OFFSHORE WIND FACTS

MARINE MAMMALS & SEA TURTLES

What you should know:

- Almost all marine animals rely on sound to meet key biological needs, such as communication, orientation and navigation, predator avoidance, and feeding.
- Pile driving is a sound-producing activity in offshore wind development that has the potential to affect marine animals. Specifically, impact pile driving is used to install monopile and jacket foundations for wind turbines. Regulatory agencies require offshore wind developers to reduce the risk of auditory injury and behavioral disturbances through a variety of monitoring and mitigation strategies.
- Although there is public concern that sound from offshore wind pre-construction activities is contributing to whale deaths and strandings along U.S. beaches, there is currently no scientific evidence to support this claim. While offshore wind activities during pre-construction do produce underwater noise, the sounds are generally lower in intensity and less disruptive than those associated with oil and gas development or military applications.
- The most common sources of mortality and injury to marine animals are collisions with boats and entanglement in ropes used to secure or mark fishing gear. To reduce the risk of lethal collisions, vessels that are involved in offshore wind activities must observe various speed restrictions. Further, offshore wind survey vessels are required to have dedicated Protected Species Observers (PSOs) or trained lookouts on board to watch for marine mammals and sea turtles, a requirement that goes above and beyond those of most other marine activities.
- While not conclusively demonstrated in field studies, some marine animals and their prey may be sensitive to changes in electromagnetic fields (EMFs) from subsea power cables. Other disturbances, such as seabed preparation or effects on currents, may negatively affect key food sources or cause marine animals to temporarily avoid the wind farm area. This is discussed further below and in Coastal and Marine Habitats.
- Offshore wind developers can significantly reduce impact intensity through the use of specific technologies and installation methods. Restorative measures may also be implemented to help reestablish habitats, and the artificial reefs that form around turbine structures have the potential to improve localized biodiversity and ecosystem health.

Spotlight Question: Is sound from offshore wind farm pre-construction surveys harming or killing whales?

Public concern has emerged over the possibility that offshore wind farm pre-construction survey activities may be linked to recent increases in whale strandings and deaths along the U.S coast. These concerns were precipitated by the Unusual Mortality Event (UME) for humpback whales, which began in 2016 (National Oceanic and Atmospheric Administration Fisheries [NOAA Fisheries], 2023a). With elevated strandings reported along the entire East Coast, some have speculated that acoustic pulses generated by these surveys might impair marine mammals' hearing and affect their ability to navigate. However, the National Oceanic and Atmospheric Administration

Fisheries (NOAA Fisheries) has reported that there is no scientific evidence linking sound from offshore wind site characterization surveys to whale mortalities (NOAA Fisheries, 2023b; NOAA Fisheries, 2023c).

As of June 2023, 200 humpback whale mortalities have been recorded as part of the UME. NOAA Fisheries preformed full or partial necropsies on approximately 40% of the whales (examinations were not conducted on carcasses that were too decomposed, floating offshore, or stranded in inaccessible or protected areas). Among those examined, many of the mortalities were attributed to ship strikes or entanglement in fishing gear (2023b; 2023c). This is especially true off the coasts of New York and New Jersey, where more whales are occupying waters in some of the busiest shipping lanes on the East Coast. Notably, NOAA Fisheries has concluded that, to date, none of the necropsy results indicate a connection between these mortalities and sound from offshore wind activities. The rise in whale deaths may instead be linked to a combination of factors, including a rebounding whale population and changes in prey distribution due to climate change. As whales follow their prey into more favorable nearshore habitats and their populations continue to grow, the likelihood of interactions with vessels also increases.

Further, the sounds generated by offshore wind farm pre-construction surveys (further discussed below in the Underwater Sound section of this summary) are fundamentally different from those produced by seismic airguns used in oil and gas surveys or tactical military sonar. Offshore wind developers primarily use high-resolution geophysical (HRG) surveys for site characterization. Unlike seismic airgun surveys, which emit intense, low-frequency broadband sounds that overlap with the hearing range of acoustically sensitive marine animals, only a few HRG sound types are detectable by marine mammals. Furthermore, HRG sound pulses are transmitted for brief, intermittent periods and in a very narrow beamwidth that is directed toward the seafloor. Any high-frequency sounds used in HRG surveys attenuate very quickly in the water. As a result, both the sound levels and the area of exposure from offshore wind surveys are orders of magnitude less than those associated with seismic airguns or military sonar, which have been in use since the 1960s (NOAA Fisheries, 2023a; NOAA Fisheries, 2023b; Taddiken & Krock, 2021; Dellagiarino, 2001).

Despite regulatory agencies affirming that there are no scientific links between recent whale mortalities and offshore wind survey activities (Bureau of Ocean Energy Management [BOEM], 2023a; NOAA Fisheries, 2023b; NOAA Fisheries, 2023c), it remains essential to carefully assess potential impacts on marine life from offshore wind development. Monitoring is a standard part of the environmental review process for all projects and will continue, particularly in light of the ongoing UME. In addition, collaborative organizations, such as the Regional Wildlife Science Collaborative for Offshore Wind (RWSC) and the New York State Environmental Technical Working Group (E-TWG) play a crucial role by bringing together expertise and knowledge across disciplines. These efforts support federal and state regulators, industry developers, and other stakeholders in making informed, science-based decisions to ensure offshore wind energy is developed in an environmentally responsible manner.

A resource for further reading on this topic is the New York State Energy Research & Development (NYSERDA)'s Environmental Technical Working Group (E-TWG)'s FAQ on Offshore Wind and Whales.

Key Species and Federal Protections

Marine mammals and sea turtles comprise 38% of the 165 marine species listed under the Endangered Species Act (ESA), including subspecies and distinct population segments (NOAA Fisheries, 2023d; Valdivia et al., 2019). Several ESA-listed marine mammals are known to inhabit waters near major offshore wind energy areas along the East Coast, including the blue whale (*Balaenoptera musculus*), fin whale (*Balaenoptera physalus*), North Atlantic right whale (NARW) (*Eubalaena glacialis*), sei whale (*Balaenoptera borealis*), and sperm whale (*Physeter macrocephalus).* Endangered or threatened sea turtle species found near these areas include the green turtle (*Chelonia mydas*), Kemp's ridley turtle (*Lepidochelys kempii*), leatherback turtle (*Dermochelys coriacea*), and loggerhead turtle (*Caretta caretta*).

The Endangered Species Act (ESA) identifies plant and animal species that are endangered or at risk of extinction and provides enforceable tools designed to prevent extinction and foster recovery of these species and their habitats. Under the ESA, conservation is enforced and aided through:

- Protection from take;
- Assessment of projects for potential impacts to listed species and critical habitats (Section 7 consultation);
- Funding;
- Recovery plan development and implementation; and
- Critical habitat designation (Gibbs & Currie, 2012).

Congress passed the Marine Mammal Protection Act (MMPA) in 1972, establishing a national policy to prevent marine mammal species and population stocks from "declining beyond the point where they ceased to be significant functioning elements of the ecosystems of which they are a part". Under the MMPA, the term "take" is used to describe any activities that "harass, hunt, capture, or kill, or attempt to harass, hunt, capture, or kill any marine mammal" (16 U.S.C. 1362). The MMPA prohibits the take of marine mammals, with certain exceptions. Federal regulators may issue incidental take authorizations that allow for the unintentional take of marine mammals during specified activities, including commercial fishing, military exercises, scientific research, and offshore wind development (NOAA Fisheries, n.d.-b). A list of offshore wind applications for these authorizations are viewable on the NOAA Fisheries website.

North Atlantic right whales (NARWs) are one of the most endangered whales on the planet. With approximately 370 individuals remaining, including fewer than 70 reproductively active females, the species is approaching extinction. NARW's face significant mortality threats, primarily from fishing gear entanglement and vessel strikes, and have been experiencing an ongoing UME since 2017. Climate change further compounds these threats by altering their habitat, migratory patterns, and prey availability (NOAA Fisheries, n.d.-a). Due to their extreme vulnerability, offshore wind regulations and policies place a strong focus on protecting the remaining NARW population.

In January 2024, BOEM and NOAA Fisheries released the *North Atlantic Right Whale (NARW) and Offshore Wind (OSW) Strategy* to promote the species recovery while continuing the responsible development of offshore wind energy. The strategy outlines actions under three main goals: Mitigation and Decision-Support Tools, Research and Monitoring, and Collaboration, Communication, and Outreach. Coordinated efforts between BOEM, NOAA, the offshore wind industry, and expert partners aim to ensure that the best available science informs monitoring and mitigation. Immediate measures include avoiding lease areas with high NARW risk, setting construction-related noise limits, and providing guidance to developers on conducting robust sound field verification (for certain activities) to ensure that expected acoustic impacts are not being exceeded. The strategy is being considered a "living" document that will be regularly evaluated and updated as new data emerge. The full report is available on the BOEM website (BOEM-NOAA Fisheries, 2023).

Rice's whales (*Balaenoptera ricei*) are another critically endangered whale species, with likely fewer than 50-100 individuals remaining. Recently recognized as a distinct species, they inhabit a region near the Florida Panhandle in the Gulf of Mexico. Their core habitat lies along the northeastern shelf break near De Soto Canyon. However, sparse vocalizations have also been detected along the shelf break closer to two wind energy areas in the north-central Gulf (Soldevilla et al., 2022; NOAA Fisheries, 2025b). Rice's whales also fall victim to vessel strikes, entanglement, and climate change effects on prey availability. Additional risks include oil spills and other pollutants, including lingering effects of the Deepwater Horizon oil spill. For Rice's whales to recover, existing and emerging threats to the species and their habitat must be addressed (NOAA Fisheries, 2025b).

While some marine mammals and sea turtle populations appear to be recovering since their listing under the ESA (Valdivia et al., 2019), they remain vulnerable to population declines as human-induced stressors increase and tip the scales against their survival. As offshore wind energy development introduces additional structures and vessel activity to marine environments, it is critical to evaluate the cumulative effects on ESA-listed species to ensure their continued protection and recovery.

Climate Change Effects

Climate change is driving increases in ocean temperatures, sea level rise, ocean acidification, and more frequent and intense storms, all of which can significantly impact marine ecosystems. Melting ice caps and warming waters are altering the availability of suitable habitats and shifting the distribution of marine animals and their prey. Elevated atmospheric carbon dioxide (CO_2) levels contribute to ocean acidification, which may reduce the abundance of key prey species for marine mammals and sea turtles. For instance, between 1982 and 2018, the average center of biomass for 140 marine fish and invertebrate species along U.S. coasts shifted approximately 20 miles north and 21 feet deeper, likely in response to warming oceans (U.S. Environmental Protection Agency [EPA], 2023). These shifts can disrupt foraging patterns for marine mammals and sea turtles, forcing them to travel farther or deeper to find food.

Increased storm activity, such as hurricanes and extreme weather events, can damage critical habitats, disrupt migration routes, and displace animals from important feeding grounds. As prey distribution changes, the distance between breeding and feeding areas may grow, potentially reducing the overall health and reproductive success of migratory species, particularly those with narrow temperature ranges or dietary requirements (Hawkes et al., 2009; Leaper et al., 2006). While the full extent of climate-related impacts is still being studied, it is likely that marine mammals and sea turtles within current offshore wind energy areas are already experiencing climate stress and may be particularly vulnerable to its effects (Gulland et al., 2022; Patrício et al., 2021; Hawkes et al., 2009). To read more on the effects of climate change visit Climate Change.

Underwater Sound Overview

Since the Industrial Revolution, human use of the ocean has expanded dramatically, introducing increasing levels of sound into the marine environment through activities such as commercial shipping and fishing, geophysical exploration, military operations, scientific research, offshore construction, and recreation. As a result, ocean noise pollution has risen significantly over the past several decades (NOAA Fisheries, 2025a). Informed estimates suggest that underwater sound levels are now at least ten times higher than they were just a few decades ago.

This anthropogenic (human-induced) sound can range from high-intensity, acute events like underwater explosions to low-level, chronic sources such as engine noise from ships (Hildebrand, 2004). Depending on its characteristics, sound is typically classified as either impulsive or non-impulsive. These classifications, combined with the best available science on species-specific hearing abilities, help to predict and assess sound effects on marine life (NOAA Fisheries, 2024). Because some anthropogenic sounds overlap with the frequency ranges that marine animals use to communicate, navigate, and detect predators or prey, exposure to such sound can have harmful effects. These include auditory injury, masking of important sounds, or behavioral disturbances that disrupt vital biological processes (Southall et al., 2021).

To understand the implications of sound on marine animals, it is important to first gain an understanding of the underwater acoustic environment. A resource for further reading on this topic can be found on the NOAA Fisheries website.

Offshore Wind Effects

Offshore wind development plays a critical role in the global transition from fossil fuels to clean, sustainable energy. When planned and implemented responsibly, offshore wind development has the potential to mitigate climate change, reduce local and regional air and water pollution, and boost employment in the energy sector. However, these benefits can be offset by harms if the development is not conducted responsibly. Many of the habitats and species that may be affected by offshore wind development are already in a dynamic relationship with existing ocean uses, natural processes, and shifts due to climate change (Kershaw et al., 2023).

Underwater Sound

Offshore wind energy projects generate both in-air and underwater sound through a variety of activities and mechanisms, with sound levels varying across each phase of the project (Amaral et al., 2020). The offshore wind farm life cycle, which includes prospecting and site surveys, construction and installation, operation and maintenance, and decommissioning (Mooney et al., 2020; Musial & Ram, 2010), generates sound that can be detectable kilometers away from the site. Key sources of sound and vibration include pile driving, vessel traffic, survey equipment, dredging, and the operation of turbines (Nedwell et al., 2003).

The rapid global expansion of offshore wind development, coupled with the push for increased energy output, suggests a likely rise in the number, size, and scale of offshore wind turbines in the coming decades (Musial et al., 2021). Consequently, the cumulative sound generated by additional and larger turbines, as well as a potentially expanded fleet of service vessels, may pose greater impacts on acoustically sensitive species. Although data on the cumulative effects of sound from offshore wind activities remain limited, the offshore wind industry is implementing a range of agency-approved mitigation and monitoring measures, as outlined in the Mitigation and Monitoring Measures section of this summary.

Pile Driving

One of the sound-producing activities that has potential to impact marine animals is pile driving. Impact pile driving is a method used to install monopile and jacket wind turbine foundations. The installation of a monopile requires one large pile driven into the seabed, whereas jacket foundation installation requires multiple smaller piles (Norro et al., 2013). Impact pile driving creates considerable levels of low-frequency, impulsive sound which radiates into the environment. This has the potential to affect sensitive marine animals.

Vibratory pile driving is another method used to drive piles into the seafloor and may be used prior to impact pile driving to ensure that the pile is stable in the seabed (JASCO & LGL, 2019). Vibratory pile driving may also be used in the installation of a retaining wall made of steel sheet piles to construct temporary cofferdams, which are water-tight enclosures built around offshore structures to remove water from the work area during assembly (Tetra Tech, 2012). During vibratory pile driving, a pile is vibrated at a certain frequency, typically between 20 and 40 Hertz (Hz), to drive it into the sediment, as opposed to hammering it from the top (Matuschek & Betke, 2009). Although the vibratory process produces lower-level, continuous sound compared to the high-amplitude, impulsive noise generated during impact pile driving, it is still considered a potential impact and is regulated accordingly.

Underwater sound levels from pile driving, and the distance the sound travels, depend on several factors, including substrate characteristics, depth, water temperature, salinity, pile diameter, and size of the impact hammer (Figure 1). Sound levels also vary throughout the pile installation process, as increasingly forceful hammer strikes are needed to drive the monopile through deeper, denser substrates. As such, sound is typically loudest toward the end of the installation (Küsel et al., 2024). Field measurements have recorded sound pressure levels at 220 dB re 1 μPa at a range of approximately ten meters, and 200 dB re 1 μPa at a range of 300 meters, depending on the pile size (Reinhall & Dahl, 2011). These sound pressure levels do exceed established marine mammal and sea turtle injury and behavioral disturbance thresholds, thus having the potential to cause such impacts (Table 1).

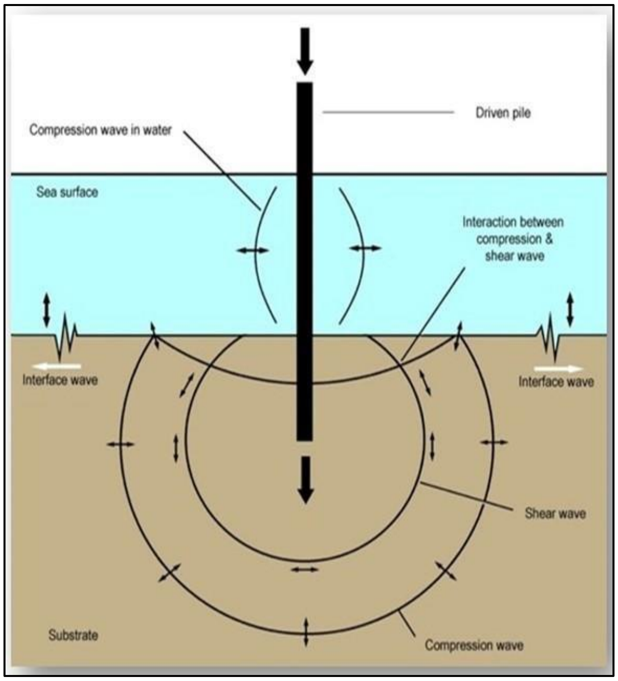

Figure 1. Diagram of sound waves generated by pile driving (Hawkins, 2022).

Table 1. Acoustic criteria for impulsive sources

Faunal Group	**PTS/Injury Thresholds**[1]		**TTS Threshold**[2]		**Behavioral Threshold**
	L-pk	SEL	L-pk	SEL	SPL
Low-frequency cetaceans	222 dB	183	216 dB	168	160 dB
High-frequency cetaceans	230 dB	193	224 dB	178	160 dB
Very High-frequency cetaceans	202 dB	159	196 dB	144	160 dB
Phocid pinnipeds (in water)	223 dB	183	217 dB	170	160 dB
Otoriid pinnipeds)(in water)	230 dB	185	224 dB	148	160 dB
Sea Turtles	232 dB	204	226 dB	189	175 dB

dB = decibel
Cetaceans = a subgroup of marine mammals consisting of dolphins, porpoises, and whales
Phocid pinnipeds = a subgroup of marine mammals consisting of the earless or “true seals” from the Family Phocidae
PTS = permanent threshold shift referenced to 1 μPa^2 s and equivalent to Lpk = zero-to-peak sound pressure level; TTS = temporary threshold shift; SPL = root-mean-square sound pressure level referenced to 1 μPa, SEL = sound exposure level
[1]PTS/injury thresholds are defined here as onset of PTS in marine mammals (NOAA Fisheries 2024) and sea turtles (Finneran et al., 2017)
[2]TTS thresholds are defined here as onset of TTS in marine mammals (NOAA Fisheries, 2024 and sea turtles (Finneran et al., 2017)

Potential behavioral effects of pile driving sound include avoidance and displacement from affected areas (Dähne et al., 2013; Lindeboom et al., 2011; Russell et al., 2016; Scheidat et al., 2011; National Science Foundation [NSF] & U.S. Geological Survey [USGS], 2011; Samuel et al., 2005; Southall et al. 2021). Potential physiological effects include a temporary threshold shift (TTS) or permanent threshold shift (PTS) in an animal's hearing ability when exposed to pile driving sound at close range. Most behavioral and physiological effects (e.g., stress responses and TTS) are expected to be short term and limited to the duration of the pile driving activity. However, chronic exposure to pile driving sound could lead to displacement from a critical feeding, breeding, or migratory area, potentially resulting in long-term effects on an individual or population (New et al., 2013; Nowacek et al., 2015; Forney et al., 2017).

Regulatory agencies require offshore wind developers to mitigate potential auditory injuries or behavioral disturbances to marine life through a range of monitoring and mitigation strategies. These strategies include establishing site-specific exclusion and harassment zones, employing PSOs, and reducing or delaying pile driving activities if marine mammals or sea turtles are detected within potential injury zones. Additional effective mitigation strategies include implementing seasonal or time-of-year restrictions on survey and construction activities, particularly during periods when at-risk species are present in high densities (Marine Mammal Commission [MMC], 2023).

The application of noise abatement systems (NAS) is particularly effective in reducing the overall acoustic energy and helping ensure sound exposure does not exceed injury and behavioral disturbance thresholds for animals that may be within range of pile driving activities (Buehler et al., 2015; Bellmann et al., 2020). While a combination of NAS (e.g., big bubble curtain, hydrosound dampers, noise mitigation screens, etc.) and noise-optimized pile driving techniques (e.g., time-limited pile driving duration and reduced hammer energy) can have an additive effect in overall sound reduction (Bellmann et al., 2020), further technological advancements are needed to significantly reduce impacts on marine mammals and sea turtles during offshore wind construction. Additional mitigation measures commonly implemented by offshore wind developers, along with innovative technologies that may be adopted in the future, are discussed in detail under the Mitigation and Monitoring Measures section below.

Vessel Noise

Another significant source of underwater sound associated with offshore wind development is vessel noise. Global maritime traffic has steadily increased over recent decades, with the world fleet now consisting of approximately 109,000 vessels weighing at least 100 gross tons (United Nations Conference on Trade and Development [UNCTAD], 2024). Although vessels servicing offshore wind operations contribute only marginally to this global increase, they still add to the overall increase in vessel traffic.

Offshore wind farms typically required different types of vessels across all phases of the project, including construction barges, support tugs, jack-up rigs, crew and supply vessels, and cable-laying vessels (Miller et al., 2018). During the operational phase, routine maintenance on turbines and transformer stations (generally conducted annually) can contribute to vessel-related noise. Sound levels from decommissioning vessels are expected to be similar to those generated during the construction phases. These vessel activities have been shown to elevate ambient sound pressure levels by 20– 30 dB within one kilometer of the turbine site (Bailey et al., 2010). While vessel noise emits lower frequencies than those produced by other high-intensity sound sources, its continuous nature and greater propagation range can cause marine animals to experience behavioral disturbances, stress responses, and acoustic masking (Erbe et al., 2018, 2019; Nowacek et al., 2007; Southall et al., 2007; Southall et al. 2021). Further these low frequencies do overlap with the auditory and vocalization ranges of many marine mammals (Piniak et al., 2012).

It is important to note that the broader impact of vessel noise is not unique to offshore wind develop, as many other maritime activities, development, and infrastructure contribute to this growing source of underwater sound.

Site Characterization Surveys

Prior to the construction of an offshore wind farm, developers must conduct detailed seabed scans to assess the geology of potential turbine installation sites. High-resolution geographic (HRG) surveys use sound to produce acoustic images of the seafloor and shallow geophysical features. These surveys help identify marine-protected species and habitats, as well as shipwrecks and archeological sites (Figure 2). HRG equipment, such as sparkers and boomers, do operate at lower frequencies that fall within in the hearing range of whales. However, the sound sources used in HRG surveys are significantly different from seismic air guns employed by the oil and gas industry. Seismic air guns are designed to penetrate deep into the seafloor and generate very high-energy, high-intensity sound levels (around 260 dB) (Hildebrand, 2004). In contrast, HRG sound sources are much lower in energy, typically around 220 dB (Ruppel et al., 2022; Crocker & Fratantonio, 2016).

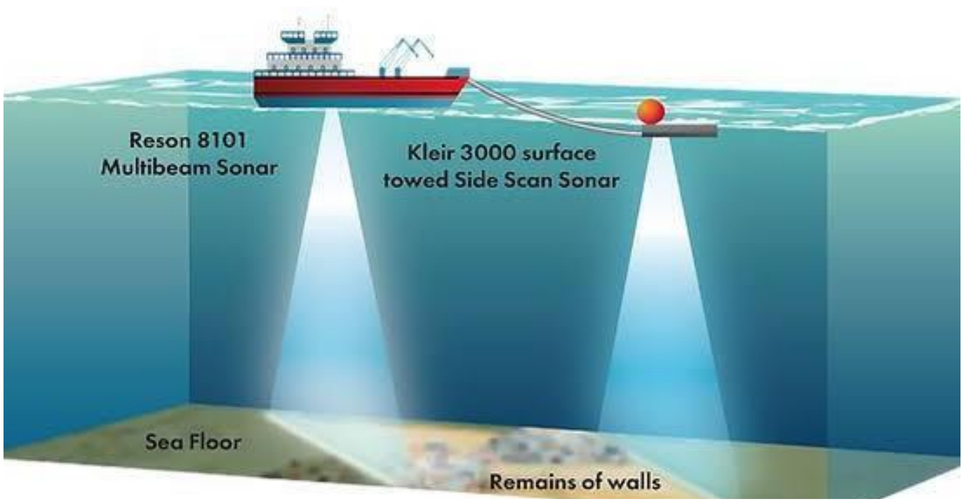

Figure 2. Conceptual illustration of typical High Resolution Geophysical (HRG) Surveys for O&G Exploration, Renewable Energy Siting, and Sand and Gravel Resource Identification. (BOEM, 2023b)

Unlike seismic airguns, which emit sound in all directions, HRG sound sources have a very narrow, focused cone of sound. As a result, an animal would have to be directly underneath the sound source for very long periods to reach exposure levels that could cause disturbance. Any high frequency sounds used in HRG surveys attenuate very quickly in seawater, meaning they travel much shorter distances compared to lower frequency sounds produced at the same amplitude. Additionally, some of HRG surveys are conducted with the source being towed or operated autonomously just above the sea floor, further limiting the size of the ensonified area (Ruppel et al., 2022). Given the high mobility of marine mammals and sea turtles, they are likely to avoid these areas and therefore avoid major impacts. If animals do encounter HRG activity, the most likely effects would be temporary displacement as they change their swimming speed or direction, or behavioral disturbances such as changes in vocalization patterns.

NOAA Fisheries asserts that there is currently no scientific evidence linking sound from offshore wind site characterization surveys to whale deaths. While equipment used for HRG surveys can produce sound that may disturb marine mammals, it does not cause auditory injury. Moreover, the area over which these sounds might disturb a marine mammal is orders of magnitude smaller than the impact areas associated with seismic airguns or military sonar (NOAA Fisheries, 2023b).

Site Preparation

Sound sources associated with site preparation for offshore wind development include those generated during cable laying and dredging activities (Nedwell & Howell, 2004). Cable laying produces sound thorough activities such as trenching, jet plowing, backfilling, and the installation of cable protection. Dredging, often used for sand wave clearance, involves the use of a hydraulic suction dredger to remove or relocate seabed sediment. The sound produced by hydraulic dredging results from the combination of impact and abrasion of the sediment passing through the dredger's internal components, and the sound of the dredger's motors. The frequency of the sounds produced by hydraulic suction dredging ranges from approximately 1 to 2 kilohertz, with reported source levels of 172 to 190 dB re 1 µPa at 3.3 feet (1 meter) (Robinson et al., 2011; Todd et al., 2015; McQueen et al., 2020). Prolonged exposure to dredging noise could lead to avoidance behaviors or communication masking in marine mammals (Todd et al., 2015; NOAA Fisheries, 2018; Pirotta et al., 2013) and sea turtles (Popper et al., 2014). Such effects can negatively impact these organisms by causing them to expend energy inefficiently. However, because site preparation is temporary and many marine animals are highly mobile, the risk of long-term disturbance is low. In fact, studies of cetaceans in and around the construction of European offshore wind farms show that while animals can and do leave the area during construction, they tend to return after the activities have concluded (Lindeboom et al., 2011).

Operational Sound

While offshore wind operational sound levels are considered relatively low compared to noise generated during construction, they do persist over the life of the wind farm and can extend 1-2 kilometers from the turbine site before being masked by ambient noise (Stöber & Thomsen, 2021). Wind turbines projected for deployment in U.S. waters are expected to be larger, up to 15 MW, compared to the average 7.4 MW turbines installed previously (Musial et al., 2021). As turbine size increases, so does the amount of sound each unit generates, highlighting the need for further research on potential impacts of larger turbines. Some wind farms consist of 100 or more turbines, and with the spatial expansion of future developments, understanding the cumulative effects of operational sound from multiple turbines across a broad area becomes increasingly important.

Operational sound of wind turbines is not expected to cause injury or hearing impairment. However, it could alter habitat suitability by changing the ambient acoustic environment within and around a wind farm (Figure 3). Depending on an animal's hearing sensitivity and its ability to adapt to low-intensity changes in the sound environment, operational noise could influence behavior, interfere with communication, or reduce feeding efficiency under certain conditions, particularly in areas within a few hundred feet of the foundations (Koschinski et al., 2003; Madsen et al., 2006; Betke et al., 2004).

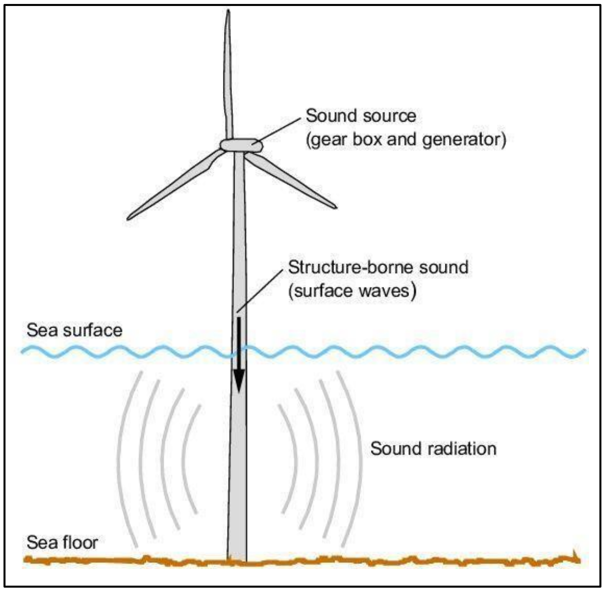

Figure 3. Mechanism of underwater noise generation by an offshore wind turbine (Betke et al., 2004).

Additional sound reduction technologies are being studied, including methods to reduce mechanical noise from wind turbines by properly shielding the nacelle (i.e., the drivetrain housing component), using sound-dampening buffer pads, suppressing vibrations, and incorporating direct drive technology (Betke & Bellmann, 2023; Jianu et al., 2012; Stöber & Thomsen, 2021). Recent advancements in offshore wind turbine design have also led to a significant reduction of overall sound by incorporating more streamlined and aerodynamic features (i.e., rounding protruding features of the towers and nacelle) (Deshmukh et al., 2019).

Risk of Vessel Strikes

Vessel strikes involving marine mammals and sea turtles are associated with vessels of all types and sizes, including commercial shipping. In most areas, offshore wind development will only increase vessel traffic by a small fraction. During construction, vessel trips to offshore wind farms are estimated at 1-15 per day, decreasing to 1-3 per day during periodic maintenance cycles in the operational phase. In comparison, over 60,000 commercial vessels already transit the sea each year (Equasis, 2015), making the additional traffic from each wind farm relatively negligible.

To mitigate the risk of vessel strikes, particularly to the North Atlantic right whale (NARW) off the U.S. East Coast, NOAA Fisheries proposed a vessel speed rule (73 Fed. Reg. 60173) for all vessels greater than or equal to 65 feet in length (NOAA Fisheries, 2008). The rule went into effect in 2009. In September 2022, NOAA Fisheries proposed amendments to the existing rule to include smaller vessels, increase the size of speed-restricted zones, and make voluntary dynamic speed areas a requirement (87 Fed. Reg. 46921). Offshore wind survey and construction vessels, regardless of size, are required to adhere to the rule and transit at a speed of 10 knots (kt) or less throughout the ten designated seasonal management areas (SMAs) between Massachusetts and Florida. This speed restriction also applies to voluntary Dynamic Management Areas (DMAs), which are activated when groups of three or more foraging NARWs are observed outside the boundaries of an active SMA.

Risk of Entanglement

Entanglement risks related to offshore wind development are typically categorized into two types:

primary entanglement and secondary entanglement. Primary entanglement occurs when marine life becomes directly entangled in offshore wind farm infrastructure, such as power cable systems or mooring lines. Secondary entanglement refers to marine life entanglement in marine debris, such as derelict fishing gear, that becomes ensnared on project equipment or accumulates around the wind farm (U.S. Offshore Wind Synthesis of Environmental Effects Research [SEER], 2022a).

Floating offshore wind, a newer technology in which turbine foundations are not fixed to the sea floor, introduces a higher potential risk of marine life entanglement due to its extensive underwater mooring and subsea power cable systems. Although this technology is still in the early stages of development, several environmental organizations have issued a set of *Recommendations to Reduce the Potential Risk of Entanglement of Marine Life During Floating Offshore Wind Energy Development*. Released in October 2022, this guidance is available on the National Renewable Defense Council (NRDC) website. For a more detailed discussion on primary and secondary entanglement and offshore floating wind, see this SEER research brief.

Offshore wind developers are required to implement mitigation measures to reduce the risk of marine life entanglement during site characterization and monitoring surveys. Entanglement risk is typically minimized by keeping all mooring lines at the shortest practicable length and using rubber sleeves or similar devices to prevent lines from looping around or entangling large marine animals. Monitoring survey vessels that deploy fixed fishing gear (i.e., trap or pot sampling gear deployed on the seabed) must carry disentanglement equipment and follow established protocols for the safe release of any marine mammal or sea turtle. Fish population surveys are typically conducted using short trawls at slow towing speeds, significantly reducing the risk of entanglement. Any incident involving the entanglement of a protected species must be reported to the National Marine Fisheries Service (NMFS) within 48 hours.

Electromagnetic Fields

Electromagnetic radiation, including low-frequency electromagnetic fields (EMFs), is generated from both natural and anthropogenic sources, such as the Earth's geomagnetic field, thunderstorms, power cables, and common household electronics. Offshore wind farms use a variety of subsea power cables for intra-turbine connections, array-to-transformer links, and transformer-to-shore transmissions (Ohman et al., 2007). These subsea power cables generate EMFs that may contribute and interact with existing sources of electric and magnetic radiation already present in the environment.

Marine mammals and sea turtles are capable of detecting magnetic field gradients under 0.1 percent of the Earth's magnetic field (Kirschvink, 1990; Normandeau et al., 2011). Since the expected magnetic fields from existing and proposed subsea power cables exceed this level, it is likely that these animals can detect even minor changes and may respond to local variations in geomagnetic fields associated with cable-generated EMFs (Normandeau et al., 2011; Walker et al., 2003). Laboratory and field studies have shown that sensitive marine species may exhibit altered behavior in the presence of EMFs, but the level of disturbance appears to be too limited to affect migration patterns or to keep animals from their preferred habitats. In other words, the ability to detect or respond to the presence of EMFs does not necessarily mean there will be impacts to a species or life stage (Copping & Hemery, 2020). Currently, conclusive evidence of impacts is insufficient and additional research is needed.

In the interim, offshore wind developers are required to implement mitigation measures to minimize potential impacts from EMFs and heat generated by subsea power cables. One key strategy involves careful siting when planning cable routes to avoid areas of special ecological interest. Permit conditions also mandate that cables be buried at appropriate depths, typically between three to six feet, which can reduce magnetic field strength at the seafloor by approximately four-fold (BOEM, 2020a). In areas where sufficient cable burial is not feasible, power cables may be protected using alternative methods such as 6- to 12- inch-thick concrete mattresses, rock berms, or other barriers to protect the cable and reduce EMF emissions. Additional mitigation techniques include helically twisting AC cables, which causes parts of the EMF to cancel each other out, lowering overall emission. For DC power cables, grouping them together can help keep EMF effects more localized and limited (Hermans & Schilt, 2022).

Presence of Structures

Artificial Reefs

Offshore wind structures can act as artificial reefs, providing hard substrates for biofouling communities (organisms including bacteria, algae, and invertebrates that attach to submerged surfaces forming complex ecosystems), and aggregating fish and invertebrates (Degraer et al., 2020; Krone et al., 2017; Langhamer & Wilhelmsson, 2009). Studies at sites such as the Block Island Wind Farm have identified a consistent pattern in the development of these communities: dense accumulations of mussels commonly colonize these novel offshore wind infrastructure surfaces (De Mesel et al. 2015; BOEM2020b; Hutchison et al. 2020). These taxa serve as a food source for fish (Wilber et al. 2022) and opportunistically colonize adjacent subtidal hard- and soft-bottom habitats (BOEM2020b).

These offshore structures may also benefit marine mammals and sea turtles by providing localized increases in food availability and shelter, particularly in areas where natural habitat may be scarce. For example, tagged pinnipeds along the British and Dutch coasts of the North Sea have been observed systematically utilizing the areas around turbine structures to forage (Russell et al., 2014). Similarly, loggerhead and leatherback sea turtles may benefit from higher concentrations of prey, such as mollusks and crabs, near these structures, suggesting their potential role as foraging areas. For more information on the reef effect created by added foundation substructures, refer to the Fish and Invertebrates and Coastal and Marine Habitat sections.

Hydrodynamics

Extensive research has been conducted to characterize and model atmospheric wakes created by offshore wind turbines. These studies inform wind facility layout design and help predict seabed scour zones. However, comparatively little research has analyzed how hydrodynamic wakes, particularly coupled with changes in atmospheric wakes, interact with the water column. While it is an active area of research, only a few studies have explored the influence of these wakes on regional scale oceanographic processes and the potential secondary effects on primary production and ecosystem dynamics.

A recent evaluation by the National Academies of Science Engineering and Medicine (NASEM) focused on the Nantucket Shoals region, an ecologically significant area for the NARW, to assess how offshore wind development could alter local hydrodynamic processes and affect prey abundance and availability (NASEM, 2023). The study concluded that while offshore wind projects may have some impact, distinguishing these effects from the broader and more significant impacts of climate change and other ecosystem stressors will be challenging. Further monitoring with sufficient spatial and temporal coverage will be necessary to adequately understand the impact of future wind farms. To learn more on offshore wind impacts on ocean hydrodynamics, see Deeper Dive: Ocean Hydrodynamics, Offshore Wind Farms, and the Mid-Atlantic Bight Cold Pool in the Resources section or see the Spotlight Question in Coastal and Marine Habitats.

Other potential impacts to biological resources are discussed in the Fish and Invertebrates and Coastal and Marine Habitat sections.

Mitigation and Monitoring Measures

While some effects may be unavoidable, all potential impacts from offshore wind projects are assessed within a mitigation framework aimed at avoiding, minimizing, or reducing adverse effects to the greatest extent possible. Offshore wind development is subject to federal, state, and local regulations. As part of the permitting process, developers must implement a variety of agency-approved mitigation measures to reduce or prevent potential project-related impacts.

Below is a summary of both conventional and innovative mitigation strategies used to address the most significant offshore wind activities, such as construction noise and vessel traffic.

Construction, Operation, and Decommissioning Sound

To minimize the effects of sound generated by offshore wind development, offshore wind developers use several mitigation and monitoring techniques developed and agreed upon during the permitting process. These strategies include:

- Shutdown and clearance zones: These zones are maximum safe distances customized to specific animal hearing groups and activities. They are monitored using visual and acoustic (i.e., Passive Acoustic Monitoring) detection. In addition, PSOs are deployed on offshore wind vessels to monitor for protected species and work with the vessel crew to initiate mitigation measures when necessary. If animals are detected within these zones, the project activities are paused until the animals move beyond of the zone of impact.
- Noise abatement systems (NAS): Quieting technologies such as bubble curtains and hydro sound dampeners are employed during noise-generating activities. These systems are considered to be particularly effective in reducing the overall acoustic energy introduced into the environment.
- Soft-start or ramp-up procedures: Gradual increases in hammer energy are implemented to deter marine mammals and sea turtles from the activity area. This gradual increase in sound level helps reduce the likelihood of startling animals with sharp, sudden changes in the sound field and gives them an opportunity to move out of the area before noise increases to higher levels (Discovery of Sound in the Sea [DOSITS], 2023).
- Dynamic restrictions: Time-of-year, time-of-day, and spatial-temporal data are used to restrict activities like pile driving during critical periods, such as marine mammal or sea turtle foraging times or migratory seasons. These restrictions help to protect vulnerable and endangered species, including the critically endangered NARW.
- Alternate foundation types and installation innovations: Future offshore wind projects may adopt alternative foundations types, such as gravity bases and suction caissons. While these foundations can reduce sound output during installation, their larger seabed footprint and potential impact on benthic habitats would need to be weighed against the benefits of reduced acoustic disturbance (Merchant, 2019). Advancements in monopile installation techniques, such as “Blue Piling Technology”, use gas combustion-generated pressure to accelerate a large column of water into the pile head, resulting in a longer blow duration. This method can potentially reduce sound levels by up to 20 dB compared to conventional hammers (IQIP, 2023).

Vessel Interaction

- There is a significant positive correlation between vessel speed and the probability that a vessel strike will be lethal. Speed restrictions, particularly those reducing speeds to 10 knots, can lower both the risk of strikes and the severity of injuries (Redfern et al. 2024).

- Vessel speed restrictions can also reduce underwater sound levels. However, the trade-off is that slower vessels may result in prolonged noise exposure and an increase in vessel transit time.
- Future offshore wind development may incorporate ship-quieting technologies such as propeller and hull modifications, as well as propeller blade injection systems that reduce propulsion sound by injecting air through the propeller blades. Noise from onboard machinery can also be minimized through vibration control measures, strategic placement of equipment within the hull, and optimized foundation structures (International Maritime Organization [IMO], 2014). Additionally, retrofitted design modifications intended to improve energy efficiency may also contribute to reduced sound levels (Gassmann et al., 2017).
- Maintaining appropriate vessel distances, with the aid of visual detection and real-time Passive Acoustic Monitoring (PAM) of marine mammals and sea turtles, helps reduce the risk of strikes by aiding vessels in avoiding critical habitats and dynamic feeding or foraging areas (i.e. jellyfish aggregations and floating vegetation). Visual detection and real-time PAM can also help identify exclusion zones and set vessel regulations (e.g. Dynamic or Seasonal Management Areas).
- PSOs are deployed on all offshore wind vessels to monitor for protected species during vessel transit, helping to avoid potential strikes (RPS, 2023).
- Vessels involved in offshore wind projects are required to follow BOEM best practices and guidelines to minimize interactions with protected species when conducting fisheries surveys (BOEM, 2023c). These practices include using the best available mooring systems and following protocols for the recovery of lost or derelict survey gear; thus, reducing the accumulation of marine debris that could pose entanglement risks. Additional measures include equipping vessels with appropriate disentanglement tools and ensuring that personnel are trained in regional protocols for disentanglement, resuscitation, handling, and reporting of animals that are incidentally caught.

Future Directions

Continued Mitigation and Adaptive Management

With the significant momentum that offshore wind development has had in recent years, continued advancements in mitigation and adaptive management strategies are essential to minimize future environmental impacts. As outlined in the previous section, mitigation strategies already employed by offshore wind projects have the potential to minimize environmental stressors. Additional innovations, including sound-reducing turbine designs, protective construction measures, and improved foundation technologies can further reduce such impacts. Integrating multiple mitigation and monitoring strategies, including real-time PAM systems, underwater drones, and satellite technologies, alongside current mitigation standards, can enhance and optimize the offshore wind industry’s ability to effectively assess and mitigate impacts while supporting adaptive management practices.

Research and Monitoring

Climate change may drive species to migrate in search of suitable habitats, potentially leading to displacement. Continuous research, combined with strategic site selection, is therefore critical to minimize and address any additional displacement effects caused by offshore wind development. Comprehensive assessments and monitoring across multiple taxa provide a deeper understanding of potential interactions and cumulative stressors on marine life, help identify data gaps, and support the development of more targeted conservation measures.

Data Sharing and Standardization

Another important aspect to consider is the standardization of data collection and sharing protocols from dedicated monitoring activities in offshore wind areas, ensuring alignment with regional standards (RWSC, 2024). Data that can be integrated into future regional-scale meta-analyses, species and habitat modeling, and other relevant studies will be vital for policymakers and managers in developing informed and adaptive management strategies.

Collaborative stakeholder engagement, incorporating best practices and lessons from previous projects, and integrating new technologies for adaptive decision-making will contribute to more resilient and sustainable offshore wind development.

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