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Docket # 23-ERDD-01 NREL RFI Response (Entangled Debris Monitoring for Floating Offshore Wind Infrastructure)

Additional submitted attachment is included below.

Request for Information

Entangled Debris Monitoring for Floating Offshore Wind Infrastructure

Docket # 23-ERDD-01

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This document provides NREL's response to the RFI for Entangled Debris Monitoring for Floating Offshore Wind Infrastructure. The questions are repeated in black, and NREL's response is provided in blue. We have responded to most, but not all, questions in the RFI.

General:

1. What technologies, equipment, and types of inspection could detect entanglement on FOSW infrastructure? What research is needed to advance these technologies? Please provide details on sensor accuracy, potential cost of the technology, and any additional hazards or conditions that can be detected/monitored?

Several technologies may be useful for detecting underwater entanglement (i.e., debris accumulation and/or entanglement of marine animals) on FOSW infrastructure. FOSW infrastructure as defined here includes turbine platforms, hanging ballast structures, mooring lines, and dynamic power cables. A high-level overview and comparison of the applicable technologies is shown in **Tables 1** and **2**. **Table 1** presents the types of relevant sensors for entanglement detection. **Table 2** presents a number of potential platforms to support these sensors, including platforms that could crawl along the mooring lines and power cables to streamline the inspection process.

Key considerations when selecting entanglement monitoring technologies include the floating support structure geometry, the water depths at which monitoring will occur, available illumination, required data resolution, power requirements, whether monitoring will be continuous or intermittent, and if intermittent, the planned frequency of monitoring events. Each technology has advantages and limitations. Therefore, a multi-modal approach to entanglement monitoring, which employs multiple platforms, sensors, and inspection types, will maximize the effectiveness and practicability of proposed monitoring programs.

The ideal approach will employ continuous monitoring—to the extent feasible and appropriate—to minimize risk of marine animal mortality due to entanglement; use remote sensing techniques to minimize health and safety risks associated with on-site divers and other field personnel; incorporate lessons learned from other subsea infrastructure monitoring programs (e.g., general subsea cable inspection projects and marine debris monitoring at existing FOSW farms); transfer minimal costs to developers in order to keep FOSW projects economically feasible; have clearly stated limitations and uncertainty parameters, and have preliminary buy-in from regulators for purposes of environmental permitting.

Table 1. *Sensors capable of detecting entanglements on FOSW infrastructure*

Sensor Type	**Type of Inspection**	**Advantages**	**Limitations**	**Estimated Purchase Cost Per Unit**[*]
Optical underwater cameras	Visual imaging	High-resolution, easy-to-interpret images Remote visual inspection	Limited detection range Limited effectiveness in poor conditions	~$500 - $50,000 (varies widely with quality and configuration)
"Acoustic cameras" (imaging sonars)[†]	Acoustic imaging	High-resolution, easy-to-interpret images Remote inspection via acoustic imagery in low-light and poor conditions	Expensive; may not be feasible at scale Detection range limited to ~10 m	~$90K - $150K
Echosounders	Acoustic imaging	Can sample large sections of the water column -Allows remote inspection via acoustic imagery -Relatively inexpensive	Data resolution varies Positive ID of entanglement events may be difficult Sound sources <180 kHz require MMPA permit	$10K - $30K
Mechanical sensors integrated with mooring lines or dynamic power cables	Detection through change in motions or loads (likely enhanced using a digital twin)	Automated, continuous monitoring of underwater mooring lines or power cables throughout the water column Real-time data communication Dual-purpose for structural health monitoring	Requires secondary methods to confirm entanglement events Sensitivity depends on advanced digital twin technology that is not yet demonstrated	$5k - $30k per unit; $15k - $200k per turbine system depending on sensor type

[*] Estimates are inexact and do not include labor or indirect costs

[†] See: Staines et al. 2020; Afzal et al. 2022; Zhou and Mizuno 2024

Table 2. *Platforms that could support entanglement sensors*

Platform Type	**Platform Placement**	**Advantages**	**Limitations**	**Estimated Purchase Cost Per Unit**[*]
Cable crawlers	Attached to mooring line or dynamic power cable with mechanism to traverse the mooring/cable	Field resident; no need to deploy from shore Capable of shuttling along power cables and mooring lines throughout the water column to confirm entanglement detections and remove debris Can recharge at FOSW turbines using wind power	Not yet developed or demonstrated Capable of frequent, but not continuous, monitoring Real-time data transmission capabilities still unknown	Unknown; prototype development estimated at $200K
Remotely operated underwater vehicles (ROVs)	Tethered to surface vessel; can move throughout the water column	Versatile data collection platforms capable of carrying a variety of sensors Well-demonstrated, commercially available technology Real-time data communication Remote inspection via optical and/or acoustic imagery Capable of direct mitigation via debris removal	Not capable of continuous monitoring Typically deployed from vessels, so transit to/from ports must be considered Tethered ROVs are at risk for colliding with FOSW infrastructure, e.g. undersea cables	$3K - $150K (varies widely with size, depth capability, and configuration)
Uncrewed underwater vehicles (UUVs)	Untethered: can move throughout the water column	Versatile data collection platforms capable of carrying a variety of sensors Well-demonstrated, commercially available technology	Not capable of continuous monitoring Limited real-time data communications Typically deployed from vessels so transit to/from ports must be considered	$100K - $300K

Substructure mounting	Mounted to the floating wind turbine platform/substructure	Direct attachment to floating system minimizes installation difficulty Easy wiring for power and data transmission Easy access for repairs or cleaning	Limited to sensing near the floating platform	Minimal cost for mounting brackets and wiring
Moored buoys	Mid-water-column buoyant platform anchored to seabed	Can be equipped with optical and acoustic sensors Very common remote sensing platforms likely be deployed at FOSW farms in other monitoring and research contexts; could leverage for purposes of entanglement monitoring Can be deployed long-term (months and years) with periodic servicing Can detect debris and entanglements near the seafloor that might be missed by other platforms	Limited to benthic and mid-water observations Limited real-time data communications	$10K - $250K Varies widely with configuration
Seabed platform (e.g., GeoSled[†])	Bottom (seafloor) mounted	Can be equipped with optical and acoustic sensors Can be deployed long-term (months) with periodic servicing Low-profile, suspended near sea floor Can detect debris and entanglements near the seafloor that might be missed by other platforms, especially in deep water	Limited to benthic observations Limited real-time data communications	$100K - $150K

[*] Estimates are inexact and do not include labor or indirect costs

[†] Developed by the Department of Ocean Engineering, University of Rhode Island

Given the technological capabilities and limitations identified in **Tables 1** and **2**, detection of underwater entanglements on FOSW infrastructure might best be accomplished via the following multi-modal approach:

1. Conduct visual monitoring of floating wind turbine platforms and nearby portions of mooring lines and power cables using optical underwater cameras affixed to FOSW infrastructure.

2. Conduct continuous mechanical monitoring of mooring lines and dynamic power cables over their full lengths using integrated sensors such as load cells and inclinometers. Established structural health monitoring methods can track component wear and degradation from marine growth. Adoption of advanced digital twinning methods could enable detection of suspected entanglement or impact events when the modeled behavior exceeds expected tolerances.

3. Investigate potential entanglements detected on mooring lines and power cables beneath the surface via deployment of underwater robotic platforms including ROVs, UUVs, and/or cable crawlers that shuttle along the length of a cable or mooring line. These platforms can include mechanical, acoustic, and optical sensors to detect and characterize entangled objects or marine growth. Some platforms could also feature brushes to remove marine growth and/or devices to remove entangled debris.

Research Needs

In order to test the efficacy and feasibility of the proposed approach, the most urgent research needs are (1) the creation of digital-twin-enhanced structural monitoring systems to detect potential entanglements, and (2) the development of cable crawler devices that can crawl along mooring lines or power cables for regular automated inspection and potential on-demand cleaning or cutting actions. Together, these two innovations would enable continuous monitoring of mooring lines and power cables suspended in the water column and prompt investigation and intervention of potential entanglement events.

For digital-twin-enhanced monitoring systems, existing commercial solutions need to be advanced to achieve a major increase in sensitivity and digital twin resolution. This can be achieved by integrating dynamic mooring line and power cable models within the digital twin and using sensor fusion approaches to combine measurements of the floating platform motions and mooring line or power cable motions to construct a full prediction of the mooring line or power cable dynamic response. With this high-fidelity digital twin, machine learning can be applied to identify expected behaviors during normal operation as a function of specific operation conditions. Confidence intervals around these expected behaviors can then serve as thresholds that can detect anomalies due to entanglement with high sensitivity.

For cable crawling devices, similar technologies already exist, which use wave energy to propel a sensor platform along a wire to perform vertical profiling in the water column (e.g., WirewalkerTM by Del Mar Oceanographic, San Diego, CA). Wave energy will not be a sufficient or appropriate power source in the context of FOSW, so an alternative power source will be needed, potentially powered by the wind system. Whatever the exact technology employed, low-wattage, low-cost power solutions will make entanglement monitoring more logistically and economically feasible. Cable crawlers would be distinct from traditional ROVs and UUVs in that they would have the ability to attach to, and travel along, power cables and mooring lines. Given that dynamic power cables are designed to have significant range of movement, platforms that are attached to these cables would have an advantage over free-swimming platforms because of their ability to monitor for cable-related entanglements more closely, thoroughly, and efficiently. Cable crawlers with these capabilities are currently undeveloped, and demonstrating the efficacy and practicability of this technology at scale will likely require extensive feasibility testing. This testing could be accomplished using both modeling approaches (e.g., mooring dynamics models and environmental impact scenario characterization) and empirical methods (test-tank and open water trials).

Many of the other platform and sensor technologies proposed here (optical and acoustic imaging technologies, UUVs, ROVs) are mature and well-demonstrated in the marine environment, and some are already being used at existing FOSW farms (e.g., Khalid et al. 2022). Demonstration of these technologies in the context of FOSW entanglement monitoring, however, is lacking and therefore and important research need.

Other key research questions related to the proposed monitoring approach:

- *What sensor thresholds trigger ROV/UUV/Cable Crawler deployments? What is the decision support framework?*
- *How best to ground-truth results from mechanical sensors (Step 2)? Infrastructure-mounted echosounders? Other?*
- *Can ROVs/UUVs/Cable Crawlers be staged from floating turbine platforms (and operated from shore), vs. being transported from shore? Can these be charged at remote docking stations powered at FOSW turbines?*

2. What types of structural integrity or environmental monitoring technologies would be practical and cost effective to couple with detecting entanglement? What research is needed to advance these technologies? For example, continuous condition monitoring of electrical array cables, export cables, or mooring line integrity. Please provide as much detail as possible on the accuracy and cost of each technology and specify which parameters or conditions can be detected/monitored?

As described in the response to Question #1, continuous mechanical monitoring of mooring lines and dynamic power cables over their full lengths could be conducted using integrated sensors such as load cells and inclinometers. Established structural health monitoring methods can track component wear and degradation from marine growth. Adoption of advanced digital twinning methods could provide significantly improved accuracy for measuring the structural health and fatigue damage on mooring lines. It could also enable detection of suspected entanglement or impact events when the modeled behavior exceeds expected tolerances. This would constitute a dual-purpose approach to entanglement and structural health monitoring.

When continuous monitoring sensors detect significant structural health concerns, an ROV/UUV/Cable Crawler could be deployed to investigate further. Examples of these instances could be suspected chain corrosion, marine growth accumulation, or buoyancy module loss of buoyancy—each of which would have a particular signal from a mooring line or power cable's tension/inclination measurements as processed by the digital twin. Deploying an inspection device could confirm the nature of the structural health concern and measure whether immediate maintenance is required or whether there is sufficient remaining capacity. This multimodal approach mirrors the one suggested above for entanglement detection, further demonstrating the dual-purpose nature of these systems.

Demonstrating the efficacy and practicability of this technology at scale will likely require extensive feasibility testing, including modeling/computer simulation approaches and empirical methods (test-tank and open water trials). Approximate costs are included in **Table 1**.

3. How does biofouling impact the accuracy and reliability of environmental and structural integrity monitoring sensors? What technologies can detect and monitor biofouling on FOSW infrastructure? What research is needed to advance these technologies? Please provide details on sensor accuracy, potential cost of the technology, and any additional hazards or conditions that can be detected/monitored?

Biofouling can interfere with the operation of optical or acoustic sensors to varying degrees. These are not new challenges and mitigations including coatings and periodic maintenance exist.

Biofouling will be detected via measurements of mooring line or cable profiles and tensions to the extent that marine growth adds weight and effects these components' dynamic response. More precise detection of marine growth can be done by visual measurements. For visual images, research is needed to better understand how to process the data received to inform an understanding of the level and growth rate of the biofouling, to inform decisions on long-term impact and potential mitigation needs.

Digital-twin-enhanced monitoring of mooring lines and dynamic cables can be developed to reliably detect marine growth if it is support by occasional spot-check visual inspection as described above. Once the response pattern of marine growth is recognized by the digital twin once, this pattern can be automatically detected in future instances without additional inspection. The marine growth rate information gathered through this method would be extremely valuable for several reasons:

- Impacts of marine growth can be filtered out from the anomaly detection algorithms to more accurately detect entanglement events.
- When marine growth exceeds safe operating limits for sensitive components such as dynamic cables, cleaning interventions can be performed on-demand, avoiding costly accidents or overconservative periodic maintenance.
- Marine growth levels are a major design challenge for dynamic power cables, but site-specific marine growth data is extremely limited, causing large uncertainties when designing cables that result in increased costs. Data collection will allow future cost reductions.

5. To what extent are permanent FOSW infrastructure-mounted sensors more cost effective than deploying specialized vessels or equipment such as ROVs and AUVs? Please take into consideration the differences in sensor accuracy and the travel time of vessels from port to the FOSW farm.

Fixed and mobile platforms each have unique advantages and limitations (see response to Question #1). Therefore, a multi-modal approach to entanglement monitoring, which employs multiple platforms, sensors, and inspection types, will maximize the effectiveness and practicability of proposed monitoring programs.

Field-resident ROVs are a major opportunity to provide the capability of ROV inspection while avoiding the delays and expense of transit from port. Large floating wind farms will provide the level of demand to justify stationing ROVs permanently at the farm, where they can dock with FOWTs or the substation and be permanently allocated to maintaining a farm.

7. What are the biggest challenges in integrating permanently mounted sensors for structural integrity monitoring or environmental monitoring onto FOSW infrastructure? Please describe any current limitations with regards to sensor placement on platforms, mooring lines, electrical cables, or anchors?

The reliability of load cells and other integrated force sensors is a long-standing challenge. Unlike other sensors such as inclinometers or accelerometers, load sensors need to be in the load path and are generally not considered robust enough to last the lifetime of a floating system (Ikhennicheu et al., 2020).

Sensor placement can be constrained by power and data transmission requirements. Sensors that are battery powered and transmit data by acoustic modem can be positioned anywhere as long as they are in acoustic transmission range, and they are accessible enough to replace the batteries. Sensors that have wired power or data cables generally need to be positioned close to the floating wind turbine platform, which provides the power source and data acquisition location, to avoid long cable lengths that could be prone to damage.

By using advanced mooring/cable dynamics models in a digital twin framework, more information can be inferred from limited sensor measurements. This approach can help when dealing with the above challenges to sensor reliability and positioning constraints.

8. What fishing gear, trash, or other ocean debris is most likely to become entangled in FOSW equipment installed in California wind energy areas? Please provide references or a strong justification.

Ocean debris consisting of macroplastics, including synthetic polymers used in fishing gear (gillnets, purse seine nets, bottom trawlers) is most likely to become entangled in FOSW subsea infrastructure. Abandoned, lost and discarded fishing gear (ALDFG), also called derelict fishing gear or “ghost gear”, is long-lasting in the marine environment, is present throughout the water column, from the surface to the seafloor (Gilman et al. 2021) and can travel long distances from the original fishing location (Stelfox et al. 2020). Given that numerous mooring lines, power cables, and hanging ballast structures will be associated with each FOSW turbine, there is potential for hundreds of such underwater structures to be present in the water column at a given wind farm. Should marine debris become involved with one or more of these structures, there is the potential for these initial ensnarements to attract additional debris, resulting in an additive effect that increases secondary entanglement risk for marine organisms.

9. In addition to cetaceans, pinnipeds, and marine reptiles, are there additional organisms that could be particularly at risk for entanglement from FOSW infrastructure?

Elasmobranchs, such as sharks and rays, as well as diving/plunging marine birds, such as gulls, gannets, and murres, could be particularly at risk for entanglement on FOSW infrastructure because of their diving and foraging habits. Smaller fish, marine invertebrates, and other organisms caught in abandoned gear could in turn attract larger predators, thereby increasing entanglement risk for a variety of megafauna (Maxwell et al. 2022).

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