseline characterization study, Scherelis et al. (2020b) measured fish aggregation metrics over 2.5 months using an integrated multi-instrument platform. Fish were significantly more abundant, less aggregated, and closer to the seafloor at night and at higher water temperatures. Fish abundance was also positively correlated with current speed, especially during ebb tides.

The turbine-mounted video camera at the Nova Innovation site recorded footage of groups of saithe/pollock throughout the year, swimming around the turbine at slack tide or low current speeds, sometimes feeding on the biofouling growing on the nacelle (Smith 2021). Most fish were observed swimming toward the seafloor once currents reached the turbine cut-in speed of 0.8 m/s.

Whitton et al. (2020) assessed fish school vertical distribution at a site targeted for deployment of a Minesto tidal kite off the west coast of Holy Island, UK, using sonars and trawl samples. Schools of sprat (*Sprattus sprattus*) and whiting (*Merlangius merlangus*) were present throughout the 3.5-month long survey and undertook diel vertical migrations to disperse at the surface in the evening and regroup at depth (on average 20 m deep) in the morning. However, fish schools were deeper in October (≈ 22 m) than in January (≈ 15 m).



Seabirds

To evaluate potential impacts of tidal turbines on seabird foraging habitats, Couto et al. (2022) conducted transect surveys to correlate seabird foraging distribution with physical hydrodynamics and prey presence. The distribution of benthic foraging seabirds was strongly associated with sandeel habitats and water velocities below 1.5 m/s. On the other hand, pelagic foraging seabirds were observed in the entire study area and their distribution was strongly associated with fast water velocities (1.5 to 3 m/s) and the presence of fish schools.

Isaksson et al. (2021) used telemetry biologgers to track habitat use by European shags (*Phalacrocorax aristotelis*) in the Pentland Firth tidal stream (Scotland). While the shags clearly used the tidal stream for foraging, few were observed at the location of the turbines within the MeyGen lease area. Johnston et al. (2021) also equipped black guillemots (*Ceppus grylle*) with GPS trackers to evaluate their use of Pentland Firth as foraging habitat. Black guillemot foraging preferences were predominantly associated with water depths of 32 m and current speeds of 1.5 m/s in the MeyGen tidal lease area, and with water depths of 25 m and current speeds of 0.8 m/s outside of the lease area.

Using small uncrewed aerial systems (UAS), or drones, Lieber et al. (2021) focused on three species of surface-foraging terns and their use of physical hydrodynamics as foraging cues in Strangford Lough (Northern Ireland, UK) around the non-operational SeaGen turbine. Terns were more likely to actively forage in turbulent areas with strong vorticity and swirling flows. Small UAS were also used to survey pursuit-diving seabirds of the auk family in the Pentland Firth and their association with bed-derived turbulent features observed at the sea surface, called kolk-boils (Slingsby et al. 2022). The auk density distribution was correlated with the periphery of kolk-boils and influenced by the current velocity and tidal phase.

Based on visual surveys by human observers and turbine-mounted video footage at the Nova Innovation site, black guillemots and European shags were infrequently observed diving in the array area, although more often at slack ebb tides and flood tides than during ebb tides (Smith 2021; Smith et al. 2021). Both seabird species were observed on the underwater video footage on a few occasions when the turbines were not operating. A European shag was seen chasing a school of fish by the idling turbine.

Benthos and seafloor habitats

An environmental survey was conducted two years after the deployment of a wave device at King Island, Australia, characterizing the seafloor habitats with underwater videos (Marine Solutions 2023). The sediment around the device was free of megafauna and macroalgae; however, the device itself was covered in green algae, snails, barnacles, and sponges. The two control sites differed from the device site; they had higher abundances of brown and turf algae, as well as fish and sea urchins.

Smyth and Kregting (2023) conducted scuba surveys to characterize the seafloor assemblages prior to the deployment of the Minesto kite in Strangford Lough, and after five years of operation. No significant differences were found in substrate type, species diversity, or species abundance over the five-year period, leading the authors to conclude that no changes in benthic habitats were detectable as a result of the kite installation and operation.

UNDERSTANDING BIOFOULING AND ARTIFICIAL REEF ASSEMBLAGE COMPOSITIONS

An additional number of studies published since the release of the *2020 State of the Science* report have focused on the marine species and assemblages growing on devices (i.e., biofouling) or the animal communities that aggregate around the devices, their mooring systems, and the cables (i.e., the artificial reef effect).

The studies assessed whether the faunal communities on or around the devices differ from those in surrounding natural habitats and may increase local biodiversity and/or modify local food webs. In addition, understanding biofouling diversity, abundance, and succession stages can also help inform device developers about antifouling strategies.

Biofouling

In Orkney Islands (Scotland), Nall et al. (2022) reported the growth of biofouling organisms, focusing on non-native species, on settlement plates of different colors and coatings. Differences in assemblage composition but not biofouling cover were observed between plate colors, although diminishing over time, while composition and cover differed between coating types. Few non-native species were observed on the settlement plates. Want et al. (2021) deployed settlement plates of various material and coatings at 25–40 m deep in high-energy and sheltered sites in the Orkneys. After a few months, a succession from hydroid-dominated to tube-forming amphipod-dominated communities was observed at all sites, while solitary tunicates dominated only at the sheltered site. Want et al. (2023) identified three biofouling assemblages based on site hydrodynamics and water depth: deep and shallow tidal, deep and shallow wave, and harbor and marina. No non-native species were detected. They also reported the first near-surface observation of large size acorn barnacles (*Chirona hameri*) on uncoated parts of a floating tidal turbine, potentially posing challenges if left unchecked.

Portas et al. (2023) used a multidisciplinary approach to understand how hydrodynamics affect biofouling communities on artificial structures in a tidal estuary in Brittany (France). Biofilm species and assemblages of macro-organisms greatly differed between sampling sites of high and low velocity, with higher proportions and diversity of macro-organisms under low shear stress conditions.

Vinagre et al. (2020) compiled a database of qualitative and quantitative information about sessile biofouling species present in European waters, including non-native species, associated with MRE devices and related infrastructure as well as other artificial substrates. The database provides information related to biofouling species composition, thickness, weight, and size.

Artificial reefs

In Sweden, at the Lysekil research site, 21 gravity-based foundations without WECs attached were installed in the mid-2000s (Bender et al. 2020). Surveys to characterize their colonization by mobile invertebrates and demersal fish were performed shortly after installation and 12 years later, and showed a clear artificial reef effect with greater species richness, diversity, and abundance at the foundations than at the control sites. At wave energy sites along the Swedish coast, Bender (2022) found that the no-take zone positively affected decapod and sea pen abundance and size, despite strong interannual variation. At the Sotenäs project site, an underwater video survey was conducted where the foundations of 34 WECs remain on the seafloor after the project was canceled (Bosell et al. 2020). Five years after installation and bottom-trawling ban, structures were heavily colonized by sessile and mobile invertebrates and fish, some of them listed as near threatened or vulnerable species. This led the structures to remain at the site as an artificial reef and no-take zone for trawling.

At the Paimpol-Bréhat tidal test site in France, Taormina et al. (2020a) monitored concrete mattresses protecting a cable during five years. These structures provided habitat for benthic megafauna, including edible crabs, European lobsters, European congers (*Conger conger*), and Ballan wrasses (*Labrus bergylta*). The degree of colonization of the structures was correlated with the number and type of available shelters. Leveraging four years of underwater imagery surveys of artificial structures, Taormina et al. (2020b) characterized the artificial reef effect and the ecological succession stages. The epibenthic communities on the artificial structures were significantly more diverse than in the surrounding natural habitats, but were not yet stabilized at a mature succession stage. They noted that community changes can still occur five years post-installation.

INCREASING THE USE OF NUMERICAL MODELS

When sufficient input of good quality data are available, numerical models allow researchers to investigate the distribution of marine species in areas suitable for MRE projects, and to assess the habitat use and connectivity within and between project sites. Ecosystem models can also be computed to investigate effects through food web networks (see Chapter 9). However, models are an estimation and will ultimately need to be tested against real data.

Baker et al. (2020) used an approach combining species distribution and hydrodynamic models to examine the impact of a potential tidal barrage on 14 species linked by predator-prey relationships. In the exercise, species of lower trophic levels were negatively affected by losing distribution areas, while higher trophic levels gained habitat behind the tidal barrage, altering the food web dynamics.

Using acoustic telemetry and physical oceanography data with a species distribution model, Bangley et al. (2022) developed a predictive distribution of striped bass (*Morone saxatilis*) in the Minas Passage of the Bay of Fundy (Nova Scotia, Canada). The model indicated that the fish were more likely to be present within the area of the FORCE tidal test site at relatively higher water temperature during late ebb tides.

Buenau et al. (2022) reviewed the modeling approaches employed for multiple stressor-receptor interactions specific to MRE, including changes in habitat. While a large diversity of applicable models exists, this study found that few had been applied in the MRE context at the time of writing. Although advocating for greater use of these models, the authors cautioned about their limitations and that good quality input data are essential, especially when pairing habitat and hydrodynamic models.

HABITAT MONITORING TECHNOLOGIES AND APPROACHES

While technologies employed to monitor benthic and pelagic habitats around MRE devices do not differ from those commonly used by other fields of marine ecology, newer technologies were recently applied in the MRE context. In addition, recent studies have looked at applying more automated ways of detecting and identifying animals around MRE devices and associated structures. More details about monitoring technologies and plans are provided in Chapter 2.

Hemery et al. (2022a) identified 120 monitoring technologies that can be or have been applied in the MRE context to survey six main habitat categories: seafloor, sediment, infauna, epifauna, pelagic, and biofouling. These technologies belong to 12 broad methodology classes: acoustic, corer, dredge, grab, hook and line, net and trawl, plate, remote sensing, scrape sampling, trap, visual, and others (e.g., environmental DNA). Visual technologies were the most common and diverse and were applied across all six habitat categories.

Hemery et al. (2022b) used a 360-degree underwater video lander for the first time around a WEC to assess its usability for monitoring the artificial reef effect of the device's mooring system. The 360-degree field of view enabled the successful recording of fish activity around the anchor during most of the camera deployments.

Costagliola-Ray et al. (2022) assessed the efficacy of UAS for collecting at-sea abundance and distribution data of surface-foraging seabirds like terns in a tidal stream environment as compared to land-based vantage point surveys. The two types of surveys provided similar results, though UAS enabled the identification of fine-scale distribution patterns. However, vantage point surveys are less dependent on weather conditions and visibility. Approach choice should thus be case specific.

To generate benthic habitat maps at MRE sites, Revelas et al. (2020) tested a new sediment profile imagery system at the PacWave test site off Newport, Oregon, alongside acoustic seafloor surveys. The results enabled the generation of Coastal and Marine Ecological Classification Standard benthic habitat maps using a repeatable and cost-effective approach.

Taormina et al. (2020c) optimized an automated process called "point count" to detect, identify, and quantify benthic organisms on still images. They successfully applied their process to images of benthic communities established on cable protection mattresses at the Paimpol-Bréhat tidal test site, where the three-dimensional structure was low and macroalgal coverage minimal.

3.4.2.
STATUS OF RISK RETIREMENT

To move forward on risk retirement for changes in habitat, OES-Environmental has developed a Habitat Change Evidence Base listing the key research papers and monitoring reports that define what the research community understands about this stressor-receptor interaction. Additionally, a Habitat Change Guidance Document was developed to evaluate changes in benthic and pelagic habitats within a general regulatory context.

The evidence base to date, along with discussions with subject matter experts, suggests that the changes in benthic and pelagic habitats caused by single devices or small numbers of MRE devices are well understood (Hemery et al. 2021b). Monitoring studies around devices and associated structures at completed and ongoing MRE projects have shown that the short-term effects (i.e., up to 3–5 years of monitoring) on species assemblages and distribution, or on sediment composition, are similar to those of other existing human activities at sea. While there will always be some differences among sites and the associated living resources, in general these studies have shown that changes in habitats from operational MRE devices are not likely to cause injury or harm to marine organisms, that severe effects can be mitigated by identifying and avoiding of fragile habitats, and that habitats recover quickly from the disturbance. In addition, habitat changes observed to date at single devices and small arrays are hardly discernable from the natural variability, especially after a dozen years (Bender et al. 2020). Subject matter experts have agreed that these studies have gathered enough scientific information to support retiring the risks related to short-term changes in habitat for new projects with small numbers of devices (one to six devices), recommending that regulators, advisors, and developers leverage the knowledge gained from previous projects and surrogate industries (Hemery et al. 2021b).

However, some remaining knowledge gaps prevent a full understanding of the effects of single devices and small arrays on benthic and pelagic habitats (Table 3.4.2). While a lot can be learned about the effects of WECs and device foundations or anchoring systems from studies conducted around fish aggregating devices, artificial reefs, or hydrographic buoys, the lack of true surrogates for tidal energy devices limits the information transfer from other marine industries. Additionally, most studies on habitat changes have been conducted so far in temperate ecosystems of the northern hemisphere. There is a lack of information regarding potential effects of MRE devices on mangrove, seagrass, coral reef, and coastal lagoon habitats more common in tropical and subtropical areas (Martinez et al. 2021; see Chapter 10).

Furthermore, guidelines are needed for spatiotemporal scales that would enable the identification of changes associated with long deployment timeframes and assess the success of monitoring and mitigation measures. Nonetheless, while no guidelines specific to MRE for monitoring marine habitats and collecting field datasets currently exist, the industry can leverage two International Organization for Standardization (ISO) guidelines (ISO 16665 on soft-bottom substrate, and ISO 19493 on hard-substrate seafloor), as well as a dozen US and UK guidelines for monitoring habitats in the context of renewable energy at large, or in the context of extractive industries such as oil and gas or dredging. More details about how these guidelines could apply in the MRE context are provided in Hemery et al. (2022c). Careful judgment is recommended when leveraging these guidelines because an abundance of sampling technologies, methods, sampling designs, and data analyses are provided, but may not always be applicable nor necessary around MRE devices.

As the MRE industry scales up to large arrays (10–30+) and moves toward the decommissioning of completed projects, significant knowledge gaps persist that prevent fully retiring the risks (Table 3.4.2). These knowledge gaps mainly relate to the fact that effects on habitats may not scale linearly with the area occupied by an array or with the number of devices, and that effects may vary across spatial and temporal scales (Hasselman et al. 2023). Numerical models can help evaluate and predict changes in habitats within and around arrays, but high-quality field datasets on both the receptors and the local and regional environmental conditions are necessary as inputs and for output validation (Buenau et al. 2022; Hasselman et al. 2023).

Table 3.4.2. Knowledge gaps by category of changes in habitats. International researchers focusing on changes in habitats caused by marine renewable energy (MRE) devices gathered at a workshop in 2021 to discuss the potential for retiring the risks associated with habitat change as well as identified the remaining uncertainties and knowledge gaps. This table summarizes, per category of habitat change, the main knowledge gaps that will help with consenting and licensing of small numbers of MRE devices once addressed (middle column), and that will help ease concerns related to deploying large arrays or decommissioning MRE (right column).

Categories	Single Devices & Small Arrays	Large Arrays or Decommissioning
Effects of installation and removal on benthos	• Post-installation monitoring is typically not completed on long-enough timeframes to fully understand effects	• Effects from decommissioning or removal are less understood due to the nascent status of the industry and will need to be carefully studied • Monitoring is still needed to support modeling and validation of the impacts of arrays
Community composition on or near devices	• Identification of the appropriate level of site-specific study and monitoring is necessary • Established guidelines, standard mitigation, and frameworks for monitoring and characterizing risks are needed • Ongoing concerns about biofouling by non-native or invasive species remain	• 1–6 devices are not expected to have effects on the seabed, but it depends on how long they are in the water and the colonizing species • Monitoring is still needed to support modeling and validation of the impacts of arrays • Lack of information about whether effects on functional diversity are similar to those observed on taxonomic diversity • The mechanisms of colonization by non-native species are not sufficiently well understood, though some data exist Examples in a variety of geographic regions are missing • Ongoing concerns about biofouling by non-native or invasive species remain
Artificial reef effect	• Remaining concerns about artificial reef effects may be better alleviated with post-installation monitoring • Uncertainties remain about whether the artificial reef is representative of the existing surrounding community or is an attraction to new species	• Uncertainties remain about whether the artificial reef is representative of the existing surrounding community or is an attraction for new species • The potential effects on fish stocks and aquaculture need to be evaluated over the long term • Apprehending local flow conditions is necessary for understanding the artificial reef effect
Habitat change overall	• Wave and tidal environments need to be considered separately • Risks to habitats in tidal environments will be more difficult to retire due to current knowledge gaps and difficulties involved in monitoring • There is a lack of guidelines on appropriate timescales for studying effects, especially in anticipation of decommissioning	• There is a lack of guidelines on appropriate timescales for studying effects, especially in anticipation of decommissioning
Learning from surrogate industries	• Unlike for wave energy environments, good surrogates for tidal environments are still missing • Data transferability from surrogate industries is important, but transferred data need to be evaluated by experts to assure their relevance for a specific project	

Source: Hemery, L.G., Rose, D.J., Freeman, M.C., Copping, A.E., 2021b. Retiring environmental risks of marine renewable energy devices: the “habitat change” case. Presented at the 14th European Wave and Tidal Energy Conference (EWTEC 2021)

3.4.3.
RECOMMENDATIONS

While some progress has been made in the last four years toward realizing the recommendations listed in the *2020 State of the Science* report (Hemery 2020), all these recommendations remain valid to date. Additional recommendations are provided below.

- MRE project proponents should consult with various actors in the targeted areas early on to assess the availability, quality, and applicability of existing datasets before collecting any new baseline habitat data. Various government agencies, academic researchers, and other entities may collect habitat-related field data (e.g., species composition, abundance and diversity, sediment characteristics, water quality parameters) in areas targeted for MRE development long before a wave or tidal project is proposed. Local users, such as Indigenous groups and commercial fishers, may also have historical knowledge of local marine habitats to share. Consultation with existing marine spatial planning commissions is also advised. When the collection of new field data is necessary, the protocols used must be similar to allow for comparison with suitable datasets. In addition, leveraging multiple datasets might help address questions at multiple spatiotemporal scales.
- A careful review of biodiversity and habitat quality indices may identify one that is more suitable to the international MRE context, or highlight a pathway for creating such a universal biodiversity and habitat quality index. While the existing indices (e.g., the AZTI Marine Biotic Index (Borja & Muxika 2005), the Benthic Habitat Quality index (Nilsson & Rosenberg 1997), or the Coastal and Marine Ecological Classification Standard (Federal Geographic Data Committee & Marine and Coastal Spatial Data Subcommittee, 2012)) are useful metrics, they are often region- or country-specific and difficult to transfer from one project to another for risk retirement purposes.
- As much as possible, automated image post-processing and annotation methods (e.g., using machine learning or other artificial intelligence approaches) should be used to dedicate most resources to species identification and data analyses (Love et al. 2023; Signor et al. 2023; Taormina et al. 2020c). Underwater still and video imagery technologies are among the most common methods used for surveying benthic and pelagic habitats (Hemery et al. 2022a); however, the data processing is cumbersome and resource intensive.
- While protocol optimizations remain necessary, the environmental DNA (eDNA) approach enables the collection of information on animals' presence, diversity, and distribution from water samples only. Conventional monitoring technologies may not always be adapted to the high-energy marine environments targeted for MRE deployments, and cost-efficient alternatives such as eDNA are becoming reliable and more mainstream (Capurso et al. 2023; Fu et al. 2021; Williford et al. 2023).

3.5.

CHANGES IN OCEANOGRAPHIC SYSTEMS ASSOCIATED WITH MARINE RENEWABLE ENERGY DEVICES

Author: Jonathan M. Whiting

The movement of ocean water is caused by large-scale forces including the gravitational attraction of the earth with the sun and moon, the rotation of the earth, and the shape of continents, surface winds, and density-driven convection currents between the ocean depths and the surface. The resulting waves, tides, and persistent ocean currents distribute heat and water masses, and materials including sediments, dissolved gasses, and nutrients, which in turn help support marine and coastal ecosystems. MRE devices deployed at sea have the potential to change flow patterns, wave climates, and remove energy from the system (Whiting et al. 2023). If large enough, these resulting changes may interrupt natural flows, changing habitats for some marine organisms and potentially affecting marine food webs (Martínez et al. 2021b). As greater numbers of devices are deployed, the resource (tidal, wave, ocean currents) is likely to be increasingly affected, changing flows, wave heights, or density structures in the ocean. Changes in oceanographic systems associated with the presence of MRE devices have not yet been observed in the ocean as only small numbers of devices have been deployed to date, resulting in immeasurably small changes. Modeling studies have focused mainly on predicting changes in oceanographic systems from large numbers of devices, often greater than 30 devices, informing our understanding of how changes compare with natural variability (e.g., De Dominicis et al. 2018). As the MRE industry establishes commercial scale arrays, field programs will be needed to determine whether changes in systems will become detectable.

Adopting terminology from Whiting et al. (2023), changes in oceanographic systems can be categorized as nearfield effects, farfield effects, and secondary effects. Nearfield effects are physical changes within a few device lengths; farfield effects are physical changes at distances of more than a few device lengths that may affect large areas or entire waterbodies; and secondary effects are changes to ecological processes and species, resulting from the changes in the physical processes. Monitoring instruments presently in use can quantify nearfield changes like turbulence but are not fit for measuring farfield effects like changes in flow that are smaller than and masked by natural variability in the system (Robins et al. 2014; Wang & Yang 2017). Numerical models are used to predict farfield effects of large arrays. However, these models have generally not been validated with post-installation field data because no large arrays have yet been deployed. The exception to this may occur from the operation of OTEC plants, which move large amounts of water vertically. See Chapter 1 for more details on OTEC. Similarly, as large-scale salinity gradients plants are developed, there will need to be some examination of potential oceanographic changes.

As the scale of tidal and wave deployment grows, it is anticipated that secondary effects may be characterized by observing the response of organisms and habitats to the physical changes in oceanographic conditions. Numerical models may provide predictions of what the secondary changes will be associated with larger physical changes.

To fill the remaining knowledge gaps around changes in oceanographic systems from MRE, the *2020 State of the Science* report, Whiting & Chang (2020) recommended further efforts be directed towards:

- Improving model validation: Creating more realistic models by increasing the use of high-quality bathymetry data and realistic device parameterization. Models can benefit from additional environmental monitoring as larger arrays are deployed;
- Assessing cumulative effects: Oceanographic systems regularly change in response to severe storms, multi-decadal weather patterns, and long-term climate shifts. Other anthropogenic pressures may also create change. Changes from MRE development should be viewed within the scale of this larger context; and
- Understanding environmental implications: Physical changes to the environment are particularly meaningful in the context of the resilience of marine populations and ecosystems to environmental pressures. Studies must compare changes from MRE with natural variability and other anthropogenic sources based on biogeochemical models, ecosystem models, and risk assessments.

3.5.1.

ADDITIONAL KNOWLEDGE GAINED SINCE 2020

Since the publication of the *2020 State of the Science* report (Copping & Hemery 2020), studies have proliferated on the hydrodynamic response from deployed tidal and wave devices that analyze array layout to optimize power production. However, fewer studies have focused on the potential effects of MRE on the nearfield, farfield, or secondary ecological processes. Recent tidal energy studies have primarily focused on characterizing the farfield effects of tidal arrays, with few studies translating the physical changes to secondary effects like sediment transport or changes in habitat extent or quality. In contrast, recent wave energy research has focused on the benefits of using WECs to protect areas threatened by coastal erosion, often using wave arrays of generally less than 30 devices.

TIDAL ENERGY

Edgerly & Ravens (2019) measured turbulence dissipation around a deployed turbine in the Tanana River, Alaska, US. Other studies have used numerical models to predict farfield effects, some informed by in situ current measurements (e.g., Rodriguez-Delgado et al. 2019; Blunden et al. 2020; Deng et al. 2020; Sánchez et al. 2022), in situ wave measurements (de Paula Kirinus et al., 2022), and flume experiments (Gotelli et al. 2019). Many studies focused on assessing farfield changes for MRE projects, where the results may be specific to a particular location as well as the size or configuration of the MRE technology to be deployed. For example, 5 to 200 turbines modeled in an archipelago showed that tidal flows were diverted away from the channel with turbines to a neighboring channel (Deng et al. 2020); 25 to 300 turbines modeled in a strait show a reduction in sediment transport (Auguste et al. 2022); and 30 turbines modeled in a channel leading to an estuary showed negligible changes to circulation and upwelling (Sánchez et al. 2022). Each study concluded that small tidal arrays do not change the system in a significant way compared to natural variability, but that large arrays have the potential to affect natural processes.

Studies have applied numerical models to determine the likelihood of tidal energy devices altering sediment transport. The results generally show that array layout determines the potential for asymmetrical modifications in flow, which may cause changes in sediment transport along the seabed and in nearshore areas (Blunden et al. 2020). Sediment transport and deposition were modeled over a ten-year period, showing a decrease in vertical circulation, the development of new lateral flows to move sediment, and an increase in bedload transport rates around the turbine due to divergence in flow (de Paula Kirinus et al. 2022). With reduced velocities resulting from flows around MRE arrays, the models demonstrated long-term sediment accumulation around the arrays (Ross et al. 2021). These model simulations show changes in sediment transport but do not provide information on the biological effects of the changes.

Additional field and modeling studies have examined secondary effects on marine organisms and habitats, based on direct observations from field data and numerical models. Monopiles in the water column were observed to enhance primary productivity in local areas by increasing vertical mixing and nutrient availability, similar to processes that occur in the wake of small islands ("island mass effect") (Haberlin et al. 2022). Aerial drone transects and hydroacoustic measurements were used to observe a seabird foraging hotspot in the wake of the deployed Strangford Lough turbine in the United Kingdom (Lieber et al. 2021). Imagery of the sea surface from an unmanned aerial vehicle showed that diving birds were associated with natural upwelling areas; these areas were shown to have increases in dissolved nutrients and biological activity including prey species for birds, as an example of a natural turbulence feature with an analogous wildlife response to tidal turbines (Slingsby et al. 2022). Vessel observations indicate that altering sandbank locations by the presence of tidal energy devices may impact the presence of sandeels, which act as prey for benthic foraging seabirds (Couto et al. 2022). These studies indicate that changes in oceanographic processes associated with the presence of individual turbines and their substructures may impact bird foraging hotspots, though it is unclear whether these changes will affect the survival or health of populations. Some of the key physical and environmental effects of tidal energy are illustrated in Figure 3.5.1.

WAVE ENERGY

Recent wave energy studies have focused on how changes to farfield effects potentially cause positive secondary effects by reducing erosion, flooding, and other effects of extreme events on coastlines. A WEC hull was designed specifically to improve coastal protection (Bergillos et al. 2019a). Other modeling studies examined the dual benefits of energy production and coastal protection (Moradi et al. 2022; Bergillos et al. 2019b), including coastal protection in mild wave climates (Rusu et al. 2021), winter storms (Onea et al. 2021), hurricanes (Ozkan et al. 2022), and in response to sea level rise (Rodriguez-Delgado et al. 2019). The studies that consider WECs for coastal protection are

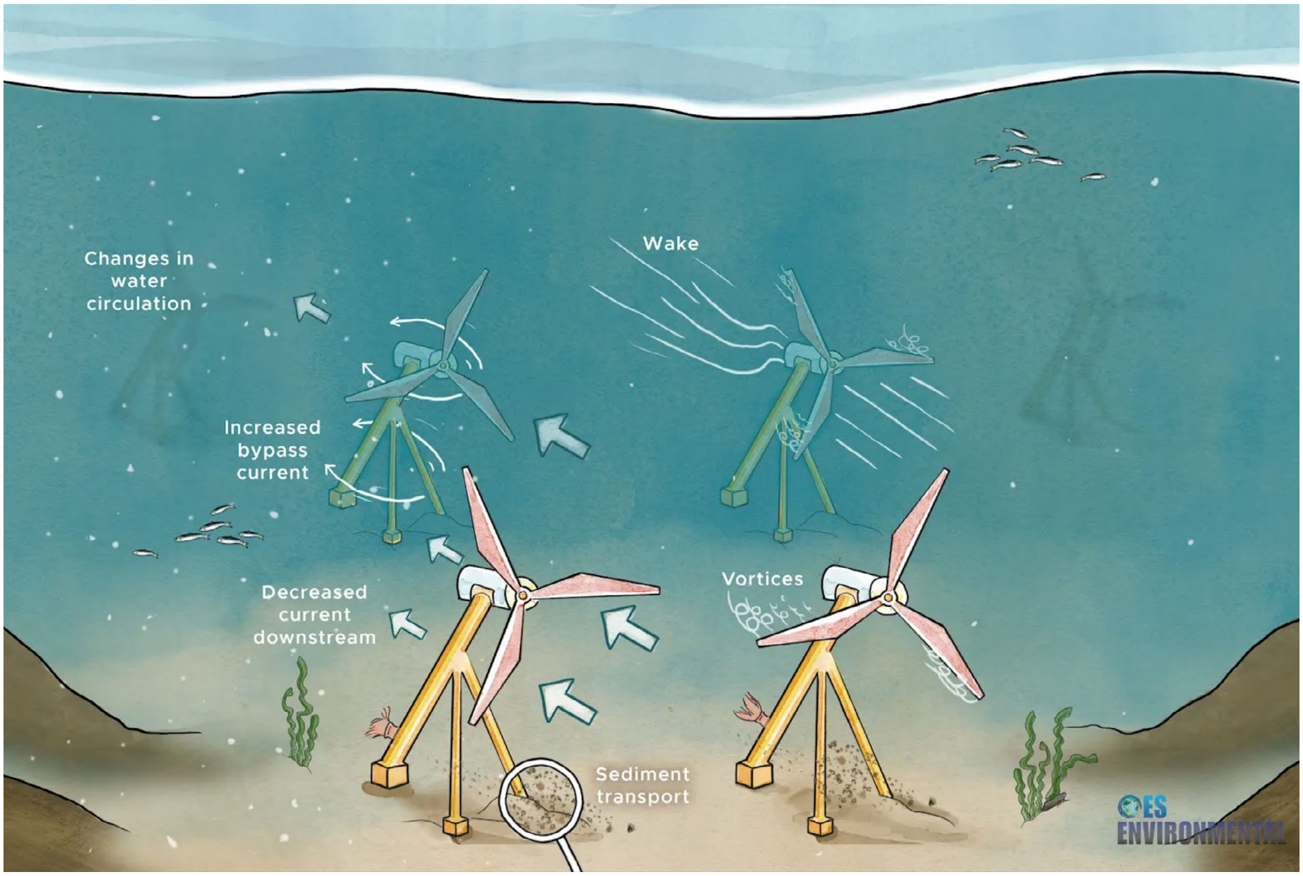


Figure 3.5.1. Schematic of a tidal energy array and the potential effects on hydrodynamics and sediment transport. (From Whiting et al. 2023)

located in southern Europe; it is not clear whether these measures will be effective on other types of coastlines. More research is needed on different archetypes of coastlines and embayment around the world to determine whether WECs can act as coastal protection for specific coastline geometries, sediment conditions, bathymetries, and wave climates.

Further studies explored the use of WECs for enhanced coastal protection by optimizing wave farm layouts. Closer spaced, denser arrays increase shoreline protection, according to modeling studies that varied the configuration of a small array at different distances from shore (Rijnsdorp et al. 2020). Bergillos et al. (2019c) used machine learning to assess wave farm layout to maximize dry beach surface as a metric of sediment accretion, a unique approach that needs validation. Distance to shore, inter-array configuration, wave direction, and seasonality are all factors that should be considered when gauging shoreline protection efficacy of WEC arrays. Some of the key physical and environmental effects of wave energy are illustrated in Figure 3.5.2.

OTEC

The return of large volumes of cold ocean water that has been used in an OTEC heat exchange process is the greatest potential environmental concern for this MRE technology (Coastal Response Research Center, 2009, 2010). The cold deep water will be brought to the surface at a temperature of about 4°C, while surface and subsurface waters will be about 24–28°C. After the heat exchange process, the cold water to be returned to the ocean is likely to be about 12–16°C (Grandelli et al. 2012), still significantly colder than the ambient surface seawater. Standard OTEC designs include discharging the cold return water at an intermediate depth, generally below the thermocline, so that the water will sink rapidly to the depth where it matches the density of the ambient seawater. The depth at which the cold water is returned is determined through numerical modeling of the structure of the water column, validated with measurements of temperature, salinity, and depth—all standard oceanographic measurements. An open-source model for the cold-water return is under development at the

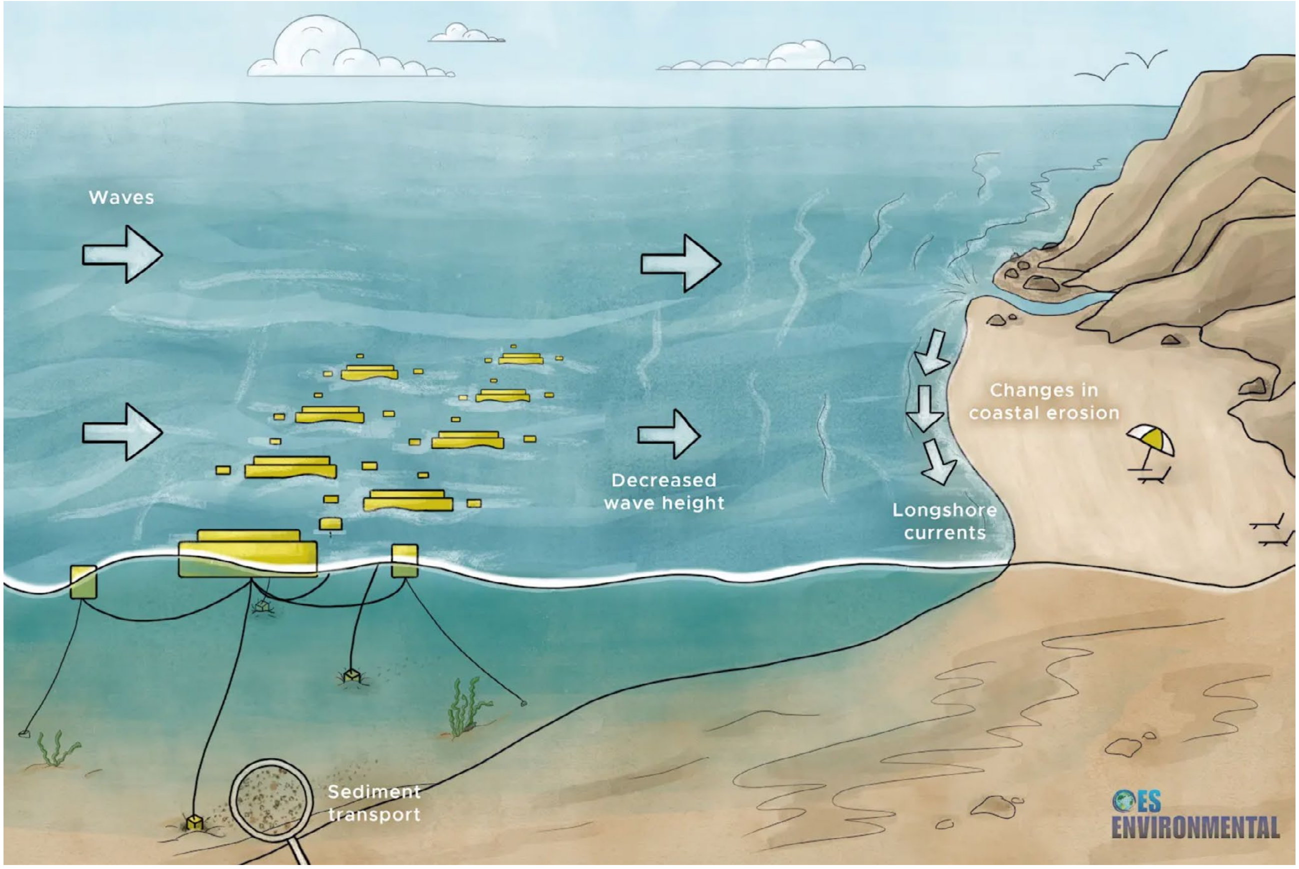


Figure 3.5.2. Schematic of a wave energy array and the potential effects on wave height, longshore currents, sediment transport, and coastal erosion. (From Whiting et al. 2023)

Pacific Northwest National Laboratory in the US and is likely to become widely used for siting and design of OTEC cold water discharge. If the cold water is returned at the correct depth to enable rapid sinking to the appropriate depths, there are likely to be no changes in the regional oceanography around OTEC plants, as they develop in the future.

SALINITY GRADIENTS

Salinity gradient power can only be generated where there is a significant difference in salinity between water bodies through an osmotic exchange process that creates concentrated seawater with approximately twice the salinity of the incoming seawater (Gallardo-Torres et al. 2012). Conditions that will allow salinity gradient power production apply exclusively to areas where large rivers empty directly into the ocean. While there may be some concerns around the need to dispose of the brine created during the process, perhaps causing nearfield increases in salinity, it is unlikely that the amount of additional salt water will affect large-scale oceanographic processes (Marin-Coria et al. 2021).

3.5.2.
STATUS OF RISK RETIREMENT

Scientific literature indicates that changes to oceanographic systems from properly sited small tidal and wave deployments will be lower than those within the natural variability of the system, allowing the risk posed to the marine environment to be retired for small numbers of devices (one to six devices). OES-Environmental has developed a Changes in Oceanographic Systems Evidence Base listing the key research papers and monitoring reports that define what we understand about the effects from changes in oceanographic systems, and a Changes in Oceanographic Systems Guidance Document to evaluate the risk within a regulatory context.

Small deployments can be defined as removing less than 2% of the total theoretical undisturbed resource (IEC TC 114 Technical Specification 62600-201). Significant effects (larger than natural system variability) are unlikely to be measurable in the nearfield, including wake recovery (Edgerly & Ravens 2019) and scour (Lancaster et al. 2022). While there is little reason to engage in extensive monitoring programs for the effects of MRE devices for small deployments (Whiting et al. 2023), there is value in conducting proper site characterization studies to inform siting of projects as well as to help validate numerical models as the industry scales to larger arrays (ORJIP Ocean Energy, 2022c).

Changes in oceanographic processes associated with large arrays of tidal or wave devices have been examined by numerical models, but most lack post-installation validation due to insufficient data. Modeling large, unrealistic scenarios that are unlikely to be implemented can exacerbate unfounded concerns among stakeholders. Farfield changes caused by MRE deployments will be site-specific and will depend on the shape of the coastline, bathymetry, flow conditions, and wave climates. Once larger arrays are deployed, changes in flow or wave height must be measured against the backdrop of natural variability in the system, seasonality, and long-term climate shifts. Large-scale anthropogenic pressures must also be considered to understand the role that MRE might play in changing oceanographic systems.

Physical changes in the nearfield and farfield may influence biological and chemical secondary effects that may shape habitats, support individual marine organisms, and affect population survivability and health. Less is known about these effects, but research on natural phenomena may serve as proxies to understand potential effects (e.g., Haberlin et al. 2022).

There are insufficient numbers of OTEC or salinity gradient plants in the world around which to gather data to address risk retirement at this time.

3.5.3
RECOMMENDATIONS

There is little reason for regulators to require extensive collection of data around MRE devices for changes in oceanographic systems until larger tidal and wave arrays are deployed (Whiting et al. 2023). However, as larger arrays are commissioned, data collected around MRE devices can be used to validate models, to understand potential effects when sited in varied coastal geometries, and to compare changes against natural variability. Data collection and models should follow established international standards such as those published by the IEC TC 114, so that changes in oceanographic systems are evaluated consistently across the MRE device archetypes. Collaboration between developers and researchers will enable field data to inform future regulatory requirements at the array scale. As larger arrays are developed, there is a

need to consider how multiple arrays may influence one another, suggesting the need for a regional planning approach such as marine spatial planning (see Chapter 6) and cumulative impacts assessment (see Chapter 9), avoiding the disorder of ad hoc development that may be proposed by individual project developers (Waldman et al. 2019).

There is a continuing need to refine numerical models for MRE interactions with oceanographic systems; in addition to improving simulations of effects, models can be used to facilitate planning for field data collection. Models should be used to explore siting challenges unique to archipelagos, straits, estuaries, or other coastal geometries. Future efforts should leverage advancements in machine learning and compare performance against traditional conceptual and physics-based models for siting deployments, parameterizing device interactions with the flow, and quantifying farfield effects. Siting of future large arrays can be effectively directed from validated models, balancing power production optimization with potential environmental effects.

The potential for WECs to provide coastal protection should be investigated with a range of wave energy archetypes (e.g., point absorbers, overtopping devices, bottom-mounted WECs, etc.), along multiple coastline geometries with differing wave power regimes. Long-term modeling studies are needed to match the temporal scale of changes to shorelines and sediment transport mechanisms, paired with the need for collection of validation data that covers multiple years of seasonal data (Ozkan et al. 2020).

As larger arrays are deployed, the importance of understanding the linkages between changes in oceanographic systems and secondary effects on habitats and populations will increase and should form the basis of new inquiries. Before large deployments are constructed, secondary effects can be explored by observing how habitats and organisms respond to natural variability, extreme events, and anthropogenic pressures.

Floating offshore wind and wave devices deployed at sea are likely to have similar effects on oceanographic systems. Similarly, fixed-bottom offshore wind and oil and gas platforms may be reasonable analogs for tidal turbine foundations and support structures. Collaboration among these industries will assist with understanding potential changes in oceanographic systems.

As deployments of OTEC and salinity gradient power plants advance, there is a need to develop standardized approaches to determine the potential risk to nearfield and farfield systems.

3.6.

ENTANGLEMENT RISK OF ANIMALS WITH MARINE RENEWABLE ENERGY MOORING LINES AND UNDERWATER CABLES

Author: Lysel Garavelli

To maintain their position on or below the surface, many MRE devices require mooring lines attached to the seabed. Underwater cables are used to carry power from MRE devices to an offshore substation or to connect devices within an array. These lines and cables are suspended in the water column and have the potential to become an entanglement hazard for marine animals (Figure 3.6.1). Entanglement occurs when an animal becomes directly entangled with mooring lines or cables. Species of concern for entanglement risk with MRE mooring lines or underwater cables are large marine mammals (e.g., migratory whales), large pelagic elasmobranchs (e.g., basking sharks), as well as other marine animals such as seabirds, sea turtles, and large fish.

Because of the slow development of the MRE industry worldwide and the lack of monitoring around these devices, the likelihood of entanglement can be inferred from other offshore industries. Unlike the unobserved occurrence of entanglement in MRE mooring lines and cables, entanglement of marine animals in fishing gear and other marine debris is widespread and relatively well understood (Hamilton & Baker 2019; National Marine Fisheries Service 2021). Potential consequences of entangled fishing gear on marine animals include negative effects on animal welfare (e.g., respiratory distress, injuries such as tissue damage, death), health status (e.g., effects on mobility, limited access to food), and populations associated with barriers to movements, migration, and reproduction (SEER U.S. Offshore Wind Synthesis of Environmental Effects Research 2022b).

As of 2020, available literature on the risk of entanglement to animals in the marine environment mostly focused on entanglement observations involving fishing gear and historical records of entanglement with submarine telecommunications cables (Garavelli 2020). Concerns were also raised about marine debris (e.g., lost fishing gear) getting caught in MRE systems

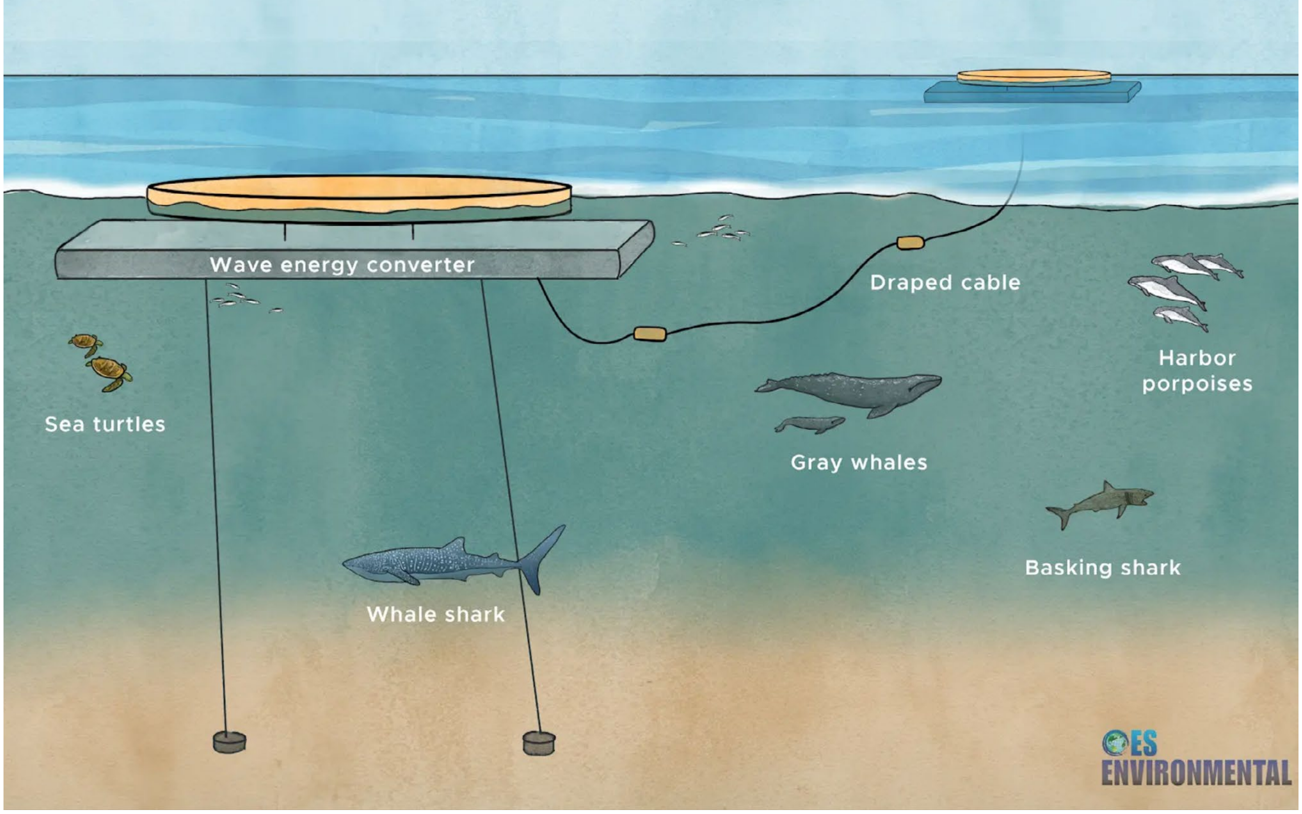


Figure 3.6.1. Schematic of wave energy converter mooring lines and intra-array cables that have a potential to pose entanglement risk to marine animals. (Illustration by Stephanie King)

and potentially affecting marine animals (also called secondary entanglement). Modeling studies predicted a low probability of entanglement, but empirical data were lacking to validate these models (Benjamins et al. 2014; Harnois et al. 2015). Studies found that the ability of echolocating marine mammals to use sound to communicate and to detect objects underwater will likely decrease the likelihood of entanglement. The risk of entanglement associated with MRE mooring lines and underwater cables has been suggested to be low as they are usually taut with no loose ends, and cannot form a loop, thus preventing the entanglement of marine animals (Benjamins et al. 2014). The potential consequences of entanglement were relatively unknown, and there remains a need to investigate how this risk may harm or injure specific marine animals. General recommendations to better understand the risk of entanglement associated with MRE devices included:

- combining modeling and field observations;
- identifying habitats and behavior or movement habits of large marine animals; and
- routinely monitoring mooring systems and inter-array cables.

3.6.1.
ADDITIONAL KNOWLEDGE GAINED SINCE 2020

Recent information on the entanglement risk of marine animals associated with MRE devices is lacking and most of the knowledge is drawn from the fishing, aquaculture, and offshore wind industries. To date, no entanglements of marine animals with MRE systems have been observed and no evidence exists to show that such event has occurred (ORJIP Ocean Energy, 2022c). However, changes in behavior of marine animals around MRE devices, such as aggregation, may increase the probability of entanglement (ORJIP Ocean Energy 2022c).

In the commercial marine aquaculture industry, the risk of entanglement for marine animals has been described in Bath et al. (2023). In most countries with marine aquaculture development, the report of entanglement events is not mandatory, and data are scarce. Most of the documented entanglement events of marine animals with marine aquaculture gear have been for marine mammals (cetaceans, pinnipeds) with net pens used for finfish farming. Other entanglement events were documented for marine mammals with finfish cages, pearl oyster farm ropes, and mussel farm spat lines. In most of these entanglement reports, the outcome was fatal for the animal. Entanglement of sea turtles was also reported at shellfish farms. Seabirds and sharks are also at risk for entanglement with marine aquaculture gear, but no such events have been reported. Slack lines and netting materials used in marine aquaculture present the highest risk for entanglement of marine animals. Such materials are not used in the MRE industry.

In addition, multiple mooring lines and cables are unlikely to be close enough for an animal to be caught between them. In the oil and gas industry, entanglement with floating cables has never been reported (SEER U.S. Offshore Wind Synthesis of Environmental Effects Research 2022b). With the growing development of the offshore wind industry, recent studies have focused on the potential effects of underwater cables associated with floating wind turbines and no instances of entanglement have been reported. Given the large spatial scale of floating offshore wind turbines and the use of taut mooring lines and cables, it is also unlikely that a marine mammal would become entangled with such structures (Farr et al. 2021; Maxwell et al. 2022). Since 2020, there have been no reports of secondary entanglement of marine animals with derelict fishing gear and other marine debris getting caught in MRE systems.

The experience from the oil and gas and offshore wind industries suggests a low risk of entanglement to marine animals from mooring lines and cables associated with MRE devices. In the vast amount of ocean, the likelihood of fishing gear being snagged on MRE devices and associated secondary entanglement is also likely to be low. Notably, a large amount of fishing gear is being abandoned, lost, or discarded around the world yearly and the likelihood of this fishing gear becoming snagged on mooring lines and underwater cables would depend on their presence around MRE systems, their types, density in the water column, and susceptibility to being transported long distances (Macfadyen et al. 2009; Richardson et al. 2019).

Concerns around entanglement and its consequences on individuals and populations are mainly related to the theoretical potential negative effects on sensitive species. For example, in several parts of the world,

species with endangered or threatened regulatory status such as the North Atlantic right whale (*Eubalaena glacialis*) or various populations of the beluga whale (*Delphinapterus leucas*) in the US and Canada, are of concern. For such species, the entanglement of some individuals could drastically impact the overall population.

The conservation status of marine animals also increases regulatory and stakeholder concerns regarding the potential effects of entanglement from MRE systems. In Wales, stakeholders (regulators, industry, and environmental organizations) were recently surveyed to collect perspectives on the risk of entanglement for marine animals related to MRE systems (ORJIP Ocean Energy, 2022d). Compared to fish and seabirds, entanglement was perceived to be the greatest concern for marine mammals, although the likelihood of entanglement was unknown. Other factors that were noted to influence the perceived level of risk were the number and tension of mooring lines, and the presence of mid-water cables (e.g., for floating devices).

3.6.2.
STATUS OF RISK RETIREMENT

OES-Environmental has developed an Entanglement Evidence Base listing the key research papers and monitoring reports that define what we understand about the risks of entanglement from MRE mooring lines and underwater cables, and an Entanglement Guidance Document to evaluate the risk within a general regulatory context.

Because mooring lines and underwater cables used in MRE systems do not have loose ends or have sufficient slack to create loops that could cause entanglement of marine animals, the risk of entanglement for a small number of devices (one to six devices) is considered low. The risk of entanglement may change when considering a large array of MRE devices with additional mooring lines and underwater cables, potentially increasing the likelihood of entanglement.

3.6.3.
RECOMMENDATIONS

Although the risk of entanglement with MRE mooring lines and underwater cables is considered to be low, strategies can be applied to minimize the risk, particularly as the MRE industry moves toward large array deployments. At the siting stage, assessing the distribution of species of concern, their migration pathways, behavior, and habitats is crucial. In the absence of information, models can aid in predicting the entanglement rate based on species of concern and the configuration of lines and cables. If the risk of entanglement is proven to be likely, there will be a need to consider designing structures and configurations of mooring lines for MRE projects that will minimize the risk of entanglement. The use of taut mooring lines will decrease the likelihood of entanglement of marine animals.

Developing technologies to monitor the tension of lines and cables using load monitoring systems, failure detection, or entanglement detection should be considered for each MRE system. In addition, periodic visual inspection of mooring lines or underwater cables with instrumentation and remotely operated underwater vehicles is recommended and will help provide information on the presence of debris or derelict fishing gear snagged on MRE mooring lines and cables. Periodic inspection of mooring lines and cables may be necessary for the health of the MRE system, so the inspection for debris can be added to the work. Any debris detected could then be removed, preferably with the technology used for inspection. Other monitoring techniques could include the use of underwater cameras to observe any debris or animals caught in cables or mooring lines.

As the MRE industry advances and array-scale deployments occur, understanding the cumulative effects of MRE systems and other surrounding offshore activities will be needed (see Chapter 9), particularly for highly migratory species. Sharing data, information, and findings across offshore industries will continue to increase the understanding of entanglement risk.

3.7.
DISPLACEMENT OF ANIMALS FROM MARINE RENEWABLE ENERGY DEVELOPMENT

Author: Lenaïg G. Hemery

Large arrays of MRE devices have the potential to trigger environmental effects not yet observable at the scale of single devices (Hasselman et al. 2023), such as the displacement of marine animals from their preferred or essential habitats or migratory routes (Hemery et al. 2024). Such effects could be particularly challenging for local populations of threatened or endangered species that have limited availability of alternative suitable habitat as marine areas face increasing pressure from human activities and the impacts of climate change. Improved comprehension of the risks and consequences of animal displacement resulting from deployment of MRE arrays is necessary; however, the current state of development of the MRE industry provides limited opportunities to understand the risks of and mechanisms that cause displacement due to the current absence of large-scale arrays.

Researchers studying displacement in the MRE context have used varying definitions depending on the specific animals or context of the study. Lacking a clear and consistent definition, investigations into the causes of displacement, species of concern, potential consequences, and methods of investigation by the international community are hampered (Hemery et al. 2024). In the context of MRE development, displacement has been referred to as the result of anthropogenic activities acting as disturbance and leading to habitat loss or a barrier effect, causing animals to avoid an area (Buenau et al. 2022; Copping et al. 2021b; Long, 2017; Onoufriou et al. 2021; Sparling et al. 2020a). Some studies postulated that displacement of fish or marine mammals would occur at spatiotemporal scales larger than those of collision avoidance when an animal approaches a turbine (Copping et al. 2021b; Onoufriou et al. 2021; Sparling et al. 2020a). While displacement is literally "the moving of something from its place or position" (Oxford Languages), the wind energy research community has often distinguished displacement from avoidance, barrier effects, or attraction (Marques et al. 2021; (SEER) U.S. Offshore Wind Synthesis of Environmental Effects Research, 2022a).

To clarify the causes, mechanisms, and consequences of displacement with respect to MRE, (Hemery et al. (2024) have proposed the following definition: "Displacement is the outcome of one of three mechanisms (i.e., attraction, avoidance, and exclusion) triggered by a receptor's response to one or more stressors acting as a disturbance, with various consequences at the individual through to population levels".

3.7.1.
MECHANISMS OF DISPLACEMENT

The physical presence of MRE devices and/or associated infrastructure such as power export cables may create a disturbance strong enough to displace some animals. Further, stressors such as the movement of devices or parts of them that could represent collision risk, underwater noise and EMF emissions, and changes in habitats and hydrodynamics may all trigger a response from animals (Figure 3.7.1). Responses may be individual-, species-, and/or location-specific, and may include attraction, avoidance, or exclusion (Figure 3.7.2):

- Attraction is defined as the intentional movement of animals toward an area within or immediately adjacent to an MRE array (i.e., going toward);
- Avoidance is the intentional bypassing of an area with MRE devices to travel in the same general direction (i.e., going around); and
- Exclusion is the departure or movement away from the area, so the animal is no longer going in the initial direction (i.e., going away from), resulting in a barrier effect that prevents animals from passing through an MRE array and/or associated infrastructure.

The effects of displacement may result in outcomes across a range of spatial and temporal scales, from short-term to long-term (e.g., temporary effects that may change over time as animals habituate to the presence of the MRE array) to permanent displacement (e.g., a species never returns to a feeding habitat on the far side of an MRE array), with spatial scales dependent on the animal's home or migratory ranges and its sensitivity to the stressors (i.e., strength of the response and distance from the stressor).

Consequences of displacement may be observed from the individual to the population level and may include changes in survivability, bioenergetics, predation, competition, connectivity, productivity, and access to essential habitats (e.g., for feeding, breeding, rearing, traveling), as well as population failure if enough individuals are affected at a severe enough level (Sparling et al. 2020b). The consequences of displacement are likely to be greater for the species with higher vulnerability such as those with very small populations, those with a high degree of specialization, those at critical life stages such as molting or breeding, and those with limited access to suitable alternative habitat locally.

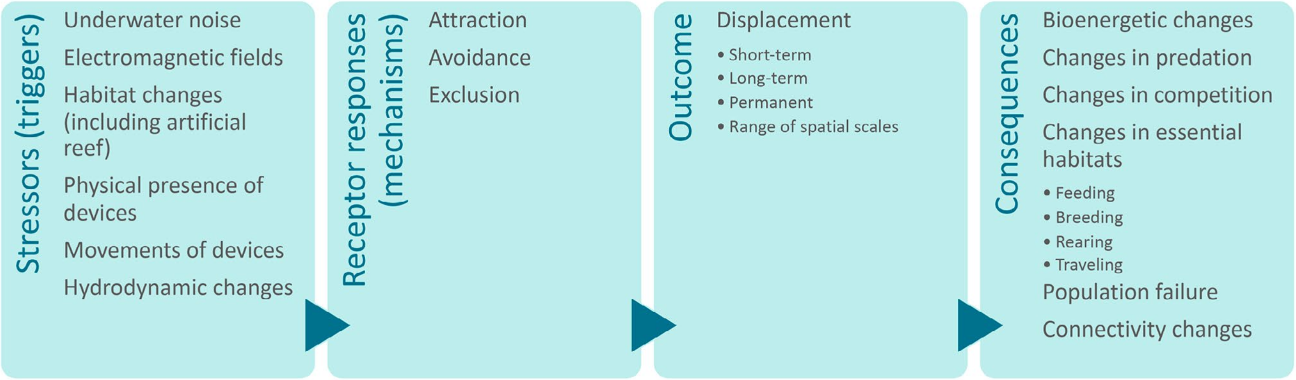


Figure 3.7.1. Displacement flow chart: displacement is the outcome of one of three mechanisms triggered by a receptor's response to stressors, with the potential for a range of consequences on marine animals that span from effects on the individual to effects on populations. (From Hemery et al. 2024)

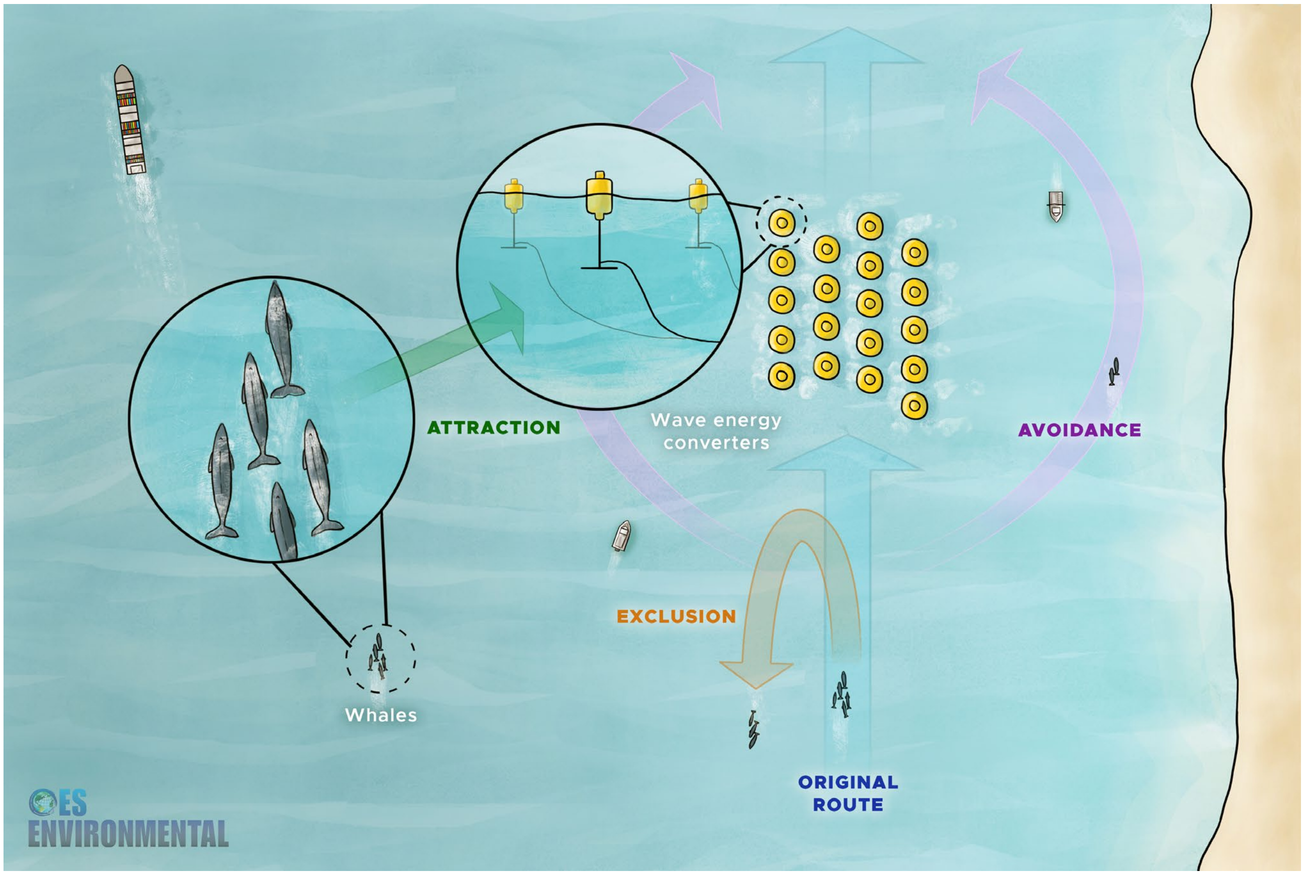


Figure 3.7.2. Mechanisms of displacement: upon encounter with an array of marine renewable energy converters, animals may exhibit no response, or exhibit an attraction, avoidance, or exclusion response that may result in their displacement from key habitats (e.g., foraging or breeding grounds). (From Hemery et al. 2024)

Displacement can affect marine species in different ways, based on their migration patterns, home range size and depth, maneuverability and swimming speed, gregariousness, etc. (Figure 3.7.3). Field observations remain essential in understanding causes, responses, and consequences of displacement for each species potentially affected. However, while many species may be affected, taking a functional approach allows for the range of species to be represented. Hypotheses can be generated for these functional groups from available literature gathered from other marine industries (Hemery et al. 2024):

- Large whales and large sharks: the physical presence of large arrays of MRE devices and associated infrastructure may create a disturbance for slow moving large species of whales (i.e., baleen whales) and sharks (e.g., basking shark); additionally, large whales may be sensitive to operation noise and vessel traffic associated with maintenance activities. Displacement could result in some bioenergetic losses if the animals are forced to prolong their migrations and/or feeding habitats become out of reach (Booth et al. 2013; Kraus et al. 2019), which could in turn affect reproductive success or survivorship.
- Small cetaceans: dolphins, porpoises, and orca may show behavioral responses to construction activities and operational noise generated by MRE devices. Impacts would most likely be site specific and result in temporary or longer term displacement (Gillespie et al. 2021; Palmer et al. 2021; Tollit et al. 2019).
- Pinnipeds: underwater noise from operational MRE devices and vessel traffic related to construction activities might cause temporary or longer term displacement of seals and sea lions (Savidge et al. 2014; Sparling et al. 2018); however, animals may quickly become habituated and return to the sites post-construction (Russell et al. 2016).
- Sirenians: manatees and dugong seem sensitive to vessel traffic and may be affected by construction activities (Hodgson & Marsh 2007); however, large MRE projects are unlikely to be developed in proximity to sirenians' nearshore suitable habitats.
- Sea turtles: while it is unknown whether MRE activities will lead to long-term displacement of sea turtles, temporary disturbance from construction noise may be observed in the form of area avoidance (Sullivan 2021).

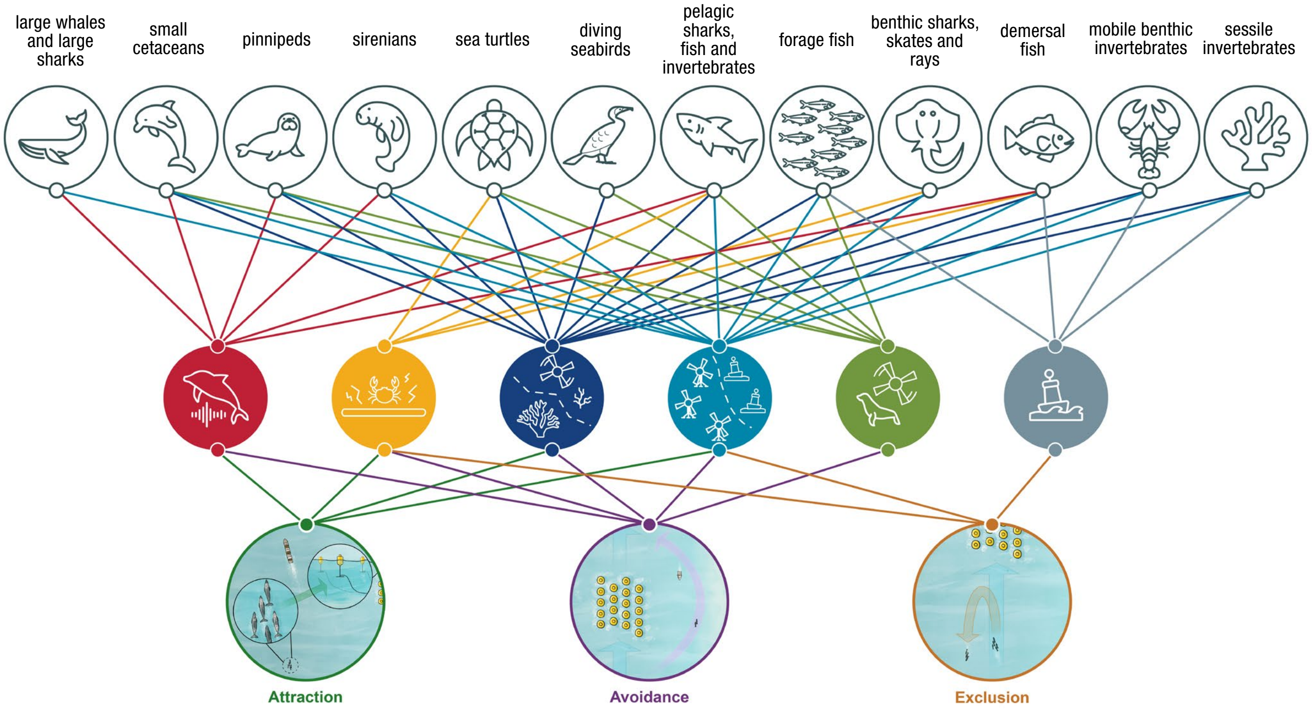


Figure 3.7.3. Potential stressors and responses for the different animal groups. Each of the three mechanisms for displacement is shown in the bottom row and connects to the six stressors, in the middle row (left to right: underwater noise, electromagnetic fields, habitat changes, physical presence of devices, movement of devices, and hydrodynamic changes). Each stressor connects to the range of marine animals that may be affected, in the top row. (Modified from Hemery et al. 2024)

- Diving seabirds: displacement of seabirds is most likely to be species- and site-specific, depending on time of year, activity of the seabirds, and a species' vulnerability to increased risk of collision, as well as food availability or attraction to new roosting habitats (Dierschke et al. 2016; Kelsey et al. 2018).
- Pelagic sharks, large pelagic fish and invertebrates: EMF from draped cables in between floating MRE devices within an array, as well as underwater noise, may attract or repulse species with specific sensitivity (Copping et al. 2021b; Snyder et al.2019); however, long-term consequences remain unknown.
- Forage fish: fish schools may avoid MRE project areas during construction activities or operation due to underwater noise, visual stimuli, or changes in flow patterns, while others may become attracted to new habitats and foraging sources (Staines et al. 2019; Williamson et al. 2019), but little is known about these effects.
- Benthic sharks, skates, and rays: MRE arrays may attract benthic elasmobranchs because of the EMFs generated by devices and/or cables, as well as the structures themselves providing new support for egg cases and habitat for prey (Maxwell et al. 2022; Snyder et al. 2019).
- Demersal fish: effects of displacement on demersal fish may be species-specific, with only some being attracted to the devices as they provide new habitats. Attraction may be more prevalent for larvae than adults as they may respond to acoustic and chemical cues; however, changes in hydrodynamics could displace some larvae from suitable habitats (Anderson et al. 2021; Langhamer 2012; van Berkel et al. 2020).
- Mobile benthic invertebrates: these animals may become attracted to arrays of MRE devices through acoustic cues or EMFs, and by the creation of the new artificial reef habitat provided by the devices and its associated infrastructure, leading to potential heightened exposure to EMF or underwater noise emissions (Anderson et al. 2021; Gill & Desender 2020; Langhamer 2016).
- Sessile invertebrates: larvae of sessile invertebrates may become attracted to MRE devices by acoustic cues and settle on the artificial structures before having a chance to reach natural habitats; this may increase connectivity between natural and artificial habitats, especially for invasive species (Adams et al. 2014; Dannheim et al. 2020; Lillis et al. 2015).

3.7.2.
METHODS OF INVESTIGATION

Displacement of key marine animals associated with MRE development should be investigated with a combination of numerical models and field-based approaches to address remaining knowledge gaps (Hemery et al. 2024). While field observations have been limited in the absence of large arrays of MRE devices, those that have happened provide essential data to inform models. Numerical models or analytical frameworks can help assess risks and consequences of displacement:

- Agent-based models are used to represent the movement of animals around MRE devices and predict their spatial distribution over time (Grippo et al. 2020; Lake et al. 2015).
- Species distribution models are used to predict the probability of species occurrence based on habitat characteristics and physical features (Baker et al. 2020; Bangley et al. 2022; Lieber et al. 2018; Waggitt et al. 2016).
- The interim population consequences of disturbance framework and the population viability analysis could be used to assess population-level effects of disturbances (King et al. 2015; Sparling et al. 2020b).
- Dynamic energy budget models are used to predict the bioenergetic consequences of a disturbance at the individual to population levels (Harwood et al. 2020).

Field data are necessary upon which to develop and validate models. As much as possible, field data should be collected using reliable methods that do not interfere with animal behavior, such as:

- Land- and boat-based surveys that are used to record surface presence and habitat use of marine animals that are occasionally visible at/near the surface, such as marine mammals, seabirds, sea turtles, and some large fish (Lieber et al. 2019; Williamson et al. 2018).
- Aerial surveillance with drones that are used for observing animals with occasional presence at the sea surface (Lieber et al. 2019; Williamson et al. 2018; Slingsby et al. 2022).
- Passive acoustic underwater monitoring approaches that use hydrophones to target sound-producing animals like cetaceans and some fish species (Porskamp et al. 2015; Palmer et al. 2021; Wood et al. 2013; Gillespie et al. 2021, 2022).

- Active acoustic monitoring approaches that use scientific echosounders and multibeam sonars to detect animals, including fish and marine mammals (Gillespie et al. 2022, 2023; Staines et al. 2019; Williamson et al. 2021).
- Telemetry arrays that use acoustic or satellite tag detections that record location and (for certain models) depth at regular intervals to track three-dimensional movements of marine animals (Hastie et al. 2016; Onoufriou et al. 2021; Sanderson et al. 2023b).
- Underwater imagery/video surveys that are used to record underwater presence and habitat use, particularly for slow-moving animals (Broadhurst et al. 2014; Hemery et al. 2022b).
- Environmental DNA that can be used to record presence and habitat use by specific species or groups of species from water samples (Dahlgren et al. 2023).

Provided that the same methods are employed to collect meaningful baseline and post-installation data, results from such monitoring campaigns around arrays and in areas used by the species of concern should provide significant information to better understand the risks and consequences of animal displacement from MRE development. However, careful attention should be given to experimental designs to collect data that will provide sufficient statistical power to detect change over time and understand mechanisms of displacement.

3.7.3.
STATUS OF RISK RETIREMENT AND KNOWLEDGE GAPS

Animal displacement is a stressor-receptor interaction that is not considered to be an issue for small MRE projects (one to six devices) and, in such, has seen little investigation to date due to the absence of large-scale arrays of MRE devices; therefore, it is not suitable for risk retirement. However, as larger projects are planned, it is important that the MRE community understands the mechanisms and significance of animal displacement around MRE projects in order to consent large arrays, having confidently assessed the potential for significant displacement effects, with the possible implementation of mitigation measures yet to be determined. Remaining knowledge gaps include information on the distribution and behavior of marine animals of concern, potential effects of specific MRE technologies and certain stressors, and interactions between animals and the technologies, as well as cumulative effects of displacement from multiple developments. While existing legislation in some jurisdictions could conceivably be used to address displacement, presently there is no explicit understanding of this risk among the MRE regulatory or research community and fit for purpose regulations are needed that will ensure that the risk of displacement does not harm marine species. Table 3.7.1 lists these remaining knowledge gaps, along with the stakeholder groups in a position to best support gathering the information, and the necessary timelines for addressing them. Investigating any or all of these gaps will significantly advance our understanding of the risks and consequences of animal displacement around MRE arrays.

3.7.4.
RECOMMENDATIONS

To progress the investigation and understanding of the risks of animal displacement around wave and tidal energy arrays, Hemery et al. (2024) have provided a definition of displacement and its mechanisms and consequences for various animal functional groups. This stressor-receptor interaction is unlikely to be a priority concern until the deployment of large MRE arrays. However, it is important to:

- Understand the potential mechanisms that cause displacement and the possible consequences to marine animals;
- Generate realistic models of such consequences, in combination with stressor-specific models;
- Identify how to best monitor and mitigate these changes; and
- Initiate monitoring as soon as larger arrays are deployed.

The remaining knowledge gaps highlighted in Table 3.7.1 should help the MRE regulatory and scientific communities prepare themselves for mitigating, observing, measuring, and characterizing animal displacement around MRE arrays to prevent irreversible consequences. The timing is right to begin discussions within the MRE community on how to investigate and address the risk of displacement, ahead of large-scale arrays being planned and consented.

Table 3.7.1. Remaining knowledge gaps to be addressed to fully understand the risks and consequences of animal displacement around marine renewable energy development, along with stakeholders best positioned to support the work, and a suggested timeline for addressing these gaps.

Remaining Knowledge Gaps	Best-positioned stakeholders	Timeline
Specific to Marine Animal Displacement:		
Species likely to be affected by displacement	Regulators / Researchers	Short term
Species behaviors and habitat use	Regulators / Resource Agencies / Researchers	Medium term
Stressors, mechanisms, and consequences of displacement relevant to each species of concern	Regulators / Resource Agencies / Researchers	Medium term
Differences in behaviors and biological rates among life stages, individuals, or populations within a species	Regulators / Resource Agencies / Researchers	Medium term
Spatiotemporal scales relevant to each species and life stage	Researchers	Short term
Consequences of displacement from individuals to population and species levels	Regulators / Resource Agencies / Researchers	Medium term
Understanding displacement in the context of climate change and other cumulative effects	Regulators / Resource Agencies / Researchers	Long term
Specific to Marine Energy Technologies:		
Array configurations (e.g., size, geometry, spatial coverage, cable route) and/or device types likely to cause displacement	Researchers	Short term
Scaling of underwater noise and/or EMF emissions to arrays	Researchers / Developers	Short term
Surrogate marine and/or terrestrial activities that inform displacement	Regulators	Short term
Specific to Monitoring Displacement:		
Commercial-off-the-shelf monitoring technologies most suitable for each species and necessary adaptation to different sites and marine energy technologies	Researchers	Short term
Necessary modifications to existing observation technologies versus development of new technologies	Researchers	Short term
Spatiotemporal scales for monitoring surveys for each species and marine energy technology, especially at large-array project level	Regulators / Researchers	Short term
Monitoring displacement in the context of climate change and other cumulative effects	Researchers	Long term
Specific to the Regulatory Context:		
Existing specific national and international regulations or statutes applicable to displacement of marine animals (related to marine energy and/or other sectors)	Regulators	Short term
Common regulations already protecting species and populations that displacement could fall into	Regulators	Short term
Any actions regarding displacement that may be required by law or recommended	Regulators	Medium term

Note: More detail is available in Hemery et al. (2024).

3.8.
CONCLUSION OF STRESSOR-RECEPTOR INTERACTIONS

Each subchapter has described our understanding of stressor-receptor interactions from MRE devices and systems, providing the most up-to-date assessments of the state of knowledge, based on published research, data gleaned from monitoring around deployed devices, modeling simulations, and the expert opinions of the many researchers who collaborate and coordinate work in this area, around the world.

The most concerning stressor-receptor interaction associated with tidal and riverine turbines is that of collision risk. The concerns continue to be focused on marine mammals, fish, diving seabirds, and in some locations, sea turtles, that might be injured or killed by colliding with moving blades. These concerns drive the single most difficult aspects of consenting these devices. Effects of underwater noise and EMFs continue to be raised in consenting approvals and requirements for post-installation monitoring, but the effects of these emissions are becoming fairly well understood. Changes in benthic and pelagic habitats are important aspects of moving towards consenting, but well-sited small arrays or single devices are generally understood to have little unique effect at the ocean scale. In the absence of dedicated monitoring, entanglement of large marine animals remains a theoretical risk that is unlikely to slow the consenting of MRE devices in the near future. Similarly, the level of potential changes in oceanographic systems from small numbers of devices is not a problem for consenting small deployments. OTEC systems provide a different challenge for consenting due to the potential oceanographic effects. Displacement remains a potential future consenting issue as larger deployments and commercial arrays are realized.

The state of knowledge of environmental effects of MRE development is changing rapidly, as more studies are completed, and more deployed devices are accompanied by planned post-installation monitoring programs. However, there remain relatively few devices operating at any one time around the world, even fewer small arrays, and as of this time, no large arrays, around which monitoring data collection and research experiments can be carried out. For the moment, the research community and the MRE industry who depend on them for answers to support consenting must continue to rely on laboratory studies, numerical models, and limited field studies.

3.9.
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