The Underwater Sound from Offshore Wind Farms

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Introduction

Efforts to reduce carbon emissions from the burning of fossil fuels have led to an increased interest in renewable energy sources from around the globe. Offshore wind is a viable option to provide energy to coastal communities and has many advantages over onshore wind energy production due to the limited space constraints and greater resource potential found offshore. The first offshore wind farm was installed off the coast of Denmark in 1991, and since then numerous others have been installed worldwide. At the end of 2017, there were 18,814 megawatts (MW) of installed offshore wind capacity worldwide, with nearly 84% of all installations located in European waters and the remaining 16% located offshore of China, followed by Vietnam, Japan, South Korea, the United States, and Taiwan. This equated to 4,149 grid-connected offshore wind turbines in Europe alone, with the number increasing annually since then (Global Wind Energy Council, 2017). In the last 10 years, the average size of European offshore wind farms has increased from 79.6 MW in 2007 to 561 MW in 2018 (Wind Europe, 2018).

On land, China leads the onshore wind energy market with 206 gigawatts (GW) of installed capacity, followed by the United States with 96 GW in 2018 (Global Wind Energy Council, 2019). Over 80% of the US electricity demand is from coastal states, but onshore wind energy generation is usually located far from these coastal areas, which results in long-distance energy transmission. With over 2,000 GW of offshore wind energy potential in US waters, which equals nearly double the electricity demand of the nation, offshore development could provide an alternative to long-distance transmission or development of onshore installations in land-constrained coastal regions (US Department of Energy, 2016). With the potential for offshore wind to be a clean and affordable renewable energy source, US federal and state government interest in development is continuing to grow. The US Bureau of Ocean Energy Management (BOEM) is responsible for overseeing all the offshore renewable energy development on the outer continental shelf of the United States, which includes issuing leases and providing approval for all potential wind energy projects.

The Block Island Wind Farm (BIWF) was completed in 2016 off the East Coast of the United States in Rhode Island and is the first and only operational wind farm in US waters to date. It produces 30 MW from five 6-MW turbines and is capable of powering about 17,000 homes. As of August 2019, there were 15 additional active offshore wind leases that account for over 21 GW of potential capacity off the East Coast of the United States.

Offshore wind farms are generally constructed in shallow coastal waters, which often have a high biological productivity that attracts diverse marine life. The average water depth of wind farms under construction in 2018 in European waters was 27.1 meters and the average distance to shore was 33 kilometers (Wind Europe, 2018). As a by-product of the construction, operation, and eventual decommissioning of offshore wind farms, sound is generated both in air and underwater through various activities and mechanisms. With the rate of wind farm development continuing to increase worldwide, regulatory agencies, industry, and scientists are attentive to the potential physiological and behavioral effects these sounds might have on marine life living in the surrounding environment. The contribution of sound produced during any anthropogenic activity can change the underwater soundscape and alter the habitats of marine mammals, fishes, and invertebrates by potentially masking communications for species that rely on sound for mating, navigating, and foraging. This article discusses the typical sounds produced during the life of

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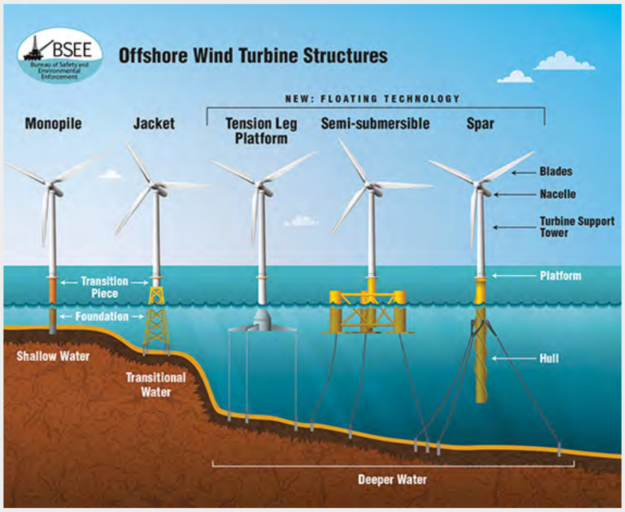
a wind farm, efforts that can be taken to reduce sound levels, and how these sounds might be assessed for their potential environmental impact.

Construction of Offshore Wind Turbines

Once the development of a wind farm has been approved, the installation of the wind turbine foundations can begin. The type of foundation used will depend on parameters such as the water depth, seabed properties at the site, and turbine size. In water depths less than 50 meters, fixed foundations such as monopiles, gravity base, and jacket foundations are used to secure the wind turbines to the seabed (**Figure 1**). A gravity base foundation is a type of reinforced concrete structure used in water depths less than 10 meters that sits on the seabed and is heavy enough to keep the wind turbine upright. A monopile foundation is a single steel tube with a typical diameter of 3-8 meters that is driven into the seafloor, whereas a jacket foundation is a steel structure composed of many smaller tubular members welded together that sits on top of the seafloor and is secured by multiple steel piles driven into the sediment (Wu et al., 2019). Monopiles can be driven to a depth of 20-45 meters below the seafloor and the piles to secure jacket foundations can be driven to a depth of between 30 and 75 meters (JASCO and LGL, 2019).

Figure 1. *Schematic showing some types of offshore wind turbine foundation structures, with the wind turbine components labeled. Image courtesy of the Bureau of Safety and Environmental Enforcement (BSEE), Department of the Interior, See https://tinyurl.com/wawb979.*



Most installed wind turbines utilize bottom-fixed foundations, but these foundations become less feasible in water depths greater than 50 meters. In the United States, roughly 58% of the offshore wind potential is in water depths deeper than 60 meters (US Department of Energy, 2016). In these greater water depths, floating foundations that are tethered to the seabed using anchors are a more viable option.

Impact Pile Driving

Impact pile driving, where the top of the pile is pounded repeatedly by a heavy hammer, is a method used to install monopile and jacket foundations and generates sound in the air, water, and sediment. The installation of a jacket foundation requires multiple piles be driven into the seabed to secure the corners of the steel structure, whereas installation of the monopile design requires one larger pile be driven (Norro et al., 2013). Impact pile driving is not used for the installation of most floating or gravity-based foundations and therefore is not an inherent part of wind farm construction if the water depths and sediment characteristics at the installation site are suitable for these alternate foundations.

The impact of the hammer on the top of the pile is the primary source of sound that is generated during impact pile driving (see tinyurl.com/tbdgsb2). High-amplitude sound pressure is generated that radiates away from the pile on an angle that is dependent on the material properties of the pile and the sound speed in the surrounding water. This angle is typically between 15° and 19° relative to the pile axis (**Figure 2**; Dahl et al., 2015b). Characteristics of the sound generated from each hammer strike are strongly dependent on the pile configuration, hammer impact energy, and environmental properties (such as the water depth and seabed properties).

In addition to the sound pressure generated in the water, compressional, shear, and interface waves are generated in the seabed that propagate outward from the pile in all directions (**Figure 2**). Compressional waves are the fastest traveling waves in the seafloor and are characterized by particle motion that is parallel to the direction of wave propagation, whereas shear waves, which arrive second, have particle motion that is perpendicular to the direction of the propagating wave (Miller et al., 2016). Interface (or Scholte) waves along the water-sediment interface occur as a result of interfering compressional and shear waves. The low-frequency and slow-moving interface waves propagate

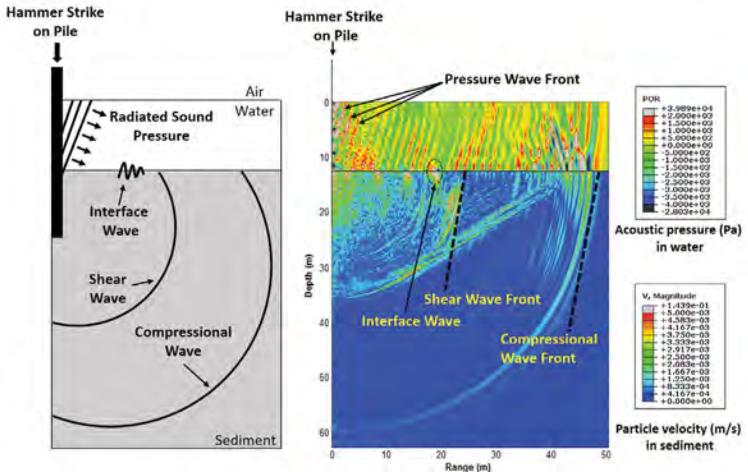


Figure 2. ***Left:*** *simplified schematic showing the types of sound generated as a result of a hammer striking a pile. Sound pressure is radiated into the water at an angle relative to the pile axis, compressional and shear waves are generated in the sediment, and interface waves propagate along the seafloor boundary.* ***Right:*** *finite-element output for the pile driving of a vertical steel pile in 12 meters of water. The seafloor is at 12 meters depth (**black horizontal line**). The acoustic pressure in the water (<12 meters) and the particle velocity in the sediment (>12 meters) generated from a hammer strike are shown. Various wave phenomena can be seen, including the sound pressure wave radiated at an angle from the pile into the water and the resulting body and interface waves in the sediment. Reprinted/adapted from Popper and Hawkins, 2016, with permission from Springer.*

over long distances and generate large-amplitude oscillations along the water-sediment boundary that have the potential to affect marine life living close to or within the seafloor sediment that is sensitive to this type of disturbance (Popper and Hawkins, 2018). The amplitude of the interface wave decays exponentially away from the interface, and, therefore, any disturbance will be noticeable only within a distance of a few wavelengths from the seafloor (Tsouvalas and Metrikine, 2016).

Measuring the Radiated Sound

The total number of hammer strikes required to drive a pile to its final penetration depth could range between 500 to more than 5,000, with the hammer striking the pile between 15 and 60 times per minute (Matuschek and Betke, 2009). On average, a jacket foundation requires three times more hammer strikes to install than a monopile and will result in a longer total piling time because the jacket design requires multiple piles to secure the structure to the seabed as opposed to a single pile for the monopile design (Norro et al., 2013). To characterize the impulsive sound generated during each hammer strike as part of impact pile driving, the sound exposure level (SEL) and peak sound pressure level metrics can be used. The SEL is a measure of the energy within a signal and allows for the total energy of sounds with different durations to be compared. It is defined as the time integral of the squared sound pressure reported in units of decibels re 1 µPa^{2}s. This metric can be used to describe the sound levels from a single strike (SEL$_{ss}$) and cumulated across multiple hammer strikes or over the duration of the piling activity (SEL$_{cum}$). When assessing the potential effect of impulsive sounds on the physiology of marine mammals and fishes, the peak sound pressure level and SEL are used (Popper et al., 2014; Southall et al., 2019).

A standard measurement method is important to ensure that independent measurements made at different wind farms can be compared. An approach for measuring and characterizing the underwater sound generated during impact pile driving is defined through the International Organization of Standardization (ISO) 18406 document (2017), which is the standard for measurements of radiated underwater sound from impact pile driving. In this standard, a combination of range-varying hydrophone deployments and fixed-range measurements are recommended to capture variation in the resulting sound field

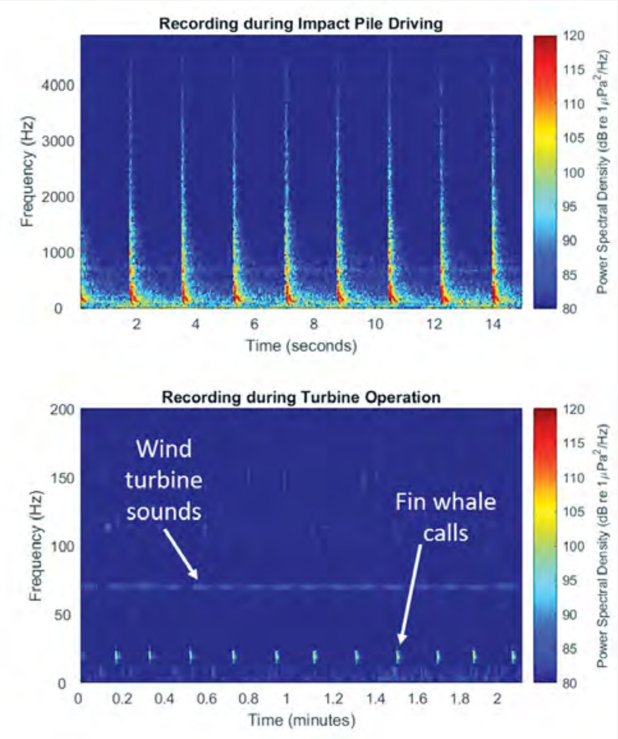


Figure 3. ***Top:*** *time-frequency representation of hammer strikes during impact pile driving at the Block Island Wind Farm (BIWF) recorded at a range of 7.5 kilometers and roughly at midwater depth.* ***Bottom:*** *time-frequency representation of the acoustic signals around 71 Hz hypothesized to be due to the operation of 1 turbine at the BIWF measured near the seafloor at a range of 50 meters while fin whales were vocalizing at 20 Hz. The received wind turbine sounds were measured at a level of 100 dB re 1 μPa root-means-square (rms) while the fin whale vocalizations were measured at a level of 125 dB re 1 μPa peak.*

with both distance and changing source characteristics. The source characteristics and resulting sound level radiated into the environment will vary during a piling sequence due to changes in the hammer strike energy, penetration depth of the pile, and depth-dependent seabed properties. Usually, the piling event will begin with hammer strikes at a lower energy before increasing to a higher strike energy to drive the pile deeper into the seafloor. As the length of the pile driven into the seafloor increases, it has the potential to encounter sediment layers with different properties that would influence the resulting radiated sound levels. This variation could be adequately captured on stationary measurement systems, ideally deployed at multiple ranges but with at least one deployed at a range of 750 meters to facilitate comparison with the large number of existing measurements at this range from other wind farm sites (Robinson and Theobald, 2017).

Frequency Content of Hammer Strikes

Impact pile driving radiates considerable levels of low-frequency impulsive noise into the environment. The majority of the energy in the resulting broadband sound field is found below 2 kHz, with spectral peaks between 100 and 400 Hz (**Figure 3**, *top*; Matuschek and Betke, 2009) , where the dispersion of shallow-water acoustic modes is present (Frisk, 1994). Measurements taken during wind farm construction in the North Sea showed similar spectra resulting from the piling of a monopile and jacket foundation (Norro et al., 2013).

Azimuthal Dependence of Radiated Sound Fields

The installation of jacket foundations sometimes requires piles to be driven on an angle inside the legs of the foundation. For example, the legs of the jacket foundations at the BIWF were hollow, steel members that were inclined inward at an angle of roughly 13° and piles were impact driven into the legs to secure the foundation to the seabed (**Figure 4**). The nonaxisymmetric orientation of the pile relative to the seabed causes an azimuthal dependence to the radiated sound field, which can result in a significant

Figure 4. *Jacket foundation in the water to the right of the pile-driving barge at the BIWF, with a steel pile section inserted into each leg at an angle of roughly 13° prior to piling. The hammer is shown positioned on one of the piles in preparation to drive the pile into the seafloor.*

variation in the received sound levels measured along different radials (Wilkes and Gavrilov, 2017). Received levels recorded on fixed-range and towed measurement systems were substantially different (~10 dB) between piles inclined in opposite directions (Vigness-Raposa et al., 2017; Martin and Barclay, 2019). These differences were observed independent of the strike energy used for individual hammer strikes (Amaral et al., 2020). The pile orientation affected the incident angle of the radiated pressure wave front on the seabed, which resulted in the directivity of the radiated sound varying based on the azimuth. The steeper the incident angle of the radiated wave front on the seafloor, the more energy was absorbed in the sediment. The azimuthal dependence to the radiated sound field and resulting sound levels are important factors to consider when determining the potential marine mammal and fish impact zones around pile-driving activities for inclined piles.

Vibratory Pile Driving

Vibratory pile driving is another method used to drive piles into the seafloor and could be used prior to impact pile driving to ensure that the pile is stable in the seabed (JASCO and LGL, 2019) or for the installation of sheet piles to construct temporary cofferdams (Tetra Tech, 2012). In this process, the pile is vibrated at a certain frequency, typically between 20 and 40 Hz, to drive it into the sediment rather than hammering the top of the pile (Matuschek and Betke, 2009). The vibratory process produces lower level continuous sounds (see tinyurl.com/st4h9tq) compared with the high-amplitude impulsive noise produced during impact pile driving. The high-amplitude pressure waves generated in the water column during impact piling are not present with vibratory piling, and the highest sound pressures are expected near the seafloor as a result of the propagating low-frequency interface waves (Tsouvalas and Metrikine, 2016). The radiated spectrum will be strongly influenced by the vibration frequency, will have peaks at the operating frequency and its subsequent harmonics, and will vary as the operating frequency is adjusted according to changing operational conditions such as sediment type (Dahl et al., 2015a). To assess the impact of nonimpulsive sound on marine life, the SEL metric is used (Southall et al., 2019).

Additional Construction-Related Sounds

The construction of an offshore wind project generates sound during other activities apart from pile driving, including during the laying of electric cables on the seabed and from the operation of the vessels used during construction. The primary source of noise during the cable laying process is from vessel operations and the potential use of dynamic positioning thrusters to hold vessels in position. An environmental assessment performed for the Vineyard Wind project off the coast of Massachusetts concluded that the sounds generated from these activities were generally consistent with those from routine vessel traffic expected in the area, and, therefore, they were not anticipated to be a significant contributor to the overall acoustic footprint of the project (JASCO and LGL, 2019).

Operational Sounds of Wind Turbines

The construction of a wind farm takes place over a period of months, whereas the typical wind farm life span is between 20 and 25 years. Once completed, the turbines will operate nearly continuously, except for occasional shutdowns for maintenance or severe weather. Therefore, the contribution of sound to the marine environment will be more consistent and of longer duration during the operational phase than during any other phase of the life of the wind farm (Nedwell and Howell, 2004). The underwater noise levels emitted during the operation of the turbines are low and not expected to cause physiological injury to marine life but could cause behavioral reactions if the animals are in the immediate vicinity of the wind turbine (Tougaard et al., 2009; Sigray and Andersson, 2011).

In some shallow-water environments, sound due to shipping traffic or storms could dominate the low-frequency ambient-sound field over the sound emitted from the wind turbines. Therefore, evaluating the relative sound levels from the wind turbine compared with those from other sources is important when considering the potential impacts to marine life. Measurements made at 3 different wind turbines in Denmark and Sweden at ranges between 14 and 40 meters from the turbine foundations found that the sound generated due to turbine operation was only detectable over underwater ambient noise at frequencies below 500 Hz (Tougaard et al., 2009).

The main sources of sound generated during the operation of wind turbines are aerodynamic and mechanical. The mechanical noise is from the nacelle, which is situated at the top of the wind turbine tower and houses the gear box and generator (**Figure 1**). As the wind turbine blades rotate, vibrations are generated that travel down the turbine tower into the foundation and radiate into the surrounding water column and seabed (Tougaard et al., 2009). The resulting sound is described as continuous and nonimpulsive and is characterized by one or more tonal components that are typically at frequencies below 1 kHz (see tinyurl.com/wke3lso). The frequency content of the tonal signals is determined by the mechanical properties of the wind turbine and does not change with wind speed (Madsen et al., 2006).

Underwater measurements taken during the operation of one of the turbines at the BIWF contained sound that is hypothesized to be caused by aerodynamic noise from the turbine blade tips that was propagated through the air, into the water, and received on a hydrophone on the seabed at a range of 50 meters (**Figure 3**, *bottom*; J. Miller, Personal observation). This sound was measured to be around 71 Hz and was lower in level than fin whale vocalizations recorded at the same time. This sound was only detectable during times when the weather was calm and there were no ships traveling in the area.

Sounds from Decommissioning

Since the first offshore wind farm decommissioning in 2015, a small number of offshore farms have been decommissioned, but the decommissioning process is generally unexplored. As more wind farms reach the end of their design life, the decision will have to be made relating to extending operations, repowering, or decommissioning. Decommissioning is typically thought of as a complete removal of all components above and below the water surface, but there is research supporting a partial removal where some of the substructure would remain in place as an artificial reef for marine life (Topham et al., 2019). In general, sound would be generated as a by-product of the process used to remove the substructures, which could include cutting the foundation piles via explosives or water jet cutting (Nedwell and Howell, 2004).

Assessing Impact to Marine Life

Impulsive sounds, like those generated during impact pile driving, exhibit physical characteristics at the source that make them potentially more injurious to marine life compared with nonimpulsive sounds, like those generated during vibratory pile driving and wind turbine operation (Popper et al., 2014; Southall et al., 2019). Sound exposure is currently assessed based on the sound pressure received in the water column, but the resulting particle motion in the water and sediment is also important when considering the potential impact to marine life sensitive to this stimulus. Additionally, the context under which an animal is exposed to a sound, in addition to the received sound level, will affect the probability of a behavioral response (Ellison et al., 2012).

Protective Measures to Mitigate Sound Levels

Various mitigation methods can be employed during each phase of wind farm development to reduce the overall propagated sound levels and potential effect on marine life. Time-of-year limitations on construction are implemented to provide safeguards for specific protected or susceptible species. Antinoise legislation in the Netherlands prohibits pile driving from July 1 through December 31 to avoid disturbance of the breeding season of the harbor porpoise (Tsouvalas and Metrikine, 2016). Off the US East Coast, an agreement was made between environmental groups and a wind farm developer to provide protections for the North Atlantic right whale by not allowing pile driving between January 1 and April 30 when right whales are most likely to be present in the project area (Conservation Law Foundation, 2019).

The use of noise mitigation systems such as bubble curtains (see tinyurl.com/v6m6ops) or physical barriers around the pile are commonly used to reduce the levels of sound generated during impact pile driving (Bellmann et al., 2017). These methods are a type of barrier system that work to attenuate the radiated sound levels by exploiting an impedance mismatch between the generated sound wave and a gas-filled barrier. Factors such as the water depth, current, and foundation type will influence the effectiveness of each system.

Ramp-up operational mitigation measures, in which the hammer intensity is gradually increased to full power, are also employed. This method aims to allow time for animals to leave the immediate area and avoid exposure to harmful sound levels, although there are no data to support the contention that this works for fishes, invertebrates, or turtles. Another mitigation method involves visually monitoring an exclusion zone around the piling activity for the presence of marine mammals. This zone is predefined based on the expected sound levels in the area and requires pausing piling activities if an animal is observed to reduce near-field noise exposure (Bailey et al., 2014).

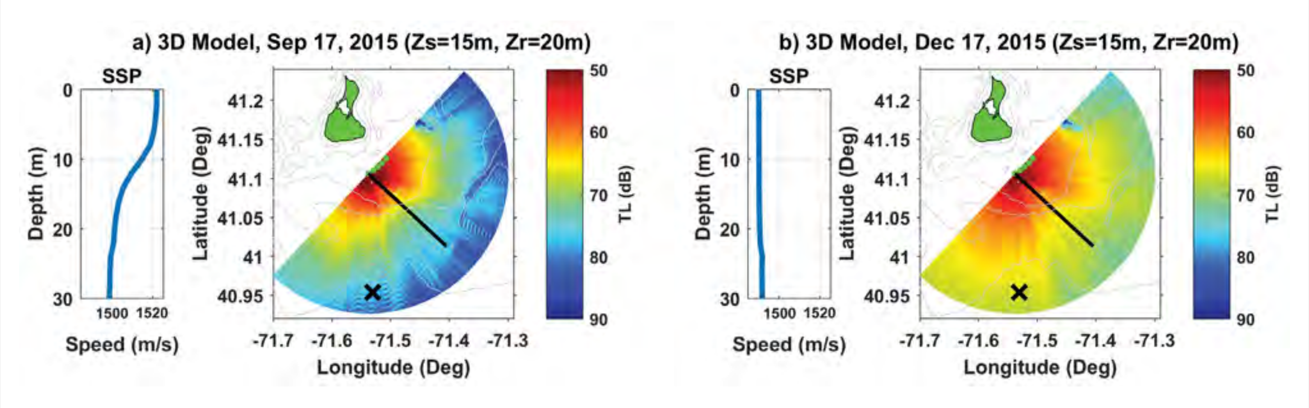


Figure 5. *Seasonal variability of underwater sound propagation in the BIWF area showing transmission loss (TL) predictions in decibels for a 200-Hz sound source in September 2015 (summer;* ***a****) and December 2015 (winter;* ***b****). The source depth (Zs) in the model was 15 meters and the receiver depth (Zr) was 20 meters. The corresponding sound speed profiles (SSP) are shown. The TL was higher in the summer compared with the winter conditions. Reproduced from Lin et al., 2019, with permission.*

Exploiting seasonal differences in the water temperature and salinity and its effect on underwater sound propagation could also be used to mitigate the impact of pile-driving noise by scheduling wind farm construction during seasons of high expected acoustic transmission loss. For example, the pile driving for the BIWF occurred during the summer season but had the construction occurred during the winter season, the received SELs at ranges greater than 6 kilometers could have been up to 8 dB higher (**Figure 5**) due to lower water temperatures causing larger acoustic impedance contrast at the seafloor (water-bottom interface) and a more isovelocity, or constant, sound speed profile (Lin et al., 2019). This difference in received sound levels is significant and highlights the effect the environmental conditions have on the overall sound propagation.

Conclusion

Ancillary sounds of varying levels and characteristics are generated during each phase in the development of an offshore wind farm. The highest amplitude sound is expected during the impact pile-driving part of the construction phase and potentially during the decommissioning phase depending on the methods employed to remove the wind turbine foundations. The installation methods used for each turbine foundation type will result in different levels and types of sounds radiated into the marine environment. The sound levels can be reduced using physical barriers, and the sound exposure of marine life can be mitigated through monitoring methods and time-of-year restrictions on sound-generating activities. The potential for acute sound exposure of marine mammals and fishes is currently assessed based on the generated sound pressure levels in the water column, but other factors such as the particle motion in the water and sediment and the behavioral response of marine life are important factors to evaluate. Although the construction and decommissioning phases take on the order of months to complete, offshore wind farms are designed to operate for minimum of 20–25 years. With the continued development of offshore wind farms worldwide there will be additional opportunities to measure the underwater sound generated during all phases and assess any potential long-term effect of this sound on the marine environment.

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