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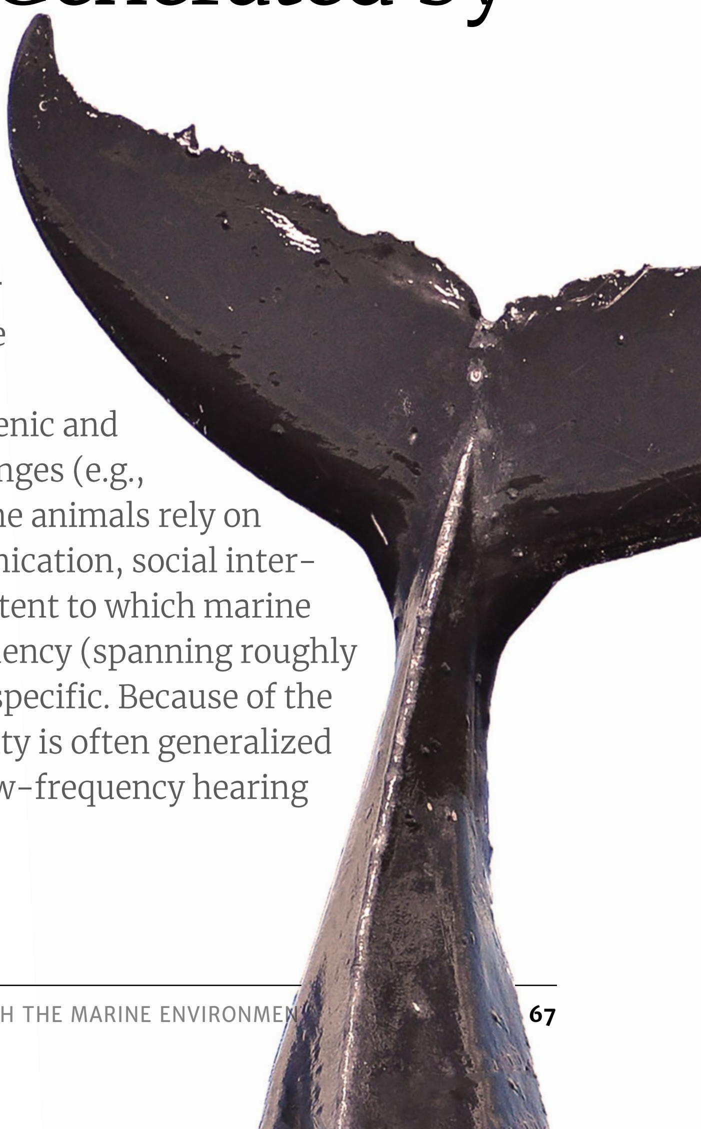
Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices



In all ocean environments, desirable locations for wave and tidal energy development have multiple natural sources of sound (e.g., waves, wind, and sediment transport), varying levels of anthropogenic and biological noise, and measurement quality challenges (e.g., flow-noise, self-noise) (Wenz 1962). Many marine animals rely on sound for biological functions, including communication, social interaction, orientation, foraging, and evasion. The extent to which marine animals detect and produce sound varies by frequency (spanning roughly four decades from 10 Hz to 100 kHz) and is taxa-specific. Because of the relatively limited data available, hearing sensitivity is often generalized to taxonomic groups (e.g., cetaceans that have low-frequency hearing specialization) (NMFS 2018).

When considering the risks to marine animals that result from any anthropogenic activity, one must consider the amplitude, frequency, and directionality of the noise source, as well as propagation losses, prevailing ambient noise, hearing thresholds, and possible behavioral responses (Figure 4.1). Measurements that support any of these individual topics can be difficult to obtain, but it is not feasible to quantify risks without first adequately constraining these factors.

As with other marine industries, there is a general interest in understanding the noise radiated by marine renewable energy (MRE) devices and whether this noise has implications for marine animals that inhabit areas in which MRE development could occur. This chapter focuses on new knowledge related to noise produced by MRE devices that has been published since 2016. While the acoustic footprint of construction and maintenance activities (e.g., vessel traffic) can be considered in a comprehensive analysis of acoustic effects, the activities that potentially cause risk are not unique to MRE devices, are better characterized, and their effects on marine animal behaviors are better understood (e.g., Holt et al. 2009; Jensen et al. 2009; Lesage et al. 1999). In addition, construction and maintenance activities are of relatively short duration in comparison to MRE device operation. Consequently, we emphasize noise produced by MRE device operation. Further, while the importance of acoustic particle velocity to fishes is widely recognized (Popper and Hawkins 2018), we only discuss radiated noise in terms of acoustic pressure. This is because in the acoustic farfield, particle velocity can be directly related to acoustic pressure (i.e., for our area of interest, these are not independent quantities).

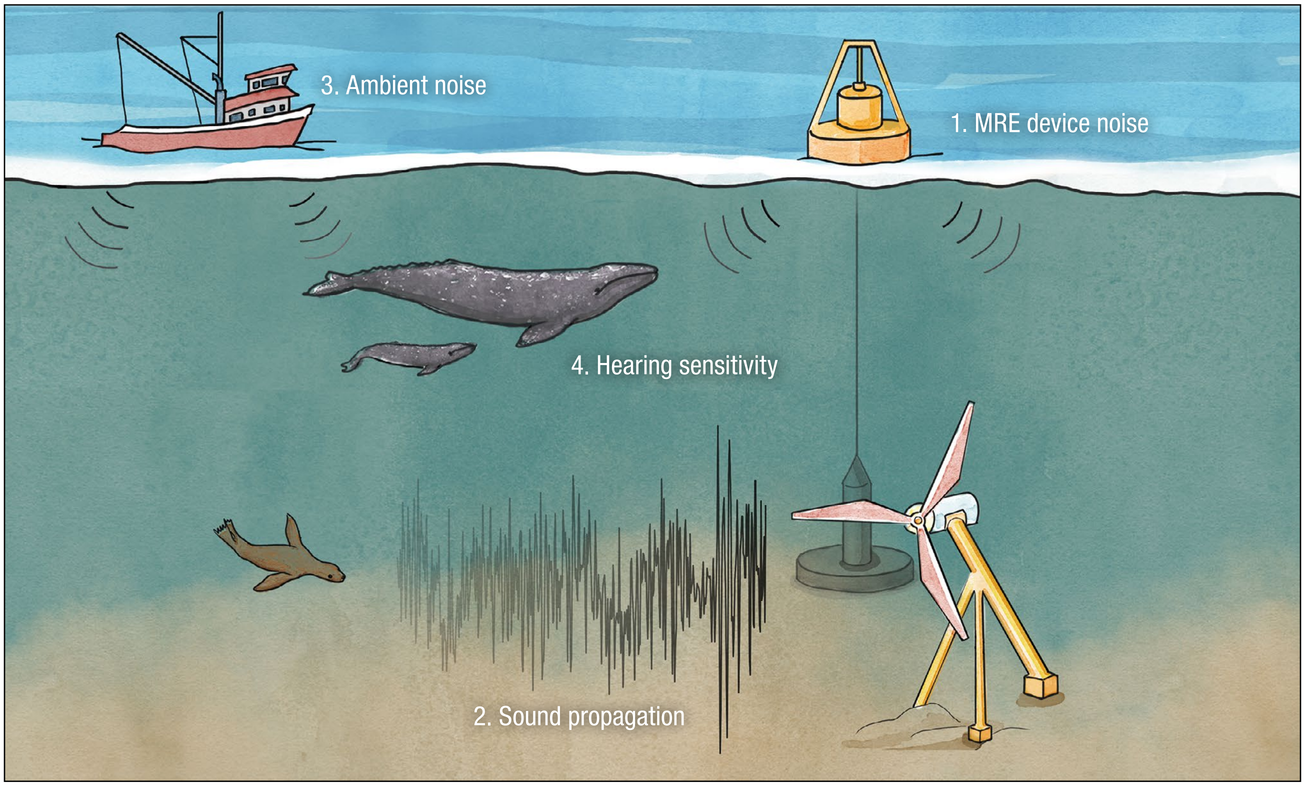


Figure 4.1. Determining the impact of radiated noise from marine energy converters is difficult and requires physical and biological inputs. (1) The sound produced by a marine renewable energy (MRE) device is affected by its design and is expected to vary with operating state. (2) As for other sources, sound radiated from MRE devices decreases in intensity as it propagates outward. The total decrease in sound intensity between a source and any location in space is affected by the frequency of the sound, water properties, bathymetry, and composition of the seabed. (3) An animal at some distance from the MRE device will receive both that sound and other ambient noise from natural, biological, and anthropogenic sources. If radiated MRE device noise is below ambient noise levels, then it cannot be detected by any marine animal and any biological response cannot be attributed to MRE device noise. (4) In addition, different marine animals have hearing sensitivities that vary both in frequency and intensity, making their abilities to detect or respond to a sound dependent on its characteristics. Consequently, even if MRE device noise exceeds ambient noise, it would still not be detectable if it is below a marine animal's hearing threshold. (Illustration by Rose Perry)

4.1.
IMPORTANCE OF THE ISSUE

Because sound is central to the way that many marine animals interact with their surroundings, and each other, the potential impacts of anthropogenic noise have received considerable attention. These impacts include auditory masking, stress, behavioral changes, and acoustic responses or injuries (Southall et al. 2007). Acoustic injuries resulting from noise exposure include temporary threshold shifts and, in extreme cases, barotrauma or death. Much of regulatory and research interest has been concerned about noise sources that are more pervasive (e.g., vessel traffic) and/or of higher amplitudes (e.g., seismic surveys), and these concerns have been extended to MRE devices (wave energy converters [WECs] and tidal, river, and ocean current turbines). Consequently, MRE device noise or its potential impacts have been the focus of multiple studies (e.g., Robinson and Lepper 2013).

Globally, the regulatory protections afforded to marine animals, particularly marine mammals (e.g., the Marine Mammal Protection Act [1972] in the United States [U.S.], the Marine Strategy Framework Directive [2008] and the Habitats Directive [1992] in the European Union [E.U.]) mandate that measures be taken to minimize any ecological impacts arising from emissions of anthropogenic underwater noise. As such, consideration of the potential impacts of MRE device noise is often required as part of the environmental assessments carried out in support of licensing processes related to MRE deployments. However, the outcomes of these requirements vary by region. In the U.S., this has included requirements for pre- and post-installation acoustic measurements around the majority of MRE deployments. In the E.U., acoustic measurements have also often been carried out but are optional, because the existing knowledge base has been sufficient to assess ecological impacts. Although significant uncertainties remain about the risks posed to marine animals by sounds generated by MRE devices, observations to date, which are summarized by Copping et al. (2016) and in the ensuing sections of this chapter, suggest that acoustic injury to marine animals from operational MRE device noise is unlikely. Further, acoustic injuries attributed to sound produced during installation are also unlikely, particularly if pile driving is not employed. While pile driving is a construction technique commonly used for offshore wind farms,[1] it is rarely used in the MRE sector and, unless device designs change considerably, this practice of rare use is unlikely to change.[2] However, radiated noise from operational MRE devices may be audible to some marine animals and could induce behavioral responses.

Because sound is one of several factors that affect animal behavior, it can be challenging to establish an *in situ* link between underwater noise and animal behavior. For example, establishing such a link has been difficult even for offshore wind (e.g., Bailey et al. 2010; Russell et al. 2016), which has been deployed at a much greater scale than MRE devices; for the acoustic effects of vessel traffic (e.g., Rolland et al. 2012), which occurs at a larger scale than any renewable energy generation in the ocean; and for seismic surveys (e.g., Przeslawski et al. 2018), which produce much higher-amplitude sound than any MRE devices. Consequently, most studies investigating the underwater noise effects of MRE deployments assess received sound levels at various distances from operating devices and compare these levels to ambient noise and/or animal hearing sensitivity as a proxy for potential behavioral responses. Because MRE device noise is radiated over a range of frequencies, knowledge of marine animal hearing sensitivity is important for establishing the context for radiated noise (Figure 4.2). As discussed in the following sections, a number of studies have found that MRE device noise only exceeds ambient noise at short distances from the source (e.g., <50 m). Under these conditions, it is unlikely that any observed *in situ* behavioral change could be attributed solely to radiated noise.

1. Pile driving involves applying impact or vibratory forces to large diameter metal piles to drive them into soft sediments. The forces applied to the pile cause sound to radiate directly from the pile, as well as secondary radiation through the sediment (Dahl et al. 2015). The pressure waves have high peak-to-peak amplitudes, which can cause acoustic injury to marine animals.

2. A number of tidal turbines use pile foundations, but they are embedded in gravity anchors or installed by drilling, which produces lower-amplitude sound than piling driving (Aquatera 2011).

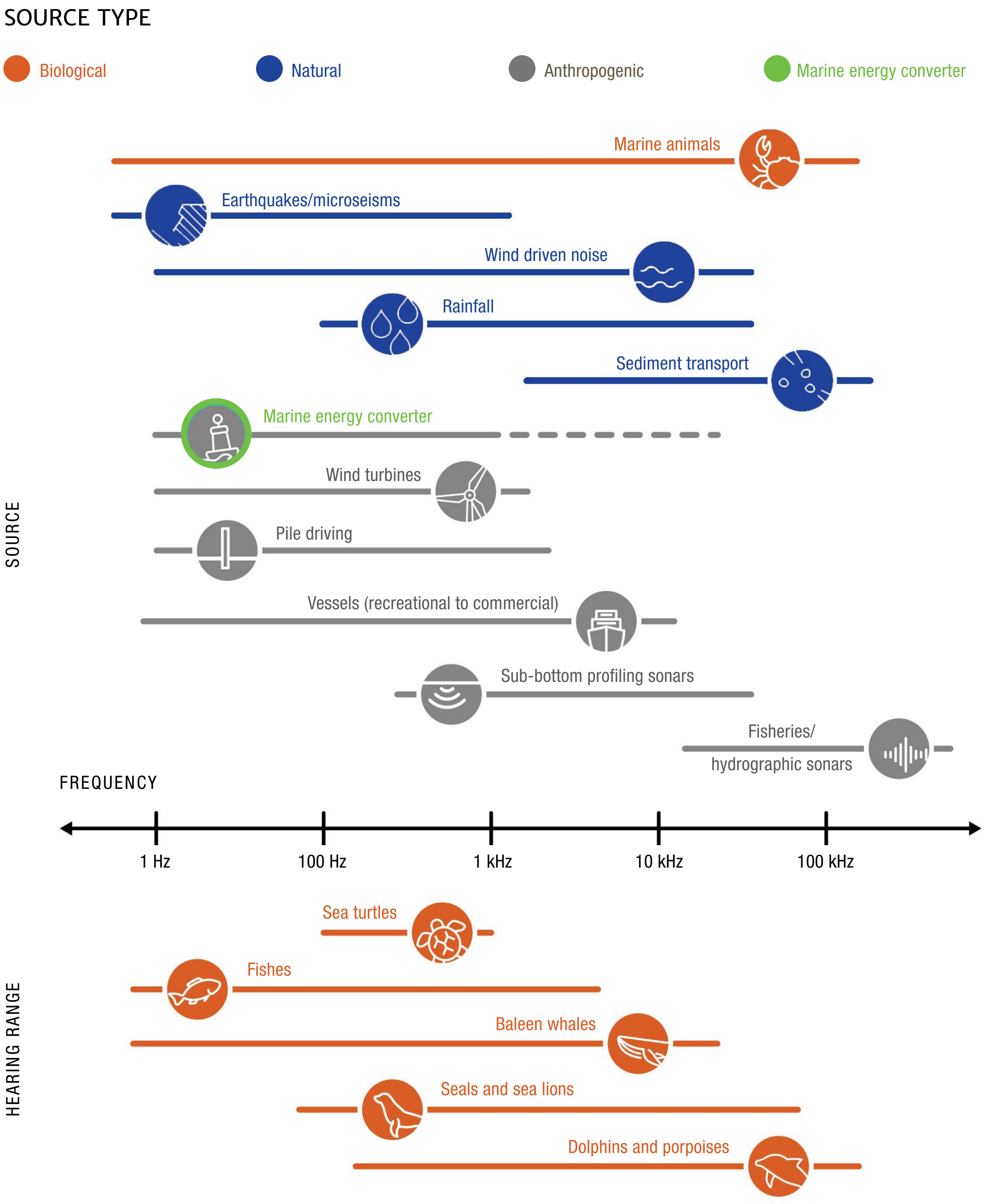


Figure 4.2. An overview of biological, natural physical, and anthropogenic noises in marine environments and the hearing ranges of marine animals. For sources, the horizontal bars denote the frequencies associated with the most energetic sound they generate. Many of these sources produce less energetic sound outside of the indicated range. 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. For hearing ranges, the horizontal bars correspond to the full range of frequencies likely audible to the groups of animals. Information used in this figure is drawn from resources including Discovery of Sound in the Sea (DOSITS) and similar figures, such as presented in Scholik-Schlomer (2015). (Illustration by Rose Perry)

4.2. SUMMARY OF KNOWLEDGE THROUGH 2016

By 2016, few studies or modeling efforts had been published that extended the knowledge of MRE device noise or its effects on marine animals. The *2016 State of the Science* report (Copping et al. 2016) addressed the effects of MRE device noise on marine wildlife described in systematic reviews, field studies, and modeling studies. The conclusions of each study varied slightly based upon its environment, marine animal presence, and proximity to coastal areas that had significant sources of other anthropogenic noise. However, all studies shared similar findings.

The first systematic review (Robinson and Lepper 2013) reported uncertainties (e.g., uncertainty in MRE device noise characteristics, marine animal response to this noise) similar to those of a contemporary report about the environmental effects of MRE (Copping et al. 2013). Even given these uncertainties, Robinson and Lepper (2013) concluded that MRE devices were unlikely to cause acoustic injury to marine animals (even during construction) and unlikely to cause behavioral effects at long distances. A second systematic review (Thomsen et al. 2015) concluded that operational MRE device noise was not of concern. Further, the authors concluded that acoustic injury as a result of underwater noise generated by MRE developments was unlikely, with the possible exception of cases where pile driving was used during construction.

In addition to these reviews, measurements of sound from individual MRE devices were conducted in several locations. Tougaard (2015), based on field measurements from the Danish coast of the North Sea, suggested that harbor seals (*Phoca vitulina*) were likely to be able to discern the noise from hydraulic pumps used during startup and shutdown for a WEC, but were unlikely to detect noise during normal operation. Similarly, Cruz et al. (2015) determined that the noise emitted by an oscillating surge WEC was minor compared to noise generated from other marine activities (e.g., sonars, ships, pile driving), but that such noise levels from WECs could elicit behavioral responses by certain cetaceans. Observations of a cross-flow tidal turbine suggested that some marine animals might detect the emitted sound, but behavioral modifications and acoustic injury were unlikely (ORPC 2014). Other studies measured radiated noise from WECs but did not draw conclusions about their potential environmental effects (Beharie and Side 2012; Lepper et al. 2012).

Modeling of radiated noise prior to 2016 was more limited. One modeling study indicated that a tidal turbine's peak noise level at 1 m would exceed hearing thresholds for some fish and marine mammals species, but that the noise levels would be unlikely to result in acoustic effects including hearing threshold shifts (Lloyd et al. 2014). Another modeling study reported that noise from a WEC could be audible to harbor seals at frequencies below 1 kHz and distances beyond 50 m (Ikpekha et al. 2014). Although this result appears to conflict with Tougaard (2015), different treatments of ambient noise account for this apparent inconsistency. Specifically, the simulations by Ikpekha et al. (2014) do not account for audibility with respect to ambient noise. When accounting for the ambient noise conditions reported by Tougaard (2015), these results are consistent and suggest the modeled WEC noise would not be audible to harbor seals, even at short ranges.

In aggregate, these studies support the assertion that underwater noise emitted by operational MRE devices is unlikely to cause acoustic injury to marine animals (Copping et al. 2013; Cruz et al. 2015; Haikonen et al. 2013; Lloyd et al. 2014; Robinson and Lepper 2013; Tougaard 2015). However, some studies suggest a possibility of behavioral responses (Cruz et al. 2015; Haikonen et al. 2013). Based on the available information at the time, Copping et al. (2016) identified the following challenges and targets for future work:

- Distinguishing an MRE device's noise from that of the ambient environment
- Establishing an international standard for measuring noise emitted by MRE devices
- Accurately modeling noise from an array of MRE devices using measurements from a single device
- Quantifying the direct and indirect effects of noise from MRE devices on animals
- Closing knowledge gaps related to hearing thresholds and threshold shifts in marine animals.

All of these challenges share features common to a variety of anthropogenic noise sources. Further, the last two items above are broad-ranging and not possible for the MRE community to address in isolation.

4.3. KNOWLEDGE GENERATED SINCE 2016

Since 2016, limited progress has been made in some of the five challenging areas targeted above. First, robustly distinguishing MRE device sound from ambient noise remains a challenge. Second, no significant attempts have been made to model arrays with high fidelity, but few arrays exist against which models can be benchmarked. Such modeling efforts require reliable acoustic source and environmental parameters (e.g., sound velocity variations in water and sediments), which are often not available when taking measurements around MRE devices or at potential deployment sites for arrays. Third, as discussed below, quantification of direct and indirect effects on marine animals has been challenging because of the limited number of MRE device deployments, large device-to-device variations in radiated noise, and the inherent difficulty of quantifying behavioral responses.

On a more progressive note, several advances have been made in understanding marine animal hearing thresholds and shifts, including updated regulatory guidance for the U.S. about appropriate weighting functions for different marine mammal hearing groups (NMFS 2018). In addition, under the auspices of the International Electrotechnical Commission (IEC) Technical Committee 114 (TC 114), an international consensus Technical Specification has been published, which lays out a standardized approach to characterizing radiated noise around MRE devices (IEC 2019). More significantly, several MRE devices have been characterized in the field and a few studies have made progress toward establishing links between radiated noise and behavioral responses. As for studies published prior to 2016, none of them suggest that radiated noise from MRE device operation is likely to cause acoustic injury.

The following subsections summarize advances in MRE device measurements, biological consequences, and measurement standards. These discussions include brief notes about methodology and key findings, but do not fully review the work; hence, readers are encouraged to consult the primary sources. The acoustic terminology used in the papers cited in this chapter is summarized in Box 4.1.

BOX 4.1.

ACOUSTIC TERMINOLOGY

In this chapter "received levels" correspond to radiated noise from an acoustic source that would be detected by a receiver (hydrophone or marine animal) at some distance away. A particular case of received levels is the "source level," which corresponds to received levels at a reference distance of 1 m from the sound source. Source levels are used in combination with propagation modeling to estimate received levels at greater distances. Other terms are described in the table below and in the online supplementary material (accessible at *https://tethys.pnnl.gov/state-of-the-science-2020-supplementary-underwater-noise*), and additional mathematical detail is included in the International Organization for Standardization (2016) terminology list and the IEC (2019) Technical Specification. For readers unfamiliar with the subject matter and standard nomenclature, many high-quality resources provide introductory material. Two recommended sources are the *Discovery of Sound in the Sea* website (*www.dosits.org*) and United Kingdom National Physical Laboratory's Good Practice Guide No. 133 (Robinson et al. 2014). For two reasons, it is important not to conflate received levels of radiated noise in water with those in air. First, the decibel scales in water and air use different reference values, so they are not directly comparable (Dahl et al. 2007). Second, because marine animal hearing is significantly different than human hearing, marine animal perception of underwater sound is considerably different than human perception of in-air sound.

Terminology	Description	Units
Sound pressure spectral density level	Sound pressure associated with a particular frequency presented with a bandwidth of 1 Hz.	dB re 1 μPa^2/Hz
Decidecade sound pressure level (decidecade SPL)	The sound pressure level (SPL) in a decidecade (one-third octave) band.	dB re 1 μPa
Broadband sound pressure level (broadband SPL)	SPL across a range of frequencies. The associated frequencies must be specified. If calculated over all measured frequencies, this is equal to the root mean square (RMS) SPL.	dB re 1 μPa
Source level	A measure of sound radiated by a source defined as the sound pressure level at a reference distance of 1 m. The associated frequencies must be specified.	dB re 1 μPa at 1 m

4.3.1. TIDAL, OCEAN, AND RIVER CURRENT TURBINES

Lossent et al. (2018) measured radiated noise from a tidal turbine and estimated its audibility for marine mammals. The authors used a drifting hydrophone (see Chapter 10, Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines) to measure radiated noise from an OpenHydro tidal turbine (axial-flow, high solidity) deployed in the English Channel (Brittany, France) at distances between 100 and 2400 m. Turbine source levels were estimated from regressions of spatially binned averages of decidecade sound pressure level (SPL). These source levels were then used with ray tracing and parabolic equation modeling to estimate the distance at which received levels would exceed relatively low levels of ambient noise typical of the open ocean, and would exceed audibility thresholds for different species. The maximum source level estimated by Lossent et al. (2018) was 152 dB re 1 µPa at 1 m in the 128 Hz decidecade band, and all other decidecade source levels fell below 137 dB re 1 µPa at 1 m. The authors noted broadband components of radiated noise at frequencies from approximately 40 to 8000 Hz, with amplitude modulations related to the turbine rotation rate. Multiple tonal components of noise were also noted between 20 and 1300 Hz. Measurements suggested the source is omnidirectional. On the basis of acoustic modeling, the authors estimated that radiated noise would exceed ambient noise at distances up to 1.5 km. When combined with hearing thresholds, maximum estimated marine mammal detection ranges were approximately 1 km.

The results presented by Lossent et al. (2018) highlight some of the challenges of separating ambient noise from radiated MRE device noise, particularly as a function of distance from the assumed source. Clear MRE device signatures attributed to the turbine were present at relatively close ranges but had low signal-to-noise ratios relative to ambient noise farther from the device. At some frequencies, regressions for propagation losses appeared to have coefficients that were inconsistent with expected range-dependent spreading and attenuation losses (e.g., cylindrical or spherical spreading), suggesting that some of this noise should not be attributed to the turbine. Consequently, for some frequencies, source levels may be biased high because of a conflation of ambient noise and radiated noise from the turbine. Direct comparisons to site-specific ambient noise, rather than literature values for relatively quiet, open ocean conditions, would better support conclusions regarding audibility ranges. While a number of statements were made regarding behavioral changes and avoidance, no direct measurements of animal behavior were made in the study.

Schmitt et al. (2018) measured radiated noise from a tidal turbine and correlated noise with operating conditions. Measurements of a ¼-scale Minesto AB subsea kite equipped with an axial-flow turbine were presented in the study. In this work, a drifting hydrophone was used to measure sound from the MRE device operating in Strangford Narrows (Northern Ireland, United Kingdom [UK]) during a period when currents were constant at approximately 1 m/s. Measured decidecade SPLs were reported for three operating conditions involving different turbine shaft speeds, kite velocities, and tether twists. Decidecade SPLs for all cases were based on average levels from 15 seconds before and 15 seconds after the hydrophone passed directly above the center of the kite's flight path (i.e., within 15 m of the kite). Given the uncertainty of the specific location of the kite, results are presented as the mean received levels over the sampling period, and multiple samples were averaged for each operational condition. Maximum decidecade SPLs reported by Schmitt et al. (2018) were less than 110 dB re 1 µPa at a frequency of approximately 300 Hz. Over much of the reported bandwidth (20 Hz to 100 kHz), observed decidecade SPLs were less than 95 dB re 1 µPa. For some operational conditions, clear modulation of the signal was observed and related to the kite's flight-path period. Results from the three measured operational conditions demonstrated that the largest differences in radiated noise were attributable to changes in the turbine speed (i.e., higher rotor speeds were correlated with increased noise levels). In comparison, changes in radiated noise due to tether twists or through-water kite speed were limited. Schmitt et al. (2018) made no attempt to address the potential biological consequences or audibility ranges of the device. Although source levels were not estimated, the distances from the hydrophone to the source in this study were on the order of tens of meters and may be considered a coarse proxy for source levels. Ambient noise levels from the site were used to contextualize radiated noise. This suggests that radiated noise from the kite exceeds ambient noise across most of the reported bandwidth at locations close to the source. However, ambient noise data were collected in 2014, while turbine measurements were obtained in 2016. Because of this temporal gap, there is some inherent uncertainty in the portions of the acoustic spectrum that were ascribed to radiated noise from the MRE device.

Risch et al. (2020) measured radiated noise from an Atlantis AR1500 tidal turbine (18 m diameter; 1.5 MW rated capacity) in Pentland Firth, Scotland (UK). The radiated noise measurements were obtained using drifting hydrophones at ranges up to approximately 2300 m, during which mean tidal currents ranged from 2.2 to 3.1 m/s. Measurements revealed that, when operating, the noise attributable to the turbine occurred primarily in the 50 to 1000 Hz range, although lower intensity device noise was observed above ambient conditions at higher and lower frequencies. Decidecade sound pressure levels showed increases of at least 30 to 40 dB relative to ambient noise for close range measurements (range less than 20 m). Turbine noise intensity increased with rotation rate, with 10 to 20 dB differences observed between the lowest and fastest rotation rates, but the frequency content was similar for all rotation rates. Broadband noise was observed at relatively short ranges (approximately 300 m or less), while, at greater ranges, observed noise was dominated by a series of oscillating tones from 100 to 2000 Hz. A high-frequency (20 kHz) narrowband tone was also identified, which was present when the turbine was in an operating mode, but did not vary with rotation rate. This noise was attributed by the authors to the generator, although no further details are provided to support this conclusion and it might be attributable to other, non-rotating system components (e.g., switching converters in power electronics). Noise increases of 5 dB or less were attributed to the turbine at ranges up to 2300 m during periods with relatively calm conditions. However, measurements suggest that beyond ranges of approximately 100 m, turbine noise is only observed above ambient noise for frequencies below 2 kHz. The biological implications for the observed variations in sound with rotational rate are briefly noted, but there is no formal analysis of detection ranges by marine animals.

Pine et al. (2019) estimated source spectral density levels from two turbines and evaluated the reduction in "listening space", a proxy for behavioral change, for harbor seals and harbor porpoises (*Phocoena phocoena*) in varying conditions of ambient noise. This study built on Schmitt et al.'s (2018) by combining source spectra for two MRE devices with seasonal ambient noise measurements and species audiograms to investigate the "listening space reduction" for harbor seals and harbor porpoises. Listening space is defined by the volume over which an animal can detect biologically relevant sound. Therefore, listening space reductions contextualize the regions of potential biological responses for the two marine mammal species. The two MRE devices considered were a tidal kite (Schmitt et al. 2018) and an axial-flow turbine (Schottel, characterized by Schmitt et al. 2015). In the case of the tidal kite, radiated noise measurements were converted to source levels using spherical spreading with the distances between the devices and the hydrophone at the closest point of approach (approximately 6 m). The ranges of ambient noise for summer and winter conditions were constrained by the 5th and 95th percentiles. Parabolic equation and ray tracing models were used to model propagation losses between the hypothetical turbines and receiver locations.

The results presented by Pine et al. (2019) demonstrate the importance of well-constrained source spectra, ambient noise levels, and species audiograms. Different patterns were present in the listening space reductions across species, seasons, and turbine types. These patterns were attributed to the relative distributions of noise as a function of frequency in the source spectra and the audiograms of the species. As a proxy for behavioral effects, listening space is conservative in that relatively large reductions still occur when received levels from an MRE device are close to ambient levels. For example, when MRE device noise exceeds ambient levels by 1, 3, and 6 dB, the respective decreases in listening space are 26%, 60%, and 84% if a representative propagation loss coefficient of 15 is applied. In the context of the measured variability in ambient noise (30 dB within individual frequency bands), these are small changes and contribute to large, implicit uncertainties in estimates for listening space reduction. Further, the conservative nature of this approach is apparent when comparing it to Hastie et al.'s (2018) approach (discussed further later in this section), in which received levels that could be correlated with observed behavioral responses exceed the source level used by Pine et al.'s (2019) analysis. In other words, while the methodology underpinning the listening space reduction accounts for key variables, because a reduction in listening space will not necessarily lead to a behavioral response, this is likely an extremely conservative proxy for behavioral change. Nonetheless, this metric may be helpful for constraining the focus areas for studies attempting to observe behavioral changes as a consequence of exposure to radiated noise from MRE devices.

Bevelhimer et al. (2016) compared measured ambient noise in a river to characteristics of turbine noise to estimate detection ranges for five fish species. Relatively few studies have considered ambient noise in rivers or the potential acoustic effects of MRE devices in riverine environments. Bevelhimer et al. (2016) compared measurements of ambient noise sources in the Mississippi River to measurements of the Ocean Renewable Power Company (ORPC) TidGen tidal turbine in Cobscook Bay, Maine. Other sources of anthropogenic ambient noise, namely different types of vessels, were noted to be of higher amplitude than the TidGen turbine. Finally, Bevelhimer et al. (2016) compared the TidGen spectrum to audiograms for five fish species, noting that the turbine noise should fall below all of their reported hearing thresholds at a distance of 21 m from the source.

4.3.2. WAVE ENERGY CONVERTERS

A limited number of new studies of noise generated by WECs have been published since 2016, but they include a study of one WEC, the Fred Olsen Lifesaver, a point absorber, which was characterized at two locations using different methodologies.

Walsh et al. (2017) measured radiated noise from the Lifesaver, during a 2-year test at the FabTest test site in Falmouth Bay, UK. The objective of the study was to evaluate the feasibility of using hydrophones at a relatively large stand-off distance from a WEC (200 m) to monitor its physical condition. No attempt was made to study the potential effects of radiated noise on marine animal behavior. Measurements were conducted using moored hydrophones at a distance of 10 m above the seabed in water depths of 25 to 45 m. Results are presented for frequencies from 10 Hz to 32 kHz. Consistent with prior studies (e.g., Robinson and Lepper 2013), because of vessel traffic, received levels were higher during installation than during operation. On average, at a 200 m distance, the WEC was undetectable in a statistical sense (i.e., deviations of, at most, 1 dB between times of WEC operation and non-operation). However, the results of a focused examination of WEC-attributed sound during periods of low ambient noise suggest a primary contribution from tonal sound at 30 Hz, 60 Hz, 80 Hz, and 100 Hz with received spectral density levels exceeding 100 dB re 1 µPa^2/Hz when the power take-off units were active, as well as periodic, intermittent sound at frequencies from 100 to 1000 Hz that were hypothesized to be a consequence of the power take-offs reaching their end stops. Because of the difficulty of definitively attributing sound to the WEC, the authors recommended that, in the future, multiple hydrophone recording systems be simultaneously deployed to localize WEC sound. A minor weakness of the Walsh et al. (2017) study was that underwater noise measurements were treated in a relatively qualitative manner, and it is not clear whether the presented information is received levels at the 200 m stand-off distance from the WEC or nominal acoustic source levels calculated using a simple propagation model.

Polagye et al. (2017) measured radiated noise from the same point-absorber WEC at a different location. After testing in Falmouth Bay, the Lifesaver was redeployed at the U.S. Navy's Wave Energy Test Site (WETS) in Kaneohe, Hawaii, U.S. Two deployments were conducted between 2016 and 2019, one at the 60 m berth and one at the 30 m berth. Polagye et al. (2017) described outcomes from fixed platform measurements on the seabed at a distance of approximately 100 m and drifting measurements, primarily at closer range, for the deployment at the 60 m berth. Drifting measurements resolved frequencies from 10 Hz to 200 kHz and were used to attribute radiated noise to the WEC and its moorings based on co-temporal comparisons between measurements in close proximity to the WEC and a "reference" site at a distance of 1200 m from the WEC. In addition to sound consistent with the power take-off reported by Walsh et al. (2017) (i.e., periodic tonal elevation from 30 Hz to 1 kHz), multiple intermittent sounds associated with the WEC or its mooring were detected at frequencies up to 200 kHz, and the highest frequencies were associated with impact noise from a failing mooring chain. At a distance of 35 m from the

WEC, the sound attributed to the power take-off had a pressure spectral density level that was approximately flat from 50 Hz to 300 Hz at ~85 dB re 1 μPa²/Hz, and declined to 70 dB re 1 μPa²/Hz at 1 kHz. All WEC and mooring sounds were detected in the fixed observations, albeit at lower amplitudes because of the greater distance between the source and the receiver. Variations in broadband (0 to 40 kHz) received SPLs as a function of wave height and period showed some dependence on sea state, but frequency-domain analysis demonstrated that this was primarily a consequence of flow-noise from wave orbital velocities close to the seabed in the 0 to 10 Hz band, which exceeded radiated noise from the WEC (Polagye 2017). Broadband received SPLs at a range of 100 m were centered around 115 dB re 1μPa, and ranged from 105 to 125 dB re 1 μPa.

Similar methods were applied to the subsequent deployment of the Lifesaver at the 30 m berth (Polagye, pers. comm.). Drifting measurements again identified elevated sound attributed to the power take-off, but at a stand-off distance of 25 m with the power take-off disabled, received spectral levels of approximately 75 dB re 1 μPa²/Hz were still present around 60 Hz, and declined to approximately 65 dB re 1 μPa²/Hz at 1000 Hz. No WEC-attributable sound was identifiable above 1000 Hz.

The measurements at WETS are also indicative of the challenge of attributing sound to a particular component of the WEC using short-duration, single-hydrophone measurements. Specifically, Polagye et al. (2017) attributed a tonal "warble" with a fundamental frequency around 790 Hz to a failing bearing on one of the power take-off units. This diagnosis was consistent with the periodicity of the sound in this frequency band having a moderate correlation with wave period and mechanical wear observed on the power take-off during an engineering inspection. Between recovery from the 60 m berth and redeployment at the 30 m berth, the Lifesaver underwent minor maintenance and, therefore the absence of this sound in measurements at the 30 m berth was considered unremarkable. However, subsequent analysis of fixed observations (Polagye, pers. comm.) during recovery of the WEC from the 60 m berth found that the warble persisted even with the power take-offs being inactive, that this sound vanished when the WEC was removed from its moorings, and that the sound then returned after the moorings were re-tensioned without the WEC present. Consequently, this sound was actually attributable to the permanent moorings at the site, not the WEC. This forensic analysis also highlights the benefits of conducting relatively long-term acoustic measurements around a WEC, including during pre-installation, installation, operation, removal, and post-removal. Another tangential benefit of such long-term monitoring, as discussed by Walsh et al. (2017), is the potential for monitoring the mechanical health of MRE devices.

4.3.3. BIOLOGICAL CONSEQUENCES OF RADIATED NOISE

As previously discussed, all of the research published prior to 2016, as well as the studies of MRE device noise reviewed in this chapter, used sound detection as a proxy for biological consequence. Since 2016, several attempts, with varying success, have been made to directly observe the behavioral responses of various species to MRE device noise. These efforts have relied on "playbacks" of MRE device noise, which isolates underwater noise effects from other, potentially confounding, effects of device presence (e.g., accumulations of prey around an artificial reef).

Schram et al. (2017) used a mesocosm experiment to investigate the behavioral responses of four fish species to simulated tidal turbine noise. The authors exposed four species of freshwater fish to turbine sound in a mesocosm setting to evaluate changes in fish location as a consequence of sound amplitude and duration of exposure. One species (redhorse suckers [*Moxostoma carinatum*]) showed some response by increasing their distance from the sound source, while the three other species displayed either a mixed or limited response. The turbine sound was based on recordings of the ORPC TidGen tidal turbine (Bevelhimer et al. 2016). The authors noted several challenges associated with interpreting and generalizing their results. First, because of the limitations of the underwater speaker system, the frequency content of the playback departed from the original measurement. Specifically, the measured sound from the turbine had its highest amplitude at frequencies less than 0.3 kHz, but the playback had a relatively flat spectrum that peaked around 10 kHz. Consequently, fish behavioral changes were interpreted relative to the broadband SPLs that were not entirely consistent with the actual structure of turbine sound. Second, the acoustic localization system used to track the fish was primarily effective in the along-pen direction, while received levels varied in the across-pen direction, particularly close to the sound source. Overall, the authors concluded that a significant behavioral response would not likely be anticipated for either short-term or long-term exposures to turbine sound.

Hastie et al. (2018) used shore observers and tagging to demonstrate the behavioral response (localized avoidance) of harbor seals to simulated tidal turbine noise in a tidal channel. To assess behavioral changes and avoidance exhibited by harbor seals exposed to tidal turbine noise, the authors tagged and remotely observed harbor seals during exposures to simulated tidal turbine noise in Kyle Rhea, an energetic tidal channel on the west coast of Scotland, UK. They evaluated the behavioral response by comparing patterns in spatially resolved abundance between periods with simulated turbine sound (playback) and periods with only ambient noise (control). The playbacks were based on interpreted measurements from the SeaGen turbine (Strangford Lough, Northern Ireland, UK) and had a broadband (115 to 3750 Hz) source level of 175 dB re 1 µPa at 1 m. Hastie et al. (2018) reported no changes in total numbers of seals in the water in the study area (defined as the distance at which harbor seals could be observed in the 450 m wide channel) between the control and playback periods. However, usage decreased between 11 to 41 percent at distances of less than 500 m from the acoustic source. Given that no differences in overall abundance were noted, these results suggested localized avoidance without a broader-scale impact. The authors extensively discussed a number of issues related to their results. First, in comparison to other measured tidal turbines, the playback source levels were of relatively high amplitude. Second, the playback sound consisted of a series of seven frequency-modulated narrowband tones from 115 to 3750 Hz. These playbacks would be a novel stimulus for the seals and may have contributed to the observed avoidance behavior. Whether or not similar behavior would be observed with any combination of lower source levels, differences in frequency content, or greater levels of habituation are unknown. The tracking tags on the seals also only reported their positions, not the received sound level, so a quantitative dose-response analysis was not possible.

Robertson et al. (2018) used shore observers to quantify the behavioral response of harbor seals and harbor porpoises to simulated tidal turbine noise in a tidal channel (Admiralty Inlet, Washington, U.S., using a method similar to that of Hastie et al. (2018). Here, an amplified recording from the ORPC RivGen turbine (unpublished data) was used as a sound source and, as for the Hastie et al. (2018) effort, the study was partitioned into control and playback periods. Broadband (30 Hz to 10 kHz) source levels were 158 dB re 1 µPa at 1 m, which was lower than the source level used by Hastie et al. (2018) (175 dB re 1 µPa at 1 m), but substantially higher than the actual RivGen turbine. Unlike the Hastie et al. (2018) effort, harbor seals showed no measurable response to the simulated turbine sound. However, because of the lower source level, harbor seals would have needed to be within 10 m of the source to experience received levels similar to those correlated with localized avoidance by Hastie et al. (2018). The difference in geographic location and turbine sound signature may also have contributed to the apparent divergence in outcomes. Over the three seasonal playback trials (each two weeks in duration, divided between control and playback periods), harbor porpoises were found to initially avoid the playback source by 300 m, but this distance declined to 100 m during the second trial, and no avoidance was apparent during the third trial. This could be an indication of habituation or increased tolerance. However, because the vessel used to deploy the sound source was only present during the playback periods (for reasons of cost), it is uncertain whether the avoidance and potential habituation were in response to simulated turbine sound, survey vessel presence, or seasonal variations in harbor porpoise behavior.

4.3.4. PROGRESS ON MODELING

The availability of numerical modeling tools should be exploited, when helpful, to support the assessment of the underwater noise impacts of MRE devices. Farcas et al. (2016) summarized considerations related to their application and parameterization for environmental impact assessment. A recent modeling result of relevance for planning the installation and subsequent monitoring of MRE devices was published by Lin et al. (2019) and focused on the use of parabolic equation modeling for propagation losses at an offshore wind site. A key finding was that seasonal differences in the water properties (well-mixed vs. stratified) resulted in considerable differences in propagation losses because of a downward refracting sound speed profile. Such findings could be used to inform construction plans to mitigate potential impacts by exploiting time periods when depth-averaged propagation losses are expected to be at a maximum. Conversely, these findings could inform monitoring plans intended to observe biological responses when depth-integrated propagation losses are expected to be at a minimum, and therefore, the signal-to-noise ratio at a given distance could be maximized.

Since 2016, relatively little progress has been made with regard to the modeling of sound produced by MRE devices. Halfa et al. (2018) focused on the development of a temporal-domain, three-dimensional finite-element sound propagation model. This model, Paracousti, has been compared to multiple analytical and modeling approaches with favorable results and facilitates the integration of multiple acoustic sources. No other efforts have developed new models for MRE device noise or focused on the development of advanced tools for propagation modeling. It is, however, noteworthy that many of the studies highlighted here used models common in other underwater acoustics applications (e.g., parabolic equation modeling, ray tracing).

4.3.5. INTERNATIONAL STANDARDS

The IEC TC 114, which develops international consensus standards for marine energy conversion technologies, has published its first Technical Specification for characterizing radiated noise from MRE devices: IEC 62600-40 (IEC 2019). The specification, developed over a 4-year period with input from multiple National Committees (Canada, France, Germany, Ireland, Netherlands, Spain, UK, U.S.), describes methods for characterizing received levels in the vicinity of WECs, current turbines (tidal and river), and ocean thermal energy conversion (OTEC) plants. The specification incorporates many of the unique considerations for observations in MRE environments summarized by Lepper and Robinson (2016).

The specification establishes two levels of characterizations. Both use the same methods for measurement, analysis, and reporting, such that the types of characterization are differentiated only by the number of required measurements and the conclusions that can be supported. The "Level A" characterization is more extensive and evaluates temporal trends (e.g., correlation between received levels and wave height and period for WECs) and spatial variability (i.e., degree of directional variations in received levels). The "Level B" characterization provides a snapshot of received levels at a single temporal condition and spatial location. These two levels of characterization recognize that radiated noise from some MRE devices may not warrant a comprehensive characterization, but that more limited characterizations should be conducted in a consistent manner for comparability across projects. Effectively, a Level A characterization is a series of Level B characterizations conducted at several temporal conditions and spatial positions.

The Technical Specification includes end-to-end requirements for acoustic measurements, including the following:

- The capabilities of the acoustic measurement system and calibration requirements
- Contextual measurements (e.g., wave height and period around WECs, current speed around tidal turbines)
- Temporal conditions and spatial locations for measurements to meet Level A or Level B characterization for each category of MRE device (i.e., WEC, current turbine, or OTEC plant)
- Data review to exclude measurements with obvious contamination from other acoustic sources (e.g., vessel traffic)
- Analysis methods to reduce acoustic measurements to sound pressure density levels, decidecade SPLs, and broadband SPLs
- Requirements for reporting temporal and spatial variations in received levels.

Crucially, IEC 62600-40 implicitly attributes all sound in measurement sequences that satisfy data acceptance criteria to the MRE device. This approach was taken because no international consensus yet exists for objectively attributing radiated noise to an MRE device. As discussed later in this chapter, this is a critical research need and, as methods are matured, they should be incorporated into subsequent editions of IEC 62600-40.

By default, measurements are required to resolve frequencies from 10 Hz to 100 kHz, though there are allowances for expanding or contracting this frequency range as warranted by specific conditions and regulatory requirements. At the lower end of this range, flow-noise, which is non-propagating sound caused by water motion relative to a hydrophone, is a concern because it has the potential to artificially inflate decidecade and broadband SPLs. Flow-noise can arise from turbulence advected over the hydrophone element and vortices shed by the hydrophone element. Consequently, the specification includes recommendations to identify the probability of flow-noise in measurements and potential mechanisms to minimize flow-noise. While flow-noise is a well-documented issue for fixed platforms in tidal energy environments (e.g., Bassett et al. 2014), experience suggests that this can also be a concern for fixed platforms in wave energy environments when wave orbital velocities extend to hydrophone depths. For example, at WETS, flow-noise periodically masked propagating ambient noise at frequencies up to 50 Hz for a fixed hydrophone at the 30 m depth (Polagye et al. 2017). In general, accurate measurement of propagating sound at low frequencies (<50 Hz) is complicated by flow-noise masking and typical roll-offs in hydrophone sensitivity when higher frequencies (>10 kHz) are also of interest.

4.4. RESEARCH AND MONITORING NEEDS TO RESOLVE THE ISSUE

Of all the outstanding research and monitoring needs, the most critical undeveloped capability is differentiating between MRE device noise and ambient noise. Such differentiation is needed to establish the true acoustic characteristics of MRE devices and estimate received levels as a function of depth and range. Although source localization is widely used in ocean environments to localize radiated noise, it has not yet been used to discriminate between ambient noise and radiated MRE device noise (i.e., frequency-dependent localization of noise sources compared to known MRE device position). In the absence of localization capabilities, there is a risk that ambient noise or, worse, flow-noise, can be conflated with MRE device noise. In such cases, estimated source levels for sound propagation studies would be biased high and potentially overstate the acoustic footprint of operating MRE devices. This difficulty is compounded if ambient noise at some frequencies is driven by the same physical processes as MRE power generation. For example, as the current speed rises, the power output and rotation rate for most turbines increase, but depending on the site, the radiated noise from sediment transport (e.g., Bassett et al. 2013) also increases and can be mistaken for MRE device noise. Despite these challenges, attempting to distinguish radiated noise from ambient contributions, even when uncertainties remain, is an important step in the process of understanding the potential consequences of radiated noise from MRE devices.

The second research need is to connect radiated noise to behavioral changes in marine animals. If the radiated noise of an MRE device only marginally exceeds ambient noise at close range (e.g., <50 m), it is not practically possible to solely ascribe a behavioral response to radiated noise. For higher received levels, the link between radiated noise and animal behavior is a complicated one to establish and is best addressed by bioacoustic specialists. However, the broader acoustic research community can support such efforts in two important ways. The first is to present acoustic data in a frequency-resolved manner that allows species-specific audibility to be taken into account. While broadband SPLs can be helpful for comparisons across MRE devices, they are insufficient for biological interpretation. Second, as discussed above, when possible, differentiating between MRE device noise and ambient noise will facilitate biological interpretation. Overall, given the potential uncertainty related to acoustic sources, ambient noise, and species-specific audiograms, behavioral response studies are only likely to provide useful information if MRE device noise and ambient noise are well characterized.

4.5.
GUIDANCE ON MEASURING UNDERWATER NOISE FROM MRE DEVICES

IEC 62600-40 provides guidance for the measurement of underwater noise around MRE devices, including instrument calibration, methods for acoustic and contextual measurements, methods for data processing, and uniform presentation of results. However, in areas where international consensus does not yet exist, several considerations are not prescriptively addressed. First, as previously discussed, no method is given to differentiate between MRE device noise and ambient noise. Second, while flow-noise is described as being problematic at low frequencies (frequencies audible only to fish and low-frequency cetaceans), no prescriptive guidance is given about its identification or mitigation. We note that it has been established that free-drifting measurements reduce flow-noise, but do not guarantee that it will be negligible, because any velocity differential between the hydrophone and surrounding water at the scale of the hydrophone element will generate flow-noise. Progress in these areas will be tracked by IEC TC 114 through an *ad hoc* group and, as international consensus emerges, improved methods will be incorporated into the next edition (nominally expected in 2024) of the Technical Specification by a Maintenance Team. Consequently, experience using the first edition of the Technical Specification should be communicated to the relevant IEC National Committees or the Convener of the *ad hoc* group. Contributors of feedback are encouraged to contact their IEC TC 114 National Committee Lead if they are from a participating country. Individuals from other countries can contact the TC 114 Chair to discuss mechanisms for involvement.

In interpreting measurements of underwater noise around MRE devices, it is important to remember that variations in received levels can be a consequence of factors other than variations in the acoustic source (e.g., seasonal changes in propagation). As explanatory factors for ambient noise are identified, they can be controlled for in experimental design and reduce the risk of ambient noise being conflated with MRE device noise. IEC 62600-40 takes steps in this direction by recommending that measurements be undertaken only in a restricted set of metocean conditions for each category of MRE device.

4.6.
RECOMMENDATIONS

We recommend two categories of activity going forward. Successful execution of these activities will not answer all the remaining research questions identified by Copping et al. (2016; e.g., effects of arrays), but will establish a strong foundation for future study.

- Expand the evidence base of rigorous, comparable acoustic measurements across a broader range of MRE devices and settings. These should be included in a publicly-accessible library of MRE device noise signatures. Direct comparisons are enabled by the measurement guidance discussed in Section 4.5, particularly Level A characterization under IEC 62600-40. Use of standardized methods will allow outcomes from individual studies to be generalized in a way that contributes to global risk identification. An improved understanding of the characteristics of the radiated noise from MRE devices and the factors that control them will facilitate effective study designs to understand behavioral responses to this noise. To achieve this, it will be necessary to establish robust methods for differentiating MRE device noise from ambient noise and, at the lowest frequencies, minimize contamination from flow-noise. Finally, challenges and recommended refinements to the methodology should be communicated to the IEC *ad hoc* group monitoring the implementation of IEC 62600-40.
- Establish a framework for studying the behavioral consequences of radiated noise from MRE devices. To fully understand the risks, it will be necessary to move beyond using audibility as a proxy for behavioral response. However, as discussed here, establishing the link between radiated noise and behavioral responses in mesocosm or field studies is challenging for a variety of reasons, including the confounding variables that affect animal behavior and the generally low amplitude of observed MRE device noise relative to ambient noise. Such links will be particularly difficult to establish for threatened or endangered species because of the low sample sizes in the field and uncertainty in their audiograms. Research community agreement on a framework for evaluating behavioral consequences could begin to answer this important question.

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NOTES

Risk to Marine Animals from Underwater Noise Generated by Marine Renewable Energy Devices

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REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
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Go to *https://tethys.pnnl.gov* for a comprehensive collection of papers, reports, archived presentations, and other media about environmental effects of marine renewable energy development.