Empire Wind: Enhancing Marine Mammal Monitoring in Offshore Wind Construction

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Abstract

Offshore wind energy is rapidly advancing, bringing new challenges in marine mammal monitoring and mitigation. In the Empire Wind I (EWI) offshore wind farm, innovative approaches have been sought to address these issues, raising the standard for balancing renewable energy development with environmental stewardship. In 2022, a panel of experts provided detailed baseline information on cetaceans in the New York Bight and guidance on state-of-the-art detection technologies. This led to a strategy that goes beyond regulatory compliance to achieve lower impact and improve detectability of potentially affected animals, involving protected species observers, passive acoustic monitoring, and sound

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field verification. Data from these oversight activities will be combined with operational logs and spatiotemporal information, offering detailed insights into the project's phases. The datasets will be accessible for research to address critical data gaps and evaluate effectiveness of mitigation measures. By combining cutting-edge technologies with a commitment to transparency and collaboration, this approach sets a unique precedent for how offshore wind projects can align renewable energy goals and marine research.

Keywords

Offshore wind · Marine mammals · Pile driving · Mitigation · Empire Wind

Introduction

As the world races to adopt renewable energy solutions to combat climate change, offshore wind farms are emerging as a key player. Multiple technical designs have been developed over the last decade, with a significant push toward larger commercial-scale wind farms. The rapid expansion of offshore wind energy is not just a technical and economic challenge but also an ecological one. Though government-designated lease areas are generally established taking into consideration the location of essential habitats for threatened or endangered species, concerns about potential impact on marine ecosystems remain. Direct physical disturbance (e.g., altered benthic and pelagic habitats) and underwater noise have been identified as the main pressures from offshore wind energy (Galparsoro et al. 2022), and therefore, many regulatory agencies enforce strict requirements for developers to mitigate impacts. Noise (i.e., anthropogenic sound) generated as a byproduct of the construction of offshore wind is of particular concern with regard to the protection of species of high auditory sensitivity such as marine mammals, fish, and species of conservation concern (CSA Ocean Sciences Inc. 2023). The construction phase is therefore the most critical for considering impacts on these groups due to pile driving and increased vessel traffic during the installation of bottom-fixed foundations (Dolman and Simmonds 2010). During operation, underwater sound levels are unlikely to reach dangerous levels or mask communication (Tougaard et al. 2009), though little is known about the long-term and cumulative acoustic effects of offshore wind farms.

Passive acoustic monitoring (PAM) has been the preferred method for recording ambient noise levels and monitoring noise impacts on marine species. For mitigation, the inclusion of PAM alongside visual data collection provides the most accurate assessment of species presence, particularly when aiming for high detection rates (Van Parijs et al. 2021). PAM provides long continuous time series with low spatial resolution, while visual surveys provide snapshots with low temporal resolution but high spatial resolution (Van Parijs et al. 2021). Therefore, a combination of methods is generally advisable.

The specific species of concern vary across regions, depending on their occurrence and protection status. The United States, for instance, is widely regarded as having some of the strictest regulations in the world for offshore wind development and marine mammal protection. US regulations, such as those enforced under the Marine Mammal Protection Act (MMPA), the Endangered Species Act (ESA), and the National Environmental Policy Act (NEPA), impose clear requirements to assess, monitor, and mitigate potential impacts on marine mammals and other protected species. Of particular concern is the critically endangered North Atlantic right whale (NARW, *Eubalaena glacialis*), with 384 individuals remaining (Linden 2025), enduring major threats such as entanglements in fishing gear and vessel strikes (Pettis and Hamilton 2025). Measures such as reduction of vessel speed, engagement of protected species observers, and passive acoustic monitoring have been implemented in critical areas for the species (BOEM and NOAA 2024). Still, the level of protection needed for NARWs to also account for the impacts of climate change, which contributes to changes in habitat as well as in prey availability and consequently affects migratory patterns, highlights the urgency in ensuring a sustainable balance between protecting marine wildlife and the global transition to renewable energy. The road to recovery for NARWs and protection of other marine species is complex and relies on identifying effective mitigation measures, integrating regulatory efforts, and using advanced research and monitoring strategies. Previous literature has shown a gap between perceived/modeled and actual risks, with the former arising from uncertainty or lack of data about the real environmental impacts of ocean renewable energy (Galparsoro et al. 2022). This uncertainty highlights the importance of robust data collection and scientific research to inform decision-making and refine mitigation strategies. Without a comprehensive understanding of the ecological impacts, both regulators and developers face challenges in minimizing direct impacts while addressing stakeholder concerns and ensuring that offshore wind projects remain viable and achieve their intended environmental and societal benefits. To address these challenges, this paper presents the strategy for the development of Empire Wind I, an offshore wind farm located in New York Bight. This project is a significant step in the US offshore wind industry and represents an opportunity to gather high-quality data on the environmental impacts of offshore wind development. The data collection process for Empire Wind I is designed to provide a detailed perspective on the different phases of construction and operation, with a focus on marine mammals, sea turtles, and fish mitigation. Through the gathering of information useful to scientific research, Empire Wind I aims to contribute to the growing body of literature on offshore wind and its interactions with marine ecosystems while setting a precedent for future projects to balance renewable energy development with marine conservation.

Approach

In 2017, Statoil Wind US LLC (now Equinor Wind US LLC) acquired the lease for the Bureau of Ocean Energy Management (BOEM) Lease Area OCS-A 0512. The Empire Wind 1 Project, an 810-megawatt offshore wind farm, is now being developed in the Lease Area by Empire Leaseholder LLC and Empire Offshore Wind LLC, affiliates, and subsidiaries of Equinor ASA. The project is located 15–30 miles

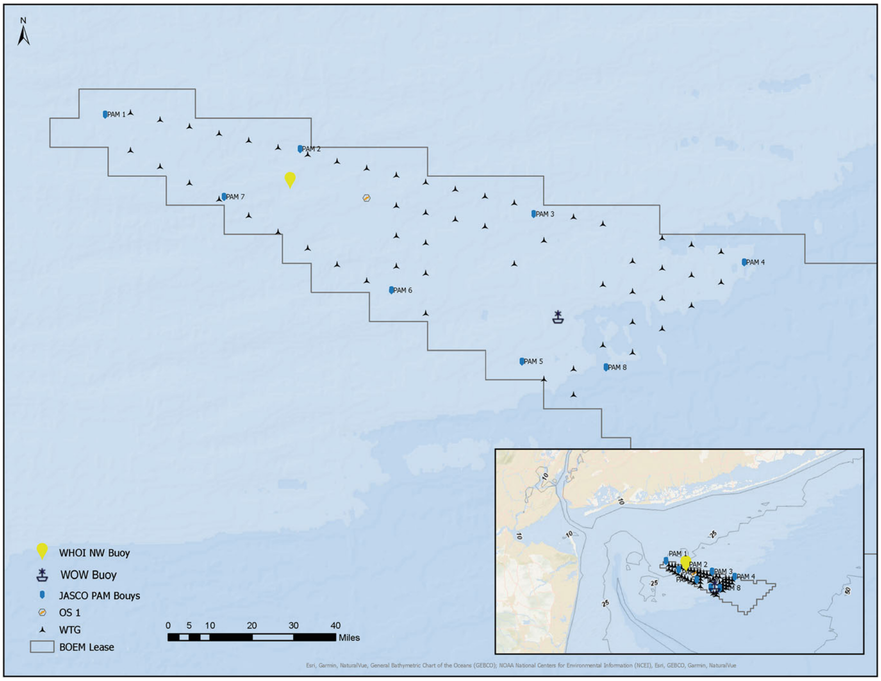

Fig. 1 Map of the lease area for Empire Wind I, highlighting the location of the turbines (WTG), PAM stations for marine mammal monitoring, and ongoing PAM research collaboration stations. (Source: © Empire Wind)

southeast of Long Island, NY, and spans 80,000 acres (Fig. 1), with water depths between approximately 23 and 41 m. The developer promptly started a program of marine biodiversity information gathering about the region, and by 2019, it had established a collaboration with the Woods Hole Oceanographic Institution (WHOI) and the Wildlife Conservation Society (WCS) to collect passive acoustic data on marine mammals. The focus to not just address regulatory mandates but also align with broader conservation goals and scientific priorities has been implemented throughout the entire process leading to and including offshore construction in 2025. To ensure high-value data acquisition, high detection capability, and low environmental impact, several stages are encompassed during the development of Empire Wind I; they include pre-construction, mitigation strategies and implementation, data acquisition, and long-term perspectives. Each stage is described below, outlining the background, methodology, and outcome of monitoring procedures.

Pre-Construction

The scientific collaboration with WHOI and WCS to develop and expand the PAM program provided valuable temporal and spatial coverage of the lease area. Two buoys detected and classified vocalizations of four whale species (fin whales, *Balaenoptera physalus*; humpback whales, *Megaptera novaeangliae*; NARW, *Eubalaena glacialis*; and sei whales, *Balaenoptera borealis*) in near real-time and archive recordings for further analysis. This effort established a baseline of whale acoustic occurrence, possible differential habitat use, and seasonal, inter-annual, and diel trends. Further, in compliance with regulations by the Bureau of Ocean Energy Management (BOEM) and National Oceanic and Atmospheric Administration (NOAA), noise impact and exposure assessments have also been conducted during the permitting phase, through acoustic modeling and analyses to estimate the potential acoustic impact ranges on high-, medium-, and low-frequency cetaceans as well as sea turtles and the Atlantic sturgeon (*Acipenser oxyrinchus*) (BOEM 2023), which are federally listed under the Endangered Species Act (ESA).

Mitigation Strategies and Implementation

Three years prior to construction, Empire Wind I consulted with a panel of leading marine mammal experts, whose input has been instrumental in designing a monitoring and mitigation approach that reflects the best available technology and updated knowledge. This collaborative effort ensured that the project generated robust, high-resolution datasets on marine mammal presence and behavior, both within and beyond regulatory compliance by testing the feasibility and effectiveness of combining multiple monitoring technologies, including near real-time PAM systems. With low impact and high detectability as a goal, the expert panel assessed the potential of visual and digital (video and infrared) surveys; 3D sonar; manned aerial surveys; satellite and autonomous aerial, surface, and underwater vehicles; tethered systems; and moored PAM and sonobuoys (Boebel et al. 2024; Baumgartner 2025). The outcome of the expert panel review and the baseline data collection, together with permit requirements, was a set of operational and technological measures that included: (1) seasonal operational restrictions, with no pile driving from January through April to avoid co-occurrence with NARW and other protected species' migration; (2) a set of clearance and shut-down zones for mitigation of pile-driving operations on marine mammals (Fig. 2); and (3) a multilevel approach where all zones are monitored using three on-duty Protected Species Observers (PSOs) onboard the pile driving vessel and an additional three onboard a dedicated PSO vessel, and near real-time data from three active PAM buoys (eight in total, JASCO OceanObserver™). Each PAM buoy mooring includes an array of four hydrophones with a sample rate of 32 kHz, placed on the seafloor and attached to a surface buoy, relying on automated contour-following detector-classifiers and human validation. Noise impact and exposure assessments assessed during the permitting phase were also validated during installation at designated ranges from each foundation using sound field measurements (i.e., sound field verification, using JASCO AMAR G4 hydrophones with a bandwidth range of 10 Hz-32 kHz).

Double Big Bubble Curtains (DBBC) were deployed on the seafloor around the foundation before and during pile driving. This process creates two concentric rows of air bubbles that absorb and deflect the pile driving noise, with the purpose of reducing the total acoustic energy released into the environment during installation.

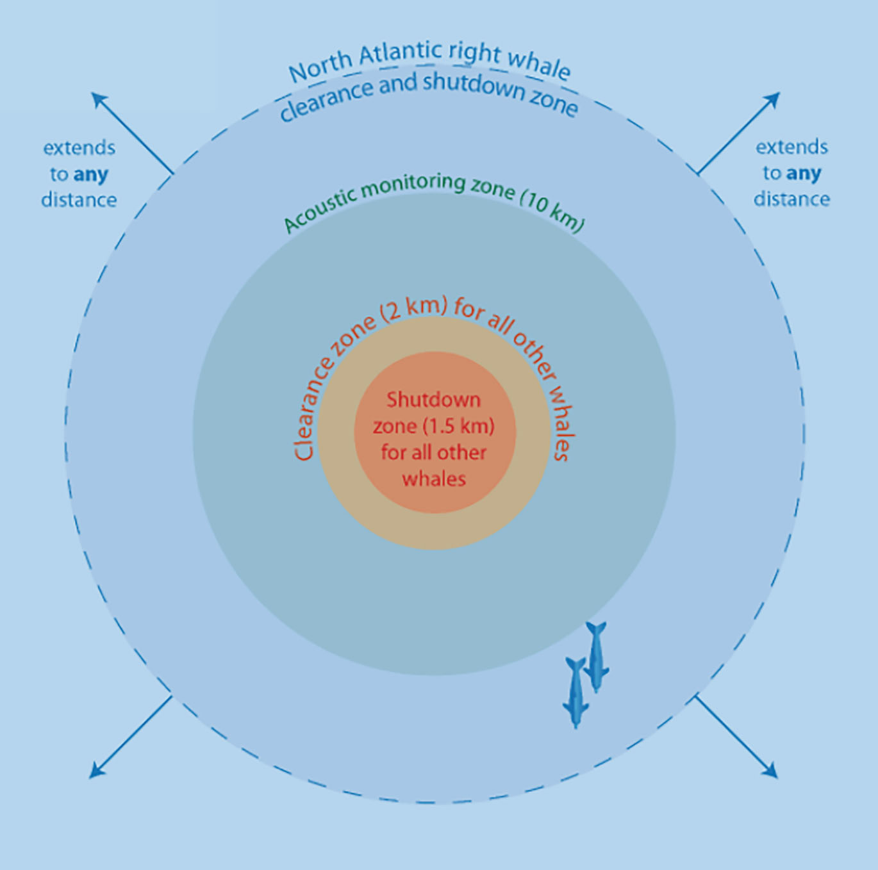

Fig. 2 Schematic of shutdown and clearance zones implemented for marine mammal mitigation. Credit: Empire Wind I. (Source: © Empire Wind)

The installation process also relies on a "soft-start," where reduced hammer energy is used at the start of piling, allowing marine mammals to temporarily avoid the area prior to pile driving at full energy, therefore reducing the risk for auditory injury. All vessels involved in the construction had a dedicated visual observer on duty to monitor protected species and enforcing vessel separation distances should an animal or group be detected.

By integrating passive acoustic monitoring and protected species visual monitoring, the project will provide detailed, spatiotemporal insights into potential effects of project construction activities on marine species in the area. Broader-scale studies, integrating satellite tag data and other project's data, could yield further information into how marine mammals may respond to construction activities. The systems deployed on Empire Wind encompass mitigation data and archival data, enabling retrospective analyses of the detections. PSO/PAM detections are based on a framework of visual and acoustic monitoring efforts, validated sightings classification and range, and mitigation triggers (e.g., shutdown). All visual, acoustic, and operational annotations are available for the clearance zones (Fig. 2) for a minimum of 60 min before, during, and 30 min after piling. Additional acoustic annotations are collected for at least 24 h immediately prior to pile driving. Sound field verification acoustic datasets include continuous acoustic recordings for 30 min before piling, during piling, and 30 min after piling for each pile at a minimum of 750 m distance from the pile. Data originating from the operational logs, such as details on the foundation structure, pile driving time, number of hammer strikes, and total energy, are also collected, together with DBBC effort and flow rate. Finally, long-term datasets were acquired from the eight PAM buoys, including acoustic recordings from the June 10 to the October 6, 2025, as well as associated metadata.

Potential Applications

The data collection effort presented here has a multitude of applications, ranging from pure research on whale behavior and acoustic fields to applied research aimed at improving tool development (e.g., near-real-time technology) and advancing our understanding of the potential effects of offshore wind on cetaceans. Integration with ongoing PAM monitoring programs further enhances research potential, contributing to a broader understanding of animal behavior and coexistence. Additionally, the potential to apply distributed acoustic sensing (DAS) using the fiber-optic cables in the Empire Wind I lease area offers an opportunity for side-by-side analysis with PAM, allowing for complementary datasets to enhance acoustic monitoring efforts and provide new perspectives on the underwater soundscape. Finally, and of equal importance is the need to assess the effectiveness of mitigation measures to ensure robust environmental protection during construction. While offshore wind developers already use noise abatement technologies, their effectiveness toward lessening potential impacts to marine animals must be better understood, also considering other species groups beyond cetaceans (Popper et al. 2022).

Long-Term Perspectives

The ecological risks related to offshore wind energy development can vary biogeographically, depending on the environmental characteristics and vulnerability of the affected area (e.g., presence of migrating species. Most publications on the impacts of offshore wind development are from studies conducted at localized scales (e.g., in very shallow waters, close to the coast, with few turbines, low production capacity, and occupying a small area) (Galparsoro et al. 2022). Real-world data collected through dedicated monitoring activities around offshore developments considering project-specific operational features is, therefore, highly valuable to overcome scientific knowledge gaps—which in turn is also relevant to policymakers, managers, decision-makers, and industry. Additionally, due to the expected increased demand for marine space, other operators are likely to coexist with offshore wind activities, leading to cumulative pressures that remain poorly understood (Gușatu et al. 2021).

In addition to pile driving, operational noise must also be considered. Offshore wind structures have an operational lifetime spanning decades, and future research should also address potential long-term effects. Pile type and materials play a key role as features affecting acoustic emissions (Stöber and Thomsen 2021; Kriesell et al. 2025) and should therefore be a major consideration in research and environmental monitoring programs to assess ecological and acoustic interactions. On the other hand, positive effects of offshore wind farms have also been identified, though they remain poorly understood. Wind turbine foundations may act as artificial reefs leading to increases in shellfish populations and, consequently, engender cascading benefits throughout the local ecosystem (Russell et al. 2014). Another possible positive effect is sheltering, since safety buffer zones around wind turbines may act as de facto marine reserves by reducing disturbances from shipping and fishing, which could increase prey abundance for top predators (Lindeboom et al. 2011). Such ecological processes, however, occur over long timescales, and further sustained research is needed to fully understand the impact of offshore wind farms across all environmental aspects.

Conclusions

The steps taken for the development of the Empire Wind I project and its innovative approach to marine mammal monitoring and mitigation are more than a localized effort. Though still in early stages, Empire Wind's strategy provides a valuable opportunity to test and refine tools for reducing environmental impacts in offshore wind development and to evaluate the strengths and limitations of these tools and gather data in real-world conditions, thus offering valuable insights to inform future projects and improve mitigation strategies. By combining visual observations, passive acoustic monitoring, and sound field verification with detailed operational logs, this project creates a dataset that will expand research opportunities. The resulting knowledge base will not only help assess the effectiveness of current mitigation strategies but also facilitate long-term ecological studies benefiting the scientific community, industry, conservation groups, and regulators.

Finally, while the approach taken by Empire Wind I represents a significant advancement in marine mammal monitoring, it also highlights the need for continued research and collaboration to address the complex challenges of offshore wind development. Collaborative studies combining developer data and external academic research are therefore recommended, aimed toward a collective endeavor to refine mitigation measures, improve data collection methods, and ensure that renewable energy development proceeds in a way that is both responsible and informed by the best available science.

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Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

References

Baumgartner M (2025) Efficacy of real-time passive acoustic monitoring near wind energy industrial activities for mitigating risks to right whales. Endanger Species Res 57:413–430. https://doi.org/10.3354/esr01432

Boebel O, Baumgartner M, Miksis-Olds J, et al (2024) Detection and monitoring of marine mammals during wind farm construction: an overview of established and emerging technologies

BOEM (2023) Nationwide recommendations for impact pile driving sound exposure modeling and sound field measurement for offshore wind construction and operations plans. BOEM

BOEM, NOAA (2024) BOEM and NOAA fisheries North Atlantic right whale and offshore wind strategy. BOEM and NOAA

CSA Ocean Sciences Inc (2023) Technical report: assessment of impacts to marine mammals, Sea Turtles, and ESA-Listed Fish Species – revolution wind offshore wind farm. CSA Ocean Sciences Inc

Dolman S, Simmonds M (2010) Towards best environmental practice for cetacean conservation in developing Scotland's marine renewable energy. Mar Policy 34:1021–1027. https://doi.org/10.1016/j.marpol.2010.02.009

Galparsoro I, Menchaca I, Garmendia JM et al (2022) Reviewing the ecological impacts of offshore wind farms. npj Ocean Sustain 1:1. https://doi.org/10.1038/s44183-022-00003-5

Gușatu LF, Menegon S, Depellegrin D et al (2021) Spatial and temporal analysis of cumulative environmental effects of offshore wind farms in the North Sea basin. Sci Rep 11:10125. https://doi.org/10.1038/s41598-021-89537-1

Kriesell HJ, Aniceto AS, Burns R et al (2025) Sound source characterization for the world's largest floating offshore wind farm Hywind Tampen. In: Popper AN, Sisneros JA, Lepper P, Vigness-Raposa KJ (eds) The effects of noise on aquatic life IV. Springer

Lindeboom HJ, Kouwenhoven HJ, Bergman MJN et al (2011) Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. Environ Res Lett 6:035101. https://doi.org/10.1088/1748-9326/6/3/035101

Linden DW (2025) Population size estimation of North Atlantic right whales from 1990–2024

Pettis HM, Hamilton PK (2025) North Atlantic Right Whale Consortium 2024 annual report card

Popper AN, Hice-Dunton L, Jenkins E et al (2022) Offshore wind energy development: research priorities for sound and vibration effects on fishes and aquatic invertebrates. J Acoust Soc Am 151:205–215. https://doi.org/10.1121/10.0009237

Russell DJF, Brasseur SMJM, Thompson D et al (2014) Marine mammals trace anthropogenic structures at sea. Curr Biol 24:R638–R639. https://doi.org/10.1016/j.cub.2014.06.033

Stöber U, Thomsen F (2021) How could operational underwater sound from future offshore wind turbines impact marine life? J Acoust Soc Am 149:1791–1795. https://doi.org/10.1121/10.0003760

Tougaard J, Henriksen OD, Miller LA (2009) Underwater noise from three types of offshore wind turbines: estimation of impact zones for harbor porpoises and harbor seals. J Acoust Soc Am 125:3766–3773. https://doi.org/10.1121/1.3117444

Van Parijs SM, Baker K, Carduner J et al (2021) NOAA and BOEM minimum recommendations for use of passive acoustic listening Systems in Offshore Wind Energy Development Monitoring and Mitigation Programs. Front Mar Sci 8. https://doi.org/10.3389/fmars.2021.760840