SEER

U.S. OFFSHORE WIND
SYNTHESIS OF ENVIRONMENTAL
EFFECTS RESEARCH

# UNDERWATER NOISE EFFECTS ON MARINE LIFE ASSOCIATED WITH OFFSHORE WIND FARMS

## MAIN TAKEAWAYS

- Underwater sound can be generated by biological, physical, and anthropogenic sources; unwanted sound sources, such as those from offshore development, are referred to as "noise."
- During offshore wind (OSW) farm construction, the driving of foundation piles into the sediment generates a significant amount of noise for certain foundation types. As a result, a number of mitigation measures have been developed to reduce noise and minimize impacts to wildlife.
- Noise levels that can cause auditory injury are likely to occur in relatively close range to the pile driving. At greater distances, the intensity of noise is reduced (due to spreading) and is less injurious, but may still affect the behavior of marine species.
- Quieting technology, such as bubble curtains, are effective at reducing noise at the source, which has benefits for all marine species. Other mitigation measures, such as protected species observers or passive acoustic monitoring, can monitor areas for sensitive marine life to ensure that construction does not occur when they are in the vicinity through shutting down and delaying pile driving activities.
- The risk to marine life from underwater noise during other phases of wind farm development (e.g., site surveys, operations, and maintenance) is considered to be lower, but further monitoring is still needed to help fill existing research needs and gaps in understanding.
- For floating foundation types, mooring line anchors can be installed using a variety of relatively low-noise methods. When impact pile driving is used for the anchors, there is a smaller anticipated acoustic impact for these smaller piles.

Please visit **Tethys** to view the literature reviewed to inform the development of this research brief.

# TOPIC DESCRIPTION

Underwater noise in the oceans can impact a variety of marine life and is a topic of international consideration for improving understanding of ocean soundscapes and effects of sound on marine organisms. When underwater objects vibrate, they create sound that travels as a pressure wave through the marine environment, including through water, the seafloor, and the air. Ocean soundscapes consist of contributions from biological sources (sounds of marine life), physical sources (sounds of the Earth), and anthropogenic sources (sounds of human activities; Figure 1). Underwater noise can travel long distances and has components of both sound pressure and vibration. It decreases with increasing distance from the source due to physical spreading and energy loss in the water column and seafloor, as well as across the sea surface. Sound can be measured with great precision in the oceans using hydrophones in different configurations to provide information on sound amplitude, frequency, and directionality.

The potential range of impacts of an OSW farm on the underwater soundscape changes throughout the life cycle of the wind farm. The four key phases of OSW development each have different noise emissions and include site surveys, construction, operation and maintenance, and decommissioning (Figure 2). During the first phase, site surveys are conducted using geophysical techniques to characterize site conditions. Notably, lower-energy (quieter) systems are used for penetrating the seafloor compared to the high-intensity air guns required to search for oil and gas deposits. The second phase of OSW development involves construction and is usually one of the shortest phases. However, the placing of the foundation via pile driving and additional construction activities have the potential to generate high-intensity noise. The third phase of the OSW life cycle involves operations with noise generated by maintenance activities and by the turbines themselves.

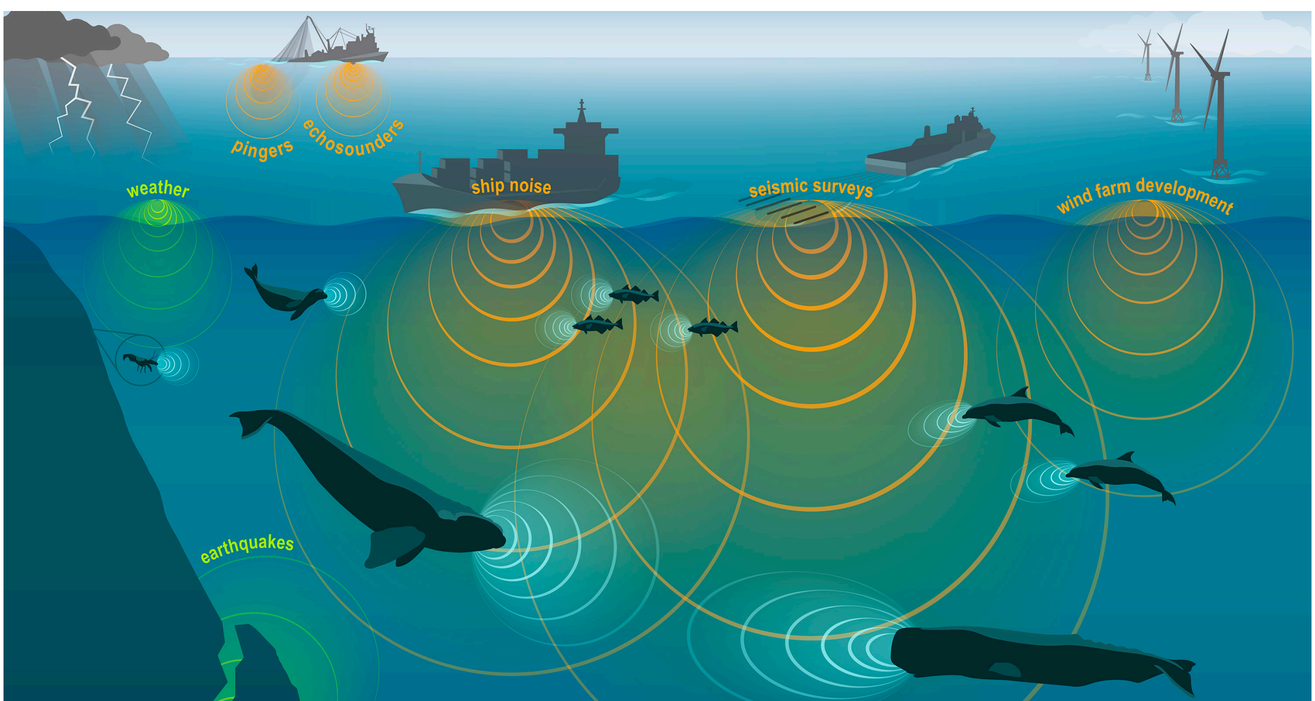


***Figure 1.*** *The marine soundscape consists of sounds made by humans (anthropogenic, orange sound waves), the environment (natural sounds, green sound waves), and biological sources (marine life: marine mammals, fish, and invertebrates; blue sound waves). Illustration from National Oceanic and Atmospheric Administration.*

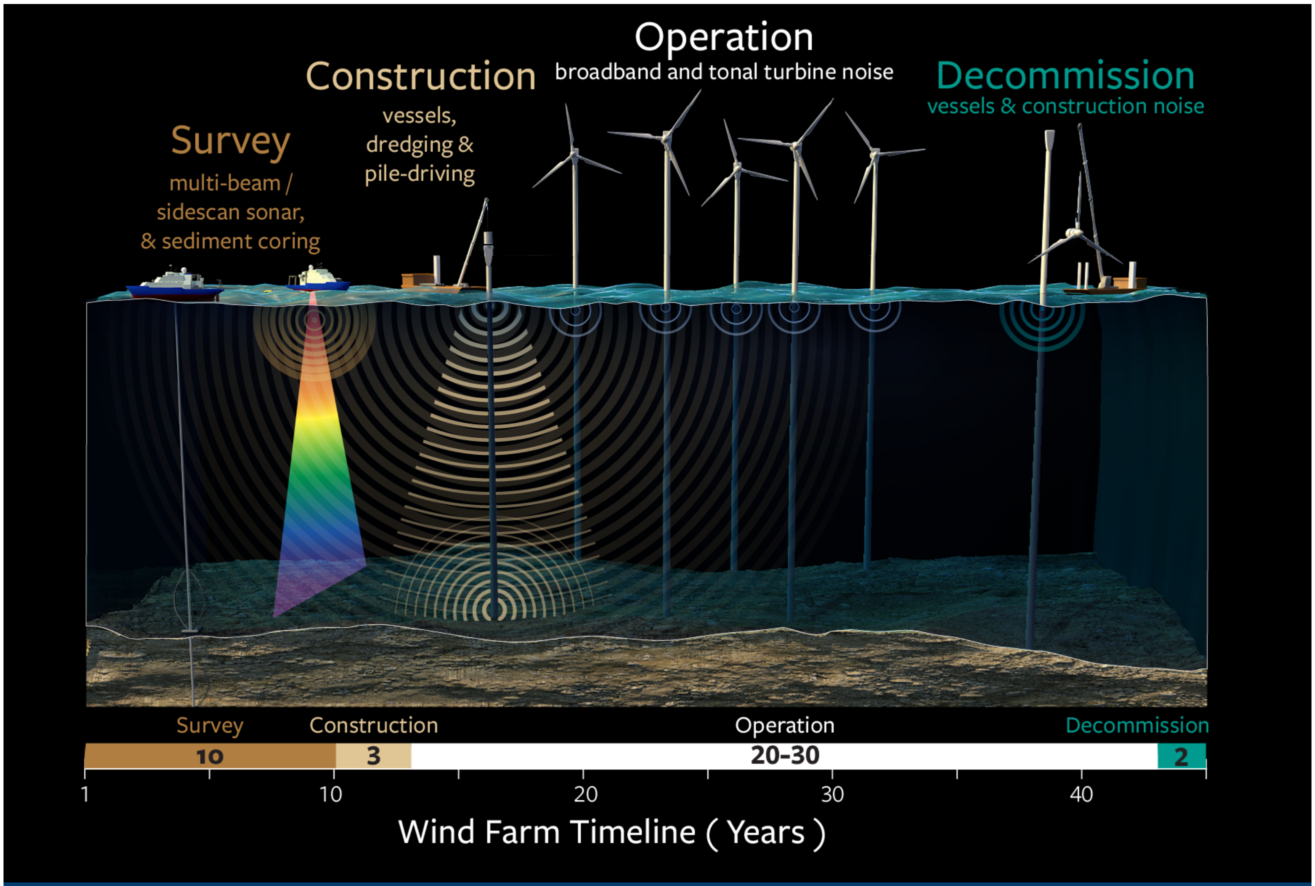


***Figure 2.*** *Underwater noise associated with the life cycle of an OSW farm area, including during site surveys, construction, operations and maintenance, and decommissioning. Illustration from* ***Mooney et al. (2020).***

## Examples of Noise Generated During the OSW Farm Lifecycle

- **Site Surveys:** A variety of sensors and platforms are used to map and investigate the seafloor during site assessment, including as part of acoustic benthic surveys using vessels (e.g., sonar and echosounders).
- **Construction:** The installation of foundations through pile driving, including for monopiles, tripods, and jacket foundations, generates more noise than other installation methods. Alternative foundation technologies that are associated with reduced noise include suction bucket, gravity based, and floating foundations.
- **Operations and Maintenance:** During this phase, underwater noise is produced at a relatively low level (compared to natural sound levels) over the 20+ year project lifetime by the rotation of the wind turbine blades; the noise is transmitted to the water by the turbine and support structure. Vessel support is required through all phases of wind farm development, including for maintenance, with its associated potential noise effects on marine life.
- **Decommissioning:** Noise during the removal of a wind farm results from the use of support vessels and specific factors associated with dismantling the various wind farm components, including turbines, embedded foundations, subsea cables, and offshore substations.

> During construction, impact pile driving can create intense sound pulses, such that noise assessment and mitigation activities are now a standard part of OSW farm permitting.

The operational noise emission from currently installed turbines is relatively low level and does not significantly exceed natural noise levels. The final decommissioning phase involves using support vessels to dismantle the various components of the wind farm and can generate noise levels with the potential to disturb marine life.

Underwater noise impacts are a factor for OSW farms built off the various U.S. coasts, with different considerations depending on whether fixed-bottom or floating wind turbines are deployed and based on differences in the marine species present. In Europe, most knowledge on the response to OSW pile driving originates from studies of porpoises, seals, and fish around smaller turbines than those now being considered for deployment. For context, large whale and sea turtle species do not live in areas where large-scale OSW development has previously occurred. Countries, such as Germany, Belgium, the Netherlands, the United Kingdom, Denmark, Japan, South Korea, Taiwan, and the United States, have legal restrictions or statutes in place that protect marine wildlife from underwater noise; these protections have been accompanied by an increasing number of underwater noise-mitigation methods. A wide variety of marine species occur in U.S. waters, and several are listed as endangered under the Endangered Species Act (ESA) (e.g., the North Atlantic right whale, killer whale, and loggerhead turtle). Mitigation and monitoring measures are required for OSW development by the Bureau of Ocean Energy Management (BOEM) through requirements of lease stipulations and required by incidental take authorizations from National Oceanic and Atmospheric Administration (NOAA) Fisheries pursuant to the ESA and Marine Mammal Protection Act. A range of fish and invertebrate species are also impacted by noise, including by particle motion (back-and-forth motion of the medium), sound pressure, and substrate vibration. In particular, particle motion is the primary acoustic stimulus for all fish and invertebrates, and thus, is an important quantity to measure for understanding the effects of noise.

# MAIN RISKS & EFFECTS

Hearing is one of the main ways marine life gather information and communicate underwater, where sound travels rapidly and over long distances. Noise may lead to physiological effects, ranging from nonauditory injury to hearing loss, or to more subtle effects, such as auditory masking (i.e., when noise interferes with the ability to communicate and hear other important sounds) or behavioral disturbance, which is more difficult to predict and quantify. Marine life, including marine mammals, sea turtles, and fish, differ in their ability to hear across sound frequencies and thus will respond differently to noises from different OSW farm activities. For example, baleen whales (e.g., blue, fin, and humpback whales) vocalize and are believed to hear well at low frequencies, whereas dolphins and porpoises vocalize and hear well at higher frequencies (Figure 3). Sound is also important to fish as they produce various sounds that are used to attract mates, ward off predators, and gather together. Marine invertebrates, like shrimp and lobsters, and other benthic organisms also rely on sound for mating and protection. Sea turtles can hear low- to mid-frequency sounds underwater, but less is known about their hearing compared to other species.

During construction, impact pile driving can create intense sound pulses, such that noise assessment and mitigation activities are now a standard part of OSW farm permitting. Noise impacts during pile driving are strongly dependent on the pile configuration, hammer impact energy, environmental properties, and species present at the pile location and in the surrounding area. The observed behavioral

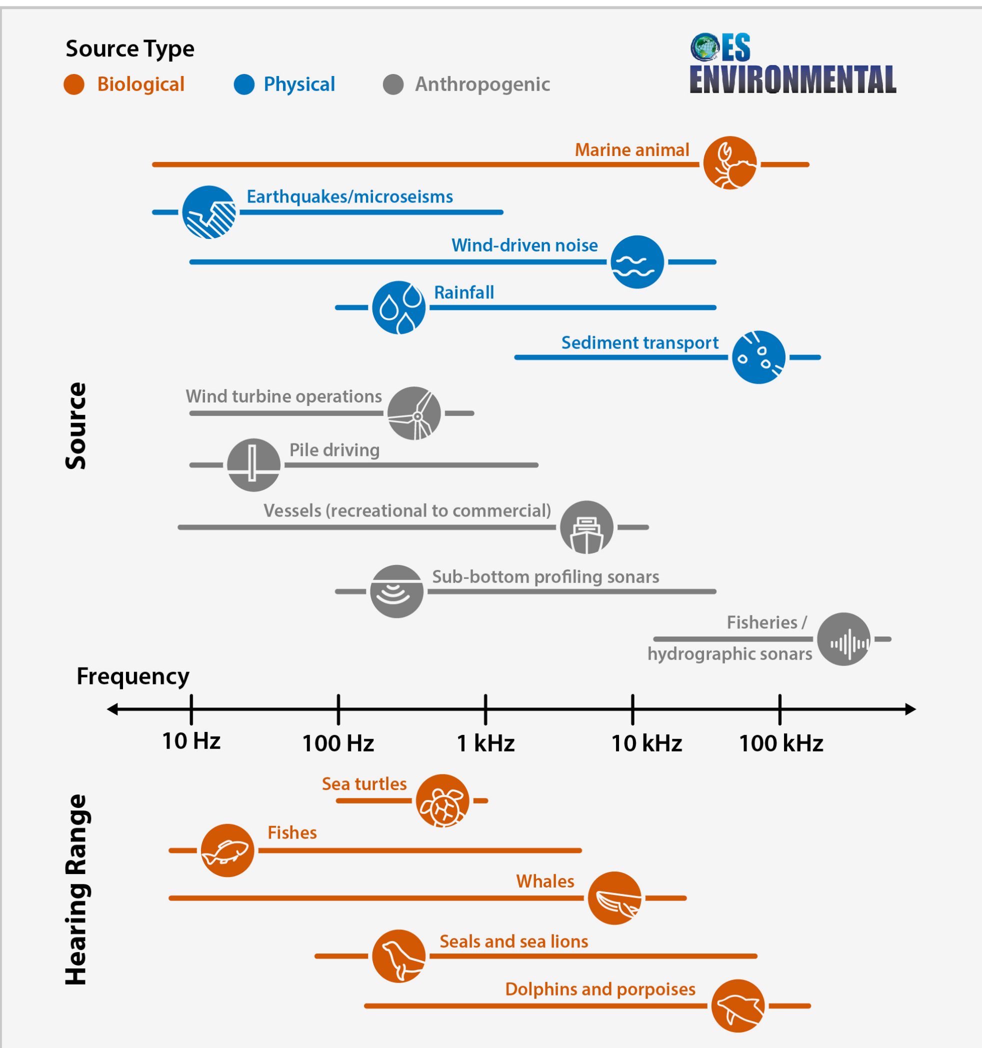


***Figure 3.*** *Comparison of frequency ranges of hearing for marine life and various sound sources in the marine environment, including from OSW activities. Illustration from Copping & Hemery 2020.*

responses of marine life to OSW pile driving noise ranges from slight disturbance to strong avoidance of the construction site. The two components of underwater sound (pressure and vibration) change significantly with distance from the source. A useful framework for describing potential noise impacts on marine species at wind farms includes the following four zones of auditory impact (listed from largest to smallest): (1) zone of audibility; (2) zone of responsiveness; (3) zone of masking; and (4) zone of hearing loss, discomfort, and injury (Figure 4). Generally, injury-causing noise levels occur within closer range to the pile driving, whereas sound levels causing behavioral effects extend significantly further from the pile. The risk of injury decreases with distance from the pile driving, but the exact distances are dependent on the nature of the sound, the environment, and the species. For floating foundation types, mooring line anchors can be installed using a variety of relatively low-noise methods. When impact pile driving is used for the anchors, there is a smaller anticipated acoustic impact for these smaller piles, compared to those used for fixed-bottom foundations.

Beyond pile driving, there are other potential impact-producing sources of noise associated with OSW farms, though at comparatively lower sound intensities. Vessel support is required through all phases of wind farm development. Ship noise can mask the communication signals of marine mammals and certain fish species, and such noise may also induce physiological stress and impair foraging and predator responses in both fish and invertebrates. During the site surveying phase, seafloor mapping is performed using multibeam, side-scan sonar, sub-bottom profiles, and other technologies that introduce sound into the water column and benthos for short time periods. These technologies operate across a range of frequencies, but with lower intensities than technologies used in the oil and gas industry, and may have the potential to cause behavioral impacts on some marine life. During the operational and maintenance phase, OSW farms can produce nearly continuous underwater sound, though at relatively low amplitudes that vary with the wind speed and turbine size. Noise levels during operation are not high enough to cause direct physical injury but may have some behavioral impacts to marine species in close proximity to the turbines. Studies have also shown that fish might adapt to noises created by OSW farms. Although there is little published literature on the decommissioning phase of OSW farms, there is the potential for masking, displacement, physiological stress, and other impacts—especially if marine life is aggregated in habitats around wind farm foundations.

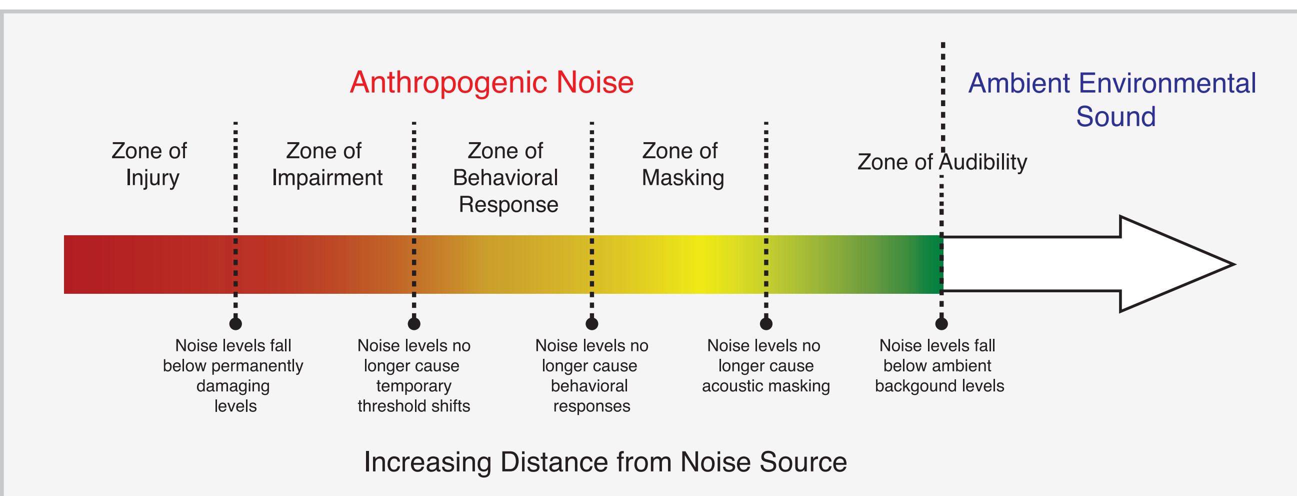


***Figure 4.*** *Framework for potential noise impacts on marine mammals based on zones of auditory impact, with distance from the sound source. Illustration from* ***Mooney et al. (2020).***

# MONITORING & MITIGATION METHODOLOGIES

Substantial progress has been made in developing methods to understand and reduce the impacts of underwater noise generated by OSW farm development. Ocean acoustic monitoring has advanced over many years to record underwater sounds using hydrophones in a variety of configurations, including on buoys and towed behind vessels. This acoustic monitoring can provide data on both marine mammal presence and underwater noise levels, including the frequency, amplitude, location, and seasonality of underwater sounds. Passive acoustic monitoring is a standard methodology used to assess the occurrence and distribution of marine life in and around the area of a wind farm, including during construction to measure potential risk to wildlife. Measurements from acoustic monitoring can be used to understand the potential impacts of sound levels on a variety of marine life, including marine mammals, sea turtles, fish, and invertebrates. A host of monitoring methods are used to estimate the distribution, abundance, and behaviors of different species, including visual surveys from vessels, the use of animal tagging, and aerial surveys to understand the distributions and behaviors of different species. These measurements can then be used to assess how many animals may be exposed to certain levels of noise.

Given the potentially high levels of sound associated with pile driving during OSW farm construction, a variety of primary and secondary mitigation measures have been developed to help reduce the impacts of unwanted noise associated with increasingly large monopiles. In Germany, mandatory legal thresholds have been introduced for the maximum level of noise that can be generated during pile driving for the protection of marine life. In the United States, sound thresholds have been identified to help assess noise impacts on marine life. Quieting technologies, such as bubble curtains and noise abatement systems, reduce the spread of noise by placing physical noise barriers around the pile (Figure 5). These noise barriers have proven to be an effective tool for decreasing the impacts of pile driving on marine life in Europe, including for porpoises; similar mitigation measures are now being used in the United States. Other noise mitigation measures include use of time-of-year restrictions, protected species observers and exclusion zones, and soft starts for pile driving.

## Examples of Noise-Mitigation Techniques

- **Quieting Technologies:** Bubble curtains are an example noise reduction technology. They work by creating a physical bubble barrier around the pile driving platform, thus reducing noise outside the curtain and helping protect marine life. Other examples of technologies include isolation casings, cofferdams, and hydro sound dampers.
- **Time-of-Year Restrictions:** Pile driving activities may be excluded during certain times of the year due to the presence of sensitive marine life during these periods. Time-of-year restrictions have been implemented for the North Atlantic right whale.
- **Protected Species Observers:** Trained observers maintain an exclusion area for certain protected species around pile driving activities. For example, if a marine mammal or sea turtle is observed entering or within the relevant exclusion zones, pile-driving activity must be shut down and delayed.
- **Soft Start for Pile Driving:** Gradual ramp up of hammer energy for impact pile driving that includes an initial set of strikes from the impact hammer at reduced energy, followed by a waiting period, with repetition of this process several times prior to initiation of pile driving.

In the United States, BOEM has identified guidelines for OSW farm construction, operations, and maintenance, which include suggested mitigation measures related to noise. Developers are guided to employ state-of-the-art, low-noise turbines or other technologies to minimize operational sound effects. Additionally, developers are expected to characterize the sound likely to be produced by their activities and to identify potential impacts of noise on sensitive biological resources or habitats, including noise source level, frequencies, and the expected sound transmission loss calculations with distance from the source. OSW developers in the United States have proposed to implement a variety of noise-mitigation measures, including soft start during pile driving, noise reduction systems, use of protected species observers, and passive acoustic monitoring—all of which are designed to reduce the risk to marine life. Further, on the Atlantic Coast, pile driving should not occur during the peak season of North Atlantic right whale occurrence. Mandatory terms and conditions and reasonable measures to minimize the extent of incidental effects on endangered species during OSW activities are issued by NOAA.

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Cumulative and population level effects of pile driving noise have increasingly become a consideration with the expansion of OSW development in some regions. The cumulative impacts of noise are considered across multiple OSW farm projects and in the context of existing pressures from other noise sources in the ocean. In Scotland, a framework was developed to assess population-level impacts of disturbance from piling noise on a protected harbor seal population near multiple proposed wind farm developments. Models of seal distribution were combined with models of noise propagation and integrated with data to

***Figure 5.*** *Air bubble curtain, seen as rings around the pile driving platform, during foundation installation for the Coastal Virginia OSW pilot project. Photo from Dominion Energy.*

estimate potential impacts, including inferring displacement and auditory injury. Several other types of population models have been developed to understand the impacts of pile driving on marine mammals, including in the North Sea, the United Kingdom, and German Bight. For example, the population consequences of disturbance model is one type of model that has been developed to assess the combined effects of individual animal exposures to stressors at the population level, and has been applied to study the effects of OSW farms.

In addition to pile driving, other aspects of wind farm activity produce noise; however, they are perceived to be of less risk to marine life than wind farm construction. In Danish and United Kingdom OSW farms, monitoring techniques have demonstrated the regular presence of harbor porpoises and seals during the operational phase without inducing significant adverse responses in these protected animals. In Europe, given little indication so far that operational noise from OSW farms impacts marine life, mitigation measures have not been a focus for development. With regard to support vessels, which are used throughout the life cycle of an OSW farm, propeller and diesel engine noise can sometimes be reduced through vessel retrofits and ship husbandry/maintenance. Accomplishing vessel quieting is not straightforward, but techniques like speed reduction and regular maintenance can significantly reduce radiated noise without requiring retrofits. Vessels can also be designed to reduce noise through changes in hull shape, engine, and propulsion method.

# KNOWLEDGE GAPS & RESEARCH NEEDS

As OSW development expands and new data are collected, research needs continue to evolve related to the understanding and minimization of noise impacts from OSW farms. Lessons have been learned from studies at European wind farms and initial development in the United States. For example, a common research need identified across multiple countries includes understanding of the impacts from OSW farms and their interaction with other pressures and cumulative impacts, at both the individual and population levels; these need to be improved using appropriate studies and tools, such as population modeling to link impacts to changes in vital rates (individual survival and fertility). In addition, new research needs have been identified for future larger-scale OSW development in the United States, including those associated with unique species, habitats, and larger turbines on the U.S. Atlantic and Pacific coasts. Some of the key overarching questions that continue to be asked in each new region of development for particular species of concern include the following:

- Could animals be displaced from the wind energy area by construction, operational, and maintenance noise?
- Could animal behavior and/or physiological parameters change in response to noise?
- Could noise disrupt fish and prey species' availability?
- How do we improve noise mitigation and monitoring to reduce potential impacts?

The level of information available and specific research questions related to the effects of OSW noise varies by species. Given the known sensitivity of marine mammals to underwater sounds and their protection in the United States under the ESA and Marine Mammal Protection Act, the impacts of noise on these species is better understood compared to other species. For marine mammals, more information is still needed on: how noise impacts accumulate over time and multiple exposures; how multiple acoustic and non-acoustic stressors interact; and how effects on individuals affect a population as a whole. For fish and invertebrates, results from studies thus far are disparate, suggesting species-specific responses. Further research on animal hearing thresholds is needed to better understand potential impacts of noise. Of the species listed under the ESA, the least amount of information exists about the impacts of underwater noise on sea turtles. There is an overall need to better understand turtle hearing to inform predictions of both physical and behavioral effects due to underwater noise.

As more is learned about OSW development, those lessons will be used to improve environmental protections for marine species. Coordination across the multiple stakeholders involved with this topic will continue to play a key role in identifying and addressing research gaps, as well as making important linkages between managers and regulators.

*For more information on the literature reviewed to develop this Research Brief, visit: [Tethys]*

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