SEPTEMBER 2025
R: 25-08-A

REPORT

UNTANGLING THE WAY FORWARD FOR RESPONSIBLE OFFSHORE WIND ENERGY:

RECOMMENDATIONS TO REDUCE MARINE LIFE ENTANGLEMENT RISKS

AUTHORS:

Irene Gutierrez

Francine Kershaw

Becca Loomis

ACKNOWLEDGMENTS

Many thanks to Natural Resources Consultants, Inc. and Andrea Folds, who took the laboring oars in researching and drafting this report. And with much appreciation to Erica Fuller who reviewed and provided feedback on this report.

NRDC Chief Communications Officer: Kristin Wilson-Palmer
NRDC Senior Policy Publications Editor: Leah Stecher
NRDC Director of Peer Review, Science Office: Laurie Geller

Cover image: © Devra via Flickr
Design and Production: www.suerossi.com

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Offshore wind is a key part of the U.S. clean energy transition, given the powerful winds off our coasts and their ability to generate power when solar sources are offline. Offshore wind will also play an important role in renewable energy portfolios around the world, with several countries in Europe and Asia making significant investments in the technology.

Wind energy is most abundant in areas with water depths greater than 60 meters; this will require floating offshore wind systems to use large cables to anchor to the seabed, as opposed to fixed foundations. These anchoring cables create concerns about the entanglement of marine life, like large whales and sea turtles.

While there have been no documented cases of marine life entanglement in floating offshore wind systems to date, the entanglement risks posed by industrial activities using similar infrastructure suggest that the same risks will apply to floating offshore wind. We have seen marine life entangled in other fixed lines and cables, causing injury and death. Moreover, lost and abandoned fishing gear and other types of ocean debris can get snagged on the ropes and cables used to anchor and stabilize floating offshore wind systems, creating additional entanglement risks. For some protected species—like the endangered North Atlantic right whale or Southern Resident orca—entanglement impacts could have negative consequences for the health of a population. It is therefore essential that all floating offshore wind developments include proactive measures to reduce entanglement risk and protect marine species.

Floating offshore wind is still a new technology—few systems have been installed globally, and none have yet been established in U.S. waters. Now is the time to get ahead of any potential entanglement issues and create monitoring and mitigation measures for future floating offshore wind platforms that protect marine life.

ADDRESSING ENTANGLEMENT RISK HAS TWO ESSENTIAL COMPONENTS: MONITORING AND MITIGATION

Offshore wind cables and lines must be monitored for entangled debris and wildlife. Effective monitoring can detect entangled wildlife and alert response crews in a timely manner. Long-term monitoring can also provide valuable information on how, where, and why entanglements occur and which species of wildlife are most vulnerable.

Mitigation measures are also essential. These include a variety of strategies designed to prevent entanglements from happening (like using rope materials that are less susceptible to entanglement) as well as quick and effective responses when entanglements occur (like following prescribed wildlife rescue protocols).

This report presents an overview of technologies that are currently available for monitoring entanglement risk and identifies additional areas requiring technology research and development. It also recommends best practices for reducing entanglement risk at all stages of floating offshore wind development, from the early phases of designing and planning, through energy generation, to eventual decommissioning of turbines. These recommendations include both monitoring and mitigation measures. While we focus on the U.S. regulatory landscape, our monitoring and mitigation recommendations could be adapted to regulatory regimes in other countries.

Offshore wind development is needed to power the clean energy transition and prevent the worst impacts of climate change, but it cannot come at the expense of wildlife. By integrating monitoring technologies into offshore wind developments and committing to strong mitigation measures, we can ensure the responsible and sustainable development of offshore wind.

INTRODUCTION

NRDC (Natural Resources Defense Council) supports responsible offshore wind development as a crucial component of the clean energy transition.[a] Offshore wind is an important domestic renewable energy source—it can tap the abundant wind energy potential in U.S. waters, advancing our climate goals by reducing dependence on fossil fuels; supply power when solar and other renewable energy resources are offline; and foster the growth of green jobs.

Fixed-foundation offshore wind, the most commonly deployed design in the United States and internationally, secures the wind turbine foundation directly to the seabed; however, it cannot be used in waters deeper than approximately 60 meters, which is often where the best wind resources are. Thus, floating offshore wind systems will be necessary for deployments in deep waters off the West Coast of the United States and other areas slated for development. Floating offshore wind is also poised to play an important role in renewable energy markets elsewhere in the world, and several countries in Europe and Asia have made significant investments to advance the technology.[1]

Unlike fixed platforms, floating offshore turbines will require extensive underwater cabling to anchor them to the ocean floor and to connect turbines to each other and to transmission cables. These lines and cables have the potential to create serious risks for wildlife. Marine life may be vulnerable to direct entanglement in the cable systems. Floating marine debris, like lost fishing nets, could become caught in cable systems, exacerbating entanglement risks. Or fishing gear already entangling an animal—a common occurrence for large whales—may become caught on floating wind cables, potentially anchoring the animal to the array. Entangled marine life could be injured, in some cases fatally, or drown; for protected species, these impacts could negatively affect the health of the species population as a whole.

It is essential that all floating offshore wind developments include proactive measures to reduce entanglement risk and protect marine species, which include thorough monitoring for entanglement and commitment to measures to minimize and mitigate entanglement risks.

This report begins by providing a comprehensive overview of technologies available for monitoring entanglement risks and goes on to identify additional needs for technology research and development. It then recommends best practices for managing entanglement risks that should be used throughout the offshore wind development process.

NRDC recognizes the immense potential of offshore wind to combat climate change, reduce pollution, and create employment opportunities, and we thus support the expansion of floating offshore wind when executed with careful consideration of environmental impacts.

a Responsibly developed offshore wind: (1) avoids, minimizes, mitigates, and monitors for adverse impacts on wildlife and habitats; (2) minimizes negative impacts on other ocean uses; (3) includes robust consultation with Native American nations and communities; (4) meaningfully engages state and local governments and other interested parties from the outset; (5) includes comprehensive efforts to avoid negative impacts to underserved communities; and (6) uses the best available scientific and technological data to ensure science-based and stakeholder-informed decision making. NRDC's commitment is grounded in the belief that protecting biodiversity and achieving clean energy goals can coexist harmoniously.

FLOATING OFFSHORE WIND SNAPSHOT

Offshore wind is a key part of the U.S. renewable energy portfolio. The Intergovernmental Panel on Climate Change has projected that wind energy will play a large role in the transition to renewable energy worldwide, given its ability to drive large greenhouse gas emissions reductions and diversify national energy portfolios.[2] According to the Department of Energy, U.S. offshore wind resources could meet the nation's electricity needs three times over.[3] Recognizing the need for offshore wind as a source of renewable energy, thirteen states have set statewide mandates or formal targets for offshore wind development, amounting to 115 gigawatts of wind energy by 2050—enough power to run more than 86 million homes.[4]

Floating offshore wind systems are necessary to achieve those goals. Approximately two-thirds of the United States' offshore wind energy potential is in waters deeper than 60 meters—such as along the Pacific Coast, in the Gulf of Maine, and around Hawaii. This will require the use of floating offshore wind platforms, as opposed to the fixed-bottom platforms already deployed along the Eastern Seaboard and proposed in the Gulf of Mexico.[5]

Floating offshore wind systems are a novel technology; they are used in few places globally. In the United States, the Bureau of Ocean Energy Management has issued more than thirty offshore wind leases in federal waters, including areas off the California coast, where floating platforms will be necessary.[6] However, to date, no floating offshore wind projects have been constructed or deployed in U.S. waters. Worldwide, only about a dozen pilot-scale (10- to 100-megawatt) floating offshore wind projects have been implemented.[7]

Source: Philipp Beiter/NREL

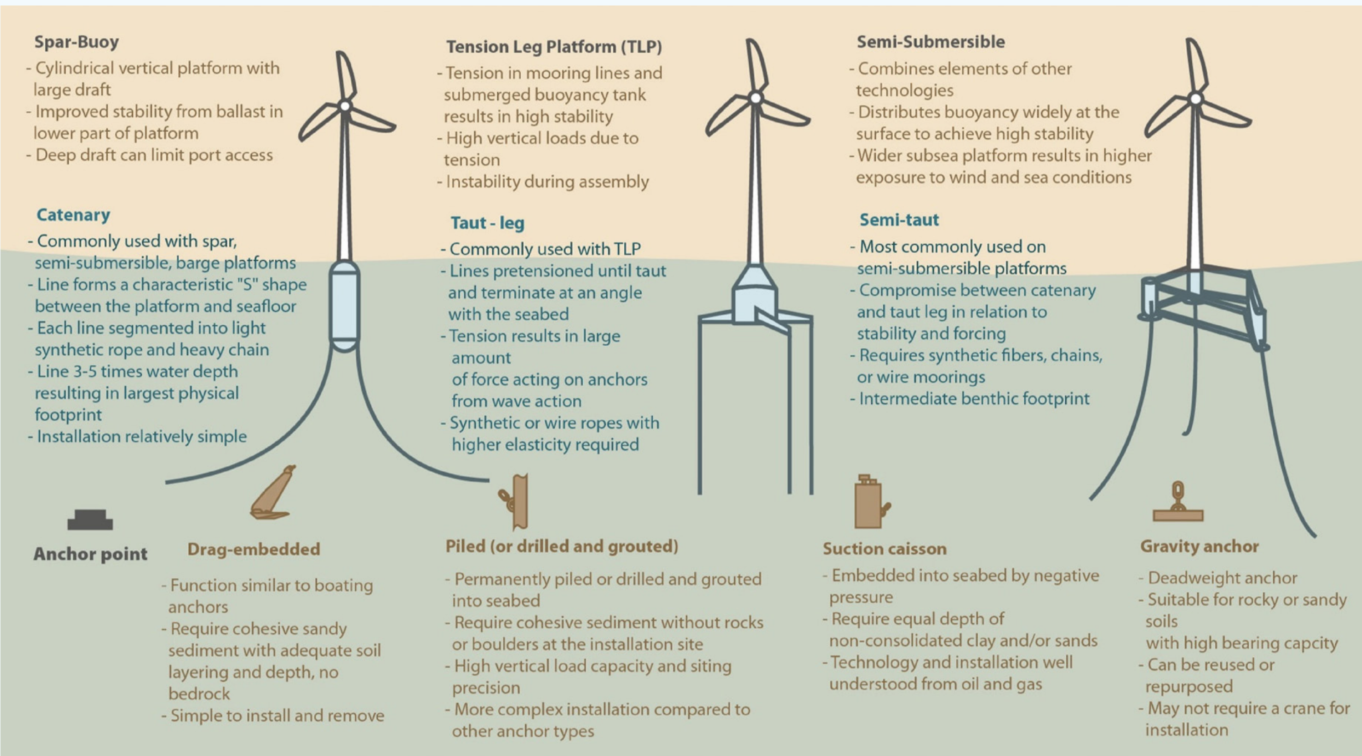
FLOATING OFFSHORE WIND PLATFORM DESIGN

Floating offshore wind platforms require extensive cabling systems to anchor them to the ocean floor, link them to each other, and carry power to shore. The resulting matrices create a sizable physical and ecological footprint, particularly for utility-scale projects (see figures 1 and 2), which can lead to marine life entanglement.

PLATFORMS: Floating offshore wind turbines are supported by submerged or semi-submerged buoyant platforms, connected to the seabed by mooring lines and to other turbines and offshore electrical substations by cables.[8] Turbines could be spaced approximately 0.5 to 1.6 nautical miles apart, depending on site conditions and turbine blade rotation diameter.[9]

The three most common floating offshore wind platform designs are the single-point anchor reservoir (SPAR), semi-submersible, and tension leg platform (TLP).[10] As with all aspects of offshore wind technology, new floating platform designs are currently being developed to improve stability, efficiency, and cost.[11]

FIGURE 1: TYPES OF FLOATING OFFSHORE WIND PLATFORMS



Source: Maxwell et al. 2022.

MOORING LINES: Platforms are stabilized by mooring lines anchored to the seabed. The three general categories of mooring lines are (1) catenary, or curved, mooring lines that hang freely in the water column, (2) tensioned mooring lines that are stretched until taut, and (3) semi-taut mooring lines that fall somewhere between the other two.[12]

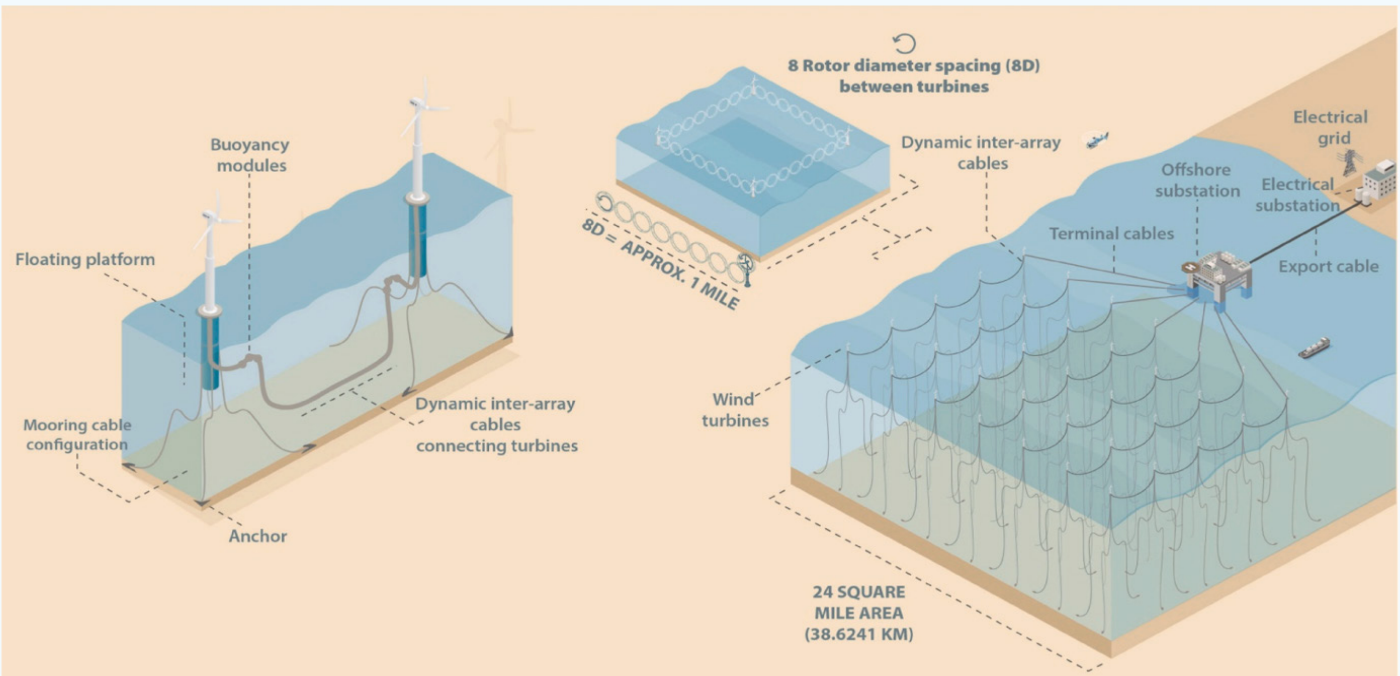
Catenary mooring systems generally consist of an upper length of lighter synthetic fiber rope or chain connected to a heavier chain that rests along the seafloor.[13] They are most commonly used in conjunction with SPAR and semi-submersible platforms. Catenary mooring lines have the largest physical and ecological footprint of the three, due to the significant proportion of the lines that lie on the seafloor and are subject to disturbance from surface wave action.[14] For example, mooring chains used in the Hywind Scotland wind farm, sited in approximately 100 meters of water, range in length from 691 meters to 875 meters, with only part of that length being suspended in the water column.[15]

Semi-taut mooring systems use a single length of high-diameter synthetic rope, chain, or wire attached to anchors embedded directly in the seafloor and can be used by semi-submersible platforms.[16] They may help decrease the overall benthic (seafloor) footprint of floating offshore wind projects by providing enough flexibility to accommodate wave action without leaving as great a length of mooring lines on the seafloor as do catenary systems.[17]

Taut line mooring systems rely on pre-tensioned, highly elastic synthetic or wire ropes and are used with TLPs. Taut lines produce the smallest physical and ecological footprint while providing high stability. The tension that achieves these benefits also severely limits vertical movement, resulting in more technically challenging installation.[18]

INTER-ARRAY CABLES: Power is transmitted from individual floating offshore wind turbines by dynamic inter-array cables that link individual turbines together in a chain, which usually connects to an offshore electrical substation and subsequently extends to an onshore landing site and power grid.[19] Depending on site depth, inter-array cables are either buried (generally in waters of no more than 100 meters deep) or left free-floating.[20] In deeper waters, both free-floating and buried inter-array cables can use large-diameter floats (approximately 2 meters in diameter) to create a "lazy wave" effect and prevent intermediate parts of the cables from touching the seafloor.[21] The dynamic range of inter-array cables protects them from load stresses associated with movement of the turbine platform due to waves, wind, and weather.

FIGURE 2: SCHEMATIC OF A COMMERCIAL-SCALE FLOATING OFFSHORE WIND ENERGY DEVELOPMENT, INCLUDING UNDERWATER MOORING AND CABLE SYSTEM



Source: Maxwell et al. 2022.

FLOATING OFFSHORE WIND SYSTEMS INCREASE THE RISKS OF MARINE LIFE ENTANGLEMENT

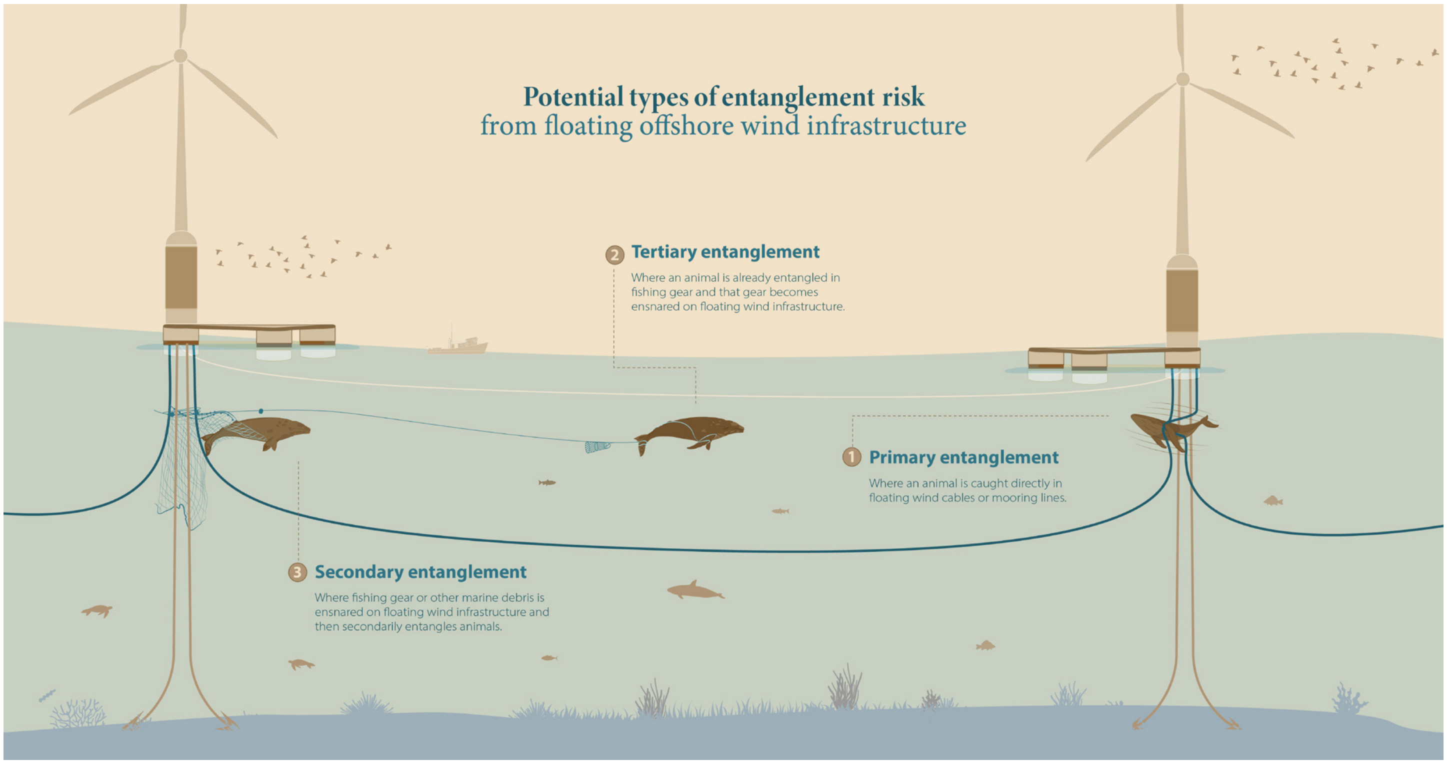
Because of the cables and infrastructure used, floating offshore wind structures create greater entanglement risks than do fixed turbine arrays. There are three classifications of marine entanglement associated with floating offshore wind: primary, secondary, and tertiary (figure 3).[22]

Primary entanglement involves animals directly ensnared in lines and cables. Secondary entanglement refers to ensnaring of wildlife by debris or other materials trapped in mooring lines, mid-water cables, or infrastructure. Tertiary entanglement occurs when debris or fishing gear already entangling an animal gets caught on project infrastructure.

Primary and tertiary entanglement are currently considered less likely to occur than secondary entanglement, but ongoing monitoring and research are needed to improve scientific understanding and risk mitigation for all three classes of entanglement.[23] A wide range of marine species including seals, sharks, fish, diving sea birds, and sea turtles could be at risk of secondary entanglement with debris ensnared on floating offshore wind infrastructure.[24] More information is needed to assess the degree of risk of secondary entanglement in floating offshore wind infrastructure, but the severity of its effects in other industrial settings is well established.[25]

A humpback whale drags entangled marine debris as it swims in Chatham Strait, Alaska.

FIGURE 3: DEPICTION OF POTENTIAL TYPES OF ENTANGLEMENT RISKS



Graphic by PACT Media.

Studies show that entanglement can cause asphyxiation, tissue damage, reduced foraging ability, impaired mobility, and impacts on fitness and population growth, especially for species with low reproductive rates.[26] Both active fishing gear and abandoned, lost, or discarded fishing gear (ALDFG) and other marine debris can cause secondary or tertiary entanglement of marine wildlife in floating offshore wind infrastructure. As more offshore wind projects are constructed, the risk of entanglement will likely increase due to the larger footprint of textured surfaces on which both derelict gear and marine life can be snagged.[27]

CURRENT EVIDENCE OF ENTANGLEMENT RISK AND INFORMATION NEEDS

Existing evidence suggests that floating offshore wind infrastructure poses a relatively low risk of primary entanglement, but more data are needed for a precise risk assessment. No primary entanglement events of large marine mammals have been documented in offshore oil platforms that use catenary mooring systems similar to those used in floating offshore wind contexts.[28] However, the lack of comprehensive monitoring of these oil and gas systems and the absence of inter-array cabling in offshore oil platforms make it impossible to rule out risk for either offshore oil or floating offshore wind arrays.[29] Certain floating offshore wind design features may partially account for the lack of documented primary entanglement events for the few projects that have been developed to date. For example, large-diameter mooring lines and chains are less likely to form loops in which marine species can become ensnared. These cables and chains are also likely large enough to be detected by many marine species with the highest entanglement risks via echolocation, vibrations, or acoustic detection.[30]

Limited monitoring data from operational floating wind projects have similarly not indicated an accumulation of secondary entanglement hazards or incidence of primary or tertiary entanglements. However, surveys of existing floating wind infrastructure have been conducted only infrequently (e.g., once every two years), so one cannot definitively rule out the possibility that marine entanglements or accumulation of entanglement hazards have occurred. It is possible that entangled animals and accumulated hazards could become dislodged or removed or otherwise disappear between surveys. Additionally, certain at-risk species (e.g., baleen whales) are not found in large numbers in areas where floating offshore wind has been developed to date, but they are present in areas slated for development, like waters off the coast of California and in the Gulf of Maine, meaning that region-specific risk assessments are required for these species.

With respect to entanglement risk, it is also important to consider the overlap of historical and potential future fishing efforts with the location of floating offshore wind projects. Derelict fishing gear constitutes a significant percentage of marine debris: The National Oceanic and Atmospheric Administration estimates that fishing gear makes up ten percent of marine debris worldwide and suggests that this will only increase with time; other studies show fishing gear representing an even greater proportion of marine debris.[31] Fishing gear (both derelict and in-use, from pot and line fisheries like crab and lobster) is responsible for a significant portion of whale entanglements; in 2022 it caused at least forty percent of such events.[32] In fact, entanglement in fishing gear is the leading cause of mortality in large whale species, like humpback and gray whales, along the West Coast.[33] The introduction of floating offshore wind infrastructure has the potential to add to or exacerbate these existing entanglement risks. Several protected species are already experiencing unsustainable levels of entanglement in these regions, further warranting a precautionary approach to managing this risk factor.

The footprint of the underwater infrastructure associated with future commercial-scale floating wind projects planned for the United States and elsewhere will also be much larger than the small-scale projects constructed to date. The risk of marine debris accumulation and entanglement risk will likely increase along with the size of the project footprint, given the increase in the number and length of cables, the number of platforms, and so on. It will be crucial to assess the cumulative effects of multiple utility-scale floating wind projects on marine life.

A sea turtle tows entangled marine debris including ropes and plastic jugs in the eastern Pacific Ocean.

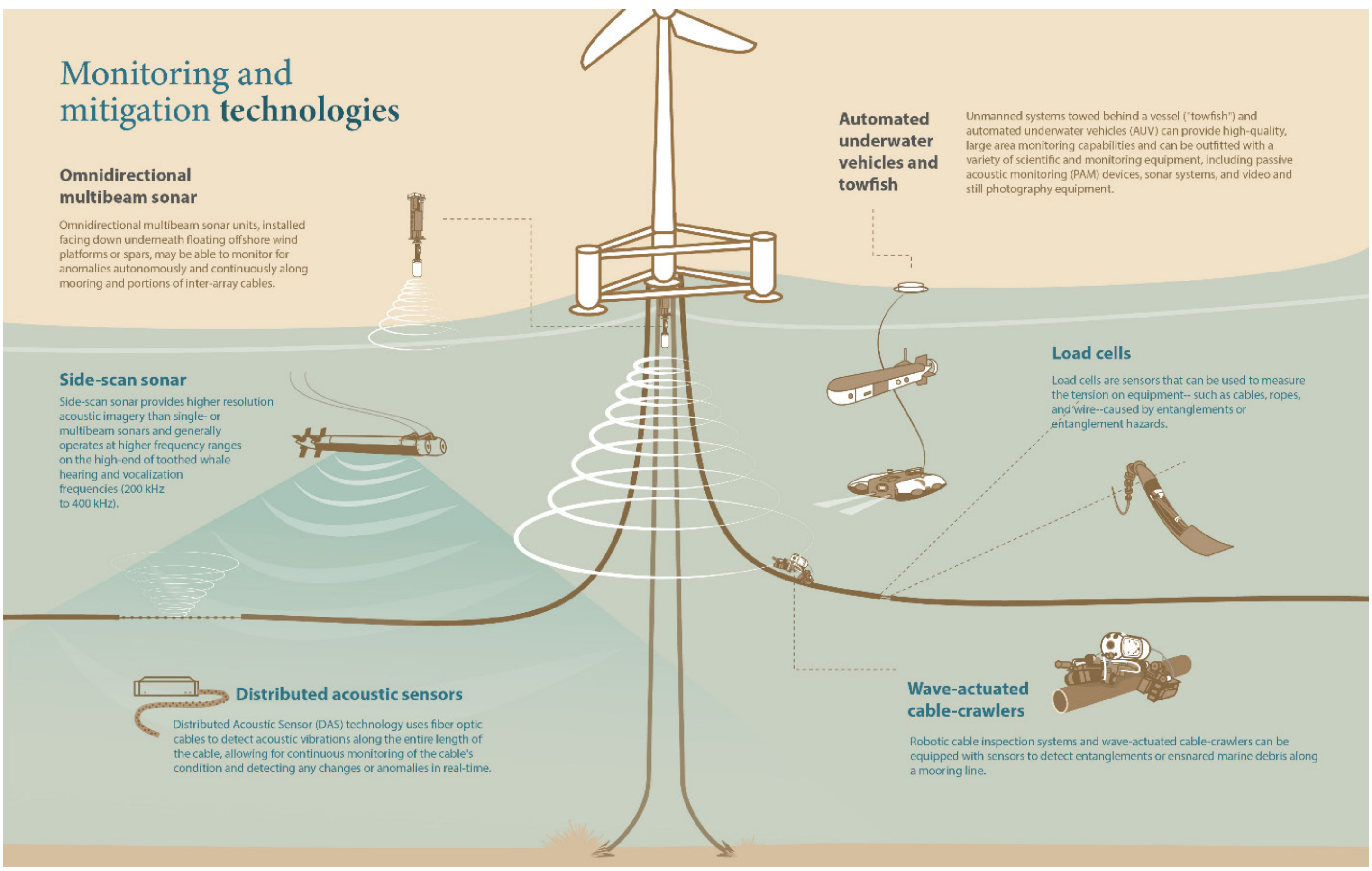
A RANGE OF MONITORING TECHNOLOGIES CAN REDUCE ENTANGLEMENT RISKS

Developing floating offshore wind responsibly will require ensuring that platforms are equipped with technologies to detect entanglement risks, enable accurate data collection on entanglement events, and allow rapid responses to free entangled wildlife. A variety of technologies already exist that could be integrated into offshore wind platforms and used to monitor for entanglement risk, from high-visual-resolution systems on automated underwater vessels to low-visual-resolution technologies like load sensors. All of these technologies would benefit from further research to fully understand their capabilities and application to detecting entanglement risks.

CURRENTLY AVAILABLE MONITORING TECHNOLOGIES

Monitoring for entanglement risk in floating offshore wind projects could deploy technologies already used in other industrial and research applications for periodic surveys of underwater infrastructure and continuous automated detection of increased load on cables. This section provides an overview of currently available monitoring technologies that may play a critical role in our monitoring and mitigation recommendations. The appendix to this report offers an overview of technology costs.

FIGURE 4: EXISTING MONITORING AND MITIGATION TECHNOLOGIES AVAILABLE FOR INTEGRATION INTO FLOATING OFFSHORE WIND SYSTEMS



Graphic by PACT Media.

UNDERWATER VESSELS AND TOWFISH

Unmanned systems towed behind a vessel ("towfish"), automated underwater vehicles (AUVs), and remote-operated vehicles (ROVs) have high-quality, large-area monitoring capabilities and can be outfitted with a variety of scientific and monitoring equipment, including passive acoustic monitoring (PAM) devices, active sonar systems, and video and still photography equipment.[34] ROVs are controlled by a human operator and connected by cables to a survey vessel, while AUVs are often preprogrammed and do not rely on an operator.[35] PAM detects wildlife through sophisticated sound-recording equipment, while active sonar systems use sound pulses to detect underwater objects.[36] A benefit of AUVs is that they can be programmed to follow a given survey path, potentially increasing the frequency of monitoring by reducing the staff, equipment, and fuel costs associated with ROVs or vessel-deployed towfish surveys.

It is important that any AUV chosen for monitoring have range and depth capabilities that allow full coverage of the floating offshore wind array footprint.

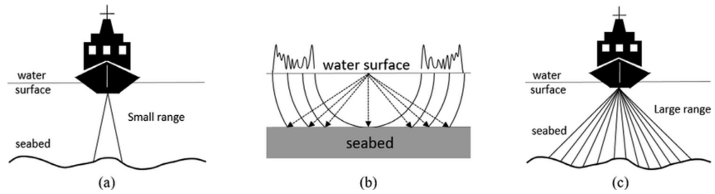
ADDITIONAL RESEARCH NEEDS

Towfish, ROVs, and AUVs are extensively used in a variety of marine applications, such as mapping the seafloor and aiding in rescue operations, and are well suited for monitoring offshore wind infrastructure.[37] However, some limited research or pilot studies will be required to ensure that these technologies can be effectively used to monitor offshore wind platforms. While there is no reason to expect that workflows and procedures will differ from other industrial applications, potential differences and challenges are unknown; therefore additional research is needed to effectively adapt these technologies for use with floating offshore wind platforms.

An adult North Atlantic right whale, trailing an entangled rope or line, swims with her calf off Cumberland Island, Georgia.

ACTIVE SONAR MONITORING AND SURVEYS

Active sonar systems—which use sound pulses to detect marine life and/or underwater objects—are extensively used for monitoring and detection in a variety of marine industries.[38] Side-scan sonar and multi-beam backscatter systems specifically are commonly used for ALDFG location and retrieval in Canadian and U.S. waters and are well suited for monitoring for entanglements and accumulation of entanglement hazards.[39]



Typical sonar: (a) single-beam sonar; (b) side-scan sonar; (c) multibeam sonar.

Source: Yang Cong et al, "Underwater robot sensing technology: A survey," *Fundamental Research*, Volume 1, Issue 3, 2021, Pages 337-345, ISSN 2667-3258, https://doi.org/10.1016/j.fmre.2021.03.002.

OMNIDIRECTIONAL MULTI-BEAM SONAR

Modern fish-finding sonar systems maximize coverage area and image fidelity with omnidirectional sonar transducers capable of monitoring a full 360 degrees. These omnidirectional units may be suited for stationary deployments facing downward underneath floating offshore wind platforms or spars where they may be able to monitor continuously along mooring and portions of inter-array cables.

However, many commercially available, omnidirectional fish-finding sonar operational frequencies overlap with those used for hearing and vocalization by baleen whales, beaked whales, Southern Resident orcas, toothed whales, fish, seals, and sea lions.[40] Care should be taken to select multi-beam systems that operate at peak frequencies above the range of marine mammal audibility and with no or minimal leakage of sound within that range. Systems should also be mountable underneath individual floating offshore wind platforms.

SIDE-SCAN SONAR

Side-scan sonar provides higher-resolution acoustic imagery than single- or multi-beam sonars and generally operates at higher frequency ranges, on the high end of toothed whale hearing and vocalization frequencies (200 kHz to 400 kHz). Side-scan sonar relies on thin, high-frequency bands shot at oblique angles to survey targets to provide high-fidelity acoustic images that enable accurate target identification; however, this technology does require that surveys be conducted close to the target substrate.

ADDITIONAL RESEARCH NEEDS

Use of omnidirectional multi-beam sonars for monitoring mooring lines will need to be field tested to determine its effectiveness in detecting both marine species presence and accumulation of secondary entanglement hazards on mooring lines and cables. In addition, research should be conducted on how multiple, continuously operating sonar units will affect the overall noise footprint of floating offshore wind farms.

LOAD CELLS AND VIBRATION MONITORING

Catenary and semi-taut mooring systems are designed to give enough dynamic range to a floating offshore wind platform to respond to changing wind, wave, and current conditions while subsea inter-array cables, especially at deeper sites, may be left free floating in the water column. It is useful to monitor these systems for additional tension or movements outside of acceptable ranges.[41] Use of load cells and vibration sensors is common practice in many marine industries—including on oil platform mooring systems and existing subsea electrical transmission cables. These cells and sensors can continuously monitor line and cable load and can trigger automatic alerts in the event of load anomalies.

Load cells can be used to measure the tension on equipment such as cables, ropes, and wires.[42] They come in many varieties, with high-capacity load shackles—U-shaped shackles that carry or contain the load—likely to be the most appropriate for the high loads and harsh environments characteristic of offshore wind operations. Additionally, load cells generally monitor either direct or indirect loads. Because indirect load cells monitor for deviations in load along all axes except the primary load axis, they may be more suitable for detection of anomalies caused by accumulated entanglement hazards or entanglements themselves. Research is currently being planned or is underway to determine if this technology is capable of detecting marine debris fouling and wildlife entanglements.

Distributed acoustic sensor (DAS) technology uses fiber-optic cables to detect acoustic vibrations along the entire length of the cable, allowing continuous monitoring of the cable's condition and detection of any changes or anomalies in real time. DAS technology works by using a laser to send pulses of light through the fiber-optic cable. When the light encounters an acoustic vibration, such as those caused by mechanical stress, it scatters and reflects back to the sensor. This scattered light can then be analyzed to determine the location, intensity, and frequency of the acoustic vibration. By analyzing these acoustic signals, DAS technology can detect changes in the cable's condition, such as cracks, breaks, or other defects. It can also identify changes in temperature, pressure, and other environmental factors that may affect the cable's performance or life-span. This technology may be able to sense unusual forces or strains on the cable caused by debris entangling marine life.[43]

A green sea turtle swims freely in Hawaiian Islands Humpback Whale National Marine Sanctuary, Hawai'i.

DAS technology has several advantages for cable monitoring, including its ability to monitor the entire length of the cable continuously, its high sensitivity and accuracy, and its ability to locate small defects before they become more serious problems.[44]

ADDITIONAL RESEARCH NEEDS

It is currently unknown whether existing load cells and vibration sensors are sensitive enough to identify an accumulation of ALDFG and/or marine entanglements in floating offshore wind infrastructure or in associated cable infrastructure like transmission cables. Testing and modeling will be required to determine the detection capabilities of commercially available load cells and vibration sensors and the parameters that could affect those capabilities (such as water depth, the depth of cable burial, and the presence of bends in the cable), and ultimately to determine whether such sensors will be suited for entanglement mitigation and monitoring.

CABLE INSPECTION SYSTEMS

Robotic cable inspection systems and wave-actuated cable crawlers are vehicles that move along the mooring cable either actively or passively (robotic systems require battery power, whereas wave-actuated technology relies on water motion and ratcheting clamps). Cable inspection systems can be equipped with sensors and have the potential to detect entanglements or ensnared marine debris along a mooring cable or anchor line. Robotic systems are currently in use in other industry contexts and are the focus of research for offshore wind applications; however, the need for a power source may present challenges offshore. Wave-actuated cable crawlers are a lower-cost option, but existing systems are focused on oceanographic data collection and are not currently compatible with the monitoring technology most useful for entanglement mitigation (i.e., sonar systems).

ADDITIONAL RESEARCH NEEDS

Significant research and development are needed to retrofit currently available cable inspection systems to be compatible with floating offshore wind mooring cables and chains.[45] Additionally, two types of wave-actuated cable crawlers researched for this document do not at present support sonar instrumentation.[46] Future development of cable inspection systems for use in floating offshore wind entanglement mitigation should focus on compatibility with sonar units, the ability to automatically clean and reduce biofouling on lines and cables, and, for robotic systems, the development of a sustainable or renewable offshore power source.[47]

FIGURE 5: COMPARISON OF MONITORING AND MITIGATION TECHNOLOGIES

Monitoring and Mitigation Technologies

Technology	Benefits	Challenges
1. Automated Underwater Vessels (AUVs), Remote Operated Vessels (ROVs), and Towfish	- Can provide high-quality, large-area monitoring. - Can reduce costs and improve safety by operating with limited human involvement. - Can carry various sensors and monitoring equipment (e.g., acoustic devices, cameras).	- Adaptation may be required for effective use in floating offshore wind contexts (e.g., optimal track lines, deployment procedures).
2. Passive Acoustic Monitoring (PAM)	- Some PAM systems can detect marine species' vocalizations in real-time and can rapidly inform mitigation responses. - Larger detection ranges (relative to visual monitoring methods) can help track species presence over wide areas. - Archival PAM systems record vocalizations over long time periods, allowing for the assessment of how risk changes over time.	- Locating a vocalizing animal requires more complex PAM systems and may not be feasible in all scenarios. - Autodetection functions haven't yet been developed for all species of concern. - Ineffective for non-vocal species, quiet vocalizations, or silent phases.
3. Acoustic Sonar Monitoring	- Suitable for detecting marine life and underwater objects. - Side-scan sonar provides high-resolution imaging, allowing detailed monitoring of cables and infrastructure.	- Overlapping frequencies with marine species' hearing ranges may disturb wildlife and require mitigation. - Requires proximity to the target, limiting its effectiveness for monitoring large areas.
4. Load and vibration monitoring (load cells and distributed acoustic sensors)	- Continuous and automatic detection of anomalies in cable tension and load. - Commonly used in marine industries, and are easily adaptable to floating wind infrastructure.	- Requires further testing to ensure sufficient sensitivity and detection capability of marine debris ensnarement and wildlife entanglements on floating offshore wind lines and cables.
5. Cable Inspection Systems (wave-actuated cable-crawlers and robotic cable inspection systems)	- Wave-actuated cable crawlers are a potential low-cost technology option, due to passive movement along mooring cables. - Robotic cable inspection systems are already used in other industry contexts and are the focus of research and development for offshore wind applications.	- Wave-actuated cable-crawlers are currently used for oceanographic data and not yet adapted to entanglement monitoring. -Robotic cable inspections systems require battery recharge and power source access, which may present challenges offshore. - Incompatible with sonar systems in current form.

Graphic by PACT Media.

RECOMMENDATIONS TO REDUCE RISK OF MARINE LIFE ENTANGLEMENT IN FLOATING OFFSHORE WIND INFRASTRUCTURE

Deep sea coral located in Cordell Bank National Marine Sanctuary, California.

In addition to integrating the monitoring technologies discussed above, the following mitigation measures should be implemented by developers to reduce entanglement risks. These measures track the mitigation hierarchy of first avoiding, then minimizing and mitigating any unavoidable adverse impacts. These recommendations address only entanglement and should therefore be considered alongside other recommendations for the responsible development of floating offshore wind projects. Advancements in floating offshore wind technology and science should also inform how these recommendations are used as entanglement risks become better understood.

FLOATING OFFSHORE WIND PLATFORMS SHOULD BE SITED AND DESIGNED TO AVOID ENTANGLEMENT RISKS.

Preventing entanglement must be a fundamental goal in floating offshore wind siting, construction, and operation and maintenance plans, with monitoring and mitigation serving as secondary and tertiary lines of defense. As part of this strategy, early-stage environmental site assessments should be conducted to avoid areas of importance to endangered and protected marine species. In the United States, environmental impact statements as well as construction and operations plans should detail mooring and inter-array cable configurations, with a focus on factors that most directly influence entanglement risk, such as diameter of cable, tautness, number of lines, and material used in lines.[48] Doing so would enhance understanding of design features' impact on entanglement risk and would support a precautionary approach to floating offshore wind operations.

AVOID LEASING IN MIGRATORY CORRIDORS, FORAGING AND SOCIALIZING AREAS, AND ANY OTHER IMPORTANT HABITAT OF AN AT-RISK SPECIES.

The siting of offshore wind projects must account for—and avoid, whenever possible—areas where at-risk species reside or engage in foraging and other key behaviors.[49] If it is not possible to entirely exclude these areas from site selection, then it is imperative to avoid areas of highest use by vulnerable species as well as high-biodiversity habitats, such as kelp forests and coral reefs, as entanglement risks may be greater in areas with a high density of sensitive species. Some technologies for monitoring entanglement risk may also be useful for characterizing marine faunal presence and use of proposed lease sites.

REQUIRE FLOATING OFFSHORE WIND ANCHORING AND MOORING SYSTEMS TO USE LARGE-DIAMETER WIRE ROPE OR CABLE AND AVOID CHAINS OR SYNTHETIC FIBER ROPES.

The specific characteristics of mooring systems, such as line material, tautness, and diameter, are critical in determining entanglement risk. Large-diameter steel wire rope or cable typically poses less risk than steel chain or synthetic fiber rope due to its smoother surface, which reduces the likelihood of snagging. Additionally, larger-diameter lines can help in maintaining tautness and avoiding loops, thereby further reducing the risk of entanglement.

REQUIRE FLOATING OFFSHORE WIND ANCHORING AND MOORING SYSTEMS TO USE TAUT OR SEMI-TAUT CONFIGURATIONS, AND AVOID CATENARY MOORING SYSTEMS.

Among the mooring system types, taut and semi-taut configurations are generally safer than catenary systems because they have less slack.

BURY INTER-ARRAY CABLES WHENEVER POSSIBLE, AND REQUIRE MINIMUM DEPTHS FOR FREE-FLOATING CABLES.

Inter-array cables linking individual floating offshore wind turbines and turbine arrays to land-based infrastructure should be buried whenever possible. This approach not only reduces the likelihood of primary entanglement but also diminishes the risk of secondary entanglement due to accumulated debris. However, the feasibility of cable burial is generally influenced by cost considerations, which can increase with site depth.

In deeper waters where burial is not feasible, the depth at which cables are suspended should account for various factors, including presence of at-risk species, conflicts with fishing activities, and effects on construction costs. In cases where burial is not practical, suspending inter-array cables at depths that fall below the deeper boundaries of the foraging zones of at-risk species is recommended.[50] In waters deeper than 100 to 200 meters, free-floating inter-array cables could be suspended between 100 and 150 meters to avoid conflicts with marine mammal foraging activity while keeping total cable costs down.[51]

USE LARGE-DIAMETER ACCESSORY BUOYS TO STABILIZE INTER-ARRAY CABLES.

Large-diameter accessory buoys, approximately 2 meters in size, can reduce entanglement risk by significantly enhancing the stability of catenary mooring lines and free-floating inter-array cables.[52] Such buoys are already used to help stabilize catenary mooring lines and free-floating inter-array cables and to protect them from stressors such as high wind, large waves, and general inclement weather. By providing additional buoyancy and stability, they reduce the risk of entanglement and ensure the durability and longevity of the mooring lines and cables in the challenging marine environment.

DESIGN INFRASTRUCTURE TO FACILITATE VISUAL OR ACOUSTIC DETECTION OF ENSNARED MARINE DEBRIS.

Infrastructure design features can facilitate visual or acoustic detection of ensnared marine debris by monitoring equipment and personnel. For example, lighter-colored infrastructure can aid the visual detection of often darker-colored marine debris, and use of textures that contrast with marine debris can aid acoustic detection at depths where light is limited.

MARINE ENTANGLEMENT MONITORING AND SURVEYS ARE ESSENTIAL FOR UNDERSTANDING AND ADDRESSING ENTANGLEMENT RISK

Continuous monitoring of tension lines and cables is critical to detect primary or secondary entanglement, mitigate harm through rapid response, and improve understanding of the risks posed by floating offshore wind development, including by establishing a baseline for entanglement events and accumulation of secondary hazards.[53] The options discussed above offer a range of tools for monitoring around floating offshore wind arrays. Determining the appropriate technology to use in any instance requires careful consideration of project needs, environmental factors, legal standards, and efficiency.

Entanglement risk may be greatest in the upper 200 meters of the water column due to relatively greater co-occurrence of species, marine debris including ALDFG, and project infrastructure. However, marine debris and various types of fishing gear could become entangled in these structures at any depth. It will be imperative that all floating offshore wind turbine arrays incorporate monitoring technology that—even if not a part of a continuous, automated monitoring system—has the capability to monitor the full depth of a given project.

The technologies described above could provide this much-needed continuous monitoring, and we outline below potential ways that the technology could be integrated into a floating offshore wind farm infrastructure. However, as we noted above, additional research is needed to develop effective monitoring systems and ensure proper application of available technology. Existing data from the oil and gas industry's experience with mooring system monitoring offer valuable insights for floating offshore wind operations.[54] Development of monitoring systems tailored to floating offshore wind activities is still necessary given key differences between the underwater infrastructure used in the two industries. As more research is conducted and as more data from floating offshore wind deployments become available, monitoring protocols could be adjusted based on whether the information indicates that more- or less-frequent monitoring is warranted.

Blue whales surfacing in the Channel Islands National Marine Sanctuary.

INSTALL LOAD CELLS AND VIBRATION SENSORS TO CONTINUOUSLY MONITOR MOORING LINES AND INTER-ARRAY CABLES FOR SUDDEN OR SIGNIFICANT CHANGES IN LOAD OR INCREASES IN VIBRATION.

Floating offshore wind mooring lines could be equipped with load cells with sufficient detection resolution to detect both significant accumulations of secondary hazards and entanglement events. Likewise, inter-array cables could have vibration and fault sensors as well as load cells at all floating infrastructure attachment points, and potentially at accessory buoy attachment points if present.

ATTACH DOWN-FACING OMNIDIRECTIONAL MULTI-BEAM SONAR TO THE BOTTOMS OF ALL FLOATING PLATFORMS.

Omnidirectional multi-beam systems with automatic detection capabilities sufficient to detect secondary entanglement hazards as well as marine species presence in and around the floating offshore wind array (e.g., Biosonics Omnidirectional Marine Life Observer) could be installed, facing downward, to the underside of each floating offshore wind platform. It is crucial to consider the impacts of underwater noise generated by these systems on marine mammals and other marine life. To minimize those impacts, multi-beam systems should operate at peak frequencies above the range of marine mammal audibility and with no or minimal leakage of sound within this range.

INCLUDE REGULAR SONAR INSPECTIONS OF ALL MOORING LINES AND INTER-ARRAY CABLES IN MANAGEMENT PLANS.

Side-scan and multi-beam sonar systems are routinely used in submerged infrastructure inspection and monitoring. As noted above, towfish, AUVs, and ROVs could all be deployed to conduct inspection and monitoring. Due to significant gaps in knowledge of the relative risk of secondary entanglement, the full length of the submerged infrastructure (including platforms, substations, mooring lines, inter-array cables, and anchors, as well as monitoring technology docking stations or other infrastructure, as appropriate) should be surveyed monthly for at least the first year of operation. Survey frequency thereafter should be informed by the findings of the first year of monitoring but should still occur at least annually. Seasonal migration, feeding and breeding activities of marine species may necessitate more frequent surveys.

Vessels deployed with ROVs or AUVs can be outfitted with sonar transponders and video cameras. The choice between ROVs and AUVs should be based on factors like the total number of floating turbines in a given array and the distance of the array from shore (i.e., its accessibility). AUV surveys may lower the overall costs of more frequent survey efforts, potentially allowing a small staff on land with a standby vessel available. ROV surveys, while more costly, offer greater flexibility and could facilitate the immediate retrieval of floating debris during line and cable inspections. Alternatively, conducting all inspection operations using a crewed vessel deploying an AUV to conduct autonomous surveys could also be an effective option, especially if the frequency of inspections drops. A vessel with an AUV specialist could conduct other routine operations and maintenance activities while the AUV completes the inspection, either running fully autonomously or piloted by the shipboard AUV specialist.

USE PASSIVE ACOUSTIC MONITORING WITHIN FLOATING OFFSHORE WIND ARRAYS TO AUTOMATICALLY DETECT THE PRESENCE OF VOCALIZING MARINE SPECIES AND TO TRIGGER FOLLOW-UP MONITORING.

Passive acoustic monitoring (PAM) technology can detect whale presence over a considerable area, with the exact detection ranges varying by species and oceanographic conditions. Existing detection algorithms can automatically identify some species-specific vocalizations in near real time, and future developments may enable the automated identification of additional species.

Protocols should be developed for use if vocalizing marine species are detected in proximity to floating offshore wind arrays. For example, a relative increase in automated PAM alerts may indicate increased species presence within an area and could be used to trigger immediate follow-up surveys of the array's subsurface infrastructure for accumulated entanglement risks. This could serve as a low-cost method for increasing on-site infrastructure monitoring for entanglement risks, within an adaptive management framework. The PAM arrays should ensure total coverage of the lease area.

Depending on the type of system and configuration used, PAM technology has several limitations, including difficulty in identifying the direction sounds originate from and difficulty in determining whether one individual or multiple individuals are making sounds. Variable rates of vocalization during different stages of an animal's life cycle can also pose problems for PAM technology (for example, right whale and humpback whale mother-and-calf pairs vocalize more as their seasonal migration progresses).[55] Given these limitations, observers and other technologies should also be used as part of monitoring systems in order to ensure more reliable data about species' presence and appropriate responses.

OPERATORS SHOULD FOLLOW STANDARD PROTOCOLS TO RESPOND TO ENTANGLEMENT EVENTS

If entanglements are identified through monitoring, it is essential to have a well-defined protocol to respond promptly and mitigate resulting harm to ocean wildlife and ecosystems. Protocols should facilitate rapid response to detected entanglements and ensure on-call availability of response teams if heightened risks for entanglement are detected. Protocols should also clearly define the working relationships among, and respective roles of, local and regional marine species rescue and rehabilitation organizations.

Our proposed initial protocols include the following:

- If monitoring reveals that sharks and/or diving or plunging marine birds are entangled in marine debris on any project structure, the lessee must promptly notify the National Marine Fisheries Service (NMFS) or U.S. Fish and Wildlife Service (USFWS), the U.S. Coast Guard, and the relevant state agency as soon as possible and no more than six hours after detection. The lessee must remove the marine debris and any entangled sharks or diving or plunging marine birds as soon as possible following discovery in a manner that is determined by the appropriate federal and state agencies and that does not jeopardize human safety, property, or the environment.
- In cases where marine mammals or sea turtles are entangled in marine debris ensnared on a project structure, the lessee must follow the Reporting Protocol for Injured or Stranded Marine Mammals or the sea turtle reporting protocol developed by the Sea Turtle Disentanglement Network. The lessee must provide federal and relevant state agencies with all available information on the incident and make such information publicly accessible.
- Finally, if monitoring shows that debris has become ensnared on any project structure without entanglement of marine mammals, sea turtles, sharks, or diving bird species, the lessee must notify the NMFS or USFWS, the U.S. Coast Guard, and, where relevant, the California Department of Fish and Wildlife within 24 hours of detection. The lessee again must remove the marine debris as soon as possible following its discovery while ensuring that human safety, property, and the environment are not compromised.

OPERATORS SHOULD MAINTAIN EQUIPMENT AND STAFF TO RESPOND TO ENTANGLEMENT EVENTS

A varied fleet of vessels is needed to aid with regular offshore wind operations and maintenance activities, and developers should ensure that at least some of these vessels have features and capabilities for secondary entanglement location and removal. These features include a boat length of 40 feet or more; winches or cranes with load capacities suitable for commercial fishing; suitability for both scuba and surface-air-supply diving; and abilities to launch, operate, and retrieve an ROV or AUV.

OPERATORS SHOULD ENSURE DATA AVAILABILITY AND TRANSPARENCY

California, Oregon, and Washington State have established systems for the reporting of lost fishing gear, and these have proved valuable in ALDFG mitigation, location, and retrieval. Floating offshore wind arrays should be integrated into existing reporting systems, with priority given to reporting fishing gear lost within proximity of currently operating floating wind arrays in order to reduce the risk of secondary entanglement. Additionally, fishers should have a system to report gear loss or ALDGF gear sightings within and near offshore floating wind infrastructure. Such a system could be integrated into existing gear-loss reporting programs, offering a streamlined method for managing and mitigating the risks associated with lost or adrift fishing gear in the vicinity of floating offshore wind projects.

Offshore wind developers should also be required to adhere to federal and relevant state derelict fishing gear and marine debris survey, disposal, recovery, and reporting requirements.

All baseline, monitoring, incident, and assessment data regarding entanglement incidents should be made publicly available and shared with standard metadata conventions used by the Marine Cadastre, the U.S. Integrated Ocean Observing System, regional ocean data portals, or other long-term collaborative data management efforts.[56] To facilitate long-term access, data could be hosted by an independent entity; for example, the Northeast Regional Ocean Council and the California Offshore Wind Energy Gateway both currently provide access to regional data on marine life, seafloor habitat, and other data relevant to planning for offshore wind development.[57]

Data should promptly be made publicly available. Frequent reporting is necessary to alert agencies, lessees, and the public to impacts in a timely manner and to enable avoidance, minimization, and mitigation of adverse impacts throughout all phases of development, operations, and decommissioning.

CONCLUSION

A number of technologies and protocols already exist that would allow floating offshore wind developers to effectively reduce entanglement risks to marine mammals and other marine life. Additional solutions on the horizon could, with adequate near-term investment, further reduce these risks. As the offshore wind industry advances, state and federal regulators, as well as developers, should ensure that these technologies and protocols are part of every floating offshore wind project. The development of an important renewable energy resource and the protection of invaluable marine species should not be in conflict. Measures must be taken now to ensure the responsible and sustainable development of the offshore wind industry.

APPENDIX: CURRENTLY AVAILABLE MONITORING TECHNOLOGIES

METHODOLOGY

The technologies presented in this report were assessed through a comprehensive literature review and outreach study examining current floating offshore wind design risk assessments, monitoring methods and constraints, and monitoring and mitigation recommendations. The literature review included peer-reviewed studies and "gray" literature such as technical reports and floating turbine array proposals from government and industry. The outreach study consisted of interviews with marine industry professionals and scientists working on solutions to address floating offshore wind monitoring needs.[b]

Tables 1 and 2 present example makes and models of different technology platforms. Some were selected from data presented in a 2020 review of subsea cable monitoring technologies.[58] Others were identified during expert interviews. In selecting sonar systems, special consideration was given to avoiding any potential adverse effects of sonar frequencies and volumes on the marine environment.

AUTOMATED UNDERWATER VESSELS (AUVS) AND TOWFISH[c]

TABLE 1: SELECT EXAMPLE AUV PLATFORMS (ADAPTED FROM ELEFTHERAKIS AND VICEN-BUENO 2020)

Make and Model	Range (km)	Endurance (hr)	Depth (m)	Supported Sensors/Capacity (where provided)
Hydroid Remus 600	133	24	600	Side-scan sonar, video cameras, still cameras
Kongsberg Munin/Henin	133	24	1,500	Multi-beam sonar, side-scan sonar, still cameras
Gavia Teledyne Marine	28–133	5–8; can be extended to 15–24 with addition of extra batteries	1,000	Optional USBL, multi-beam sonar, side-scan sonar, camera

ACOUSTIC SONAR MONITORING AND SURVEYS

SIDE-SCAN SONAR

TABLE 2: SELECT EXAMPLE MULTI-BEAM AND SIDE-SCAN SONAR UNITS (ADAPTED FROM ELEFTHERAKIS AND VICEN-BUENO 2020)

Make and Manufacturer	Sonar Type	Platforms	Max. Depth (m)	Max. Range (m)	Frequency (kHz)	Beam Angle (°)
Kongsberg em2040-04	Multi-beam	AUV	6,000	400	200/300/400	165
Teledyne Seabat T20-S	Multi-beam	AUV	6,000	400/225	200/400	170
Biosonics Omnidirectional Marine Life Observer	Multi-beam	Fixed	NA	200 to 400	200	360
R2Sonic 2026	Multi-beam	Vessel, ROV, AUV, Autonomous Surface Vehicle (ASV)	4,000	800	100/200/450	2/1/0.45
Klein UUV-3500	Side-scan	AUV	6,000		75/100/400	
Kongsberg Geoswath Plus	Side-scan	AUV	4,000	200/100/50	125/250/500	0.85/0.75/0.5
Klein System 5900	Side-scan	Towfish	750	N/P	600	NA

b This section was developed in consultation with contracted third-party researchers.

c Tables of example technologies are provided only for AUVs and sonar units due to the large diversity of commercially available models.

MONITORING COST ESTIMATES FOR PILOT AND COMMERCIAL-SCALE FLOATING OFFSHORE WIND ENERGY PROJECTS

Cost estimates presented in Table 3 were developed using example technology for each of the monitoring systems recommended. Once selected, sales quotes were obtained for all example technologies. Theoretical cost per individual floating offshore wind turbine, as well as for 50- and 100-turbine arrays, were also calculated. Cost estimates for applying monitoring recommendations were developed using scale data provided by a theoretical pilot-scale (9-turbine) array developed by Pacific Northwest National Laboratory and a projected commercial-scale (100-turbine) array proposed for the California coast.[59]

Our choice of examples for presented cost estimates should not be taken as an endorsement of one make or model over another; rather, examples were chosen as being representative of the capabilities and technical specifications suited for offshore wind monitoring and survey work. The number of units per individual floating offshore wind turbine were dependent on whether the technology would need to be installed on every mooring line or on the floating platform. For technologies used on an array-wide scale, the number of recommended units was based on detection area (PAM) or range and endurance (AUV). It is possible that larger arrays could benefit from bulk ordering, but this was not considered while developing estimates.

TABLE 3: SELECTED MONITORING TECHNOLOGIES AND ESTIMATED COST AT PILOT SCALE (9 FLOATING TURBINES) AND COMMERCIAL SCALE (100 FLOATING TURBINES)

Equipment	Monitoring Type	Utility	Make	Model	Est. Cost	Units per turbine	Pilot-Scale Array (9 turbines)	Commercial-Scale Array (100 turbines)
Passive acoustic monitoring	Fixed continuous	Automated acoustic alerts		Real-time alert cable system w/ 2, 4 hydrophone arrays	NA	NA	$1,500,000 per year	$1,500,000 per year
Omnidirectional sonar	Fixed continuous	Automated perimeter alerts and continuous sonar monitoring of mooring lines	Biosonics	Omnidirectional Marine Life Observer	$250,000	1	$2,250,000	$25,000,000
Load cells	Fixed continuous	Automated detection of load anomalies	Scotload	150-ton load shackle bundle	$7,722	5	$347,490	$3,861,000
Vibration monitor*	Fixed continuous	Automated detection of excess vibration or movement	NA	NA	NA	4	NA	NA
AUV**	Regular surveys	Automated or remote piloted platform with multi-beam sonar, side-scan sonar, and real-time video instrumentation	Teledyne Marine	Gavia	$1,500,000	NA	$3,000,000 (2 units)	$7,500,000 (5 units)
Boat and towfish/ROV	Regular surveys	Surveys of mooring lines		NA	$8,000 to $20,000 per day	NA	$16,000 to $40,000 (estimated two days of work)	$160,000 to $400,000 (estimated 20 days of work)

Multiple make options exist for several of the technologies represented in this table and for that reason, specific makes are not listed.

* *Several options are currently in development and may be available within one year of this report.*

** *Total AUVs per project were calculated assuming (1) vessel deployment within the floating offshore wind array; (2) theoretical maximum AUV range of 133 km; (3) Four 1-km survey lengths consisting of three mooring lines and a single inter-array cable per floating turbine; (4) at least one backup AUV.*

Monitoring technologies and protocols for floating offshore wind infrastructure will likely be similar across projects regardless of mooring design.[60] However, the mooring system, along with the total number of floating turbines in each array, determines the footprint of an individual floating turbine and of the overall project and may affect the costs of comprehensive monitoring systems. Catenary mooring systems with their more extensive footprint will potentially be more costly to monitor.

ENDNOTES

1 Angel McCoy et al., *Offshore Wind Market Report 2024 Edition*, National Renewable Energy Lab, August 2024, https://docs.nrel.gov/docs/fy24osti/90525.pdf; Global Market Insights, *Floating Offshore Wind Energy Market Size*, February 2025, https://www.gminsights.com/industry-analysis/floating-offshore-wind-energy-market; Global Wind Energy Council, *Floating Offshore Wind—A Global Opportunity*, March 2022, https://www.gov.br/mme/pt-br/assuntos/secretarias/sntep/geracao-energia-eletrica-offshore/estudos-e-documentos-base/gwec-report-floating-offshore-wind-a-global-opportunity.pdf.

2 Hoesung Lee et al., *Climate Change 2023: Synthesis Report*, Intergovernmental Panel on Climate Change, 2023, 27–28; https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf.

3 U.S. Department of Energy (hereinafter DOE), *Advancing Offshore Wind Energy in the United States: U.S. Department of Energy Strategic Contributions Toward 30 Gigawatts and Beyond—Highlights*, March 2023, 5, https://www.energy.gov/sites/default/files/2023-03/advancing-offshore-wind-energy-highlights.pdf.

4 McCoy et al., *Offshore Wind Market Report 2024*; AJ Dellinger, "Gigawatt: The Solar Energy Term You Should Know About," CNET, March 22, 2024, https://www.cnet.com/home/solar/gigawatt-the-solar-energy-term-you-should-know-about/.

5 DOE, *Advancing Offshore Wind Energy,* 7–8; Sara Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology for Marine Species and Habitats," *Journal of Environmental Management* 307, no. 5 (April 2022): 114577, 10.1016/j.jenvman.2022.114577; Walt Musial et al., *2016 Offshore Wind Energy Resource Assessment for the United States*, National Renewable Energy Laboratory, September 2016, 15–16, 34; https://www.nrel.gov/docs/fy16osti/66599.pdf.

6 U.S. Congressional Research Service, *Potential Impacts of Offshore Wind on the Marine Ecosystem and Associated Species: Background and Issues for Congress*, January 19, 2024, 2, https://crsreports.congress.gov/product/pdf/R/R47894; Bureau of Ocean Energy Management (hereinafter BOEM), "California Activities," (accessed August 19, 2025), https://www.boem.gov/renewable-energy/state-activities/california.

7 California Energy Commission, "Assembly Bill 525: Offshore Wind Strategic Plan—Vol. II Main Report," January 2024, 8, https://www.energy.ca.gov/data-reports/reports/ab-525-reports-offshore-renewable-energy.

8 Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology."

9 Steven Benjamins et al., *Understanding the potential for marine megafauna entanglement risk from marine renewable energy developments*, Scottish Natural Heritage Commissioned Report No. 791, 2014, https://tethys.pnnl.gov/sites/default/files/publications/SNH-2014-Report791.pdf; Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology"; BOEM, *California Offshore Wind Draft Programmatic Environmental Impact Statement: Volume I*, November 2024, ES-6, https://www.boem.gov/sites/default/files/documents/renewable-energy/state-activities/2024_1021_CA_PEIS_Vol_I_508c_0.pdf.

10 U.S. Offshore Wind Synthesis of Environmental Effects Research (hereinafter SEER), "Risk to Marine Life from Marine Debris & Floating Offshore Wind Cable Systems," Winter 2022, https://tethys.pnnl.gov/sites/default/files/summaries/SEER-Educational-Research-Brief-Entanglement-Considerations.pdf; Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology."

11 Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology."

12 Ibid.

13 Ibid.

14 Ibid.

15 Statoil, "Hywind Scotland Pilot Park Project, Plan for Construction Activities," 2017, https://tethys.pnnl.gov/sites/default/files/publications/Statoil2017.pdf.

16 Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology."

17 Ibid.

18 Ibid.

19 A. Copping and M. Grear, "Humpback Whale Encounter with Offshore Wind Mooring Lines and Inter-Array Cables," prepared by Pacific Northwest National Laboratory for BOEM, October 2018, https://www.boem.gov/sites/default/files/environmental-stewardship/Environmental-Studies/Pacific-Region/Studies/BOEM-2018-065.pdf; Benjamins et al., "Understanding the potential for marine megafauna entanglement risk"; Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology."

20 Statoil, *Hywind Scotland Pilot Park, Environmental Statement*, April 2015, https://tethys.pnnl.gov/sites/default/files/publications/Hywind-Pilot-Park-Environmental-Statement.pdf; Copping and Grear, "Humpback Whale Encounter."

21 Copping and Grear, "Humpback Whale Encounter"; Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology."

22 SEER, "Risk to Marine Life from Marine Debris"; Hayley Farr et al., "Potential Environmental Effects of Deepwater Floating Offshore Wind Energy Facilities," *Ocean & Coastal Management* 207 (2021): 105611, https://doi.org/10.1016/j.ocecoaman.2021.

23 Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology"; Farr et al., "Potential Environmental Effects."

24 Benjamins et al., "Understanding the potential for marine megafauna entanglement risk".

25 Ibid., at 4-6.

26 SEER, "Risk to Marine Life from Marine Debris"; Benjamins, "Understanding the potential for marine megafauna entanglement risk" at 11–12.

27 Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology."

28 Ibid.

29 SEER, "Risk to Marine Life from Marine Debris."

30 Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology."

31 National Oceanic and Atmospheric Administration (hereinafter NOAA), NOAA Marine Debris Program, "Impact of 'Ghost Fishing' via Derelict Fishing Gear," last updated March 20, 2024, https://marinedebris.noaa.gov/wildlife-and-habitat-impacts/impact-ghost-fishing-derelict-fishing-gear; L. Lebreton et al., "Evidence that the Great Pacific Garbage Patch Is Rapidly Accumulating Plastic," *Scientific Reports* 8 (2018): 4666, https://doi.org/10.1038/s41598-018-22939-w.

32 NOAA Fisheries, *National Report on Large Whale Entanglements Confirmed in the United States in 2022*, January 2024, https://www.fisheries.noaa.gov/s3//2024-01/National-Report-Large-Whale-Entanglement-2022-508.pdf. See also NOAA Fisheries, "2023 West Coast Whale Entanglement Summary," (accessed August 19, 2025), https://storymaps.arcgis.com/stories/267aaa6e6a494d44be437b597f3993a3.

33 See BOEM, *California Offshore Wind Draft Programmatic Environmental Impact Statement* at 3.3.6-17.

34 See, e.g., Delphine Durette-Morin et al., "The Distribution of North Atlantic Right Whales in Canadian Waters from 2015–2017 Revealed by Passive Acoustic Monitoring," *Frontiers in Marine Science* 9 (December 2022), https://www.frontiersin.org/journals/marine-science/articles/10.3389/fmars.2022.976044/full; Dimitrios Eleftherakis and Raul Vicen-Bueno, "Sensors to Increase the Security of Underwater Communication Cables: A Review of Underwater Communication Monitoring Sensors," NATO STO Center for Maritime Research and Experimentation, 2020, https://www.mdpi.com/1424-8220/20/3/737.

35 NOAA National Ocean Service, "What Is the Difference Between an AUV and a ROV?," last updated June 16, 2024, https://oceanservice.noaa.gov/facts/auv-rov.html.

36 Ella Browning et al., *Acoustic Monitoring: Passive Acoustic Monitoring in Ecology and Conservation*, World Wildlife Fund, 2017, https://www.wwf.org.uk/sites/default/files/2019-04/Acousticmonitoring-WWF-guidelines.pdf; NOAA National Ocean Service, "What Is Sonar?," last updated June 16, 2024, https://oceanservice.noaa.gov/facts/sonar.html.

37 NOAA, "Echo Technology," *Ocean Explorer*, revised October 27, 2009, https://oceanexplorer.noaa.gov/projects/thunderbay01/echo/echo.html; U.S. Department of Homeland Security, "Side-Scan Sonar," *TechNote*, July 2008, https://www.dhs.gov/sites/default/files/publications/SideScanSonar_TN_0708-508.pdf.

38 NOAA National Ocean Service, "What Is Sonar?"

39 Joan Drinkwin, Kyle Antonelis, and Max Calloway, "Methods to Locate and Remove Lost Fishing Gear from Marine Waters," prepared by Natural Resources Consultants for the Department of Fisheries and Oceans, Canada Sustainable Fisheries Solutions and Retrieval Support Program Activity 5 (Part B), March 2022, https://www.researchgate.net/publication/368751774_Methods_to_Locate_and_Remove_Lost_Fishing_Gear_from_Marine_Waters_Prepared_for_Department_of_Fisheries_and_Oceans_Canada_Sustainable_Fisheries_Solutions_and_Retrieval_Support_Program_Activity_5_Part_B.

40 Sofie M. Van Parijs et al., "NOAA and BOEM Minimum Recommendations for Use of Passive Acoustic Listening Systems in Offshore Wind Energy Development Monitoring and Mitigation Programs," *Frontiers in Maritime Science* 8 (October 2021), https://www.frontiersin.org/journals/marine-science/articles/10.3389/fmars.2021.760840/full; Rianna Burnham et al., "Spatial Impact of Recreational-Grade Echosounders and Implications for Killer Whales," *Journal of Maritime Science and Engineering* 10, no. 9 (2022): 12167, https://www.mdpi.com/2077-1312/10/9/1267; Marla M. Holt et al., "Vessels and Their Sounds Reduce Prey Capture Effort by Endangered Killer Whales (*Orcinus orca*)," *Marine Environmental Research* 170 (August 2021), https://www.sciencedirect.com/science/article/pii/S0141113621001859); Erin A. Falcone et al., "Diving Behaviour of Cuvier's Beaked Whales Exposed to Two Types of Military Sonar," *Royal Society Open Science* 4, no. 8 (August 2017), https://doi.org/10.1098/rsos.170629.

41 Alexandra Ciuriuc et al., "Digital Tools for Floating Offshore Wind Turbines (FOWT): A State of the Art," *Energy Reports* 8 (November 2022): 1207–28, https://doi.org/10.1016/j.egyr.2021.12.034.

42 See, e.g., U.S. Cargo Control, "Straightpoint Load Monitoring Loadcells," (accessed August 19, 2025), https://www.uscargocontrol.com/collections/straightpoint-load-monitoring-loadcells.

43 Mike Clare, *Submarine Cable Protection and the Environment*, International Cable Protection Committee, April 2024, 5, https://www.iscpc.org/publications/submarine-cable-protection-and-the-environment/ICPC_Public_EU_April_2024.pdf.

44 See, e.g., European Geosciences Union, Seismology ECS Team, "What Is Distributed Acoustic Sensing?," December 2, 2023, https://blogs.egu.eu/divisions/sm/2023/12/02/what-is-das/.

45 Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology."

46 Del Mar Oceanographic, "Wirewalker Wave-Powered Profiler," (accessed August 19, 2025) https://www.delmarocean.com/; McLane Research Laboratories, "Prawler," (accessed August 19, 2025) https://mclanelabs.com/prawler/.

47 Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology."

48 Ibid.

49 Francine Kershaw et al., *Monitoring of Marine Life During Offshore Wind Energy Development—Guidelines and Recommendations*, Natural Resources Defense Council, March 2023, https://www.nrdc.org/sites/default/files/ow_marine-life_monitoring_guidelines.pdf.

50 Copping and Grear, "Humpback Whale Encounter."

51 Ibid.

52 Ibid.

53 Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology"; see also KOWL, "Project Environmental Monitoring Plan: Kincardine Offshore Windfarm Project," 2019, https://tethys.pnnl.gov/sites/default/files/publications/KOWL-Project-Environmental-Monitoring-Plan.pdf

54 Ciuriuc et al., "Digital Tools for Floating Offshore Wind Turbines."

55 Samuel R. P.-J. Ross et al., "Passive Acoustic Monitoring Provides a Fresh Perspective on Fundamental Ecological Questions," *Functional Ecology* 37, no. 4 (April 2023): 959–75; https://besjournals.onlinelibrary.wiley.com/doi/10.1111/1365-2435.14275; D. A. Cusano et al., "Implementing Conservation Measures for the North Atlantic Right Whale: Considering the Behavioral Ontogeny of Mother–Calf Pairs," *Animal Conservation* 22, no. 3 (June 2019): 228–37, https://zslpublications.onlinelibrary.wiley.com/doi/full/10.1111/acv.12457; Van Parijs et al., "Minimum Recommendations for Use of Passive Acoustic Listening Systems."

56 We recommend incorporation of the detailed recommendations for data transparency and equitable data sharing found in Amy Trice et al., *Challenges and Opportunities for Ocean Data to Advance Conservation and Management*, Ocean Conservancy, 2021, https://oceanconservancy.org/smart-ocean-planning/take-deep-dive/oceandatareport/. See also the California Ocean Observing Systems Data Portal, https://data.caloos.org/.

57 For information, see the *Northeast Ocean Data Portal Work Plan*, https://neoceanplanning.org/data-issues/northeast-ocean-data-portal-work-plan/; the California Offshore Wind Energy Gateway, https://caoffshorewind.databasin.org/; or the California Ocean Observing Systems Data Portal, https://data.caloos.org/

58 Eleftherakis and Vicen-Bueno, "Sensors to Increase the Security of Underwater Communication Cables."

59 Trident Winds LLC, *Unsolicited Application for an Outer Continental Shelf Renewable Energy Lease*, January 2016, https://www.boem.gov/sites/default/files/renewable-energy-program/State-Activities/CA/MBO-BOEM-20160114-Unsolicited-OCS-Lease-Request_PUBLIC.pdf; Copping and Grear, "Humpback Whale Encounter."

60 Maxwell et al., "Potential Impacts of Floating Wind Turbine Technology."