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# Potential Environmental Effects of Marine Renewable Energy Development—The State of the Science

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**Abstract:** Marine renewable energy (MRE) harnesses energy from the ocean and provides a low-carbon sustainable energy source for national grids and remote uses. The international MRE industry is in the early stages of development, focused largely on tidal and riverine turbines, and wave energy converters (WECs), to harness energy from tides, rivers, and waves, respectively. Although MRE supports climate change mitigation, there are concerns that MRE devices and systems could affect portions of the marine and river environments. The greatest concern for tidal and river turbines is the potential for animals to be injured or killed by collision with rotating blades. Other risks associated with MRE device operation include the potential for turbines and WECs to cause disruption from underwater noise emissions, generation of electromagnetic fields, changes in benthic and pelagic habitats, changes in oceanographic processes, and entanglement of large marine animals. The accumulated knowledge of interactions of MRE devices with animals and habitats to date is summarized here, along with a discussion of preferred management methods for encouraging MRE development in an environmentally responsible manner. As there are few devices in the water, understanding is gained largely from examining one to three MRE devices. This information indicates that there will be no significant effects on marine animals and habitats due to underwater noise from MRE devices or emissions of electromagnetic fields from cables, nor changes in benthic and pelagic habitats, or oceanographic systems. Ongoing research to understand potential collision risk of animals with turbine blades still shows significant uncertainty. There has been no significant field research undertaken on entanglement of large animals with mooring lines and cables associated with MRE devices.

**Keywords:** marine renewable energy; environmental effects; risk retirement; stressor-receptor interactions

## 1. Introduction

The global decarbonization and reduced demand for fossil fuels is strongly linked to the diversification of national energy portfolios around the world directed at reducing the consequences of climate change [1,2]. Marine renewable energy (MRE) is an emerging industry that has the potential to play an important role in climate change mitigation by providing a clean and renewable source of energy, reducing greenhouse gas emissions, and redirecting the energy industry towards achieving a sustainable future [3]. MRE devices harvest energy from the movement of water (including in estuaries and large rivers), as well as from temperature and salinity gradients in the ocean [4].

The acceleration of MRE research and development around the world stems from interest in developing secure locally derived energy sources that have the potential to combat the effects of climate change, such as ocean acidification and increasing ocean temperatures [4]. Deleterious effects of climate change are already affecting many marine and coastal resources, and they will continue to affect the health, reproductive capabilities, and biodiversity of fish, invertebrates, marine mammals, seabirds, sea turtles, and other living organisms [5]. Similarly, climate change effects will erode the beneficial human uses we derive from the harvest and aquaculture of seafood organisms, as well as degrade coastal habitats that provide erosion and storm protection [6]. As progress is made mitigating climate change, the potential benefits of MRE can add significant value. Investments in the MRE industry can provide social and economic benefits, support coastal and port infrastructures, and provide energy diversification and resilience [7]. However, an overall increase in the understanding of MRE development is needed to catalyze innovation and commercialization, as well as overcome industry challenges including cost, engineering complexities, reliability, lengthy permitting timelines, and environmental concerns [7,8].

As a locally derived energy source, MRE generated from waves, tides, and rivers is more predictable, consistent, and continuous than either wind or solar power [4]. Often deployed in harsh marine environments, MRE devices must be fully marinated, and, as a consequence, they may require relatively lower maintenance than other forms of offshore energy [9–11]. Efforts are underway to identify MRE uses within the “blue economy”, where MRE may be able to provide power to legacy and emerging maritime industries to reduce their reliance on non-renewable sources of fuel and water [7,8]. For many emerging blue economy industries such as offshore aquaculture and ocean observations, power is very expensive and delivery can be challenging. Similarly, MRE may be able to meet power and freshwater needs of remote coastal and island communities. In addition, the placement of MRE devices may create new habitat types, especially for commercially important species like crab and lobster [12]. Although difficult to quantify, MRE development can benefit local communities of fish and other organisms [13], and it can enhance certain portions of coastal economies [14].

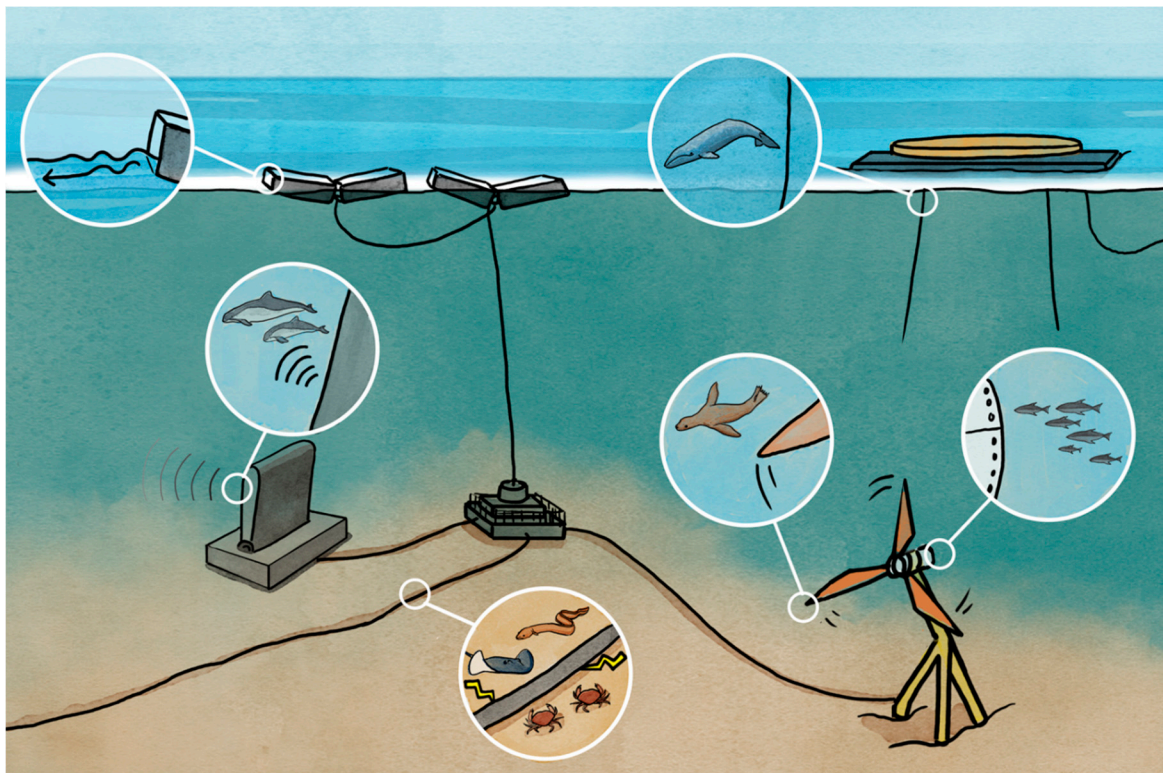
To date, there is a limited number of full-scale deployments of MRE devices worldwide [4], with most devices being turbines deployed in tidal waters or large rivers, and wave energy converters (WECs) deployed in areas with significant wave resources. As a result, the paucity of environmental baseline and post-installation data has led to a high degree of uncertainty among regulators and stakeholders during the permitting or consenting process (hereafter permitting), increasing the perception of risk of many potential interactions between MRE devices and marine animals, habitats, and ecosystem processes [15]. However, while it is important to acknowledge the possibility that actual risk may be present, the lack of data continues to confound the difference between actual and perceived risks. Risk is defined as the interaction between the probability or likelihood of the occurrence of a given event, and the consequences should such an event occur [16]. Ultimately, the risk an MRE device may pose to marine animals, habitats, and the environment is a function of the attributes of the MRE device, including device structure and whether the device is submerged, floating, or surface-piercing (static or dynamic); the type of resource (wave, tidal, or riverine); and the spatial scale of a particular installation (single device or arrays) [17].

Over the past decade, understanding of potential environmental effects across multiple scales has significantly increased as a result of a focus on two general categories of monitoring questions: (1) scientific questions that focus on the actions and interactions of organisms as they encounter devices in their natural habitat, and (2) questions related to the context and environment in which MRE devices are placed to inform the design of robust monitoring programs and mitigation measures, if needed. As the MRE industry advances and these questions are answered as a result of increased monitoring and data collection, the body of knowledge surrounding the potential effects of MRE development will continue to grow, informing perceptions of risk. It is possible that, as more definitive data are collected, the evidence base established from our growing knowledge about the nature of specific stressor-receptor interactions may help determine which interactions have sufficient evidence and where significant

uncertainties remain. However, actual risk to marine animals, habitats, and the environment may continue to present challenges to permitting large-scale development. The objectives of this review are to (1) summarize the current knowledge around the major stressor-receptor interactions and management strategies that support permitting of MRE projects, and (2) propose a path forward to increase our level of understanding of these interactions and to broadly apply the management strategies.

## 2. Methods

The community of researchers examining MRE interactions with animals, habitats, and ecosystem processes has generally coalesced around the terms, stressors (i.e., those parts of an MRE system that can cause stress, injury, or death) and receptors (i.e., marine animals, habitats, and ecosystem processes), as defined by Boehlert and Gill [18]. After about a decade of research, the stressors that appear to present the greatest risk include the moving blades on turbines, as well as potential interactions with mooring lines, anchors or foundations, power export cables, and the emissions and interactions that can result from any of these parts [17]. The receptors include the marine and riverine animals living in and traversing the vicinity of an MRE development; the habitats into which the devices are deployed; and oceanographic processes, such as the natural movement of waters, wave heights, sediment transport, and the concentrations of dissolved gases and nutrients that support marine life [17]. It is the interaction of stressors and receptors that can be examined through observations, laboratory and field experiments, and modeling studies (Figure 1).



**Figure 1.** Interactions between stressors and receptors associated with marine renewable energy devices are depicted, top left to bottom right: changes in oceanographic processes, underwater noise, electromagnetic fields, mooring entanglement, collision risk, and changes in habitats. (Illustration by Rose Perry.)

The stressor-receptor interactions that are addressed in this review are those for which considerable research has been directed to assess the level of risk to animals, habitats, and natural processes, and to attempt to decrease the level of uncertainty around these interactions. All of these interactions are of

importance for tidal and river turbines, as well as WECs, with the exception of collision risk, which is applicable only to turbines:

- (1) Collision risk with turbine blades;
- (2) Effects of underwater noise on animals;
- (3) Effects of electromagnetic fields (EMF) on animals;
- (4) Changes in benthic and pelagic habitats;
- (5) Changes in oceanographic processes;
- (6) Entanglement of animals with mooring systems.

In addition, the data collection needed to determine the social and economic benefits and effects of MRE is presented. The potential benefits of applying certain management measures, including marine spatial planning, adaptive management, and risk retirement, to the permitting and operation of MRE projects are also demonstrated.

The information brought together in this paper is the culmination of an extensive process of examining publicly available information compiled either from peer-reviewed scientific literature or reports published by researchers, developers, and government agencies, all of which represent the state of knowledge for the MRE industry. This voluminous material appears in total in the Ocean Energy Systems (OES)-Environmental 2020 State of the Science report [17]. The present paper summarizes and makes available the most compelling findings. The State of the Science report includes information from monitoring, baseline assessments, and investigations of environmental effects for specific MRE projects, research studies that support specific MRE projects or address environmental interactions broadly, and guidance and assessments commissioned by governments and regulatory bodies to assist with the responsible development of the MRE industry. At this time, most results have been gathered around single MRE devices, or very small numbers of devices. The effects of arrays on the marine environment are not addressed.

The information gathered and analyzed for the 2020 State of the Science report, and summarized here, was compiled to help inform regulatory and research investigations about potential risks to marine and riverine animals, habitats, and the environment from tidal, river, and wave energy installations. This information can also be used to assist MRE developers when considering design engineering, siting, operational strategies, and monitoring options for projects that minimize encounters with marine and riverine animals and/or diminish the effects if such encounters occur. Used in conjunction with site-specific knowledge, the information from the 2020 State of the Science report may simplify and shorten the time to permit deployments, from single devices through large-scale arrays.

### 3. Results

The current state of knowledge for each of the stressor–receptor interactions, as well as the collection of data describing social and economic benefits and effects and management measures, is presented separately.

#### 3.1. Collision Risk around Turbines

The potential for marine and riverine animals to encounter and collide with tidal and river turbines continues to present challenges for permitting developments due to the associated uncertainty and knowledge gaps related to collision risk [19]. To date, knowledge of the actual risk of collision to marine mammals, fish, and seabirds with turbines is limited because the frequency of occurrence and consequences are unknown. However, key progress is being made to better understand collision risk, informed by research studies and post-installation monitoring of operational devices.

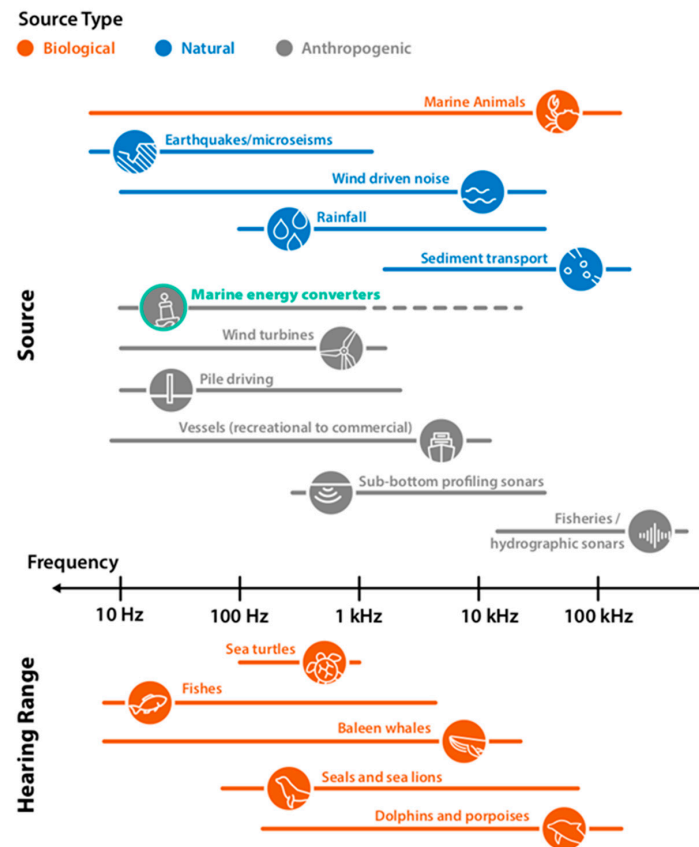
Although there is no evidence to date to show that direct interactions with turbines will cause measurable harm to individual marine and riverine animals or populations, collision risk remains a key issue for the future growth of the industry [20]. Much of the research that focuses on collision risk examines marine mammals and fish in the vicinity of turbines, although challenging oceanographic

conditions in turbulent and often murky tidal or river waters make direct observations very difficult [21,22]. In addition, collisions or even close encounters of marine mammals, fish, and diving seabirds with turbines are expected to be rare, requiring continuous monitoring to develop datasets. To date, no collisions of marine mammals or seabirds have ever been observed, while only a few observations have shown fish in contact with turbines or other MRE infrastructure, resulting in no obvious damage to the fish [23]. Considerable progress has been made in the area of marine mammal collision risk modeling, yet field-monitoring data are still needed to validate or augment predictive or simulation-based models [24,25]. Modeling analyses suggest that the likelihood of “serious injury” from collision risk to marine animals varies by species and the amount of space the turbine takes up in a passage [26,27], and indicate that predictions of risks are extremely sensitive to behavioral assumptions, such as avoidance or fine-scale evasive responses [24–28]. Studies of fish interactions with turbines in laboratory settings have increased the understanding of collision risk for fish, including understanding fish avoidance behavior around operating turbines [23,29,30]. To understand seabird collision, studies generally investigate habitat use and fine-scale interactions with turbines and seek to develop monitoring techniques; however, it is still unknown how seabirds interact with operational turbines, making it difficult to predict how devices might affect individual birds at MRE sites [22,31–33].

### 3.2. Risk to Marine and Riverine Animals from Underwater Noise Generated by MRE Devices

Anthropogenic sound in the marine environment may affect the way that many marine animals interact with their surroundings and may also affect communication, social interaction, orientation, predation, and evasion (Figure 2; [34]). Impacts may include auditory masking, stress, behavioral changes, acoustic responses or injuries, and, in extreme cases, barotrauma or death [35]. Risks to marine animals from anthropogenic sounds, including the operation of MRE devices, vary with the amplitude, frequency, and directionality of the noise source, as well as propagation losses, prevailing ambient noise, animals’ hearing thresholds, and possible behavioral responses [34]. Turbines and WECs both produce operational underwater noise, most commonly from the power take-off systems or generators, although some sound may be produced from mooring systems in the water column as well [36]. Noise emissions from offshore construction activities, such as pile driving, may cause considerably more stress to marine animals; however, generally, MRE devices are not piled and do not require extensive construction at sea [20].

Research aimed at understanding marine animal hearing thresholds and shifts has helped form regulatory guidance for the United States (U.S.) that describes the limits for underwater noise likely to cause injury or harassment of marine mammals and fish [37,38]. To date, the underwater noise output from several types of turbines and WEC devices has been characterized in the field using an accepted international specification [39]. None of these measurements suggest that the U.S. regulatory thresholds will be exceeded, although there is a need to continue to characterize underwater noise outputs from devices. In addition, a few studies have made progress toward establishing links between radiated noise and behavioral responses [40–42]. One of the major challenges to understanding the potential effects of underwater noise from MRE devices remains our ability to differentiate between MRE device noise and ambient noises in the ocean. To date, there is no evidence that operational noise from MRE devices harms marine animals physically or behaviorally [43], although there is a need to characterize the sound output from additional types and designs of turbines and WECs.



**Figure 2.** Overview of biological, natural, and anthropogenic noises in marine environments and the hearing ranges of marine animals. In the case of marine energy converters, the dashed line at higher frequencies conveys scientific uncertainties about the upper frequency limit of their radiated noise. (Illustration by Rose Perry.)

### 3.3. Risk to Animals from Electromagnetic Fields (EMFs) Emitted by MRE Cables

Although EMFs occur naturally in the marine environment, several anthropogenic activities create altered or additional sources of EMF, including those from MRE power export cables carrying electricity to shore [44]. Export cables are commonly buried or laid on the seabed, while inter-device cables may be suspended in the water column. While the electrical field can be shielded, measurements of the magnetic and induced electrical fields emitted from cables and energized devices are used to evaluate EMF emissions. The response of marine animals to EMFs depends on the electro- and magneto-sensitivity of the animal, most notably in certain elasmobranch, teleost, and invertebrate species [45]. The probability of an encounter with an EMF depends on the animal’s movement and distribution, life stage, and spatiotemporal use of the environment where the EMF occurs [44,46,47]. Individual species’ responses may include altered avoidance or attraction behavior, and a variety of other behavioral, physiological, developmental, and genetic responses [44,48–50].

Present understanding of the interactions between EMFs and marine animals has benefited from laboratory experiments and field studies using surrogate cables, largely with benthic fish and invertebrates [49–51]. However, significant gaps remain in understanding how pelagic species (e.g., sharks, marine mammals, fish) may react to dynamic cables suspended in the water column [52]. The levels of EMF reported in many field and laboratory studies are much higher than those expected from MRE export cables [53] and the evidence to date suggests that the levels are unlikely to keep animals away from their preferred habitats or affect migration patterns [54,55]. There is a need, however, to better understand the likely EMF emissions from MRE cables, based on the configuration and electricity loads of specific cables, to identify potential effects, particularly as the MRE industry scales

up to large-scale arrays [52]. Although burial of cables and other measures such as placement of concrete mattresses are not considered to be effective ways to mitigate magnetic emissions into the marine environment, burial separates most sensitive species from the source of the emissions [56].

#### 3.4. Changes in Benthic and Pelagic Habitats Caused by MRE Devices

The installation of MRE devices generally requires gravity foundations, pilings, or anchors that may alter benthic habitats, along with mooring lines, transmission cables, and mechanical moving parts in the water column that may affect pelagic habitats [4]. The presence of these structures on the seabed or within the water column has the potential to alter species occurrence or abundance at a localized scale and may lead to artificial aggregating of animals or changes in animal behavior [12,57–60]. These changes may theoretically lead to indirect effects such as recruitment of non-native invasive species or increases in biomass [61,62]. During MRE device installation, the loss of benthic habitat caused by the footprint of anchors and foundations can be avoided or mitigated when vulnerable habitats have been identified and avoided during the siting process [63]. Cable laying or burial may also disturb habitats, but studies have shown that the benthic communities and habitats recover at about the same rate as natural growth [47,64,65] and any negative effects are quickly dissipated with distance from MRE structures [66]. Evidence of changes in benthic and pelagic habitats from other marine uses, such as offshore wind, oil and gas, and navigation buoys, may be comparable to those caused by MRE installations [57]. While the ecological footprint of a single deployed MRE device may be relatively limited, an array of devices may act as a network of interconnected artificial reefs [57]. MRE projects may also act as marine reserves, which can promote the recovery of local species because their presence reduces fishing activity [62]. This artificial reef effect may spread at the ecosystem scale, affecting the structure and functioning of local and regional food webs in unknown ways. Additional information will be needed from specific project sites to assess the degree to which artificial reefs and reserves may affect larger areas of the ocean.

#### 3.5. Changes in Oceanographic Systems Associated with MRE

The deployment of MRE devices has the potential to affect both near- and farfield oceanographic systems such as water circulation, wave and current action, and sediment transport [67,68]. While a small number of MRE devices is not likely to result in significant biological changes, larger-scale array deployments (likely 10 to 100 s of MRE devices) may disrupt natural processes driven by tides, waves, and ocean currents [69,70].

To date, few field studies have measured the effects of MRE devices, as potential changes are unlikely to be measurable within a system's natural variability for small numbers of deployed devices. Laboratory flume studies help understand wake recovery and turbulence due to tidal energy extraction (e.g., [71,72]), which can support the understanding of potential effects. Until large arrays are deployed and field measurements are collected, numerical models provide the greatest insight into the potential effects of MRE deployment on oceanographic systems, although relatively few modeling studies address environmental effects directly (e.g., [73–75]). However, model validation is needed through additional field data collection.

#### 3.6. Entanglement Risk with MRE Mooring Systems and Subsea Cables

Many MRE devices require mooring systems (i.e., mooring lines, anchors) to maintain their position on or within the water column, and draped inter-array cables to connect devices to one another or to offshore substations. These mooring systems and cables may present entanglement or entrapment hazards for some marine animals [76].

The likelihood of an encounter between marine animals and MRE mooring systems and subsea cables is a function of the line or cable configuration and depth, and the animal's size and behavior [77]. The animals considered to be most at risk of encounters with MRE mooring systems and subsea cables are large migratory baleen whales because of their migratory patterns and feeding behaviors [78].

Research on marine mammal risk in general focuses on observations of injury and mortality caused by entanglement with fishing gear (e.g., nets of slack lines) or submarine telecommunications cables, each with a loose end or loop that could ensnare an animal [78,79]. These risks are poorly understood, largely because of the lack of empirical data and focused studies. MRE mooring lines and cables have no loose ends and are sufficiently taut that no looping can occur, and entanglement has not been considered a significant issue of concern within permitting processes for small numbers of MRE devices. However, the risk of animal entanglement in anthropogenic debris caught in MRE device moorings and subsea cables persists [47,80].

### 3.7. Social and Economic Data Collection for MRE

MRE development can bring social and economic benefits to a region, including the stimulation of economic development, production output, regional development, and tourism, along with the generation of employment and revenue [81]. However, if not carefully and sensitively sited and implemented, MRE development could have adverse social and economic impacts including conflicts with existing marine uses (such as with local fishing and recreation), visual obstruction, and economic effects if the local supply chain is not engaged and leveraged [82]. There is a need to collect social and economic information consistently and comparably over time to understand baseline and long-term assessments, social changes (e.g., social structures, schools, housing, services), and economic changes (e.g., employment, wages, and local supply chain). There are no standardized data collection processes to decrease the uncertainty around how social and economic benefits and effects of MRE development are measured [83,84]. Recommendations to improve social and economic data collection include: reviewing and cataloguing planning tools and databases; developing guidance for data collection efforts by developers; building incentives to collect and publicize social and economic data; using flexible approaches to planning; proportionately correlating impacts and required data collection to the size of a project; and engaging stakeholders throughout the process [85].

### 3.8. Management Strategies for Permitting MRE Projects

It is the perception of the MRE industry that projects take an inordinately long time to permit and that the data collection requirements for baseline assessments and post-installation monitoring are onerous [20]. At the same time, the regulatory community must ensure that populations of animals, habitats, and natural processes are protected using existing laws and regulations; their tasks are complicated as MRE technologies are new and relatively untried, and are often deployed in high-energy parts of the ocean for which there is little information. A number of management approaches are being used to address siting, permitting, monitoring, and, where necessary, mitigating the effects of MRE development with the aspiration that these management measures might help accelerate permitting while protecting marine and river resources. Three of the measures that are applicable to MRE development include marine spatial planning (MSP), adaptive management (AM), and risk retirement (RR), that may operate individually or in combination with the others, within existing regulatory structures. Each is briefly described here.

MSP is a process used to balance the needs of marine users and uses by applying principles that are derived from land-use planning [86]. The approach depends on the development of a significant geodatabase of existing resources and uses, and on significant involvement with stakeholders. MSP has been effectively implemented in other marine development and resource use projects (e.g., [87]). MSP has also been used to inform siting and monitoring needs for MRE projects in Europe and some parts of Asia, as well as for a few projects in North America and Australia [88], but has not yet been widely adopted. However, there is growing interest in its continued application in the siting and permitting of offshore renewable energy development [88].

AM was developed to provide flexibility and decrease uncertainty around natural resource management, to complement the precautionary principle, and to allow for effective mitigation [89]. Sometimes characterized as “learning by doing”, AM allows some degree of flexibility in monitoring



and mitigation for projects going forward. This process has been used in several nations to work within MRE permitting processes, to decrease uncertainty around potential environmental effects of MRE devices, and to provide transparent access to available monitoring data [90,91]. When AM is agreed upon as a management measure for a specific MRE project, an agreement is often developed between the project developers and the regulators, allowing (at times) other parties to become signing partners. The agreement helps manage the collection and application of post-installation monitoring data to help guide future actions [92].

Working with the 15 nations that have come together under OES-Environmental (<https://tethys.pnnl.gov/about-oes-environmental>), the process of RR was developed to make existing datasets on MRE environmental effects widely available through an organized process [15]. RR is used to support siting, permitting, and monitoring of MRE projects by reducing the need for new studies for each interaction at every MRE project, relying instead on results and lessons learned from monitoring around already-permitted MRE projects and peer-reviewed research [15,93]. RR is not designed to take the place of any existing regulatory or management actions in any jurisdictions, but to support the efficient application of existing information, with the purpose of decreasing the time and resources needed to permit future projects. At this time, virtually all the evidence that has been examined for RR is derived from and applicable only to interactions with small numbers (one to three) of MRE devices.

#### 4. Discussion

Based on the current state of knowledge [17], questions remain that will require additional research to adequately characterize and evaluate the risk to the marine environment from MRE development. Much of the information that is presently available has been gleaned from research studies or preliminary monitoring results concerning small numbers of turbines or WECs, generally one to three devices.

Significant amounts of data have been collected to define the risk from small numbers of MRE devices and to bring some level of certainty to the stressor–receptor interactions around turbines and WECs that have been presented here. Those interactions that have best been described and understood include the following: the potential effects of underwater noise from MRE devices, effects of EMF emissions on marine animals, and changes in habitats. For each of these stressors, work remains to be done to ensure that the data collected to date are reproducible and reflect the overall likely effects of the range of MRE devices being developed and installed. Other stressors have been examined and thought not likely to cause significant risk to the environment for small numbers of devices, but a lack of direct data makes it necessary to revisit these stressors as the MRE industry builds out to large commercial arrays, including changes in oceanographic processes and entanglement of marine animals. Collision of marine animals with turbines continues to be the stressor for which the most research effort has been expended, but it remains the most elusive in providing estimates of risk to marine mammals, fish, diving seabirds, and sea turtles. There is also a need to determine whether MRE development will provide benefits or have negative social and economic effects on local communities and regional jurisdictions, as development occurs. The key knowledge gaps and remaining questions are described below in more detail.

##### 4.1. Additional Research Needed to Verify and Understand Results

Collision risk continues to be a difficult interaction to characterize because observations in high-energy environments are challenged by fast-moving and often turbid waters; and the instruments and platforms built for this purpose are just coming online [94,95]. In addition, there is general consensus among the research community that collision events (or even very close encounters) are likely to be very rare, particularly for larger marine animals with good sensory capabilities and strong swimming skills [96]. Further work is needed on the likelihood of death or sublethal effects when a marine animal encounters a turbine [26,97,98], as well as the population-level risks associated with an encounter. Even as efforts to characterize the risk of collision with single turbines are underway, there

is little sense of how animals might perceive large arrays of devices, making it difficult to extrapolate the information around early MRE projects [95].

The most critical research and monitoring needs for understanding the risk underwater noise poses to marine animals involves the ability to accurately measure the acoustic output of an MRE device, differentiating the sound against often high levels of ambient noise [43]. Developing a library of sounds from different turbine and WEC configurations and types would help highlight that the sounds are unlikely to exceed U.S. regulatory thresholds, and therefore unlikely to cause harm or create additional needs for data collection at each new project [15,43]. Uncertainty remains in the methods used to relate the behavioral responses of specific marine animals to the range of frequencies and sound levels from single MRE devices [43]. Acoustic propagation models can be used to extrapolate the underwater noise from single devices to larger MRE arrays, and apply them to predict likely effects, but additional data are needed to verify the use of acoustic models in the high-energy environments where MRE is harvested [43].

Field and laboratory studies have provided reasonable confidence that the EMF levels emitted from MRE cables are unlikely to cause significant risk to benthic or pelagic animals. However, there are no standardized methods for measuring EMFs in the marine environment, or threshold levels against which to measure the emissions, particularly on a regulatory basis [52]. Evidence has shown that larger MRE arrays may increase the potential risk to sensitive marine receptors and require additional investigation, but no harm is likely to occur [52].

Assessment of the overall harm from changes in benthic or pelagic habitat, particularly as larger MRE arrays are deployed, requires that data be collected and surveys carried out at appropriate spatial and temporal scales. Such data collection campaigns will make it possible to distinguish between potential effects from devices and natural variability, coupled with a better understanding of thresholds of habitat alteration that are thought to be significant consequences [99,100]. Numerical modeling can help set boundaries for significant changes in benthic and pelagic habitats [62,101,102]. Although few MRE devices have been in the water long enough to be decommissioned, existing information from the MRE industry and other offshore industries that interact in the ocean in similar ways indicate that there may be positive effects of leaving at least some substructure in the environment [99].

Until large arrays are deployed and oceanographic measurements collected, numerical models are the only tools that provide any indication of how oceanographic processes are likely to be affected by larger MRE arrays. In the absence of calibration data, these models only provide an estimate of what might happen as MRE projects expand [103]. The effects modeled from very large arrays (1 GW or more) indicate the potential for substantial changes in the marine environment, although most are highly dependent on the device layout, channel geometry, habitat type, and flow patterns [103]. The process of modeling interactions of MRE devices with the ocean creates a level of uncertainty that may propagate through subsequent steps in estimating power outputs and effects [104]. It will also be important in the future to examine other forcing functions, such as climate change, to determine the potential effects of MRE devices on water flow, wave height, and sediment transport [105].

With little direct data collection possible for examining potential entanglement of marine animals in MRE mooring lines and cables, future data collection efforts remain to be undertaken once larger MRE arrays are deployed and operated over a period of years [17,76]. Concerns about entanglement in abandoned fishing gear on mooring lines may need to be examined in future, in conjunction with the fishing industry to whom the gear belong.

Displacement of animals due to the presence of MRE devices has not been examined for small numbers of devices; however, as larger arrays are deployed, there will be a need to examine whether migratory animals change their paths to avoid MRE projects, perhaps preventing them from reaching critical or preferred habitats.

There is a need to collect data and information to determine a baseline for potential social and economic benefits and effects of MRE development, as well as collection of data throughout the life of an MRE project, to calibrate and assess the predictions of social and economic effects or benefits

made during permitting and assessment. Two levels of data area needed: (1) strategic-level activities and measures that meet objectives of local, national, and regional policy, which should generally be collected by governments at the appropriate scale; and (2) project-level activities and measures that meet objectives on a local scale, such as within a municipality or community, that should be collected by MRE project developers [85].

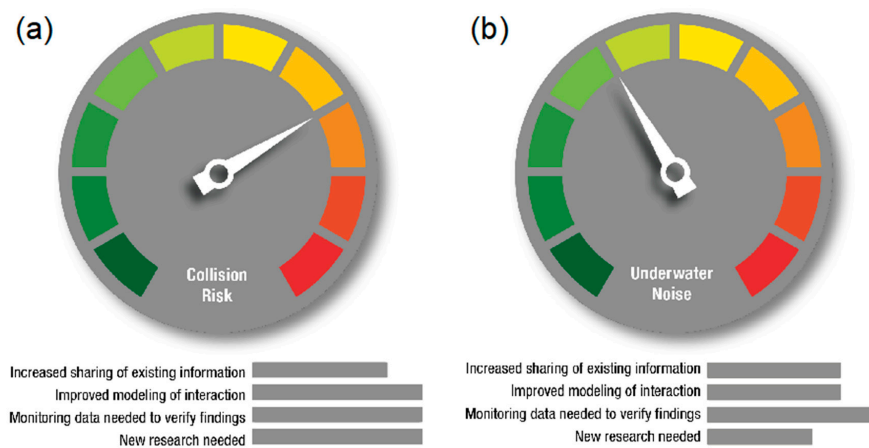
#### 4.2. Key Strategies for Accelerating MRE Development Responsibly

The body of knowledge surrounding the potential effects of MRE development can be used to help streamline permitting processes and support the responsible development of MRE through the implementation of strategies such as MSP, AM, and RR. However, these strategies need to be applied carefully and will yield the greatest return if they are used consistently and shared internationally. In particular, several overarching goals should be considered:

- (1) Data and information transfer. Carrying out a process of assessing and organizing datasets and knowledge from already permitted MRE projects and associated research studies, as well as lessons learned from other offshore industries, will make information readily accessible and transparent. Using open-source models and codes, as well as publicly accessible archives of data and model outputs, will make necessary data readily available. These steps can help all stakeholders, including MRE developers and regulators, to make informed decisions for siting and permitting [106].
- (2) Proportionate effort and costs. The effort to collect and analyze data around a specific stressor-receptor interaction should be related to the size of the MRE project and the likely risk to the specific animals or habitats of concern. Applying datasets and information from already permitted projects and appropriate research studies, augmented by site-specific data needed to validate their use, should help identify the adequate level of effort [106]. The accumulated evidence on stressor-receptor interactions can be applied to ensure that the highest risk interactions receive the appropriate attention and data collection efforts. Other interactions, for which the level of risk has been shown to be low, should be retired, or downgraded, to reduce data collection and effort.
- (3) Applying principles of MSP and AM. The permitting and social acceptance of a proposed MRE project can be helped by applying information gathered through stakeholder engagement and data gathering associated with MSP in the region of a proposed MRE project [88]. Similarly, the application of AM as a means of iteratively learning more about potential environmental effects of MRE devices can assist with efficient and effective permitting processes and ensure that post-installation monitoring is useful and appropriate [107].

#### 4.3. Trends in MRE Environmental Effects

Documenting the level of perceived risk for each stressor-receptor interaction over time can help provide a baseline against which future understanding can be measured. For this documentation, we propose a series of dashboards that include a dial that uses shades of green to indicate a well understood and relatively low risk from a stressor to yellow and red that indicate increased levels of risk. The dashboard also features a bar graph to indicate actions that may help the level of understanding of the interaction, and therefore the risk, progress towards green, including the following: increased sharing of available information, improved modeling of the interaction, monitoring data needed to validate models, and new research needed. While a dashboard has been created for each interaction [17], the examples of collision risk and underwater noise are presented here (Figure 3a,b, respectively).



**Figure 3.** Dashboards that demonstrate the understood level of risk for specific stressors (dial on the top, with red being the highest level of risk), as of 2020, with indication of a pathway forward to further understand and lower the perceived risk of the stressor (bar graph on the bottom). (a) Understanding and path forward for collision risk of marine and riverine animals with turbines is summarized in this dashboard. (b) Understanding and path forward for effects of underwater noise from marine renewable energy devices on marine animals is summarized in this dashboard. The dashboards were drawn in the style of Copping and Kramer [108] and updated with recent information. (Illustrations by Robyn Ricks.).

## 5. Conclusions

This paper highlights recent findings on stressor-receptor interactions and environmental risks of MRE, as well as providing perspective on those risks, and describes a path forward to decrease uncertainty and provide clarity in support of siting and permitting MRE projects. The collation of information on potential environmental stressor-receptor interactions provides insight into the current state of the knowledge, defines needs for social and economic data collection, and presents management strategies that collectively can help to advance the establishment of the MRE industry. With increased understanding of potential environmental effects, perceptions of risk can be informed, and barriers to permitting may be decreased. For nations of the world to establish this low-carbon sustainable, renewable energy source, there is a need for significant international collaboration among MRE device and project developers, regulators, researchers, and funding agencies. This collaboration must include transparent sharing of existing information, as well as identification and implementation of strategic research projects to fill key gaps in knowledge.

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