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Review

# Are fish in danger? A review of environmental effects of marine renewable energy on fishes

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ABSTRACT

Many fish species are threatened worldwide by overfishing, contamination, coastal development, climate change, and other anthropogenic activities. Marine renewable energy (MRE) is under development as a sustainable alternative to carbon-based energy sources. Regulators and stakeholders worry that MRE devices will add another threat to fish populations already under pressure. This paper reviews the current knowledge of potential effects of MRE development on fish. These may include collision with devices that may lead to injury or death; underwater noise generated by MRE devices that may affect fish behavior and health; electromagnetic fields from power cables and other electrical infrastructure that may lead sensitive fish species to approach or avoid them; changes in critical fish habitat, including nursery, feeding, and spawning grounds; shoaling of fish around MRE devices; and displacement of fish populations or communities around arrays of multiple MRE devices. Field- and laboratory-based studies that have examined fish presence, avoidance, and evasion around MRE devices suggest that collisions are rare. Progress is being made on data collection and modeling tools to estimate fish encounter rates with MRE devices, the consequences of collisions, and population-level ecological risks. Similarly, studies exposing fish to turbine-generated noise and electromagnetic fields demonstrate little effect on fish behavior; in fact, MRE device noise falls below reported hearing thresholds. Inquiries into the effects of MRE devices on fish are ongoing, and research is needed to ensure the health of fish populations while facilitating the sustainable development of renewable energy sources.

## 1. Introduction

Threats to marine organisms from warming and acidification of ocean water, as well as other outcomes of climate change, are well recognized (e.g., Doney et al., 2009; Fabry et al., 2008). In addition to these threats, many fish species are under pressure worldwide by overfishing, contamination, coastal development, and other anthropogenic activities (Greene et al., 2009; Reynolds et al., 2002; Winfield, 2004). Additional threats emerge from new industries, encroachment of shoreline and coastal development, and increased use of ocean space in support of the "Blue Economy" (i.e., "the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean ecosystems"; Lee et al., 2020; OECD, 2019; World Bank, 2019)—all placing additional pressures on critical habitats and migratory pathways, and contributing to mounting stress on commercial and recreational fisheries and other fish communities.

Marine renewable energy (MRE) is a recent entry into the renewable energy portfolio. MRE has the potential to produce low-carbon energy from the movement of ocean water (primarily), specifically the tides, ocean currents, waves, the flow of large rivers, as well as differentials in the temperature and salinity of ocean water. MRE can be a part of the solution for decarbonizing the oceans and adapting to the effects of climate change (IRENA, 2019). Most MRE devices that have been deployed to date are instream turbines that harvest energy from tidal or river currents, or wave energy converters (WECs) that harvest energy from the oscillation of waves (Fig. 1). These devices are therefore the focus of this paper. Instream devices most often take the form of turbines placed on the sea- or riverbed or suspended from floating structures, and

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they differ from traditional hydropower dams or tidal barrages because they do not block the flow of water. WEC development to date has embraced many different forms and structures (Fig. 1) that harvest waves in different parts of the water column, using a variety of physical principles (Borthwick, 2016; López et al., 2013). Though offshore wind is another source of renewable energy on the ocean, it is considered separately from MRE and is not the focus of this paper (though some offshore wind studies are cited because their effects overlap with MRE effects on fish).

While MRE can help mitigate some threats of climate change, the development of the offshore renewable energy industry may also pose further risks to fish, including diadromous (i.e., those that migrate between the ocean and freshwater for life cycle closure) and marine species. This paper reviews the current knowledge of the perceived threats to fish as a result of MRE development, and highlights what is known about the associated level of risk from this industry. The authors have chosen this focus because there are few assessments pertaining to fish in the literature, compared to those for marine mammals or seabirds (Copping and Hemery, 2020). This assessment places considerable emphasis on questions related to the methods and uncertainties surrounding measuring the effects of MRE devices on fish because they are currently the most pressing concerns. MRE is harnessed in the most energetic parts of the oceans (e.g., tidal channels, large wave areas nearshore) in which widely accepted measurement techniques and instruments for assessing fish populations and interactions with underwater objects are often ineffective (Hasselman et al., 2020). A review that highlights the understanding of the current status of effects of MRE on fish, and how effects are evaluated, is thus timely.

As one of the most recent marine industries, MRE has largely concentrated on engineering design for device survivability in dynamic marine environments. This focus has led to successful deployments of individual pilot- or commercial-scale devices in Europe, the Americas, Asia, and Oceania (Ocean Energy Systems, 2019), and the first commercial-scale array of instream tidal turbines in Scotland in 2018 (Black and Veatch, 2020). However, the developing MRE industry has posed a challenge for regulators and stakeholders of the marine environment because there is no established understanding of the potential risk these novel devices pose to marine animals and their habitats. Research in this area, augmented by monitoring programs around early devices, is shedding light on potential risks. Researchers examining MRE interactions with marine animals and habitats have generally coalesced around terminology of 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), *sensu* Boehlert and Gill (2010). In-depth examination of the stressor-receptor interactions associated with MRE systems has been summarized by the Ocean Energy Systems (OES)-Environmental collaboration of 16 nations under the International Energy Agency's OES consortium (Copping et al., 2016; Copping and Hemery, 2020).

There are six identified stressor-receptor interactions between fish and instream turbines or WECs that could potentially result in harm:

- collision with moving parts of MRE devices;
- exposure to underwater noise from operational devices;
- exposure to electromagnetic fields (EMFs) from power export cables and energized devices;
- changes in habitats due to the presence of devices;
- MRE systems acting as fish aggregating devices (FADs); and
- displacement of fish populations.

With the exception of displacement, these interactions have all been examined to varying extents. Major international efforts have organized to understand the potential risks of each, to identify knowledge gaps, and to devise a path forward for understanding and "retiring" potential risks (Copping and Hemery, 2020). It is also important to note that there may be secondary or cumulative effects of MRE development on fish that

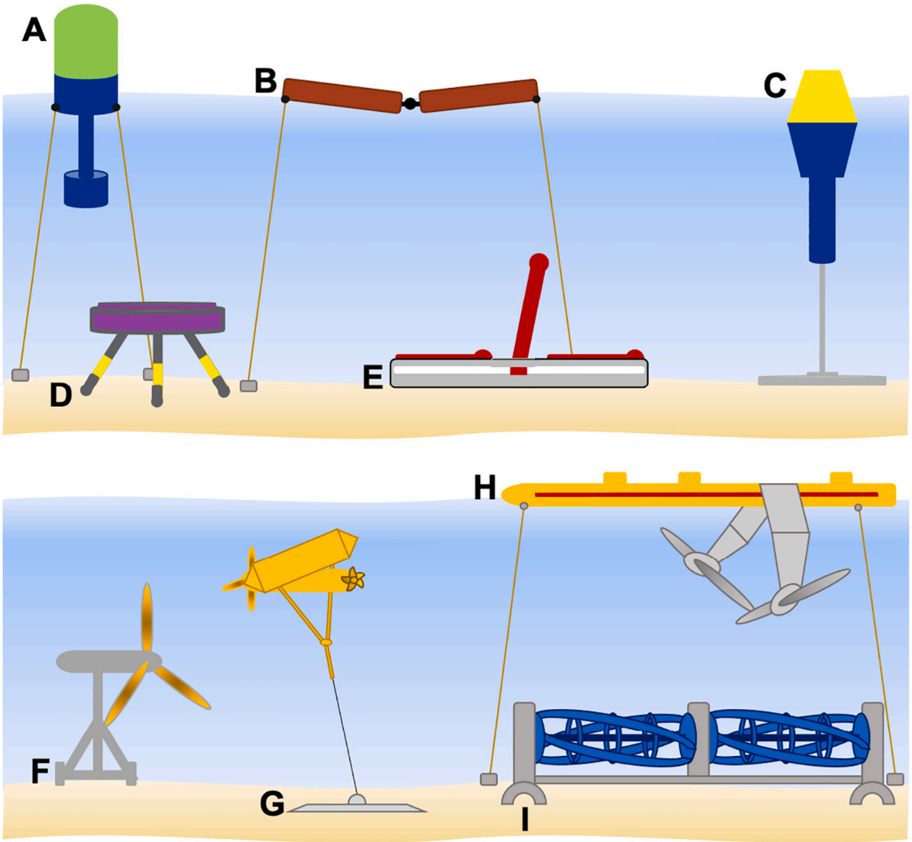

**Fig. 1.** Technological diversity of wave energy converters (top panel) and instream tidal/river energy devices (bottom panel): (A) surface point absorber with mooring lines and anchors; (B) surface attenuator with mooring lines and anchors; (C) bottom-mounted point absorber; (D) submerged point absorber; (E) oscillating wave surge converter; (F) bottom-mounted axial flow turbine; (G) tidal kite with tether and mooring system; (H) surface axial flow turbine with mooring lines and anchors; and (I) bottom-mounted cross flow turbine.

are not yet known, or for which the magnitude of risk is currently unidentified.

## 2. Review methods

The assessment of the potential effects of MRE devices on fish was carried out by examining the literature in the field. This literature review considered any marine, diadromous, or freshwater fish, at any life stage, that would potentially interact with MRE devices. A few journals are devoted to MRE development, and none is dedicated to examining MRE environmental effects. The evidence reviewed herein was derived from four sources of information:

1. Analogs that can be drawn from other maritime industries and development in oceans and rivers. These include underwater noise from shipping, underwater construction, and offshore wind turbines; EMF emissions from energized power and communication cables; as well as changes in benthic and pelagic habitat related to various industries.
2. Field studies carried out around MRE devices and appropriate surrogates. These include determining what populations and life stages of fish might encounter MRE devices and the interactions of fish with turbines, and some aspects of habitat change in areas around MRE devices and export cables.
3. Laboratory and flume experiments, in which evidence includes interactions of fish with turbines in flumes, and exposure of fish to EMFs from cables and laboratory instruments.
4. Models that explore mechanisms and consequences of fish interacting with MRE devices. This model-derived information includes potential upper estimates for fish colliding or interacting closely with turbines to simulate collision risk, models of acoustic and EMF emissions from MRE devices and cables, and some habitat loss models.

To our knowledge, the 2016 and 2020 State of the Science reports on environmental effects of MRE development around the world (Copping et al., 2016; Copping and Hemery, 2020) are the most comprehensive documents that review environmental effects of MREs. These reports contain thorough literature reviews that include peer-reviewed journal articles and conference proceedings, as well as grey literature. For the present review, we relied on these State of the Science reports (Table 1) and augmented the information with additional documents (mainly journal articles) found through keyword searches in *Web of Science* and the *Tethys* knowledge base, a database devoted to compiling information about the environmental effects of wind and MRE (Whiting et al., 2019).

The references used in this review are a subset of those in the 2016 and 2020 State of the Science reports, because these reports contained duplicate references, and, in many cases, grey literature that was eventually published in peer-reviewed journals. In the latter case, we only refer to the peer-reviewed journal articles. From the broad literature survey, this paper compiles the most likely risks of MRE development for fish, identifies key knowledge and data gaps, recommends a path forward to fill those gaps, and attempts to reach a level of understanding of how MRE devices can be safely deployed and operated while posing minimal risk to fish.

**Table 1**
Number of documents pertaining to fish reviewed for this study, compared to the 2016 and 2020 *State of the Science* (SoS) reports about the environmental effects of marine renewable energy development around the world.

| Stressor/source | This review | 2016 SoS | 2020 SoS |
|---|---|---|---|
| Collision risk | 23 | 43 | 29 |
| Underwater noise | 40 | 2 | 4 |
| Electromagnetic fields | 21 | 19 | 31 |
| Changes in habitat | 42 | 20 | 22 |
| Displacement | 9 | – | – |

## 3. Potential threats to fishes

This section considers threats to fishes from MRE devices, starting with the risk of greatest concern (collision risk), followed by successively lower risks from underwater noise, electromagnetic fields, changes in habitats and fish aggregating devices, followed by the threat about which the least is known – displacement – and ending with cumulative effects of MRE devices on fishes.

### 3.1. Collision risk

There is potential for individual fish and fish schools to encounter the rotating blades of instream tidal/river turbines. This can occur either because fish are unaware of the presence of the turbine, are unable to direct their movement enough in fast-moving waters, or are attracted to the shelter or food sources around turbines and associated infrastructure. A collision with a rotating turbine blade could cause injury or mortality to fish; although it is important to note that, in comparison to conventional hydropower turbines, instream tidal/river turbines move much more slowly, generate very little change in pressure, and are placed in areas where there is ample room for fish to pass by (Sparling et al., 2020). WECs do not have moving parts in the water column that are similar to tidal turbines, and they are not placed in high-speed currents, so the risk of collision and harm related to WECs is considered to be negligible (Copping et al., 2016).

Collision risk considers the likelihood of moving components of MRE devices, namely blades and rotors, striking animals (Wilson et al., 2007). While collisions between fish and static portions of the MRE system are possible, observations to date do not indicate that harm is likely to occur (Matzner et al., 2017). Several factors contribute to collision risk and can be divided into two broad categories: the physical characteristics of MRE devices, and the characteristics of animals that inhabit the deployment area. Here, we focus on how collision risk relates to the abundance and distribution of fish at MRE sites (i.e., their likelihood of encountering a device), and their behavior adjacent to devices. These biological characteristics have been measured in pre-deployment ("baseline") surveys, as well as by post-deployment monitoring. Collision is challenging to observe in a field setting, but laboratory studies have provided preliminary information about collision, injury, and mortality rates. Models have also been used to further explore potential fish–MRE device encounter and collision rates.

#### 3.1.1. Pre- and post-deployment field studies

Baseline studies at proposed MRE sites typically focus on understanding the pre-deployment spatiotemporal distribution of fish to predict encounter rates with proposed devices. This information is challenging to collect at the energetic locations targeted for MRE development, where physical sampling (e.g., with nets) can be severely constrained (Vieser et al., 2018). The primary methods for data collection at tidal energy sites have been acoustic, either active (i.e., scientific echosounders) or passive (i.e., acoustic telemetry) (Fig. 2). The metrics most commonly collected in acoustic assessments include: fish presence/absence, density, school presence and size, for active acoustics; and movements of tagged individuals, for passive acoustics. Though not without their own challenges at highly energetic sites—e.g., entrained air contamination (Fraser et al., 2017; Sanderson et al., 2017; Viehman et al., 2018) or flow noise (Keyser et al., 2016; Stokesbury et al., 2016)—the use of acoustic methods to gather information has significantly improved our understanding of fish use of tidal energy sites.

A recurring finding of the existing baseline studies is that fish density, distribution, and movements at tidal energy sites are highly variable and strongly related to environmental factors, including seasonal, lunar, diel, and tidal cycles (Gonzalez et al., 2019; Keyser et al., 2016; Scherelis et al., 2020; Viehman and Zydlewski, 2017; Viehman et al.,

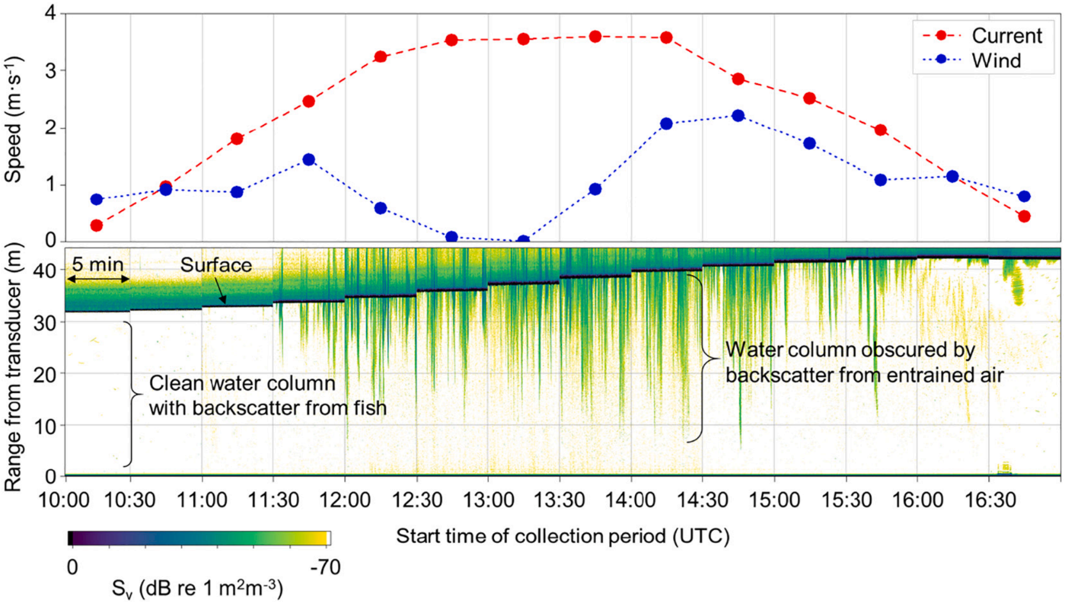

**Fig. 2.** Example of active acoustic data (echogram) collected by an echosounder over a 7-hour period at a tidal energy test site (lower panel), and the speed of the tidal current and wind (upper panel). The echosounder is bottom-mounted, pointing toward the surface. At the start of the echogram, the current speed is low, allowing for clean acoustic readings (backscatter) from throughout the water column in which fish can be identified. As current speed increases, air is entrained from the surface, contaminating the acoustic signal throughout the water column.

2015, 2018; Whitton et al., 2020; Wiesebron et al., 2016b), hydrodynamics (e.g., tidal currents, turbulence; Scherelis et al., 2020; Stokesbury et al., 2016), and suspended particulate matter (Whitton et al., 2020). The nature of these relationships varies within and across studies, highlighting the importance of considering fish species and life stages alongside site-specific physical characteristics when evaluating device effects. Understanding how fish use a site prior to device deployment is essential when designing monitoring plans that can detect device effects amid high natural variability (Gonzalez et al., 2019; Horne and Jacques II, 2018; Wiesebron et al., 2016a,b).

Post-deployment research has tended to focus on understanding fish behavior around devices at the individual and group levels (Bevelhimer et al., 2015; Fraser et al., 2018; Hammar et al., 2013; Matzner et al., 2017; Viehman and Zydlewski, 2015; Williamson et al., 2019). These studies all observed some level of device avoidance, ranging from small adjustments in swimming direction or speed to more extreme modifications of trajectory (e.g., bursts of upstream swimming). Observed responses to devices have also included entrance into the rotor-swept area, milling in the turbine's wake, and passing through the turbine passively. Behaviors varied with fish characteristics (e.g., size, species, whether individual or schooling), current speed, light level, and turbine motion. When evaluating collision risk, results of these studies highlight the importance of considering the species and life stages of fish encountering turbines, in the context of the environmental factors affecting cues available to fish and potentially modulating their responses.

Effects of MRE devices on fish behavior have also been inferred by examining changes in other metrics, such as fish presence/absence, density, or school size. Fraser et al. (2018) and Williamson et al. (2019) found significantly higher school numbers and smaller school sizes in a turbine support structure's wake, compared to a control site, until flow speeds surpassed 1 m/s. This may reflect fish using the hydraulic shelter provided by a support structure, as well as a physical limitation on active fish behavior imposed by high current speeds. Another study compared an index of fish density at a tidal energy device to a reference site, before and after device deployment (Staines et al., 2019). Lower fish densities during construction and maintenance periods suggested greater avoidance of construction activities than the operating device.

### 3.1.2. *Laboratory studies*

Additional information about individual fish behavior and collision rates has been gathered by laboratory-based studies (Amaral et al., 2015; Berry et al., 2019; Castro-Santos and Haro, 2015; Zhang et al., 2017), because collision and resulting injury or mortality are difficult to observe in field settings (Viehman and Zydlewski, 2015). Laboratory studies have involved releasing fish up- or downstream of a scaled turbine in a flume under varying current speeds and turbine operational states, then recording fish behavior and instances of collision, injury, and mortality. These studies have all concluded that while turbine operation affected fish behavior (e.g., avoidance, impedance of upstream movement), injury and mortality rates were low; observed and modeled survival rates were 95–100%. Zhang et al. (2017) found avoidance behavior increased as the rotational frequency and tip speed of the turbine increased, and fish size and swimming ability relative to current speed was cited as an important factor influencing their ability to avoid turbines. The extent to which laboratory results may be extrapolated to field conditions remains to be determined.

Collisions in flume experiments are rare, so Bevelhimer et al. (2019) sought to quantify mortality rates of fish subjected to blade strike. They exposed three species of freshwater fish to simulated blade strikes, and found that strike location, blade orientation relative to the fish, and blade thickness and velocity all affected mortality rate. Results such as these can aid in mitigating negative effects on fish through appropriate turbine design.

### 3.1.3. *Modeling studies*

Models are necessary to link observations from diverse datasets into a cohesive picture of fish interactions with MRE devices. Modeling has so far drawn on data from baseline and post-deployment studies to explore potential rates of fish encounters with devices, conditions influencing fish behavior near devices, and collision risk. Viehman et al. (2018) estimated the probability of fish in the Minas Passage, Canada, encountering a proposed turbine to be less than 0.1%, using measured vertical distributions and assuming a uniform across-channel distribution. Using two active acoustic datasets, modeling by Shen et al. (2016) indicated that the maximum likelihood of a fish upstream of a device encountering the turbine would be 5.8%. These authors also noted that fish numbers began to decrease as far as 140 m upstream of the device. This apparent avoidance behavior was examined further using an individual-based model framework (Grippo et al., 2017), which suggested this avoidance was more likely due to turbine-generated noise than to local hydrodynamics. Collision risk has been modeled using the physical characteristics of proposed MRE devices and of Atlantic salmon, *Salmo salar* (e.g., body size, abundance, swimming ability; Xodus Group, 2016). For a device array scenario of 200 10-bladed devices, collision risk was estimated to be 0.007% or less, depending on fish life stage. Collision risk modeling by Hammar et al. (2015), informed by field observations of fish behavior in fast currents, suggested fish size and species were important factors influencing the probability of collision and injury.

### 3.2. *Underwater noise*

Anthropogenic noise in the world's oceans originates from a variety of sources (e.g., shipping, petroleum exploration, and military exercises), and the MRE industry will contribute additional noise that may affect fish. All fish species rely to some extent on their ability to detect underwater sound, which informs their perception of their environment to forage, escape predation, and reproduce (Parmentier and Fine, 2016). Naturally occurring abiotic sound sources (e.g., breaking waves, earthquakes) and biological sound sources (e.g., snapping shrimp, various fish) combine with anthropogenic noise to create a complex soundscape that covers a wide bandwidth (Wenz, 1962). Many fish detect sound as a combination of particle motion and sound pressure via ear structures and/or the swim bladder (Popper and Fay, 2011; Popper and Hawkins, 2018; Popper et al., 2003). Fish also detect low-frequency sounds at close range (1–2 body lengths) using their lateral line system (Webb, 2013).

Impulsive, high-source-level noise from pile driving, explosions, and air guns can cause permanent hearing threshold shifts for fish, internal tissue damage, and even mortality (Hawkins and Popper, 2017). However, unlike bottom-based offshore wind turbines, MRE devices are seldom mounted on piles, so installation noise from pile driving is generally not a concern. Operational noise from tidal turbines and WECs originates from the power take-off (generators and associated mechanical components) and from the rotating turbine blades, although MRE mooring systems may also generate underwater noise. Determining the effects of anthropogenic sources of underwater noise on fish requires knowledge of noise-production activities and characteristics of MRE devices (e.g., bandwidth and amplitude), natural ambient sound levels in the activity area, sound propagation predictions based on modeling, and effects on fish at different distances from the noise source (Hawkins and Popper, 2016).

#### 3.2.1. *Noise measurements of MRE devices*

A number of studies have provided measurements of underwater noise that could be detected by fish, based on bandwidth and amplitude at various ranges from the sound source. To date, most underwater noise measured from operational MRE devices falls under 10 kHz, and the majority falls under 1 kHz (Polagye and Bassett, 2020). Walsh et al. (2017) measured the noise generated by a WEC to be between 10 Hz and 32 kHz at 200 m, and found that certain frequencies (i.e., 30, 60, 80, and 100 Hz) produced amplitudes >100 dB re μPa at 1 m when producing power. Additional measurements would be required at varying ranges to determine the overlap with fish hearing thresholds, and to identify the minimum distance at which fish behavioral response is likely. Polagye et al. (2017) conducted measurements of the same device as Walsh et al. (2017), installed at a different location, using a combination of stationary hydrophones (long-term data collection) and drifting hydrophones (for measurements close to the WEC), and found broadband received sound pressure levels (SPLs) between 105 and 125 dB re μPa at 1 m at a range of 100 m. Schmitt et al. (2018) used drifting hydrophones to measure underwater SPLs for a subsea tidal kite equipped with an axial flow turbine across several operating conditions. Although specific ranges of SPL measurements were not determined, average values were calculated for a 30 second window as the hydrophone drifted by the device (typically within 15 m). The maximum calculated SPL value was 110 dB re μPa at 1 m at 300 Hz. While the hearing range for fish extends from 10 Hz to 4 kHz, most species detect sound between 50 Hz and 1 kHz (Hawkins and Popper, 2018), which overlaps with the frequency range of operational noise generated by MRE devices (Bevelhimer et al., 2016).

#### 3.2.2. *Potential effects of MRE-generated noise on fish*

The noise from MRE devices is within the hearing range of many fish species but occurs at much lower volumes than other operational noises at sea (like ship propellers) and is unlikely to cause harm to fish tissues (Halvorsen et al., 2011). However, operational noise may mask sounds from certain fish species and have an effect on their hearing ability (Polagye and Bassett, 2020) or may affect fish behavior (e.g., avoidance) or movement in an area (displacement). The effects of MRE-generated noise on fish are described in several studies. Bevelhimer et al. (2016) reviewed the hearing ranges and thresholds of five fish species (paddlefish [*Polyodon spathula*], lake sturgeon [*Acipenser fulvescens*], black bass [*Micropterus* spp.], Chinook salmon [*Oncorhynchus tshawytscha*], and American shad [*Alosa sapidissima*]) and compared the recorded noise of a single instream tidal turbine to other anthropogenic (e.g., vessels of various sizes), abiotic (e.g., heavy rain), and ambient noise. These species were found to be unlikely to hear the noise measured from the instream turbine at 21 m; however, this range is likely to be species-specific. Schramm et al. (2017) used acoustic tags to examine the movement behavior of redhorse suckers (*Moxostoma* spp.), freshwater drum (*Aplodinotus grunniens*), largemouth bass (*M. salmoides*), and rainbow trout (*O. mykiss*) in the field, in response to a recording of noise as a surrogate for that of an instream turbine. Sustained playback of the recording generated the greatest response for redhorse suckers, whereas a mixed response was observed for freshwater drum, and no change in movement was detected for largemouth bass or rainbow trout.

Underwater noise from MRE devices that overlap with fish hearing ranges and have high enough amplitude to be detected could also mask fish communication. Certain fish species create low-frequency sounds (e.g., drumming or stridulating) to find mates, and other behaviors important for survival and fitness (Rountree et al., 2002; Webb et al., 2008) that can be masked by anthropogenic noise (Ramcharitar and Popper, 2004). Buscaino et al. (2019) measured the noise before, during, and after the installation of a WEC in the Mediterranean. Noise was greater after device installation when the WEC was producing power, although the frequencies of the highest amplitude noise varied. At 40 m range, local fish choruses (likely communication sounds from *Scorpaenidae* sp. or *Terpontidae* sp. fish) may have been masked by noise from the WEC when generating power during wave heights of 2.2 m. For comparison, the authors pointed out that a passing vessel recorded at the site was louder than the WEC at all frequencies above 100 Hz (Buscaino et al., 2019).

#### 3.2.3. *Underwater noise thresholds for fish*

In the United States (U.S.), the behavioral threshold currently applied by the National Marine Fisheries Service (NMFS) is 150 dB μPa at 1 m root mean square (Stadler and Woodbury, 2009; Tetra Tech Inc., 2013). A simple practical spreading attenuation equation allows for calculation of the range at which the amplitude values measured *in situ* decrease below the current behavioral threshold (NMFS, 2012), providing the distance past which no behavioral effect on fish would be expected.

More recent interim guidelines are described by Popper et al. (2014), using a subjective approach (where appropriate) to define the relative range from a noise source and relative risk for different groups of fish. These guidelines recommend separate groups for categorizing hearing capabilities: fish with and without swim bladders that are sensitive to particle motion only, and fish with swim bladders that are sensitive mostly to sound pressure. While most underwater noise studies quantify sound pressure for understanding the effects of noise on fish behavior (Hawkins and Popper, 2017), prioritizing particle motion research (i.e., developing affordable technologies to quantify particle motion, establishing measurement standards and metrics) and establishing sound exposure criteria for particle motion (Popper and Hawkins, 2018) are required if the best science is to contribute toward setting realistic and meaningful noise thresholds in the future.

### 3.3. *Electromagnetic fields*

Power generated by instream tidal turbines and WECs must be transmitted to shore, or to other uses at sea, through power cables. While power cables running along the seabed and (to some extent) in the water column can be shielded to contain the electrical field, shielding does not prevent magnetic fields or the potential for induced electrical fields. Although only certain fish species have the sensory apparatus to detect EMFs, those that live in close proximity to seabed cables (demersal fish and those that hunt at depth such as some elasmobranchs) may be exposed to EMFs (Gill and Desender, 2020). Pelagic fish may have some minimal exposure as they swim past cables running from surface MRE devices to the seabed, or cables draped in the water column between devices.

The earth's magnetic field naturally produces EMFs, as do other natural sources such as lightning. Cables emitting EMFs have been prevalent in the oceans for many decades, including cables carrying power to offshore islands from mainland grids, telecommunications cables, and cables from offshore platforms for oil and gas production (EPRI, 2013; Meißner et al., 2006). In addition to cables, MRE-associated EMFs in the ocean are produced by offshore substations where multiple power cables converge, and to a small extent, by the movement of operational systems such as rotating turbine blades. EMFs are made up of two components: the electric field (E-field) and the magnetic field (B-field). While the electric field can be shielded and is not transmitted through seawater, the magnetic field continues to reach the marine environment through water or sediment. In addition, an induced electric field (iE-field) is generated with movement through the magnetic field, by water currents or movements of an animal.

With the advent of offshore renewable energy, increased focus has been placed on the potential effects of EMFs on marine biota. Studies that examine EMF emissions from offshore wind power cables started in the 2000s as this new power source was installed in Europe (Gill et al., 2009). As MRE technologies have progressed, regulators and stakeholders have expressed concerns about the potential deleterious levels of exposure for marine organisms, prompting a further increase in studies (Gill et al., 2014). Demersal and some pelagic fish, along with certain invertebrate species, have been the focus of most EMF studies associated with MRE or offshore wind development. Field studies of EMF effects have been carried out on some offshore energy export cables as well as surrogate power and telecom cables (Gill and Desender, 2020). Laboratory studies have informed the sensitivity of certain fish species, some of which are pertinent to MRE development, and modeling efforts have examined the likely emissions from MRE cables.

Fish have been shown to be sensitive to EMFs, based upon their orientation in the water column and prey location (Kirschvink, 1997; Tricas and New, 1997). However, it is generally accepted that the limited levels of EMFs from small numbers of MRE devices are unlikely to significantly affect fish (Gill et al., 2014). The species most commonly studied for EMF sensitivity include elasmobranchs (sharks, skates, and rays), agnatha (lampreys), and bony fish (teleosts and chondrosteans). The greatest likelihood of exposure of fish to MRE cables is thought to be for demersal fish that live near the seabed, in addition to sensitive life history stages from embryos to larvae, especially those with long incubation periods (Nyqvist et al., 2020).

#### 3.3.1. *Field studies*

Because few MRE devices are deployed worldwide, most field studies of EMF exposure have used energized cables or other surrogates for MRE power export cables. Two experimental mesocosms were developed in the United Kingdom to investigate the response from several species of fish and other marine organisms, using EMF levels comparable to those of offshore wind cables. Compared to the control mesocosm, the energized cable elicited a response from catsharks (*Scyliorhinus canicula*), which were attracted to the cable and slowed their swimming speed in its vicinity, and from thornback rays (*Raja clavate*), which increased their movement and hunting behavior in the vicinity of the cable (Gill et al., 2009). Other studies using energized cables showed changes in behavior, such as slower swimming speeds in the vicinity of the cable for European eels (Westerberg and Lagenfelt, 2008) and for sharks, salmonids, and sturgeon (Gill et al., 2014; Öhman et al., 2007).

A field study in the southeastern U.S. measured EMF emissions in the water column from live submarine cables. The investigators also monitored fish species, abundance, and presence/absence over a reef. No definitive changes were noted in abundance or behavior in a wide variety of reef fish species (Kilfoyle et al., 2018).

An experiment in San Francisco Bay (U.S.) examined the migration of Chinook salmon and green sturgeon (*A. medirostris*) across a 200 kV high-voltage direct current (HVDC) subsea cable. The salmon migration was found to be largely unchanged, although the patterns of movement indicated that the cable itself or other anthropogenic magnetic fields (e.g., those from large metal bridges) affected some changes in movement (Wyman et al., 2018). Similarly, green sturgeons were not found to significantly change their migratory patterns (Kavet et al., 2016). Little skates (*Leucoraja erinacea*) in Long Island Sound (U.S.) were shown to cross a 300 kV HVDC transmission cable but tended to show behavioral responses to the presence of the energized cable (Hutchison et al., 2020).

#### 3.3.2. *Laboratory studies*

Laboratory studies of EMF effects on fish have concentrated most commonly on developmental stages of freshwater fish, from embryos through larval stages, and have experimented with the effects of the B-field. The propagation of the B-field does not differ between freshwater and seawater, however the E-field and the iE-field are only present in seawater.

Laboratory studies that exposed rainbow trout eggs and larvae to static B-fields over a duration of 36 days did not show any effects on survival, time to eggs hatching, larval growth, or swimming ability, but the yolk sac absorption rate increased (Fey et al., 2019a). Smaller yolk sacs and faster absorption were also noted in Northern pike (*Esox lucius*) (Fey et al., 2019b). Another study noted that fish may hatch one day earlier in the presence of an EMF signal for common whitefish (*Coregonus lavaretus*) and vendace (*C. albula*) (Brysiewicz et al., 2017). Other developmental and physiological effects have been noted in the presence of EMF signals, including a decrease in the activity of intestinal enzymes, proteinases, and glycosidases in crucian carp (*Carassius carassius*) (Kuz'mina et al., 2015); changes in intracellular calcium ions in crucian carp, roach (*Rutilus rutilus*), and common carp (*Cyprinus carpio*) (Kantserova et al., 2017); and nuclear abnormalities in cells of rainbow trout (Stankevičiūtė et al., 2019). All these studies used B-field intensities in the range of millitesla, much higher than the micro- or nanotesla measured in the vicinity of underwater cables (Gill and Desender, 2020).

### 3.4. *Changes in habitats and fish aggregating devices*

All tidal turbines and WECs deployed to date require some connection to the seafloor, either through placement of a gravity foundation or with anchors embedded in the seabed. The benthic habitat directly under the foundation or anchor will be disturbed or removed, as will the habitat area along the run of the power export cable from devices to shore. Similarly, mooring lines and cables in the water column that connect the device to the seabed and/or transmit power from devices to shore will alter pelagic habitat. The presence of MRE devices and associated lines, floats, and other gear placed on the surface, subsurface, or seabed, may act as artificial reefs and FADs, attracting species of fish that seek shelter (Hemery, 2020). The presence of benthic organisms that colonize MRE system parts is likely to be an attractant to fish as a food source.

Whether MRE devices are seabed-mounted or floating, spanning part or all of the water column, they interact in some capacity with benthic and/or pelagic fish habitats. Apart from "ecological foundations" laid out at the Lysekil research site in Sweden without generators (Bender et al., 2020), no habitat studies have been conducted for the few multi-year MRE deployments that have taken place. However, some inferences can be made from short-term deployments and from surrogate industries (e.g., offshore wind, oil, and gas). Some effects, observed or expected, are thought to be harmful to fish habitats (e.g., alteration of spawning grounds during installation), but most are unlikely to cause harm and might even be considered beneficial, enhancing fish habitats and stocks (e.g., artificial reef effect).

Many benthic habitats in areas potentially targeted for MRE development have been recognized as being essential fish habitats, such as eelgrass beds (e.g., Lazzari, 2015), structure-forming coral and sponge systems (e.g., Miller et al., 2012), and rocky reefs (e.g., Paxton et al., 2017). Because it could harm spawning or nursery grounds, inappropriate siting within such habitats would be detrimental to many fish species, but such effects can be avoided with careful habitat characterization during a project's planning phase (Witt et al., 2012). When habitat loss cannot be avoided, it can be compensated by creating new habitat, such as transplanting eelgrass beds to a nearby location (Langhamer, 2012). The installation phase may also be detrimental to fish and their habitats, especially if transmission cables are buried in the sediment. Jetting and ploughing methods, commonly used to dig trenches and bury cables, rework and resuspend soft sediments. The resulting turbidity can persist for several days, limiting the light penetration and impacting the ability of fish to detect their prey (Taormina et al., 2018). Sediment resuspension may also release pollutants, such as heavy metals, hydrocarbons, and microplastics. Similarly, the decommissioning phase may resuspend sediments and pollutants and affect fish until the sediments settle back. Adverse effects on fish habitats during the operational phase of MRE devices are thought to be limited to the alteration of sedimentary and hydrodynamic regimes at different scales, which may become more prominent at larger scales of MRE arrays (Miller et al., 2013; Whiting and Chang, 2020). These changes in oceanographic systems could alter fish behavior and migration patterns, but they still remain to be observed.

Fish use all areas favorable to MRE deployments, but their usage varies depending on whether sites are wave-dominated or current-dominated. Demersal and pelagic fish often aggregate around new artificial structures. This common phenomenon is called the thigmotactic response, by which fish tend to "move toward structured rather than bare, featureless habitat" (Brickhill et al., 2005). Artificial reefs and FADs exploit this behavior to attract fish for either conservation or fisheries purposes. MRE devices, especially WECs and associated mooring systems, may act both as artificial reefs via structures laid on the seafloor, such as foundations and mooring anchors, and as FADs due to surface or mid-water structures, such as floating WECs (Bender et al., 2020; Callaway et al., 2017; Kramer et al., 2015; Langhamer and Wilhelmsson, 2009). However, a fundamental difference between MRE devices and artificial reefs or FADs is that the effect is only secondary for MRE devices, because they are not designed specifically with habitat enhancement effects in mind (Witt et al., 2012). Many man-made structures other than MRE devices act as artificial reefs: offshore wind turbines (e.g., Langhamer, 2012; Wilhelmsson et al., 2006), oil and gas platforms (e.g., Claisse et al., 2014), and shipwrecks (e.g., Arena et al., 2007). In addition, while non-buried cables without specific protections do not seem to attract more fish than the surrounding environment (Love et al., 2017), various fish species have been shown to aggregate around cable protections, such as rock dumping and concrete mattresses (Bicknell et al., 2019; Taormina et al., 2018). Not all fish are attracted by artificial structures (e.g., Langhamer et al., 2018), and the thigmotactic response may be species-specific. In contrast, instream energy devices may not attract fish as strongly as WECs because of the high flow velocity, which could prevent fish from detecting and/or aggregating around the structures. However, some attraction effect has been observed around tidal turbines during slack tide and low current speeds (<1 m/s; Broadhurst et al., 2014; Fraser et al., 2018; Williamson et al., 2019). These observations suggest an alternating FAD effect at tidal sites: during slack tide, fish may have more control over where they go, potentially aggregating around MRE devices as they might at wave energy sites and FADs in other locations; during peak flow in areas with strong currents, fish may have little control over where they go, and consequently may be less likely to intentionally aggregate around MRE structures.

In addition to providing attractive structure in otherwise structureless areas, MRE devices could also provide food for many fish species. A diversity of motile reef animals, especially fish, feed on the biofouling organisms and their litter falls on the surrounding seafloor, as observed around WEC foundations with cods, wrasses, and gunnels (Langhamer and Wilhelmsson, 2009). Demersal and pelagic fish of all sizes can then benefit from this abundance of prey and aggregate around the artificial reefs (Callaway et al., 2017; Coates et al., 2016). However, due to the strong flows in tidal channels, biofouling and litter falls may be minimal at tidal turbine sites, providing little food for fish and other motile organisms. MRE devices and their biofouling communities could also provide protection to many fish species, particularly juveniles and small species. Fish have been observed hiding in nooks and crannies in the foundations of WECs and instream turbines, and along wind turbines foundations and their scour protections and cable protections (Bicknell et al., 2019; Langhamer and Wilhelmsson, 2009; Wilhelmsson et al., 2006).

Because arrays of MRE devices will have several lines and cables extending past the devices themselves in the water column and on the seafloor, an exclusion zone is often implemented around devices to close the area to fishing activities to avoid entanglement, particularly from trawls, nets, or dredges (Bell et al., 2010; Inger et al., 2009). With the fishing pressure removed (or at least decreased), offshore energy developments may act as marine reserves or marine protected areas for species that have short mobility ranges, especially those targeted by recreational or commercial fisheries (Coates et al., 2016). However, the reserve effect may be limited for wide-ranging and highly migratory fish species, similar to what is observed in other marine protected areas (Breen et al., 2015). Numerical models have shown that the exclusion zone and reserve effect could lead to a general biomass increase in the system (Alexander et al., 2016; Raoux et al., 2017). In these models, most of the fish species preying on organisms known to aggregate on artificial structures saw a biomass increase. As a cascading effect, top predators also saw their biomass increase. Both models and field observations noted that the reserve effect may be felt beyond the fishery exclusion zone due to potential for spillover of fish away from the refugium, and become beneficial to local fisheries (Alexander et al., 2016). Yet, these effects are more likely to be observed at wave energy sites, which more closely resemble offshore wind sites with more resident fish populations. Tidal energy sites may see more transient and migratory fish passing through, and may therefore have a limited reserve effect.

### 3.5. *Displacement*

There have never been large numbers of MRE devices in the water, so the question of whether large arrays of turbines or WECs will create a barrier effect or displace fish from their preferred feeding, resting, nursery, or migratory habitats has not yet been investigated. However, as MRE deployments and commercial arrays become more common in the oceans, there may be a need to revisit this potential risk to fish.

Fish may become displaced from their preferred or essential habitats (i.e., foraging, mating, rearing, or nesting grounds) if the installation of arrays of MRE devices leads to a partial or complete loss of habitat. Similarly, an array of MRE devices placed in a line or large installation might cause a disturbance that acts as a barrier, causing resident fish to move away from the area and/or migratory fish to modify their routes (Copping et al., 2014). Many fish species migrate over various spatial and temporal scales, usually between breeding, feeding, and/or wintering sites (Dingle and Drake, 2007). Displacement of fish from their preferred habitats is likely to occur across much greater spatial and temporal scales than the avoidance behavior of individual fish or schools of fish when faced with an instream tidal or river turbine.

At present, there are no field studies that address displacement of fish from MRE arrays, due to the absence of large arrays operating. As the MRE industry moves toward commercialization, these studies may become pertinent.

Siting arrays of MRE devices away from migration corridors may be crucial to avoiding large-scale displacement of fish populations (Rothermel et al., 2020). As discussed in the previous sections, EMFs, underwater noise, or a combination of both have the potential to disturb fish or create barriers, which could displace them from their preferred habitats (Boehlert and Gill, 2010). While some fish have been shown to aggregate around the artificial structures that are WECs (Langhamer and Wilhelmsson, 2009) and potentially instream tidal turbines at low current speeds (Broadhurst et al., 2014; Fraser et al., 2018; Williamson et al., 2019), others have been found to show avoidance of tidal turbines (Bevelhimer et al., 2017; Grippo et al., 2017). This suggests that the potential for displacement of fish due to the presence of a small number of tidal turbines in high-flow areas may be low.

### 3.6. *Cumulative effects of MRE development and other anthropogenic stressors on fish*

With additional information being gathered about the potential effects of MRE devices on fish and fish populations, and the industry progressing from single devices to commercial-scale arrays of turbines or WECs, questions arise about how the additional stresses might act synergistically with existing and future anthropogenic activities. Many of the fish populations of concern around MRE devices, such as species of Pacific rockfish (*Sebastes* spp.), are those already under stress from fisheries, coastal development, and contamination in nearshore coastal areas (Levin et al., 2006), and they are often listed as (critically) endangered by the International Union for Conservation of Nature (Fig. 3). Effects of climate change have already caused shifts in fish distributions, which may bring species that have not been considered to be of concern into the range of MRE devices (Rijnsdorp et al., 2009). Activities such as the development and operation of offshore wind farms, oil and gas exploration and development, coastal and trans-oceanic shipping and cable laying, and the diversity of nearshore development that can affect migratory routes, nursery grounds, and essential fish habitats must be examined in conjunction with MRE stressors. These and other synergistic activities must be assessed to determine potential deleterious contributions that MRE stressors might have on fish. In addition, as MRE development moves forward, it will be important to consider the additive stresses that multiple MRE projects within a water body or stretch of coastline might have on fish populations, e.g., resulting in displacement.

## 4. Path forward

While there remains a great deal to understand about the threats to fishes from MRE devices, mitigation and management measures are under development to address known risks. This section reviews those measures and highlights key knowledge gaps.

### 4.1. *Mitigation measures*

As the MRE industry moves forward with pilot and demonstration deployments of individual MRE devices and early commercial arrays, plans for mitigating risks to the environment will be investigated. Because collision with turbines is generally seen as the greatest risk to fish, measures that might reduce the risk for fish and other animals have been considered (Copping, 2018). While some attempts have been made to slow or stop turbine blade rotation in the presence of marine mammals (Keenan et al., 2011), these measures are technically difficult and may cause damage to the MRE devices. However, considerable efforts are being made to observe and monitor potential interactions of instream turbines with fish. Effective mitigation strategies will be supported by improved understanding of encounter rates and interactions of fish with turbines. Mitigation of acoustic outputs from WECs and instream turbines has not been attempted to date, but efforts are underway internationally to measure the operational acoustic output of the devices, and to compare those outputs with regulatory guidelines (IEC, 2019; Tetra Tech Inc., 2013). EMF emissions are not easily mitigated

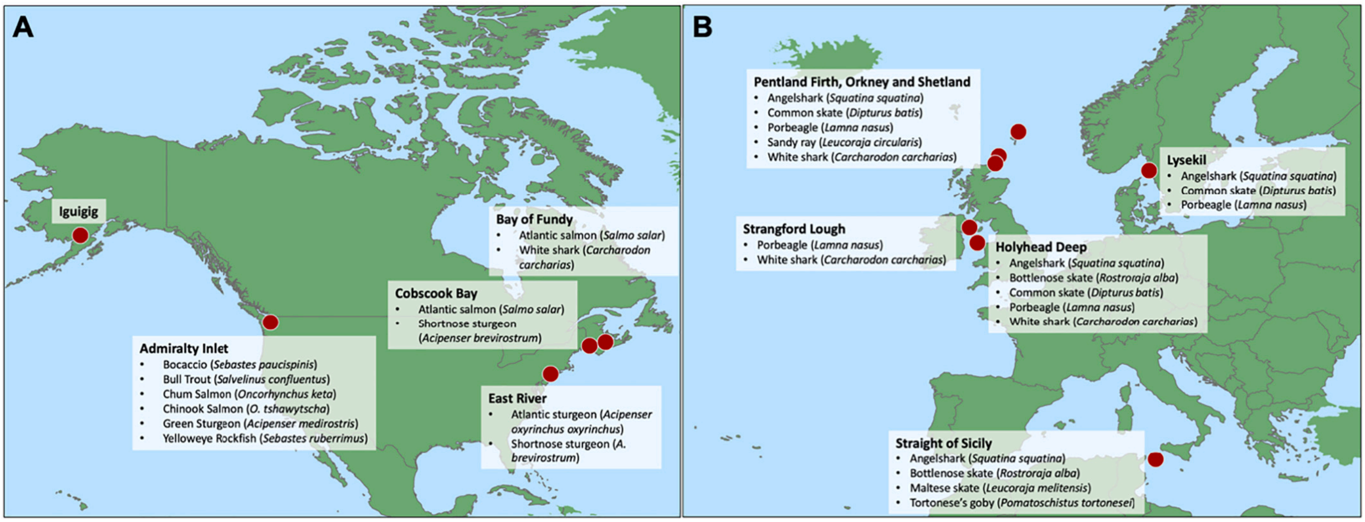

**Fig. 3.** Critically endangered and endemic endangered fish species (as listed by the International Union for Conservation of Nature [IUCN]) at the marine renewable energy sites in North America (A) and Europe (B) mentioned in the present study. Species of concern not listed by the IUCN (e.g., Striped bass in the Bay of Fundy (*Morone saxatilis*), Sockeye salmon at Igiugig (*Oncorhynchus nerka*)) were omitted from the figure.

because cables emit EMFs into the environment directly as B-fields and create iE-fields in the seawater. In addition, there are no regulatory standards to determine acceptable levels of EMF in the ocean. Cable burial does, however, separate most demersal and benthic animals from the maximum EMF emissions at the cable surface, owing to the physical distance between the seabed surface and the cable (Gill et al., 2014). Mitigation for loss or alteration of benthic or pelagic habitat has generally not been considered, but projects are usually carefully sited to avoid rare and fragile habitats such as rocky reefs within expanses of soft-bottom habitat, eelgrass beds, or deep-sea corals and sponges (Copping, 2018).

### *4.2. Management of MRE development*

A number of management approaches are being used to address the need to site, permit, monitor, and, where necessary, mitigate MRE development. Three of the most commonly used measures, which are not unique to MRE, are described here, each operating individually or in combination with the others as well as with more standard management approaches such as the precautionary principle.

Marine spatial planning (MSP) is a process used to balance the needs of marine users and uses and has been effectively implemented in other marine resource development (Ehler, 2008). In Europe and parts of Asia, and to a lesser extent in North America and Australia, MSP has taken into account the needs and restrictions associated with MRE development. Although MSP has not been adopted widely, there is considerable interest worldwide in refining the processes to manage offshore renewable energy development (ETIP Ocean, 2020; O'Hagan, 2020).

Adaptive management (AM) is a process sometimes stated as “learning by doing” that allows for greater flexibility in managing natural resources (Williams, 2011). AM approaches have been encouraged in many nations as a means of managing permitting processes for MRE projects, allowing all parties to decrease the uncertainty associated with effects and to manage the high cost of collecting relevant information around MRE devices. These measures often are noted in agreements between MRE developers and regulators, sometimes involving other interested parties, that manage the process of post-installation monitoring and use the data collected to guide future actions (Jansujwicz and Johnson, 2015).

Risk retirement (RR) is an organized method of making existing datasets of MRE effects widely available to support siting, permitting, and monitoring, and applying a consistent process for assessing the information (Copping et al., 2020). The concept behind RR is that new studies of each interaction may not be needed for every deployment of an MRE device, but all parties can rely instead on established studies and datasets (Copping et al., 2020). RR will not take the place of any existing regulatory or management actions in any jurisdiction, but by bringing consistency and available datasets to bear, the length of time and cost of permitting processes might be lowered.

### *4.3. Key knowledge gaps*

Considerable uncertainty remains around the various stressors discussed in this paper, and understanding how they interact with fish (individuals to populations) will require targeted research and likely a number of years of monitoring data collected around operational MRE devices. The greatest obstacle to understanding MRE device effects on fish is a lack of empirical information, both on the biological context of MRE devices (e.g., how fish use MRE sites, pre- and post-device deployment) and on the MRE devices themselves. Metrics of fish presence and distribution at MRE sites are highly variable but appear to be correlated to environmental factors, including hydrodynamics and tidal, diel, and seasonal cycles. The biophysical linkages that drive these correlations are poorly understood and require ongoing research. Without a good understanding of the species and life stages of fish located in areas suitable for MRE development, and the processes driving their presence and distribution, our ability to predict how MRE devices might affect fish is limited. Although there is a need to move toward tracking key biological metrics over time to detect effects of MRE devices (e.g., with before-after-control-impact or other strategies), few such studies have been undertaken to date. This is partially due to operational challenges, and partially due to deployments being scarce, of short duration (e.g., a few months or less, with devices not always fully operational for that time), and logistically difficult to align with biological study designs and methods. The high-energy locations where MRE projects are sited challenge our ability to gather this necessary baseline information, and to monitor MRE device effects post-deployment. The emerging instruments and platforms used to examine MRE sites will continue to require significant modification for survivability and adequate data collection in these unique environments (Hasselman et al., 2020).

Collision risk remains the most uncertain of the stressor interactions with fish. Regulators and stakeholders appear to face this uncertainty by assuming that fish will be routinely killed by instream tidal and river turbines, putting endangered and stressed fish populations further at risk (Sparling et al., 2020). Prior to 2018, underwater noise from MRE devices was considered a high risk to fish, but development of an international standard for measuring noise from MRE devices (IEC, 2019) and guidance on acceptable levels of underwater noise for fish in the U. S. (Popper et al., 2014) has helped chart a path forward to decreasing concerns about this risk. EMFs are becoming accepted as being of relatively low risk at MRE power-generation levels, and changes in the habitat and aggregation of fish around MRE structures are in many cases considered comparable to what has already been well documented at other offshore developments (Kramer et al., 2015). Displacement of fish populations has not yet been evaluated.

The most important areas for investigation of potential effects on fish from MRE devices are delineated for each stressor in Table 2.

The lack of technology convergence around MRE devices (particularly WECs; Fig. 1) continues to challenge our ability to estimate how the physical, acoustic, and electrical aspects of the devices might interact with fish. At this time, each type or configuration of MRE device must be evaluated individually to determine how its characteristics relate to different fish species' and life stages' sensitivities (e.g., to sound and EMF), which may additionally be modified by local environmental conditions, including high flow, turbulence, and noisy ocean and river conditions. Behavioral responses are additionally likely to vary by fish species, life stage, and motivation (migration, feeding, spawning, etc.), and to be affected by environmental factors (such as physical forcing by strong currents). Though some observations of fish responses to deployed MRE devices have suggested avoidance due to visual, acoustic, and/or hydrodynamic cues, we have not yet determined the specific stressors responsible for the behavior, nor their relative importance. Laboratory environments may be well suited to defining particular stimulus-response relationships but must be scaled carefully to be indicative of field conditions.

As more data are gathered to address these knowledge gaps, modeling approaches will become increasingly essential for linking datasets, scaling effects from individual to population levels, and tying impacts on fish into larger ecosystem processes. Validation with empirical observations is a major obstacle for existing modeling endeavors, and incorporating disparate datasets across wide-ranging scales, collection methods, and technologies will also require innovative modeling approaches. In addition, a set of commonly accepted management practices could help standardize how we measure effects on fish, and determine the significance of these effects on fish populations. For example, efforts by the international collaboration OES-Environmental have developed methods for applying datasets from licensed MRE projects to new MRE applications (OES-E, 2021).

**Table 2**
Key knowledge gaps for understanding potential risks to fish from marine renewable energy development, arranged by stressor-receptor interaction.

| Stressor-receptor interaction | Key knowledge gaps |
|---|---|
| Collision risk | • Fish use of the environments targeted for marine renewable energy (MRE) development (e.g., fast tidal currents, large waves), and likelihood for interacting with devices or arrays.<br>• Fish sensory and motor abilities, modified by MRE environmental conditions (e.g., noisy or highly turbulent environments).<br>• Collision risk models that accurately reproduce the close interactions and collisions of fish with turbines.<br>• Optical and active acoustic observations that document close encounters and collisions for model validation.<br>• Accurate population assessments and methods of monitoring endangered fish to determine risk to species from individual collisions. |
| Underwater noise | • Measurements of underwater noise from operational MRE devices to determine if they exceed recommended noise levels for harm to fish.<br>• Ambient noise measurements in MRE areas to determine whether device noise exceeds or adds to the background levels.<br>• Improved sound propagation models that simulate sound spreading from devices in high-energy waters.<br>• Measurements and standards for particle motion as well as sound pressure for full context of fish reception of sound. |
| Electromagnetic fields | • Measurement of magnetic fields from specific power export cable configurations and power levels to estimate EMF exposure.<br>• Studies to determine which diadromous and marine fish species are EMF sensitive and may react to export cable signatures.<br>• Estimates of cumulative EMF effect levels that may cause harm to endangered fish. |
| Changes in habitat | • Determination of the spatial extent of habitat change that will affect populations of endangered demersal fish.<br>• Studies of potential beneficial effects on endangered fish populations from exclusion around MRE developments. |
| Displacement | • Models of displacement effect on endangered fish populations that examine mechanisms of displacement. |

## 5. Conclusion

Inquiry into the effects of MRE devices on fishes is in its infancy, and ongoing research is needed to ensure the health of fish populations while also facilitating the development of sustainable energy sources. The state of investigation and knowledge of effects of MRE devices on fish is such that focus is largely on developing and testing methods that can accurately observe and measure key interactions, as well as defining and decreasing the uncertainty of these effects (Hasselman et al., 2020; Sparling et al., 2020). Where possible, the results of these studies have indicated the most likely effects and pinpointed the necessary next steps for filling remaining knowledge gaps. Some studies described here have focused on the abundance, diversity, and distribution of fish at MRE sites, but they all highlight the difficulty of carrying out surveys in highly energetic marine environments and the need to adapt standard data collection and processing approaches to these areas of the ocean (e.g., Fraser et al., 2017; Viehman et al., 2015).

Marine and diadromous fish populations are likely to be strongly affected by ocean warming, changes in coastal watershed precipitation patterns, ocean acidification, and other aspects of the changing climate (Rijnsdorp et al., 2009). With the anticipated increase in MRE deployments around the world, there will be a need to anticipate how fish populations and critical habitats will be affected under climate change scenarios, and how the effects of MRE deployment and operation will cumulatively interact with other anthropogenic activities in the oceans and coastal regions.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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