Investigation of the Challenges of Offshore Wind in Ultradeep Water

Aubryn Cooperman, Matt Hall, Stein Housner, Cris Hein, Patrick Duffy, Daniel Mulas Hernando, Lucas Carmo, Felipe Moreno, and Walt Musial

National Renewable Energy Laboratory

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List of Acronyms

AHTS	anchor handling tug supply (vessel)
BOEM	Bureau of Ocean Energy Management
CapEx	capital expenditures
DEA	drag embedment anchor
DLC	design load case
EMF	electromagnetic field
HMPE	high-modulus polyethylene
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
IEA	International Energy Agency
MBL	minimum breaking load
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
ROV	remotely operated vehicle
SEPLA	suction-embedded plate anchor
TLP	tension-leg platform
VLA	vertical load anchor

Executive Summary

Floating offshore wind technology allows offshore wind energy systems to be deployed in water depths that are inaccessible with conventional fixed-bottom technology, of which more than 60 GW is already installed. Several floating offshore wind energy pilot projects have demonstrated reliable operation of the technology in water depths between 200 m and 300 m. Building on that experience, commercial-scale projects are being developed in areas out to 1,300 m depths. In some regions there is substantial resource potential for wind energy generation in even deeper waters; however, increasing depths may introduce new challenges for installation, maintenance, and repair. In this report, we consider technical, environmental, and economic challenges for floating offshore wind energy in ultradeep water, defined here as depths between 1,300 m and 3,000 m.

Co-Use and Environmental Challenges

One of the motivations for considering offshore wind in ultradeep water is a perceived reduction in the potential for conflicts with other ocean users and a reduction in wildlife interactions. However, more baseline data collection and studies on human and animal use patterns are required to confidently assess and quantify the potential reduction of impacts of offshore wind in ultradeep areas. The following environmental effects might be considered: (1) changes to oceanic dynamics due to energy removal and modifications, (2) electromagnetic fields, (3) habitat alterations to benthic and pelagic fish and invertebrate species, (4) underwater noise, (5) structural impediments to wildlife (including entanglement), (6) changes to water quality, (7) vessel traffic and navigation, and (8) co-use changes for recreation or commercial fishing (Boehlert and Gill 2010; Copping et al. 2016; Farr et al. 2021). In general, these effects may be relatively low to moderate in ultradeep waters, but there is uncertainty resulting from a lack of information on current environmental conditions far offshore. Monitoring technologies can be adopted to address the need for data collection and provide input into the development of mitigation strategies. In ultradeep waters it may be more difficult to access monitoring devices for installation, data retrieval, and maintenance. Considering other ocean users, the general approach we propose to reduce conflict is to minimize the size of floating wind turbines' mooring line footprints. Early engagement with stakeholders and coordination will be essential to lessen co-use conflicts and environmental impacts for successful development of ultradeep floating offshore wind projects.

Technical Challenges

Our assessment of potential technical challenges focused on the most common technologies that have been proposed or demonstrated for floating offshore wind at shallower depths. The introduction of novel concepts that may be appropriate for ultradeep locations in the future was beyond the scope of this report. The main challenges we identified involve underwater components such as electric array and export cables, anchors, mooring lines, and their methods of installation. Systems above the waterline are generally not anticipated to undergo significant changes between deep and ultradeep sites. The support structure design may experience incremental design changes to address dynamic response concerns of the full system.

Electric Cables

Floating offshore wind farms will require dynamic cables that are designed to accommodate the motion of the floating platform, wind, and water. In ultradeep water, cables (and their accessories such as splice joints and buoyancy modules) must be designed for higher hydrostatic pressure with depth. Suspending dynamic array cables at a prescribed depth between floating platforms avoids this increased hydrostatic pressure and significantly reduces the total amount of cable required at ultradeep depths. However, there is no industry experience in the implementation of a suspended cable array extending over a large area such as an offshore wind farm. As such, suspended dynamic cables may require more sophisticated design tools and analysis to reduce risk. It should be noted that this issue is not unique to ultradeep water and is likely to be encountered in the current California lease areas. Export cables will require a dynamic section between a floating offshore substation and the seabed; beyond that point, static cables can be used. Static cable designs for ultradeep depths are currently in use for subsea interconnections between onshore electrical grids. Both array and export cables will be more challenging to install in ultradeep water. Cable lay vessels must be able to support the weight of a cable extending from the surface to the seabed, requiring larger vessels with increased carousel capacity and specialized cable lay equipment for ultradeep depths.

Anchors

Anchors for ultradeep floating offshore wind need to be able to resist sustained vertical loads applied by mooring configurations that offer the smallest anchor circle radius, such as taut moorings. They should also be easily and quickly installable to minimize installation time on-site. With these criteria in mind, we carried out a qualitative survey of many different types of anchors that are used in various marine applications. Figure ES-1 highlights several anchor types that are likely to be suitable for floating offshore wind in ultradeep water. The colored bar along the bottom of Figure ES-1 is green for anchors that may be suitable in many conditions, and yellow for anchors that may have more limited application.

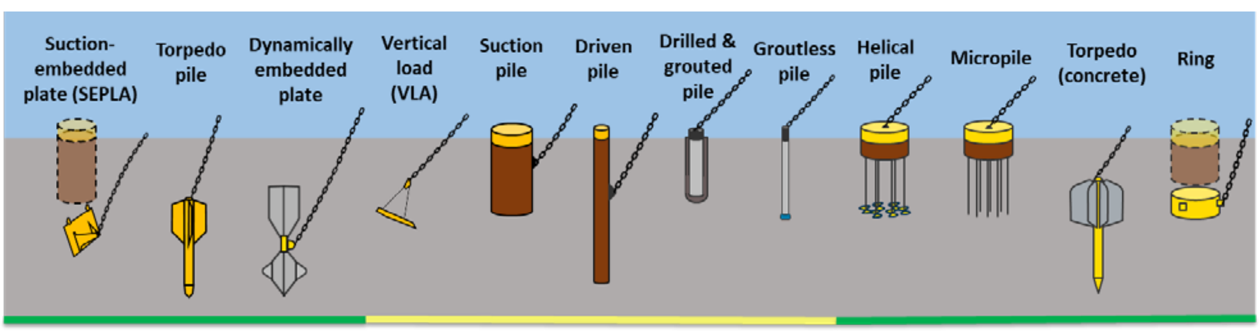

Figure ES-1. Suitable anchor types for ultradeep offshore wind applications

Illustration by NREL

Mooring Systems

Mooring system design selection is extremely sensitive to ultradeep water. The study considers ultradeep mooring systems from the standpoint of anchor spacing, mooring line weight and material usage, and cost. All three of these variables limit ultradeep mooring designs.

Figure ES-2 illustrates four different mooring configurations that could be used for floating offshore wind turbines: tension-leg platform (TLP), taut, semi-taut, and catenary. Each mooring type is shown connected to the same turbine to compare the relative spatial extent of each configuration at the same depth. As depth increases, the distance from the turbine increases proportionally. Therefore, in ultradeep waters, catenary and semi-taut configurations are disadvantaged due to their large radius, which would consume a large amount of lease area.

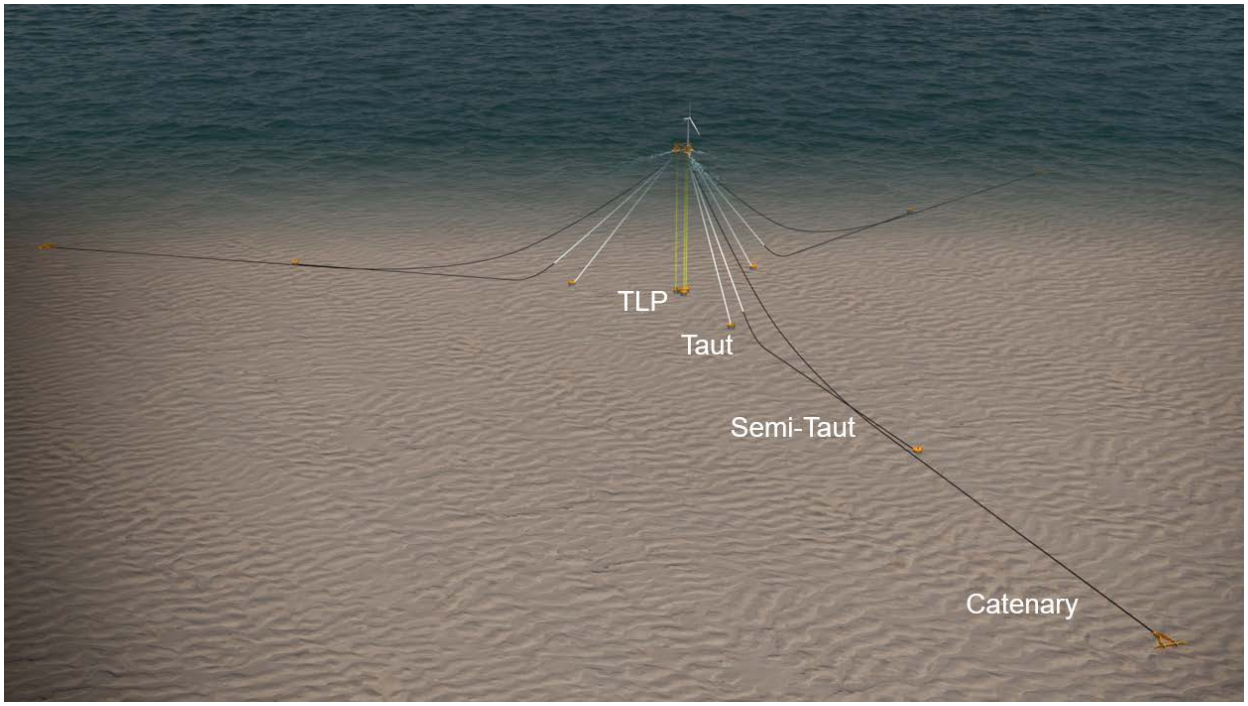

Figure ES-2. Mooring system configurations showing relative seabed area required for each type

Illustration by Joshua Bauer, NREL

Material selection for each mooring configuration also affects suitability for ultradeep waters. The weight of steel chain segments (shown in black in Figure ES-2) makes catenary configurations infeasible at ultradeep depths. Synthetic materials used for rope (shown in white) or TLP tendons (shown in yellow) are typically close to neutrally buoyant and do not add excessive weight.

The contour plots in Figure ES-3 show cost surfaces generated by an optimization tool for catenary, semi-taut, and taut designs, where white space signifies that no designs were able to satisfy line tension and seabed contact criteria for that combination of depth and anchor spacing. No catenary designs satisfy the design criteria at depths greater than 1,500 m, and a relatively limited number of semi-taut options appear feasible. Taut design solutions were obtained for all combinations of depth and anchor radius at lower cost than the other two configurations.

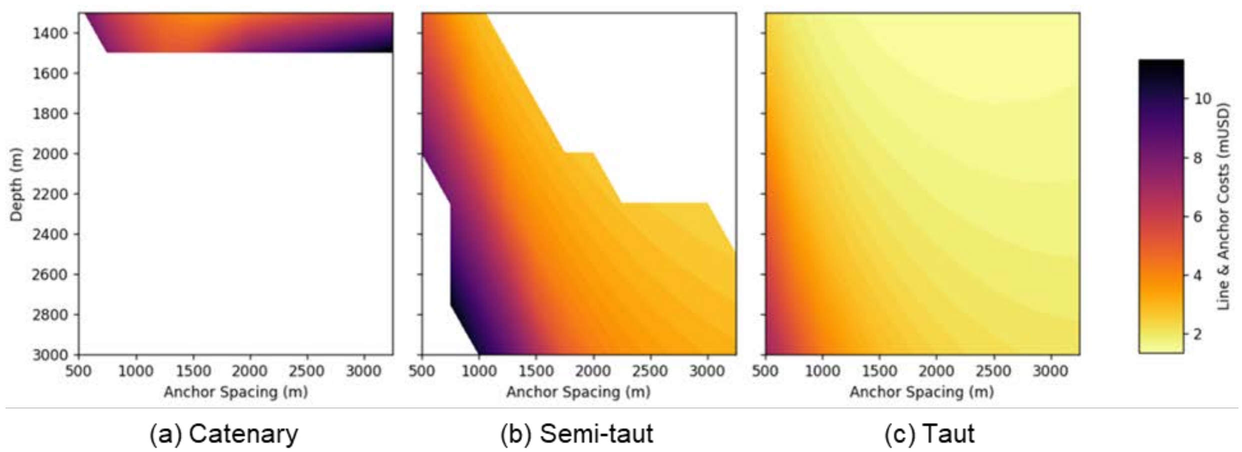

Figure ES-3. Costs for three mooring system configurations as a function of water depth and anchoring radius

The analysis showed that taut moorings and TLP designs are the most likely configurations for ultradeep waters. To investigate these designs further, we developed a set of reference designs for taut and TLP mooring configurations sized for a range of ultradeep water depths between 1,300 m and 3,000 m. We were able to use an existing reference platform design (Allen et al. 2020) without modification for the taut moorings, but there was not a comparable open-source design available for TLPs. We developed the representative design shown in Figure ES-4. In contrast to the semisubmersible with taut moorings, the TLP substructure varied with depth. We found that as the depth increased, longer and thicker pontoons were required to meet the heave and pitch natural frequency constraints for TLP designs.

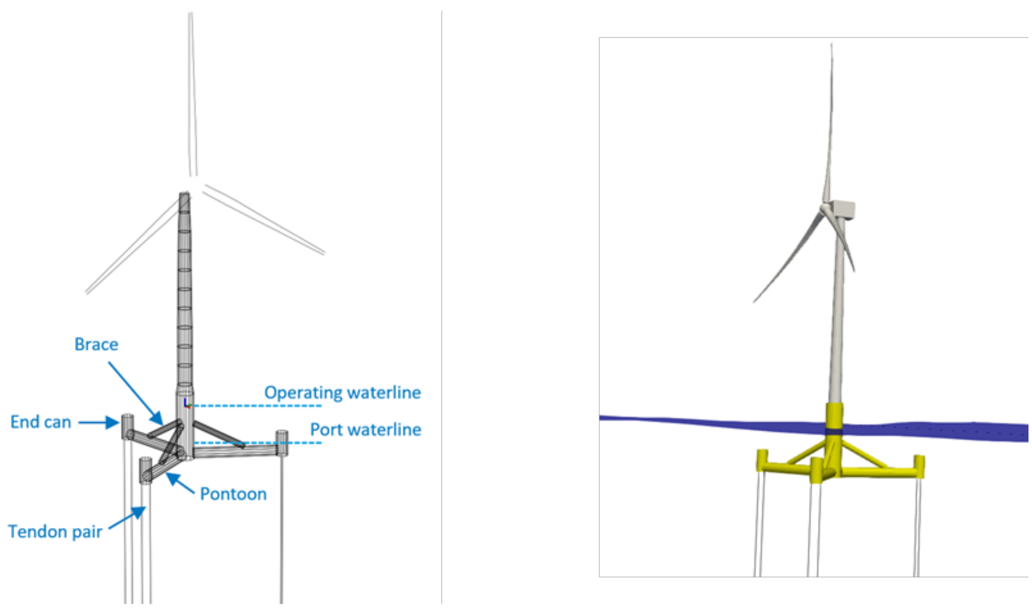

Figure ES-4. Selected TLP topology for reference design

Illustration by NREL

Figure ES-5 summarizes the key metrics for the reference TLP and taut mooring system designs. The anchoring radius is the distance from the wind turbine (undisturbed) position to an anchor. The TLP anchoring radius goes from 66 m to 79 m between 1,300 m and 3,000 m water depth, and the taut moorings go from 910 m to 2,100 m at a fixed angle of 55°. The small anchoring radius of the TLP is a significant advantage of this configuration.

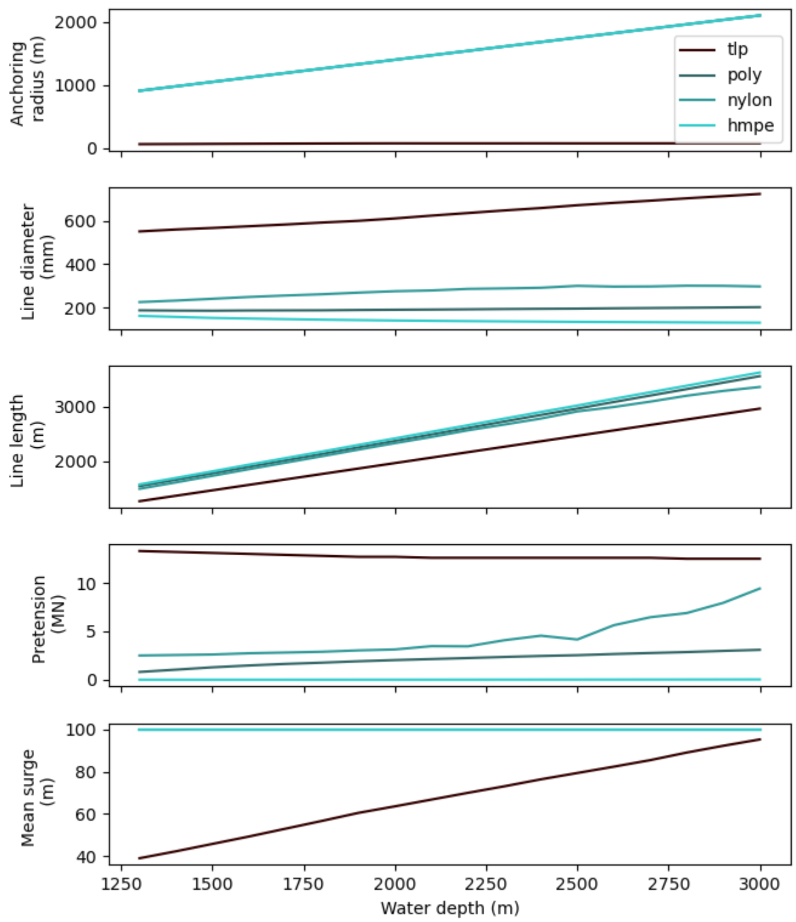

Figure ES-5. Key metrics from TLP and taut reference designs

Line diameters for the taut designs vary from 130 mm to 300 mm, depending on the material used. Nylon is the least stiff (most compliant) of the materials considered and requires the largest diameter to meet the maximum tension without breaking. At the deeper end of the range, 300-mm nylon lines are approximately the diameter of the largest ropes currently manufactured. The stiffest material we modeled is high-modulus polyethylene (HMPE) for both taut and TLP moorings. For taut moorings, HMPE allowed the smallest line diameters; however, TLP tendons at these depths require a large cross section to achieve the necessary stiffness to meet natural frequency constraints for platform heave and pitch motions. The resulting TLP tendon diameters are significantly larger than currently manufactured rope sizes.

Line lengths scale with water depth; the taut lines require additional length as they spread out from the floating platform, whereas the TLP tendons attach to the platform underwater and can be slightly less than the water depth. The mean surge in Figure ES-5 is equivalent to the watch circle radius because we are modeling an extreme load case that results in maximum displacement, which is constrained to 100 m for these designs. All of the taut designs reach this constraint, but the watch circle radius for the TLP designs is less than 100 m in all cases.

Among all the metrics shown in Figure ES-5, the line diameter for TLPs and the anchoring radius for taut designs represent the most significant challenges for their respective configurations in ultradeep water. HMPE is costly at currently manufactured diameters; at the much larger diameters presented here for TLP designs, the tendons would be a major system cost driver. The anchor radius for taut mooring systems influences the wind plant layout, limiting capacity density, or generating capacity, within a given area.

Capacity Density

Figure ES-6 shows how the reference taut mooring system design could be used in a floating offshore wind array. The orientation of the mooring systems alternates between rows to avoid crossing lines. The anchors must be placed within the boundaries of a lease area, which creates a region along the edge of the array that cannot be utilized for wind turbine positions. The minimum spacing between turbines varies with depth. At 1,300 m, these minimum spacings allow for capacity densities comparable to typical fixed-bottom capacity densities between 2 and 9 MW/km^2. At 3,000 m, however, capacity densities are limited to approximately 3 MW/km^2. Lower capacity densities imply that a wind plant in 3,000-m water would require close to 180% more space than an equivalent plant in 1,000-m water.

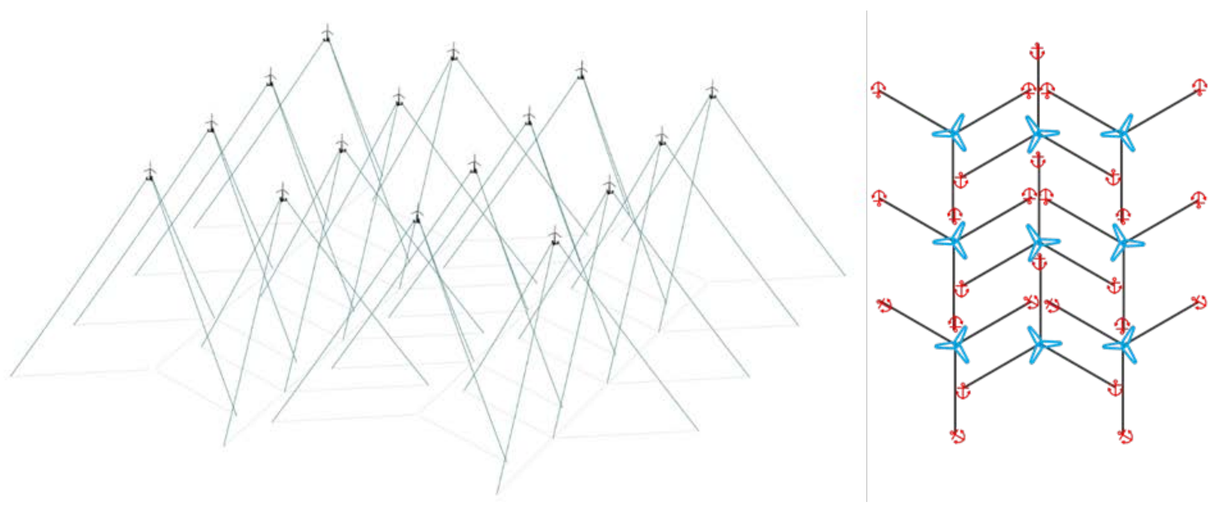

Figure ES-6. (Left) Array of semisubmersibles with reference taut polyester mooring systems at 3,000-m water depth; (right) top-down view of array highlighting wind turbine positions (blue), mooring lines (black) and anchors (red)

Illustration by NREL

The increased space required for spread moorings, additional material needed for mooring lines and electrical cables, and longer installation times for floating offshore wind plants in ultradeep water all impact capital expenditures (CapEx). We modeled CapEx for 975-MW wind plants in 1,000 m and 3,000 m of water and found that CapEx increased by 24% for the wind plant at the ultradeep site relative to same configuration at the deep site (Figure ES-7). This cost increase represents a significant challenge to the viability of ultradeep water offshore wind projects.

Although operational expenses were not in the scope of this study, it is reasonable to assume that they would also increase to some degree due to the challenges of accessing ultradeep sites.

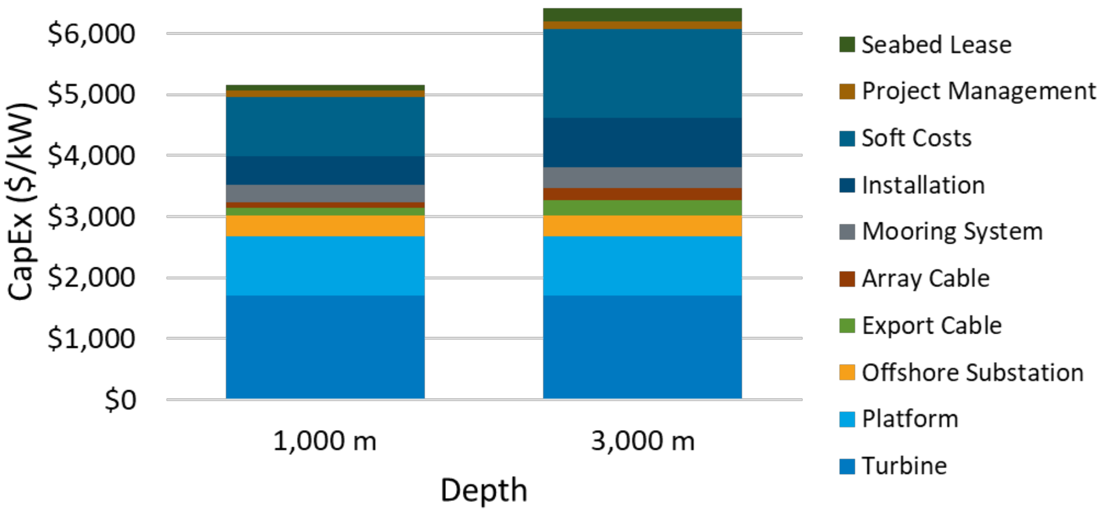

Figure ES-7. CapEx comparison for 975-MW wind plants with taut moorings at 1,000-m and 3,000-m water depths

These CapEx values represent our best estimate of costs for floating offshore wind plants with access to a mature supply chain, adequate vessel availability, and supporting infrastructure such as ports and transmission. The floating offshore wind industry is in its infancy and gigawatt-scale projects have not been developed anywhere in the world. More experience with larger floating arrays and deployment in deep water will provide valuable learning on which to base new design concepts and develop better estimates of the cost of ultradeep wind plants in the future.

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1 Introduction

Offshore wind energy is being deployed across the globe, with installations totaling 72.5 GW at the end of 2023 (Global Wind Energy Council 2024). The majority of these wind turbines are installed on fixed-bottom foundations in water depths of less than 60 m. Over time, as the available shallower sites are occupied, the average depth of offshore wind projects has increased from approximately 10 m in 2005 to nearly 40 m in 2022 (Musial et al. 2023). In deeper water, fixed-bottom foundations become infeasible and floating platforms are required. As of 2023, the operating capacity of floating offshore wind totaled 236 MW (Global Wind Energy Council 2024). These pilot projects are located in water depths of 60–300 m. Future deployments are expected in deeper water, for example, areas leased for offshore wind development off California contain water depths up to 1,300 m. To avoid known conflicts with existing ocean users, even deeper locations have been proposed for offshore wind development, including in the Central Atlantic and offshore California, but the technology challenges have not yet been evaluated. (Bureau of Ocean Energy Management 2022; California Energy Commission 2024c).

This study provides a detailed examination of the challenges of deploying offshore wind energy in ultradeep water. Various sources define ultradeep water at different depths ranging from 5,000 ft (1,500 m) to 10,000 ft (3,000 m) (Caudle and McLeroy n.d.; DNV 2016; U.S. Energy Information Administration 2016). In this study, we consider the existing California lease areas between 500 m and 1,300 m to represent deep water and define water depths between 1,300 m and 3,000 m as ultradeep. We identify qualitative (and where possible, quantitative) differences between floating offshore wind technology and installation in ultradeep water relative to deep water.

This study is not a technical feasibility assessment of any floating offshore wind system or component.

2 Technology Overview

This section provides an overview of the technical characteristics of floating wind energy systems and considerations for their use in ultradeep water. We focus on current floating wind technology that has been demonstrated in shallower depths, assuming relatively minor changes to the overall design concepts as they are scaled to ultradeep water depths (1,300–3,000 m). These scaled designs have not been optimized for ultradeep water, and other, novel technologies may be more suitable. This analysis does not address in detail technologies for ultradeep water that require a departure from conventional solutions.

The primary offshore wind plant components that must be altered to go from deep water to ultradeep water are the floating platforms (or substructures), their mooring and anchor systems, and the offshore electrical infrastructure. Wind turbines are unlikely to require significant adaptations for use in ultradeep water relative to other floating wind energy systems. This overview focuses on floating wind turbine support structures—floating platforms, mooring lines, and anchors—as well as array and export cable systems. Installation challenges in ultradeep water, such as farther distances from shore and more demanding specifications for installation vessels, are included in the analysis as important factors for the suitability of subsystems in ultradeep water. Reliability implications are also noted. Each topic area is discussed in more detail in the following sections.

2.1 Floating Platform Substructure

2.1.1 Substructure Types

Floating support structures can generally be categorized according to three design archetypes related to how they achieve static stability after installation. The three stability classes that correlate to each design archetype are ballast-stabilized, buoyancy-stabilized, and mooring-stabilized. Ballast-stabilized designs have a deep substructure draft with ballast to achieve stability through a low center of gravity. Buoyancy-stabilized designs have a wider substructure with a large footprint at the waterline to provide stability through water plane area. Mooring-stabilized designs use taut and stiff tendons to provide stability through mooring line tension. The most common examples of these stability classes are spars, semisubmersibles, and tension-leg platforms (TLPs), respectively (Figure 1), but there are other substructure types, including some that use multiple methods to achieve stability.

Figure 1. Common floating support structure types for floating offshore wind. From left to right: spar, semisubmersible, and tension-leg platform.

Illustration by Joshua Bauer, NREL

These substructures and their mooring systems are designed to provide the stability necessary for efficient turbine operation and system survivability for site-specific environmental loadings like wind, waves, and ocean currents.

Floating substructure sizes are not expected to change significantly for use in ultradeep water. The environmental loadings from wind and waves in ultradeep water are likely to be similar to environmental loadings in shallower water because wind and waves exhibit only mild spatial variability across different water depths (Zheng et al. 2016). Although currents at some locations can vary significantly within the water column, which will affect the mooring system, the magnitude of the current at the top of the water column where the substructure floats is not expected to vary significantly across different water depths. Consequently, changes in platform design due to changes in environmental loading are expected to be small and not directly linked to water depth.

Ultradeep water necessitates significantly longer mooring systems, which would motivate changes to mooring-stabilized platform designs but not other platform types. For ballast- and buoyancy-stabilized designs, longer mooring lines are likely to consist primarily of lightweight synthetic fiber rope that would likely not add weight to the platform when floating. However, they may produce higher static and dynamic tensions on the platform, which may require a small increase in the size of the platform. For mooring-stabilized designs, an increase in tendon length due to an increase in water depth without altering any other parameters will result in tendons that provide less stiffness to the floating platform. Enlarging the tendon diameters or using different tendon materials can compensate for the loss in stiffness, but these changes may require larger changes to the platform topology to ensure stability. More details on mooring-stabilized platforms are provided in Section 6.2.

2.1.2 Installation and Repairs

The process for installation of the floating platforms is also likely to remain the same for projects in ultradeep water. The substructure is expected to be constructed at port in a sheltered harbor where it can be set in the water for wind turbine assembly, installation, and commissioning. The whole system can then be towed from port to site and connected to the preinstalled mooring system. Different towing vessels, or a larger number of vessels, may be required to support changes in substructure size and longer voyages, but the general outline of the process remains the same. Repair and maintenance procedures are also not expected to change, given the consistency of substructure sizes.

Although the installation and repair processes are likely to remain the same for a given platform design, processes differ somewhat between platform types. Towing requirements, in particular, vary. Buoyancy- and ballast-stabilized platforms can typically be towed by a standard anchor handling tug supply (AHTS) vessel with sufficient bollard pull, in some cases supported by one or more additional tugboats. Mooring-stabilized platforms are not stable until they are moored and require specialized purpose-built or retrofit vessels for installation.

2.2 Mooring Systems

Mooring systems are the part of the support structure that provides stationkeeping—preventing the floating system from drifting away from its assigned location. They also provide stability in mooring-stabilized designs like TLPs. The primary components of mooring systems are mooring lines and anchors. First, we focus on the mooring lines, which are most directly affected by water depth.

2.2.1 Mooring Line Configurations

Mooring lines determine a floating platform's stationkeeping behavior by providing restoring forces that resist lateral motions, confining the platform to a predetermined envelope. The horizontal motion envelope of the floating platform is defined as the watch circle (although it is not necessarily circular). A stiff mooring system will restrict platform offsets and reduce the watch circle area, whereas a more compliant mooring system will allow larger platform offsets and increase the watch circle area. While providing the required stiffness to keep platform offsets within allowable limits, the mooring lines should also be compliant enough to ensure that wave-induced platform motions do not cause excessive mooring line load peaks. The exception is tension-leg mooring lines, or tendons, which are designed for high tension and high stiffness to restrict platform motions in the direction of the tendons.

Important technical challenges for mooring line configurations in ultradeep water are:

- Weight: Longer lines increase mooring system weight for steel mooring materials.
- Stiffness: Longer lines reduce the overall elastic stiffness of rope mooring lines, regardless of the mooring line material used. This makes platform offset limits more difficult to attain and less stiff (more compliant) materials harder to use. More details on mooring system stiffness can be found below and in Section 6.
- Space: Longer lines occupy a larger footprint and may motivate wider turbine spacing.

- Materials: Mooring lines in ultradeep water will require a combination of more length, larger diameters, and/or high-performance materials. Each of these factors increases costs and may exceed the capacity of current supply chains.

There are also important challenges related to anchors and installation, which are covered in Sections 2.2.2 and 2.2.3, respectively.

Mooring lines can generally be categorized into four main configuration types: catenary, taut, semi-taut, and tension-leg (Figure 2):

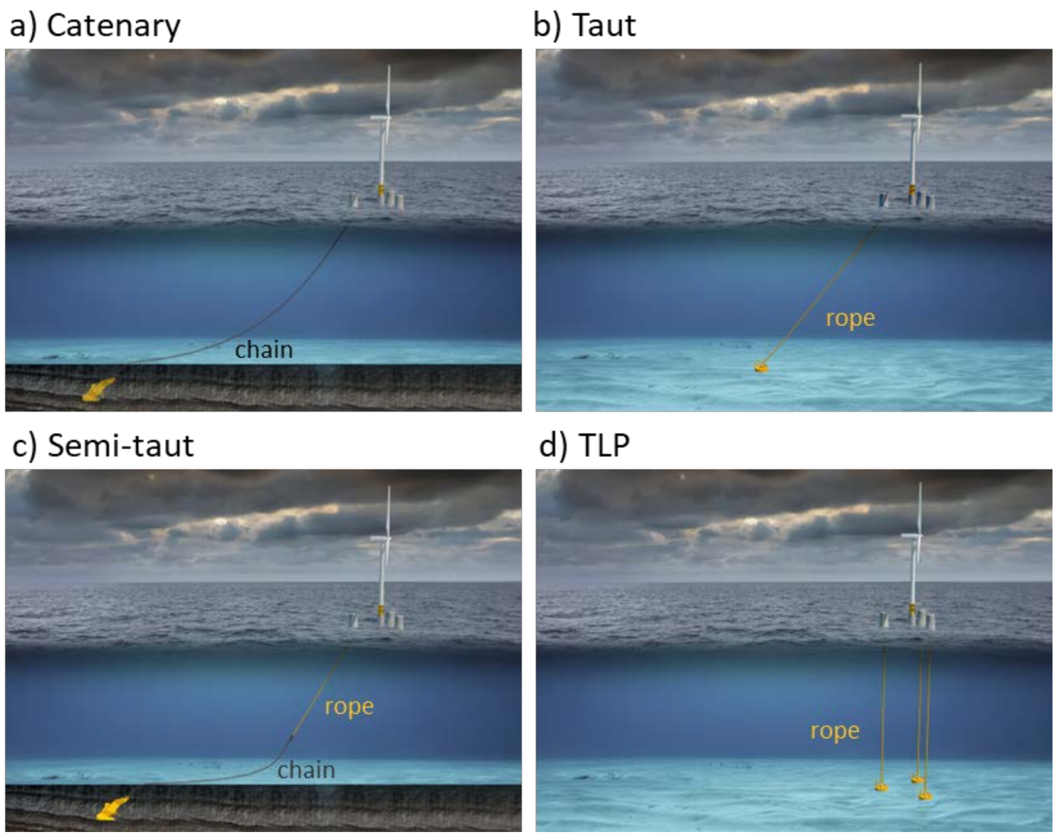


Figure 2. Four common mooring line configurations.

Illustration by Joshua Bauer, NREL

- Catenary mooring configurations (Figure 2a) typically consist of steel chain—potentially with added sections of steel wire rope—and provide stability to a floating platform based on their weight and curved profile. They require some amount of chain to remain on the seabed to avoid extreme anchor loads and therefore require a relatively large anchor radius (the horizontal distance from platform center to the anchor). At ultradeep depths, the weight of catenary mooring configurations is problematic in terms of both line tensions and burden on the floating platform. Previous analyses by the National Renewable Energy Laboratory (NREL) have indicated excessive weight at a depth of 1,000 m, meaning greater depths are even less suitable. With the additional challenges of fatigue life, high cost, and limited production capacity for large amounts of steel components, catenary mooring configurations can be considered inapplicable to ultradeep waters.

- Taut mooring systems (Figure 2b) consist primarily of synthetic fiber rope and rely on the rope's elasticity to provide the desired compliance and restoring stiffness on the platform. Taut polyester rope mooring systems are used in the oil and gas industry in ultradeep water. Common rope materials for floating wind applications are polyester and high-modulus polyethylene (HMPE), though other materials such as nylon and liquid-crystal polymers could also be considered. In contrast to the steel chain or wire used in catenary systems, synthetic fiber ropes are close to neutrally buoyant (they have approximately the same density as seawater), avoiding issues with weight. Taut mooring systems typically only have seabed contact near the anchor where the padeye can be below the mudline. A short section of chain is often used for any portions that touch the seabed to prevent abrasion that could occur if the rope made connect with the seabed. Steeper angles between the mooring line and the seabed allow for relatively short anchor radii, which is advantageous in deeper waters.
- Semi-taut mooring configurations (Figure 2c) combine aspects of catenary and taut configurations. They typically consist of a fiber rope section that spans most of the water column and a chain section that connects to the anchor and lays some length along the seabed. The platform restoring stiffness is provided by a combination of the weight of the chain and the elasticity of the rope. Their anchor radii are typically somewhere between the anchor radius of a catenary and a taut mooring configuration. Semi-taut mooring configurations share many similarities with taut configurations for ultradeep water because the taut rope portion will be sized in accordance with the water depth, while the chain portion would generally not change in size. The main differences in a semi-taut configuration are that the chain will require a moderately larger anchor radius than the taut mooring and provide some additional compliance (or stiffness reduction) to the mooring system. In shallower areas semi-taut configurations can use low-cost drag embedment anchors, but in ultradeep water these anchors would require more time to install and result in less precise positioning. As a result, semi-taut configurations, while feasible, appear more challenging than taut configurations.
- Tension-leg mooring configurations (Figure 2d) typically have a vertical or near-vertical inclination and are typically made with very stiff materials to restrain the platform from any appreciable motion along the taut leg's axial direction. TLPs used in the offshore oil and gas industry have typically used steel pipe tendons for their high stiffness, although their significant weight and installation complexity means that other materials like strong synthetic ropes may be preferable for floating wind applications. The main challenge for tension-leg moorings in ultradeep water (analyzed in Section 6.2) is achieving sufficient stiffness over the water depth with cost-effective materials. Tension-leg moorings have unique advantages in that their vertical orientation avoids the space challenge of other configurations and has a smaller footprint within the water column.

Mooring lines often include additional components beyond those listed above, including chain sections at the anchor and platform to facilitate attachment and tensioning and to avoid abrasion from seabed contact. Clump weights and buoyancy modules are also sometimes included to improve the performance of the mooring system.

Each of the mooring systems shown in Figure 3 have three mooring lines that extend to individual anchor points in the seabed. Up to eight mooring lines per turbine have been used in floating offshore wind demonstration projects. More complicated mooring system topologies also exist, such as shared anchor arrangements, that involve multiple mooring lines from adjacent turbines connecting to common anchor points. Shared mooring arrangements involve mooring lines that run directly between turbines. Hybrids between these two sharing approaches are also possible. Use of shared anchors is feasible in ultradeep water, provided that the seabed conditions and desired turbine spacing allow for a layout in which the anchor points coincide. Relative to shallower sites, shared anchor configurations in ultradeep water sites may benefit less from horizontal load cancellation due to the larger vertical loads, but reducing the number of anchors is likely to lower total cost and installation time at any site. Shared mooring arrangements also benefit from reducing the anchor quantity as well as the mooring line length.

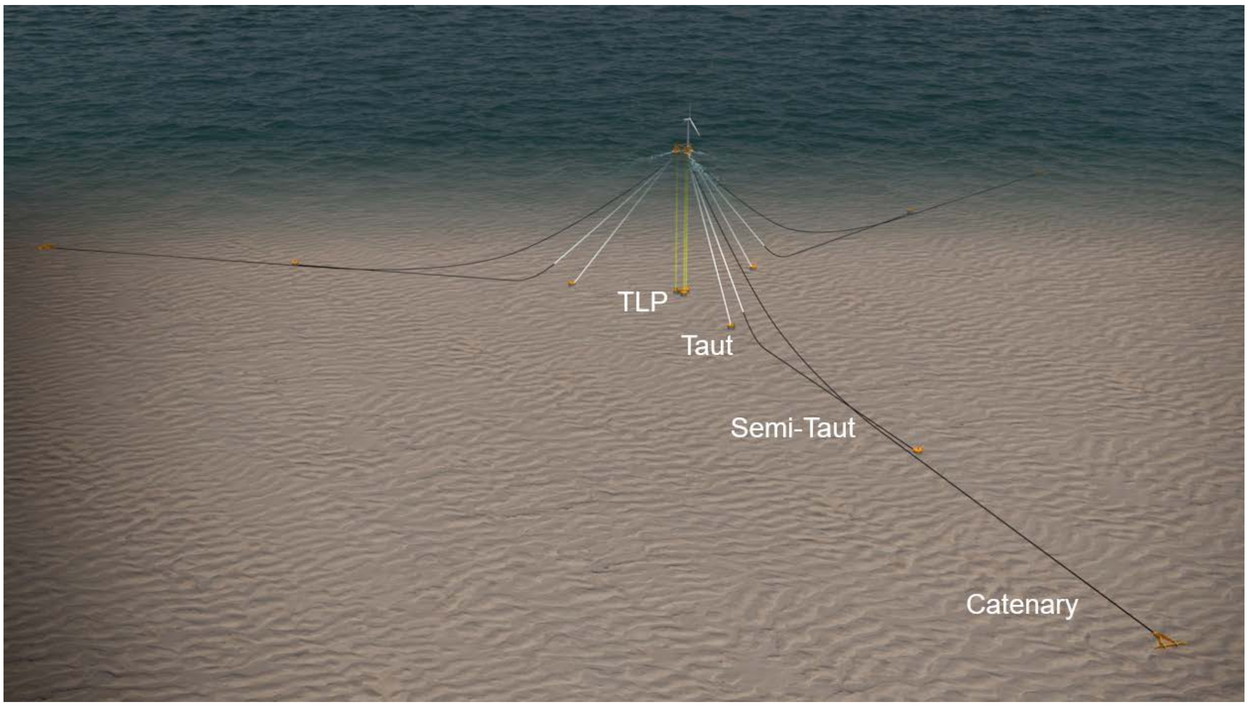


Figure 3. Examples of mooring system configurations to scale relative to each other.

Illustration by Joshua Bauer, NREL

2.2.2 Anchor Types

Anchors secure mooring lines to the seabed and transfer the mooring loads to the seabed. The anchor technology used in a mooring system must be compatible with the mooring load magnitudes and directions, the seabed bathymetry, and the seabed soil conditions.

Many anchor technologies are established or have been proposed for permanent mooring of offshore structures. Figure 4 shows eight anchor types that can be considered for floating wind systems in ultradeep water. Drag embedment anchors and vertical load anchors resist loads through a large plate area perpendicular to the load. Suction piles rely on a combination of friction, suction, and lateral bearing resistance in the soil. Many anchor varieties are distinguished by installation method, though their holding capacity mechanisms typically are either plate-like or pile-like. More detailed descriptions of anchor types are provided in Section 4.2.

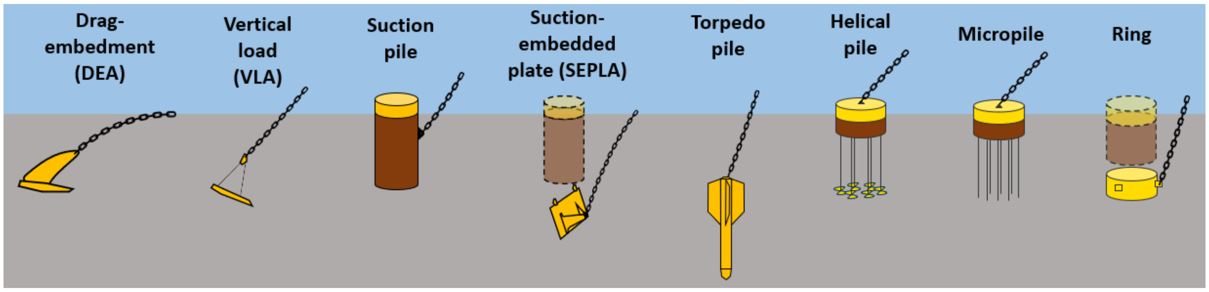


Figure 4. Anchor technologies for offshore wind energy.

Illustration by NREL

In ultradeep water, anchoring suitability is primarily affected by the local seabed soil and slope conditions, the need to support more vertical mooring load directions, and the capacity and availability of installation vessels and equipment. In general, the anchor types that can sustain vertical loads, function in muddier, flatter seabed conditions, and be efficiently installed are feasible for ultradeep water. These include vertical load anchors, suction-embedded plate anchors, suction piles, torpedo anchors, variations on these concepts, and some newer anchor types such as helical anchors. A summary of feasible anchor types is given in Section 4.4. Section 4.2 provides a more detailed exploration of anchoring feasibility for ultradeep water.

2.2.3 Installation and Reliability Considerations

The installation requirements of ultradeep mooring systems may be affected by increased mooring line length, increased mooring line diameter and longer installation times associated with lowering mooring lines, anchors, and any underwater installation equipment (such as a remotely operated vehicle [ROV]) to deeper depths. More AHTS deck space, more AHTSs, or more trips to and from port may be necessary to support the larger sizes and weights of mooring components required.

Installation processes for different anchor types are described in Section 4.3.3 along with a qualitative assessment of their suitability for ultradeep depths. Ultradeep water does not necessarily warrant new anchor technologies, but it is possible that the greater depth could result in reduced ability to position, inspect, and test anchors, depending on the installation method. For example, anchors that are dragged through the seabed will likely have less certainty in their final embedded positions and would be more difficult to monitor, but anchors that are slowly lowered to the seabed and embedded using an ROV would have much less sensitivity to depth.

Mooring system reliability is not expected to be inherently different for ultradeep waters. Water depth does not play a notable role in the strength or reliability characteristics of mooring components, and the nature of the mooring system loads is not expected to be more severe in ultradeep water. For the most part, the same types of mooring components can be used from shallow to ultradeep waters. The most likely difference could come in the use of stiffer mooring materials, which could result in changed load-bearing qualities; however, ultradeep mooring systems are still expected to follow the same design requirements and safety factors. Qualification of new mooring materials should minimize changes in reliability.

Mooring system inspection and repairs at ultradeep water depths are likely to become more costly, based on existing technology, due to the increased time required to access ultradeep mooring lines and anchors for inspection or repair. The difficulty of access could lead to longer downtimes if a component were to fail. Any equipment, such as ROVs, used for inspection and repair would need to be certified to operate at the relevant depth. As the depth increases, options for off-the-shelf equipment become fewer and more expensive.

2.3 Array and Export Cables

Offshore wind farms require array cables to transfer electricity between individual wind turbines and offshore substations, and one or more export cables to transfer the total electricity generated from the offshore substations to the electric grid. Array cables typically use high-voltage alternating current (HVAC). Export cables transmit more power over greater distances so generally have higher voltages and may use high-voltage direct current (HVDC) to reduce losses over long distances. For floating wind turbines, portions of array and export cables move with the floating platforms and need to be designed to accommodate that motion. These are called "dynamic" cables, whereas cables that lie on or below the seabed are referred to as "static" cables.

2.3.1 Static Cables

Static subsea power cables suitable for offshore wind are also used to connect electrical grids between islands or across water boundaries. Subsea interconnectors have been built in ultradeep water, and new cable installations may increase the maximum depth. The deepest HVDC interconnection cable to date is located at a depth of 1,640 m, a cable under construction will reach 2,200 m depth, and another interconnector is proposed in water depths up to 3,000 m (Prysmian Group 2024; Sangar 2024). HVAC cables have been installed at 1,000-m depth, and cable manufacturers assert that these cable designs can be used down to 3,000 m (Hellenic Cables 2022; Prysmian Group 2020). Relative to cables in shallower water, the overall cable diameter and the amount of internal protection components at ultradeep water depths may be larger to compensate for the increase in hydrostatic pressure with depth.

If offshore wind plants in ultradeep waters are located farther from shore than deep-water projects, the length of static cable required would increase. An increase in electrical losses can be expected for longer HVAC export cables, which typically makes HVDC more advantageous for distances greater than 70–100 km to the point of interconnection. Increased export cable length may also correspond with a higher potential for cable routes to encounter geohazards or conflict with other ocean uses.

Although export cables can use static cable for the majority of their length, connecting to floating offshore substations will require a segment of dynamic cable between the substation and the seabed, with a transition joint between the two types of cable. Array cables will require a higher proportion of dynamic cable than export cables. They may consist entirely of dynamic cable if they are fully suspended or if analysis of a specific cable layout determines that it is more efficient (considering cost, installation, and reliability) to use continuous segments of dynamic cable as opposed to transitioning to dynamic cable on either end of a static segment.

2.3.2 Dynamic Cables

Dynamic cables are typically double-armored to have greater fatigue resistance, tensile strength, and bending stiffness than equivalent static cables and have correspondingly higher cost.

Compared with static cables, dynamic cables are heavier, have a larger outer diameter, and are less flexible (i.e., have a larger minimum bend radius) (Ikhennicheu et al. 2020). Dynamic cable systems also include ancillary equipment such as bend restrictors and abrasion-protection sleeves to protect the cable and buoyancy modules to maintain the desired profile through the water column (Figure 5).

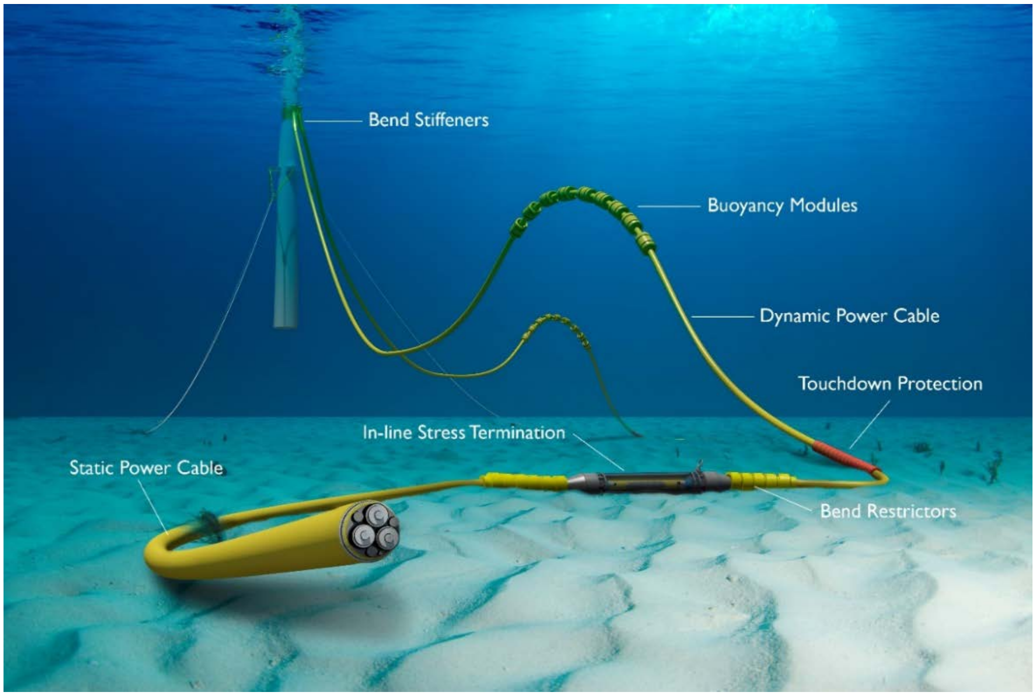


Figure 5. Dynamic subsea cable system components.

Illustration by Joshua Bauer, NREL

Figure 6 shows three common dynamic cable profiles. The most common is the lazy wave shape because it allows the largest range of motion (Rentschler et al. 2020). For deeper waters, the steep-wave profile allows a reduction in space and cable length. Fully suspended cable profiles have also been proposed to further reduce cable length (Ahmad et al. 2023; Schnepf et al. 2023). Suspension below the euphotic zone (defined by the depth of sunlight penetration, around 200 m depending on ocean conditions (National Oceanic and Atmospheric Administration [NOAA] 2024)), may reduce the potential for marine growth (biofouling) and interaction with vessels and some marine species (Rapha and Dominguez 2021). Suspending dynamic cables also provides an opportunity to limit the hydrostatic pressure that the cable must be designed to withstand based on its depth. Fully suspended dynamic cables experience less deflection than other profile types in normal operating conditions, because their overall change in extension is determined by the relative motion between turbines, and turbines in an array tend to have very similar offsets.

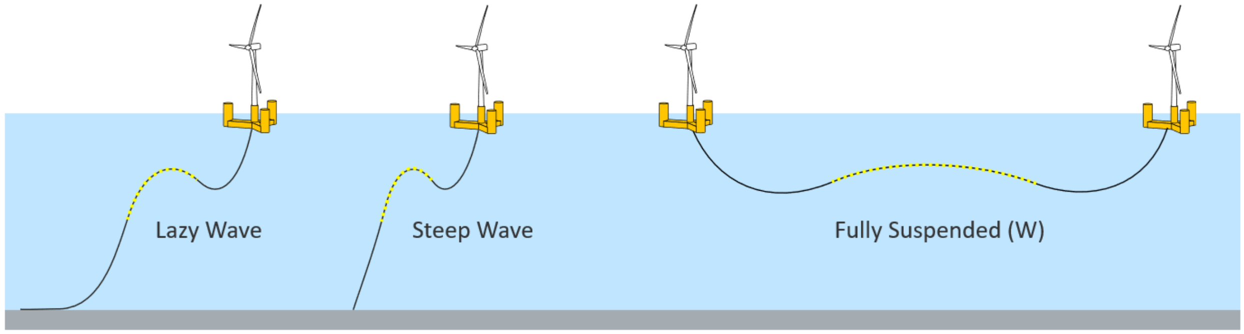


Figure 6. Three common dynamic cable profile shapes

Illustration by NREL

Dynamic cable designs in ultradeep water are influenced by several factors that may require changes from shallower water designs that are currently under development:

- The greater water depths will entail longer dynamic cable segments to reach the seabed and, as a result, increased overall cable lengths. This has a relatively small effect on export cable length but a large effect on array cable length if they are laid on the seabed between turbines.
- To avoid excessive cable tension from greater cable length (weight), additional distributed buoyancy modules or multiple buoyancy sections may be needed.
- Transition joints from static to dynamic cable sections will need to be designed for higher hydrostatic pressure in ultradeep water.
- Given conventional platform motions but larger water depths, the change in cable profile across all platform motions decreases, making more compact and material-efficient profiles possible, partially mitigating the increase in cable length.
- Use of fully suspended array cables that can extend tens to hundreds of meters below the waterline depending on the design may be preferable to significantly reduce cable lengths. Additional work is needed to understand the potential benefits and disadvantages of this approach considering cable motion and interaction with marine life and other ocean users.

2.3.3 Installation and Repairs

The installation of array or export cables requires specialized cable lay vessels equipped with carousels and reels to hold the cable and maintain appropriate tension and bending limits while lowering the cable into the water. Other vessels like tugboats or ROVs can also be used to support operations such as joining cable segments and connecting cables to floating turbines and substations. Cable burial requires additional specialized equipment. Static cables may be buried in trenches, covered using rock or concrete mats, or laid on top of the seabed. The cable protection approach along each segment of the cable route from landfall to wind plant site is determined by a cable burial risk assessment, which considers factors such as seabed conditions, seismic activity, commercial fishing, and proximity to shipping routes (Carbon Trust 2015). In ultradeep water, burial may not be feasible or necessary. Subsea interconnectors in deep water have been laid on the seabed without burial below depths of 400–600 m (Ardelean and Minnebo 2015).

At ultradeep depths, the weight of cable hanging in the water column as it is being laid is a significant installation challenge. The cable hangs in a catenary shape from the cable lay vessel to the seabed; as the catenary becomes longer with depth, its increasing weight places greater demands on the capacities of the installation vessel and its onboard equipment. Additional requirements include greater deck space and larger equipment to increase the amount of surface area of the cable that can be "gripped" as it is lowered. The incorporation of cable accessories (e.g., bend restrictors or buoyancy modules) for dynamic cables also add complexity to the installation process. Although some new and under construction vessels are anticipated to be capable of laying cable in 3,000 m of water (Jan De Nul 2024; Prysmian Group 2021), many cable lay vessels in the existing fleet are limited to non-ultradeep depths.

Cable repairs require similar equipment as installation. A typical repair process for a static cable involves raising cable segments on either side of the damaged location from the seabed to a cable lay vessel, where any damaged portions can be removed and a new segment spliced in. The new segment must be at least twice the water depth to permit each end of the original cable to be lifted to the surface. The new length is then laid to one side of the repaired cable in a horseshoe or omega shape known as a repair bight. The additional space required for a repair bight is a key consideration in determining the spacing between parallel cables. In ultradeep water, cable repair is expected to be more costly than in shallower water due to longer repair bights, the need for larger vessels, and increased time required to complete a repair. Mitigating these challenges may motivate the development of new cable installation and repair methods.

Repair methods for dynamic cables are less well established. Because (at least) one end is located near the surface where the cable is attached to a floating platform, a dynamic cable repair does not require the same additional space as a static cable repair. Depending on the length of the dynamic cable, it may be more practical to replace the entire dynamic cable segment rather than making a repair.

2.4 Supply Chain and Infrastructure

Because floating offshore wind energy is a nascent industry, supply chains are still developing. Supply chain considerations are different for each component. Two parameters that are relevant for understanding where supply chain challenges may arise for floating offshore wind in ultradeep water are the level of specialization (i.e., is a component only used for floating offshore wind, or is it used for other applications?) and the depth sensitivity. A component that ranks highly on both these metrics may face more challenges meeting the required specifications and production quantities for an ultradeep floating wind project. Table 1 assesses these supply chain considerations for each major component.

Table 1. Assessment of Supply Chain Factors for Ultradeep Floating Offshore Wind Components

Green, yellow, and red shading correspond respectively to low, medium, and high specialization or sensitivity

Component	Specialization for Floating Offshore Wind	Sensitivity to Ultradeep Water Depth
Wind Turbine	Medium: the same turbines are used throughout the offshore wind industry	Low
Floating Platform	High: specific to floating offshore wind	Low
Offshore Substation	High: similar components as fixed-bottom offshore substations, but must be adapted for floating	Low
Mooring Line	Medium: used in other marine industries, but floating offshore wind may involve larger sizes and greater quantities	High: mooring line length (and possibly diameter) increases with depth
Anchor	Low: used in other marine industries but floating offshore wind involves greater quantities	Medium: anchor selection may be depth dependent
Static Power Cable	Low: used for subsea grid interconnectors and fixed-bottom offshore wind	High: cable specifications are depth-dependent
Dynamic Power Cable	High: specific to floating offshore wind	High: cable specifications are depth-dependent and cable length increases with depth unless fully suspended

Infrastructure needs for floating offshore wind energy development in ultradeep water are likely to be similar to those for other floating offshore wind locations. In general, the various components—including wind turbine blades, nacelles and towers, floating platforms, mooring chain, wire or rope, anchors, power cables, and offshore substation topsides—are manufactured either domestically or internationally and transported to one or more ports that support the construction and installation of the floating wind systems. The wind turbines and floating platforms are deployed from a staging and integration port, whereas other components may be staged at the same port, at a separate laydown port, or shipped directly from where they are manufactured. A schematic of an example offshore wind energy staging and integration port is provided in Figure 7.

Figure 7. A schematic of an example offshore wind energy port supporting floating wind turbine deployment.

Graphic by Besiki Kazaishvili, NREL

Relative to deep-water sites, offshore wind projects in ultradeep water may require additional storage or quayside space for some components. Ultradeep mooring systems and cables are likely to require more space because the total material requirement for these components is highly dependent on depth. Recommended port facilities for a floating wind plant in water depths of 800–1,000 m include 5–15 acres (2–6 hectares) of laydown space with a minimum bearing capacity of 500 psf (2.4 t/m^2) for mooring and anchor storage, and 3–7 acres (1–3 hectares) of laydown space with a minimum bearing capacity of 1,000 psf (4.9 t/m^2) for staging of array and export cable carousels (Lim and Trowbridge 2023). In ultradeep depths, double or triple the area could be required for mooring and cable laydown. Increased mooring and cable quantities may also motivate the use of larger installation vessels for these components. Larger vessels with greater carrying capacity would help reduce the number of trips between laydown facilities and the wind plant site. Cable lay equipment for ultradeep water also requires greater holding capacity for the weight of longer cables. Port infrastructure requirements for these larger vessels are unlikely to exceed the recommended criteria for staging and integration ports—for example, a channel depth of 38 ft (11 m) is sufficient for the largest AHTS and cable lay vessels with drafts close to 30 ft (9 m)—however, opportunities for component laydown at smaller ports may be limited if those ports are unable to accommodate larger vessels.

2.5 Conclusions

Ultradeep depths have a significant impact on mooring system design, which we consider in more detail later in this report. Mooring line configurations for ultradeep water require long lengths to reach the seabed. The weight of catenary moorings increases with length, becoming problematic near a depth of 1,000 m and infeasible at ultradeep depths. Taut and semi-taut mooring lines have a larger horizontal footprint in ultradeep water relative to typical spread mooring systems in shallower water. Semi-taut configurations are more challenging at ultradeep depths, but even taut mooring footprints may become large enough to impact turbine spacing (see Section 7.1). The increase in length for taut mooring configurations can be mitigated to some extent by adopting steeper mooring line angles (see Section 6.1). Tension-leg mooring configurations do not occupy significantly more space in ultradeep water but may need to consider alternative tendon materials to provide the required mooring system stiffness (see Section 6.2). Steeper taut moorings and vertical TLP tendons will also affect anchor selection by imposing more vertical loads on the anchors (see Section 4.2).

In addition to the mooring system, we considered potential challenges for other floating offshore wind components in ultradeep water. All typical floating wind turbine support structure topologies (e.g., spars, semisubmersibles, and TLPs) are feasible for ultradeep water. Substructure sizes may increase slightly to compensate for higher mooring forces or less stiff mooring systems, particularly for TLPs.

Some existing static cable designs may be suitable for ultradeep offshore wind applications where the cables are laid on the seabed. Challenges associated with ultradeep depths include reinforcement against increased hydrostatic pressure and the need for cable lay vessels that can maintain higher tension during installation to support the weight of a longer cable hanging in the water column. Dynamic cables will be required to connect between floating platforms or from a floating platform to a cable on the seabed. If the dynamic cables are fully suspended, there would be little difference between deep and ultradeep applications. Dynamic cables that reach the seabed would need to be designed to withstand increased hydrostatic pressure and would also require installation vessels capable of bearing the weight of a cable extending to the seabed.

Supply chain challenges are more likely to arise for components that are specific to floating offshore wind and sensitive to depth, including mooring lines and dynamic cables. The infrastructure requirements for floating offshore wind systems in ultradeep waters are expected to be similar to those for shallower depths. Longer mooring lines and cables and a greater number of anchors may necessitate increased storage or quayside space, but in general port facilities that support floating offshore wind energy projects are expected to be able to accommodate vessels and components for ultradeep waters.

3 Environment and Co-Use

Floating offshore wind turbines can expand siting options for offshore wind energy development into deeper waters, beyond the limitations (e.g., approximately 60 m water depth) of fixed-bottom wind turbines. The potential environmental stressors of floating offshore wind may be similar regardless of whether they are sited in ultradeep waters or more shallow areas, but the footprint of ultradeep offshore wind energy may be larger given the increases in water depth. Several environmental interactions include fisheries, entanglement risk, underwater noise, vessel navigation, and habitat alterations. The influence of these on potential receptors will vary based on habitat type, ecosystem processes, and species occurrence. This section describes the potential co-use and environmental concerns of floating offshore wind energy and potential differences that may occur in ultradeep waters.

The environmental and co-use concerns included in this section were derived from stakeholder input and supplemented by reviewing the existing literature. NREL contacted 32 individuals from key stakeholder groups. Of this group, 11 responded, representing industry, government agencies, researchers, and nongovernmental organizations. The focal areas of respondents ranged from general knowledge on offshore wind energy and environmental effects to subject matter experts on benthic habitat, fish/fisheries, invertebrates, and marine mammals. The focus was on the effects related to mooring lines and anchors, but responses also discussed other potential effects related to the platforms and cables. This overview does not reflect an exhaustive list of potential environmental and co-use effects of floating offshore wind energy in ultradeep waters, such as those related to vessel traffic or collision risk or displacement/avoidance for birds and bats.

3.1 Potential Environmental Concerns for Ultradeep Floating Offshore Wind

3.1.1 Uncertainty

A summary report on the potential environmental effects of ultradeep floating offshore wind energy by Farr et al. (2021) noted that because the technology needed to support floating offshore wind energy is still in its infancy, the potential environmental effects on the marine environment are speculative. However, it is possible that the environmental effects of ultradeep floating offshore wind systems could include (1) changes to oceanic dynamics due to energy removal and modifications, (2) electromagnetic fields (EMF), (3) habitat alterations to benthic and pelagic fish and invertebrate species, (4) underwater noise, (5) structural impediments to wildlife (including entanglement), and (6) changes to water quality (Figure 8; Boehlert and Gill 2010; Copping et al. 2016; Farr et al. 2021).

In general, these effects may be relatively low to moderate in ultradeep waters, but there is uncertainty resulting from a lack of information on current environmental conditions far offshore (Farr et al. 2021). Respondents' comments highlighting this uncertainty are reported in Table 2. In general, the co-occurrence risk for many species decreases farther out to sea, but the spatial distribution and timing for many species is unknown. Vulnerability to stressors from offshore wind development also varies by species. Models can be generated on the best available science to evaluate potential impacts. As an example, Rockwood et al. (2024), generated spatial models evaluating the potential impacts of offshore wind energy development on wildlife, habitats, and co-use along the California coast. This updated report added 17 new species and two new habitat types, but recognized that there remain data gaps, for species, species use patterns, and co-use activities.

Thus, there is a need for more baseline data collection and studies on human and animal use patterns in these ultradeep areas. Long mooring lines may introduce new environmental considerations, with issues potentially accentuated by greater depth. The specific impacts depend on the species present and their vulnerability, particularly at the shelf break where species composition changes. These data gaps challenge regulatory agencies in evaluating potential impacts, especially on special status and migratory species.

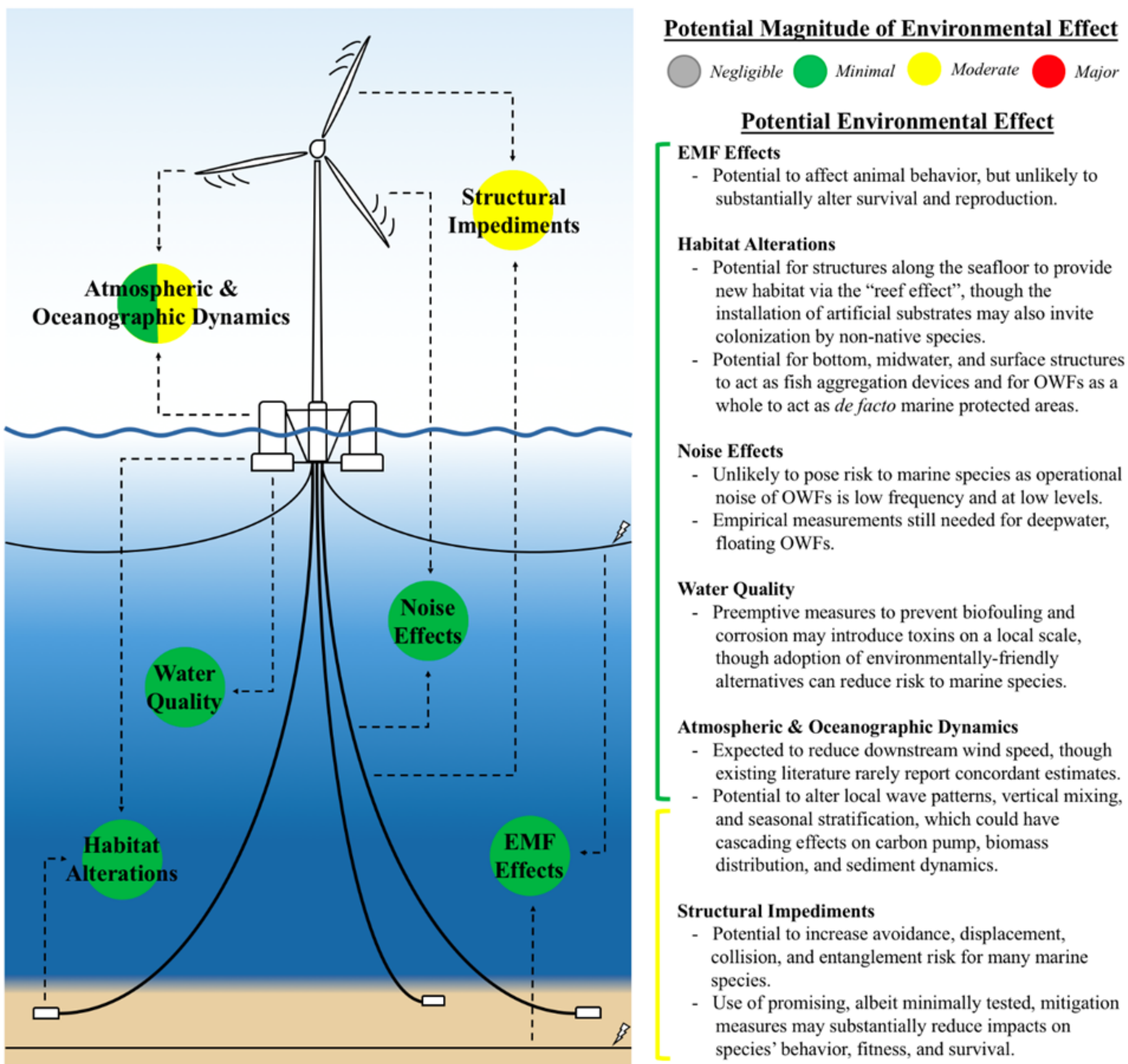


Figure 8. Type and magnitude of potential environmental effects of ultradeep floating offshore wind energy. The magnitude of effects was determined by using the four-level classification scheme (negligible, minor, moderate, and major) used to characterize impact levels for biological and physical resources defined in Minerals Management Service (2007).

Illustration from Farr et al. (2021)

Table 2. Comments From Respondents Highlighting Uncertainty

Although the distribution of marine species further offshore is less well characterized, the same potential impacts of disturbance, displacement, collision, and entanglement would still be factors for consideration with ultradeep floating offshore wind development. There is little information available about current environmental conditions that are far offshore, and potential impacts should be considered.
The co-occurrence risk for a lot of species of immediate concern seems to decrease farther out to sea; however, the same potential risks are still a concern (e.g., entanglement, benthic disturbance, displacement, etc.).
Concern about how much information exists on those ultradeep areas that limit our ability to project risk. There is a lack of baseline data.
Studying human and other animal use patterns would be worthwhile for getting a full picture of how the risks differ from currently proposed areas.
In general, animal and human use patterns differ in deeper waters. Density of animals and people seem to generally decline the farther from shore you go.
Mooring lines that are long may also trigger environmental considerations not thought before.
Issues may largely be the same, but potentially accentuated with the longer depth. A lot of animals aggregate on the seafloor, but little data on fish and invertebrates in the area where floating ultradeep wind energy may exist. Still must figure out how the mooring lines look. Can they come straight down and then out or do they come straight out?
It comes down to what species are there and their vulnerability. At the point where the shelf drops off, there is a decrease in species, so there may be a shift in species affected. However, it may depend on the location and how far off the shelf break.
Data on the ecology of marine species and habitats generally decreases with increasing distance from shore. These data gaps can present challenges to regulatory agencies when evaluating potential impacts, especially to special status and migratory species.
Unsure about the potential wake effects and mixing effects in the region.
A lot of this depends on what turbine platforms, mooring lines, anchors, and cables look like and what the wind farm layout will be.
Pacific is a unique system because of its huge upwelling ecosystem. Must acknowledge that there is a lot we don't know and admit the impacts and trade-offs.

3.1.2 Co-Use Issues

Knowledge gaps remain about how best to co-locate floating offshore wind energy with other activities, including scientific surveys and commercial fisheries (ORE Catapult and Xodus Group 2022). Table 3 summarizes comments from respondents on this topic. The implications are likely site-specific and will be determined by the characteristics of the wind plant, including mooring line and cable configurations, anchor technologies, and wind farm design and location (ORE Catapult and Xodus Group 2022). In general, reducing the size of floating wind farm mooring line footprints may reduce conflict with co-users.

In addition, siting offshore wind in ultradeep waters (approximately 50 miles from shore) can reduce interactions with nearshore fisheries and surveys by avoiding direct conflicts with bottom trawl, commercial salmon troll, and fixed gear groundfish fisheries (personal communication from respondent). However, fisheries for highly migratory species like albacore might still be affected, though they typically set gear closer to the surface, potentially allowing for fishing among turbines. Export cables could impact fisheries or surveys if not buried deeply or covered adequately. Uncertainty about mooring line and dynamic cable movement may deter commercial fishing or scientific surveys within the footprint of floating offshore wind farms, regardless of depth, due to entanglement risks. Despite these concerns, the larger area of free space offshore could make co-use more feasible, with less impact on fisheries given the distance from shore.

Table 3. Comments From Respondents on Co-Use of Ultradeep Waters

Siting offshore wind in ultradeep waters (approximately 50 miles from shore) would decrease direct displacement of some fisheries that use areas closer to shore. Moving into ultradeep waters would avoid direct conflict with the bottom trawl fishery and commercial salmon troll fishery on the north coast and the fixed gear groundfish fishery on the central coast. Fisheries for highly migratory species (i.e., albacore) could still be impacted in ultradeep waters; however, these fisheries typically set gear closer to the surface which may allow for fishing to take place among turbine arrays. Export cables running to shore could potentially impact fisheries if they are not buried to a sufficient depth or covered with a trawl-friendly concrete mattress.
Given the uncertainty regarding the level of movement of mooring lines, commercial fisheries may not be willing to fish within the wind farms, no matter the water depth. A question to resolve is whether mooring lines in deeper waters have a larger radius for movement compared to mooring lines in shallower waters? That might push safe fishing effort further from the edge of the farm. I believe this would be true for both mobile and fixed gear, as fixed gear fishermen will have long buoy lines that they would not want to get tangled in a mooring line.
Positives could be a larger proportion of free space, so co-use could be more feasible. Fishing activity would be pelagic and not towed gill. Mostly gill nets. May be less of an impact on fisheries given the distance from shore.
Impediments to conducting NOAA scientific surveys and safety risks around offshore wind turbines for NOAA scientific operations. Fixed sampling stations should be avoided and a buffer included allowing NOAA vessels to continue accessing sampling sites.
Evaluate available fisheries resource and fishing vessel data to help inform the location, spacing, and orientation of wind farms as well as to inform cable corridors to shore. Avoid placing structures within or near areas of high fishery resource or fishing activity concentration. Consistent layouts between adjacent leases may minimize navigational hazards and provide a more uniform grid to facilitate fishing, transit, and search and rescue operations.
Compensatory mitigation to address unavoidable impacts to fishing operations and fishing communities should address both economic and social/cultural impacts.

3.1.3 Marine Mammal Interactions

Noise and entanglement are two main concerns for marine mammals, but they can also impact sea turtles and certain species of fish. With respect to noise, floating offshore wind will have a different noise profile during construction and operations, relative to fixed-bottom offshore wind. Further research is needed to understand the noise associated with the installation of different anchor types and the noise emitted from mooring and dynamic cable systems. The operational phase may have distinctive noise profiles related to vibrations or snapping of mooring lines or cables suspended in the water column (ORE Catapult and Xodus Group 2022). These noises may be detectable to some marine mammals and fish. Particle motion, or the movement of water molecules generated by floating structures such as mooring lines and cables, may also influence behavior or interfere with sound detection (Farr et al. 2021). However, it is unlikely that noise and particle motion will cause physiological damage (Wahlberg and Westerberg 2005; Marmo et al. 2013).

Entanglement is another concern for floating offshore wind farms (Figure 9). Entanglement is separated into primary entanglement with mooring lines and cables, and secondary entanglement with derelict debris (e.g., fishing gear) that may become ensnared with mooring lines and cables. (Maxwell et al. 2022). Factors that may influence entanglement include biological factors, such as body size, flexibility, and ability to detect mooring lines and cables, and physical factors, including the type of mooring system, mooring line characteristics, tension characteristics, and turbine array configuration (Benjamins et al. 2014; Farr et al. 2021). Primary entanglement is likely to be low given that animals may detect the larger-sized diameter (e.g., 100–240 mm) and rigidness of mooring lines and cables (Benjamins et al. 2014). Secondary entanglement represents a greater risk because of the smaller sized diameter of fishing gear (e.g., 1–7 mm; Wilcox et al. 2014). Biofouling of platforms, mooring lines, and cables may increase snagging of debris and derelict fishing gear (Maxwell et al. 2022). Entanglement with derelict fishing gear represents one of the greatest threats to cetaceans worldwide (Baulch and Perry 2014; NOAA 2018) and annual reported humpback whale entanglements have increased on the U.S. west coast (Lebon and Kelly 2019).

Entanglement may be more pronounced in baleen whales (Benjamins et al. 2014). In addition to their body becoming entangled (as may happen with toothed whales, sea turtles, and fish), baleen whales tend to forage with open mouths, and objects entangled in mooring lines and cables may become lodged behind their jaws (Sharp et al. 2019). Deep-water species, like elephant seals and beaked whales, may also be impacted by ultradeep projects because they forage in deeper habitats (Robinson et al. 2012). Respondents’ comments regarding potential impacts to marine mammals are quoted in Table 4.

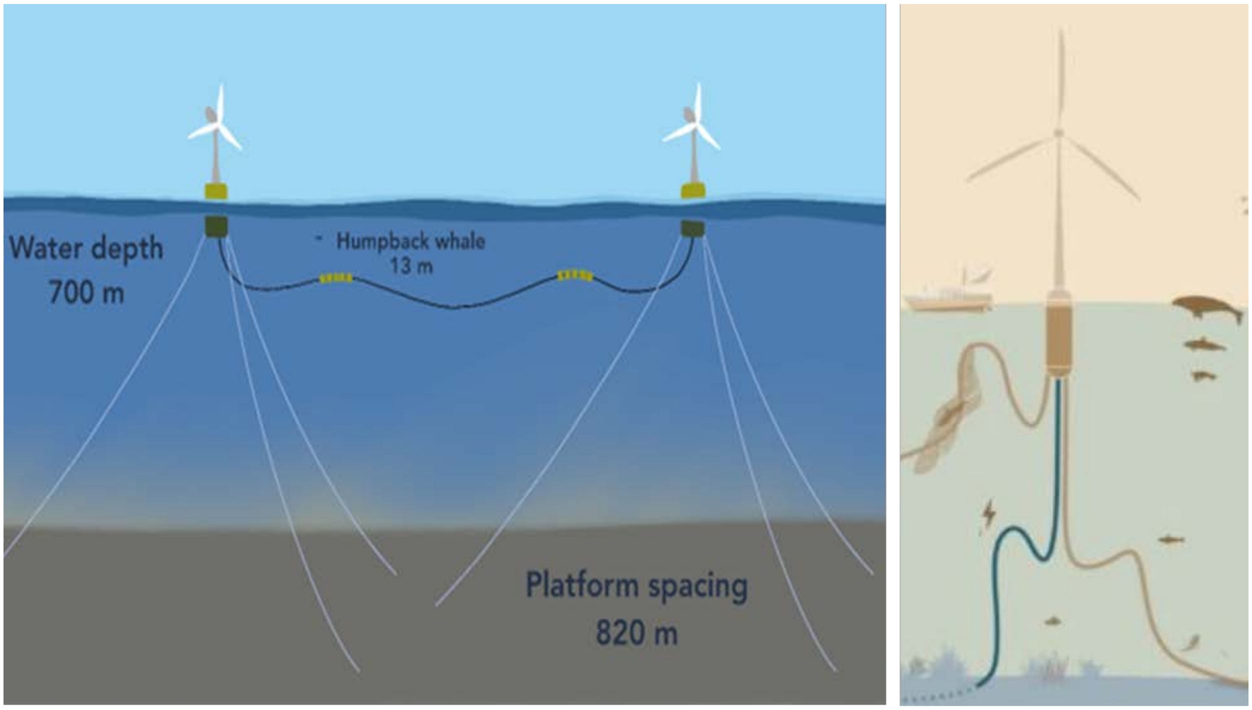


Figure 9. (left) Illustration of the relative scale of an encounter of a whale with floating offshore wind cables and mooring lines. (right) Image of potential secondary entanglement.

Left image from Molly Grear, Pacific Northwest National Laboratory; right image adapted from Maxwell et al. (2022)

Table 4. Comments From Respondents on Marine Mammal Interaction

Concern about lunge-feeding whales around infrastructure—could have impact when forage fish tend to aggregate around infrastructure.
There will likely be specialists (e.g., deep-water species) to consider. For example, elephant seals feed at about >500 m deep well offshore.
Beaked whales and other deep divers might be more impacted than for some of the shallower projects (which might be closer to baleen whale migratory corridors and might overlap with coastal species).
Generally, the shift to deeper habitat would likely impact species foraging at these depths (some pinniped and deep diving cetaceans). Sound propagation during construction might also increase with larger zones of ensonification and more difficulties containing sound with bubble curtains.
Geophysical surveys (e.g., using sound to map the ocean floor) and other wind energy activities, offshore and nearshore, may emit noise at a level that could impact biologically significant behaviors (e.g., foraging, migrating, resting, reproduction) of marine mammals, listed species, and fish stock.
Frequent monitoring of inter-array cables and mooring lines to detect marine debris that could pose entanglement risk to marine species and requirements for timely removal of any debris to minimize entanglement risk.

3.1.4 Electromagnetic Field Impacts

EMFs are generated by the flow of electricity through a conductor, and their influence on fish and invertebrate species is a concern (Gill et al. 2014). Many species, including sharks, lobsters, fish, and sea turtles are sensitive to EMF fields (Gill et al. 2014). EMFs may result in physiological impacts, such as altered development, and behavioral effects, such as attraction, avoidance or impaired navigation or orientation (Gill et al. 2014; Thomsen et al. 2015). Some species use geomagnetic fields to orient themselves during local or migratory movements (Peters et al. 2007). The inability to detect or respond to natural magnetic signatures may alter fish survival, reproductive success and migration (Normandeau et al. 2011). Table 5 reports respondents' comments on EMF.

As floating wind farms in ultradeep water are planned at increasing distances from shore, longer and higher-capacity subsea cables will be required to interconnect facility components with each other, to the sea floor, and to shore (Figure 10). For example, use of inter-array cables suspended within the water column rather than solely along the seafloor may increase the scope of EMFs in the water column and potentially interact with a greater diversity and abundance of marine organisms (Farr et al. 2021). Although there are limited data on the impacts of EMFs from cables suspended in the water column (Gill and Desender 2020), EMFs emitted from these cables may be less than those from export cables because of the lower amount of power being transmitted (Thomsen et al. 2015; ORE Catapult and Xodus Group 2022). Overall, research to date indicates that the effect of anthropogenic EMFs on species appears to be minor, but there are still large gaps in understanding the interaction between EMFs and pelagic, demersal, and benthic species (Copping et al. 2016).

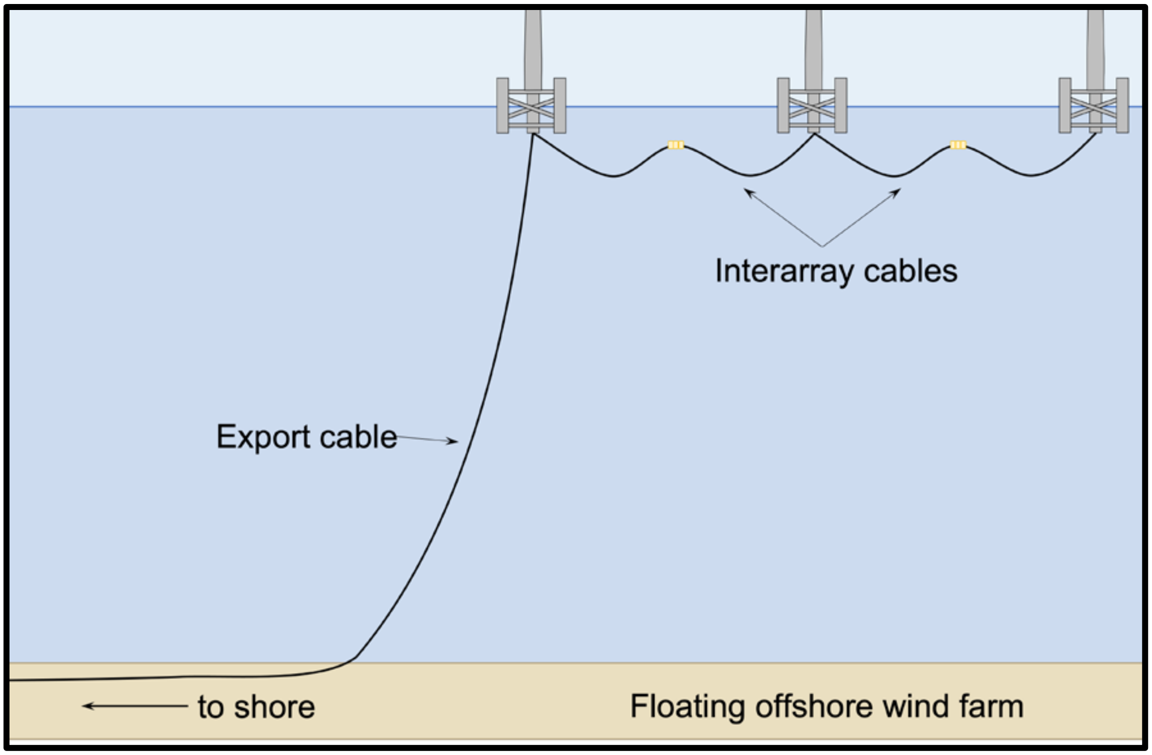


Figure 10. An illustration of how electrical cables may be used at floating offshore wind farms. Inter-array cables connect between individual turbines and the combined energy is transported to shore with an export cable.

Figure from Pacific Northwest National Laboratory

Table 5. Comments From Respondents About Electromagnetic Fields

For environmental implications, would the actual cables carrying the electricity be longer in deeper waters? Fishermen and scientists may have more questions about longer cables potentially releasing EMF over greater distances.
If there are EMF implications, there is more cabling and perhaps more of an issue.
Impacts of EMFs on marine animal sensory systems and movements (e.g., sea turtles, some marine mammals and elasmobranchs).

3.1.5 Benthic Environment

Benthic environments are adapted to natural disturbances, which can increase nutrient accessibility and recycling (Harris 2014), but additional disturbance from mooring lines, cables, and anchors may exacerbate the frequency and intensity above natural levels (Maxwell et al. 2022). The impacts of the different forms of marine renewable energy development on benthic habitats have been widely studied, indicating potentially large changes in sedimentation regimes, scouring and resuspension of sediment, and impacts to habitat forming species or structures (Miller et al. 2013; Hutchison et al. 2020). Floating offshore wind farms may cause increased sedimentation from scouring by anchors and other components that are moved by waves or currents (Davis et al. 2016). Increased sedimentation could impact benthic fish populations by contaminating spawning habitat quality (Wenger et al. 2017). It can also clog the feeding apparatus of suspension-feeding organisms, such as bivalves, sponges, and sea squirts (Davis et al. 2016). The duration of sediment suspension may last hours or days and will depend on sediment type, with finer-grained particles remaining in the water column longer and traveling further distances (Taormina et al. 2018). The lasting effects on the benthic habitat may depend on the resilience of the local flora and fauna (Taormina et al. 2018). Mitigating scour and sediment disturbance has been a focus for fixed-bottom structures but not for floating offshore wind anchor systems (Wei et al. 2024). Specific comments from respondents are quoted in Table 6.

Table 6. Comments From Respondents on the Benthic Environment

Seafloor habitats and biodiversity are a lot less characterized and understood at these greater depths, and a lot patchier than in shallower waters. Initial site characterizations would be even more crucial to not affect the rare hard(er) bottom habitats.
Anchor systems may be different (larger) but represent a permanent impact. The amount of movement and scouring may be minimized because of the depth.

3.1.6 Habitat Creation

The deployment of novel structures in the marine environment may induce physical changes in habitats that have the potential to alter species composition and abundance at localized scales or provide opportunities for colonization by new species (Figure 11; Copping et al. 2016; Hammar et al. 2016; Langhamer 2012). On the seafloor, the mooring anchors and subsea cables may function as artificial reefs by introducing hard substrate that can become colonized by invertebrate and reef-associated fishes (Langhamer 2012). The installation of artificial hard substrates may also invite colonization by non-native (invasive) species, whose threat to marine biodiversity can have far-reaching ecological and economic consequences (Molnar et al. 2008). New hard structures may serve as stepping stones for disease or invasive species, which could be transferred to shore via vessels used for construction, operation, or maintenance. The location of ultradeep water floating offshore wind farms may make these pathways less likely (Farr et al. 2021).

Midwater and surface structures, namely, mooring lines and floating substructures, may similarly act as fish aggregation devices (Kramer et al. 2015) as well as settlement surfaces for invertebrate and algae. Hundreds of different fish species from dozens of taxonomic families aggregate around floating structures (Castro et al. 2002), suggesting that floating offshore wind may attract a variety of species and potentially alter species composition in midwater and surface ecological communities. In instances where fishing activity is restricted near offshore wind farms they may act as de facto marine protected areas, creating refuges for some marine species, increasing local abundances and generating spillover effects to adjacent areas (White et al. 2012; Wilhelmsson and Langhamer 2014; Hammar et al. 2016). However, one study indicated that the infrastructure in the water column and at the surface may not act as fish aggregation devices that would attract pelagic fish in temperate waters as much as they might in tropical waters (Kramer et al. 2015). Table 7 reports comments from respondents about habitat creation.

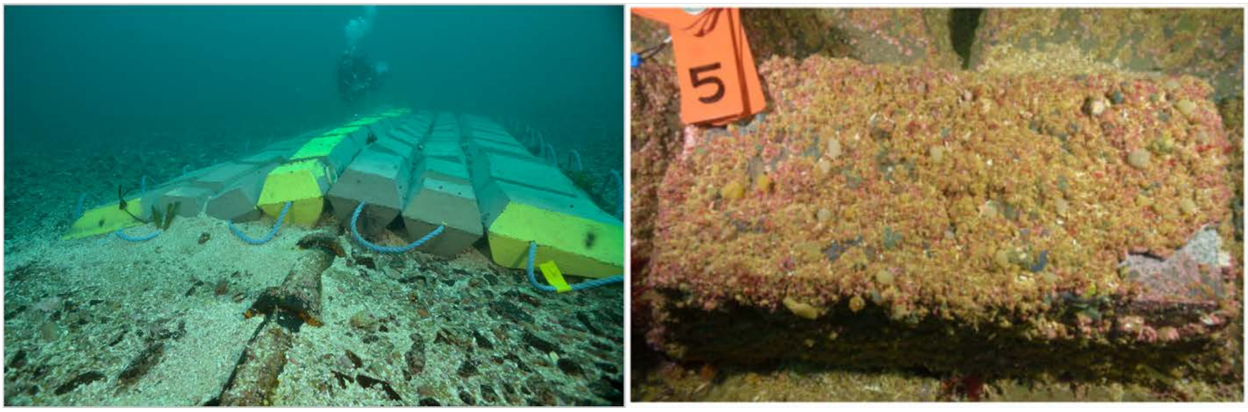


Figure 11. (left) Newly installed concrete mattress over partially exposed subsea cable. (right) Close-up image of a concrete mattress that has been colonized by organisms after installation.

Images from Taormina et al. (2020)

Table 7. Comments From Respondents on Habitat Creation

Depending on the area of the ocean, would there be certain types of pelagic commercial or recreational fish that may be attracted to the mooring lines? (We see this with some fish that are attracted to buoys further offshore.) Would this potential attraction affect the population at all?
Are fish aggregated around the lines because of the growth on the lines (creating habitat and foraging) in the photic zone? However, if there is aggregation, then it may bring in higher predators and marine mammals that there is an entanglement issue. Could also attract birds and put them at risk of collision.
Species may be attracted to the scour site because it creates new habitat potential (e.g., scavenging species).

3.1.7 Other Potential Environmental Issues

The use of chemicals to control biofouling could have environmental effects. Biofouling is the accumulation of flora and fauna on human-made structures (Figure 12). Biofouling can increase the (1) potential for derelict fishing gear to become ensnared, (2) weight and drag on mooring lines and cables, and (3) corrosion and degradation of wind turbines and associated infrastructure. The growth must be removed before the mooring line or cable can undergo routine inspections (Maduka et al. 2023). To counter these effects of biofouling, antifouling chemicals are often used to control biofouling, but understanding their performance requires long-term monitoring. Their environmental effects may not be known for several years after application (Maduka et al. 2023). Some previously used applications (e.g., self-polishing co-polymers) have been banned or are only granted limited use (e.g., tin-free self-polishing paints (Banerjee et al. 2011; Abioye et al. 2019). Other chemicals are still in use, and there remains a trade-off between their use to keep platforms, mooring lines, and cables clean and increasing pollutants in the vicinity of the wind farm (Maxwell et al. 2022). Given the increased distance from shore and the long mooring lines and cables for ultradeep offshore wind farms, monitoring and removing biofouling becomes increasingly complicated and expensive (Maduka et al. 2023). Additional environmental issues identified by respondents are listed in Table 8.

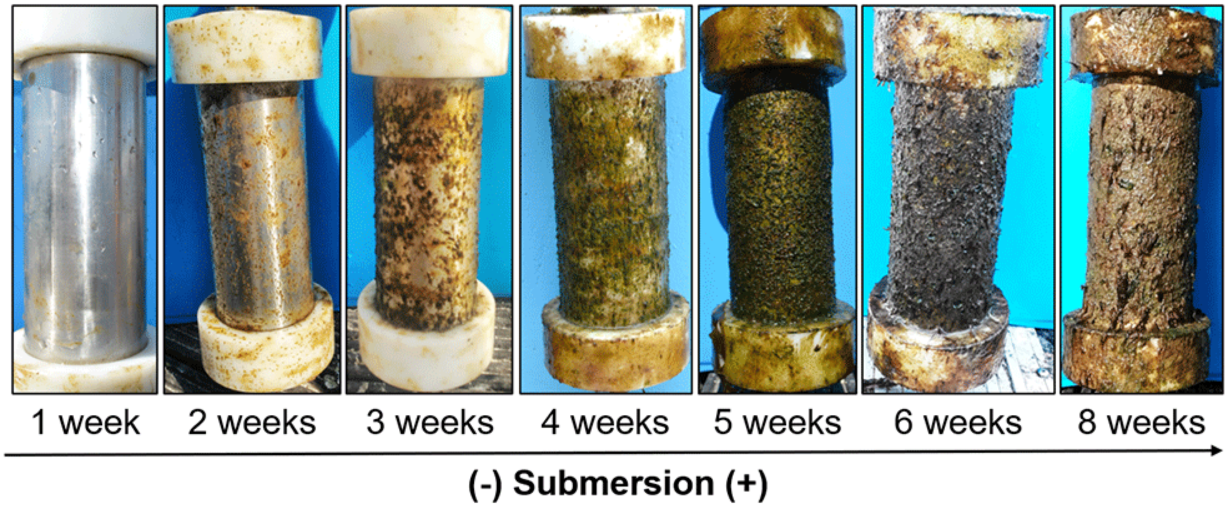


Figure 12. Biofouling after 1-week intervals from 1 to 8 weeks.

From Vinagre et al. (2022)

Table 8. Comments From Respondents on Other Potential Environmental Issues

There are potential physical and chemical changes to the oceanographic and meteorological environments.
Chemical and toxic pollutant runoff into the water from increased vessel traffic and shoreside activities.
The impacts of unintended discharges or spills could be higher given the long distance from shore and the increased logistics and response time.
Some of the impacts depend on whether these will be hybrid facilities (i.e., wind and hydrogen) and what are the implications of producing hydrogen in the area.
Concern about locating near continental shelf drop-off - impacts on upwelling.
Impacts from full build out on wind fields and other oceanic and atmospheric processes, particularly seasonal upwelling and the resulting effects on nutrient transport, vertical mixing, and eddy and front formations.

3.2 Challenges and Opportunities for Environmental Coexistence and Co-Use with Ultradeep Floating Offshore Wind

Challenges for environmental coexistence and co-use with ultradeep floating offshore wind (summarized in Table 9) include the difficulty and expense of conducting environmental studies and servicing monitoring equipment far from shore, as well as evaluating and monitoring habitat changes due to new structures. Technology limitations for power sources, data transfer, storage, and long-term automation also pose challenges. Structural integrity and security in remote areas are concerns, as is the potential for increased disturbance from longer power cables.

Opportunities include collecting data in rarely studied deeper waters, potentially reduced conflict with human and animal use patterns, and leveraging wind energy to power autonomous environmental monitoring technologies. Ultradeep offshore wind platforms may provide infrastructure to install remote sensors, including passive acoustic monitoring and infrared cameras. These and other sensors may serve as an alternative to human observers stationed in remote locations. There is also potential for coexistence with fisheries by avoiding the siting of wind plants closer to shore where different fishing gear is used. Additionally, rerouting ship traffic farther offshore could provide economic benefits and avoid conflicts with national marine sanctuaries.

Table 9. Comments From Respondents on Environmental Monitoring and Coexistence

Conducting environmental studies and servicing monitoring equipment farther from shore is more challenging and could potentially limit the amount of data collected. There is also the challenge of evaluating and monitoring how changes in habitat type from placement of hard structures in pelagic and benthic habitats will influence species distribution and habitat associations. Offshore wind developments in ultradeep water would provide the opportunity to collect data in deeper water that is less frequently studied.
A major challenge is that the farther from shore, the more difficult and expensive it is to collect baseline data, monitor, and act if there are issues (e.g., remove gear that entangles on mid-water cables). Technology is still a challenge for power sources, data transfer, data storage, robustness, long-term automation, etc. that would be ideal for getting much farther offshore. The opportunities would include the potential for less conflict with human use and animal use patterns. Presumably, the farther offshore, the larger the amount of cable needed to bring power to shore, which means that cable will cross more area and/or disturb more of the bottom.
One challenge is the structural integrity and security of the whole system in these extremely remote areas.
A key opportunity would be to leverage the wind energy output to power autonomous environmental monitoring technologies on the spot.
Platforms of opportunities (passive acoustic monitoring and infrared cameras) in these deeper regions might provide better information about species presence and habitat use of species that are difficult to access. Likely opportunity for coexistence for fisheries because of the potential aggregation of pelagic fish.
Overall, might be more conducive to coexistence because you are going to avoid the more coastal species and colonial species.
Likely to avoid onshore/offshore movement corridors for birds and pinnipeds.
The established ship traffic may overlap with potential ultradeep water locations. Shipping co-use PAC/PARS process is a large, complex process that relates to economics and safety. Study on the east coast looking at cost of routing ships farther offshore and having additional space for offshore wind energy. One of the findings was that there was an economic benefit to having ships farther offshore.
Need to avoid conflict with national marine sanctuaries.

3.3 Existing and Emerging Technologies to Monitor and Mitigate Potential Effects

Below are lists of some monitoring and mitigation technologies and methodologies provided through stakeholder feedback (see notes in Table 10).

Monitoring Technologies Include:

- **Sensors**
    - **Passive acoustic monitoring:** Microphones and hydrophones that detect audible and ultrasonic sounds of calling birds, bats, and marine mammals to determine presence and activity patterns. These systems can be installed on buoys and offshore wind farm infrastructure.
    - **Remote sensing:** Thermal cameras, visual cameras, and satellite imagery that detect birds, marine mammals, and sea turtles to determine presence and habitat use. Sensors can be placed on a variety of technologies, including unmanned aerial systems, autonomous underwater vehicles, and satellites.
    - **Animal tagging:** Radio tags and GPS tags can be placed on birds, bats, fish, marine mammals, and sea turtles to track movement patterns in relationship to weather or marine conditions and habitat.
- **Platforms for sensors**
    - **Automated data buoys:** Infrastructure used to place sensors, including meteorological, oceanographic, and biological sensors.
    - **Distributed acoustic sensing:** Uses existing fiber-optic cables to monitor whale presence, currently explored in the Atlantic.
    - **Fish aggregation devices:** Structures that attract fish that can be equipped with monitoring devices for fish biomass and aggregation.
    - **Remotely operated vehicles:** Mobile vehicles that can be equipped with a variety of monitoring devices. Often used to assess benthic habitat.

Mitigation Tools Include:

- **Siting:** Primary method to avoid conflicts with sensitive habitats, migration pathways, aggregations, and existing uses.
- **Robust data collection:** The use of various technologies and methodologies to gather comprehensive data on species spatio-temporal distribution and human use patterns to minimize impacts.
- **Noise mitigation techniques:** Installation methods (e.g., vibratory hammers) and noise abatement/reduction technologies (e.g., bubble curtains) used to reduce impacts on marine mammals typically during construction of monopiles for fixed-bottom offshore wind energy.
- **Clearance zones, shutdown zones, and seasonal restrictions:** Established to protect sensitive species during construction and operational phases of development.
- **Adaptive management:** Real-time monitoring and response to adjust monitoring plans and refine environmental assessment strategies.
- **Autonomous approaches:** Use of crawlers for mooring line integrity assessment, debris removal, and repair.

Challenges for using monitoring and minimization technologies include the need to test their efficacy in offshore environments and the difficulty in identifying direct impacts from offshore wind developments. In addition, monitoring and minimization approaches are expensive, particularly farther from shore and in deeper water.

Table 10. Comments From Respondents on Technologies to Monitor and Mitigate Potential Effects

Monitoring tools include (1) acoustic monitoring systems for marine mammals and birds and bats, (2) remote sensing using unmanned aerial systems, autonomous underwater vehicles and satellites, and (3) automated data buoys and existing platforms can also be involved as they are equipped with meteorological and oceanographic sensors with the ability to collect real-time data on weather, wave conditions, and water quality. Water quality can be further analyzed through physical sampling conducted across the lease areas for environmental assessment surveys. This method provides important data to address existing gaps and supports ongoing monitoring efforts. Additionally, tagging of marine animals and aerial animal species (e.g., birds, bats) with GPS tagging or physical observations can be used to track their movements and behavior patterns around wind farm areas. All these methods must be tested in the offshore environment and assumptions should not be made about their efficacy until they are tested.
Mitigation can prove to be more challenging as identifying potential impacts resulting directly from offshore wind, and the extent of them, are still unknown. However, various tools and methods can help mitigate potential effects. Siting is the primary way to avoid conflicts with sensitive habitat, migration pathways, aggregations and existing uses. Requiring developers to obtain robust data about marine and aerial species spatial distribution patterns as well as any existing human use will be critical to avoid or minimize impacts from siting. Noise mitigation techniques may reduce impacts to marine mammals that enter high-risk areas during construction. Exclusion zones and seasonal restrictions can also be set up to protect sensitive species during construction and operation. Adaptive management will also be an important approach to enable real-time monitoring and response, allowing for adjustments of the monitoring plan and to better plan environmental assessments to refine strategies.
Distributed acoustic sensing, which uses existing fiber optic cables to listen to whales. Starting to be explored as an option in the Atlantic. However, it might not be in the right areas, but could be helpful for monitoring.
Examples of technologies are included in the NOWRDC database and the Tethys Monitoring and Mitigation Technologies Tool. Part of the challenge around technology though is that it is disincentivized in our current regulatory environment - there are not good processes for allowing use of new technology, NEPA [National Environmental Policy Act] and consultation work is being done in a very prescriptive way, specifying the technology in a way that prohibits use of new and emerging technology. Investment in technology is not resulting in updates to monitoring requirements, so industry lacks incentives to support technology.
Fully autonomous approaches will be crucial, like crawlers for assessing mooring line integrity and making initial cleaning/repairs.
Infrared and passive acoustic monitoring technologies might provide some answers related to species presence.
Acoustic technologies to look at aggregation/biomass (fish). Fish aggregation devices that include monitoring devices. Assessing changes at depth in the benthic environment is going to be difficult because of the depth. ROV technology is expensive. Satellite imagery can be used for biofouling.
Acoustics for marine mammals.
No significant difference in the types of technologies for the upper water column or seabirds. Using acoustics for marine mammals, visual surveys would increase costs.

3.4 Recommendations for Engagement, Research, and Outreach During Development, Operation, and Decommissioning

Respondents provided several general recommendations as summarized here and detailed in Table 11:

- Early engagement with fishing communities, Tribal nations, and other stakeholders to address potential conflicts and explore coexistence at ultradeep sites.
- Improving communication and coordination with collectives and chairpersons/coordinators can help leverage the fishing industry for data collection and pilot projects.
- Increasing transparency in Bureau of Ocean Energy Management (BOEM) decision-making processes and clarifying roles and responsibilities between agency staff and leaseholders.
- Collaborating with the Pacific Fisheries Management Council, the Responsible Offshore Development Alliance, and other fisheries advocacy groups can increase data collection and compilation.
- Collaborating with federal and state agencies from planning through decommissioning is crucial to minimize impacts on environmental and anthropological resources.
- Improving outreach, research, and engagement, coupled with targeted communication and collaboration, will be essential for the successful development of ultradeep floating offshore wind projects

In addition, there are specific recommendations for the different phases of a project:

- During the planning phase, it is crucial to gather comprehensive commercial and recreational spatial data to avoid fishing areas and consider potential shifts in fisheries due to climate change to prevent future conflicts. Using NOAA's National Centers for Coastal Ocean Science for modeling suitability will help with understanding the relative conflicts and identify the most suitable locations for development. Additionally, engagement with communities and Tribes should occur before designating wind call areas to address concerns and incorporate local knowledge.
- During the siting phase, it is essential to connect fishermen with engineers to co-design wind farms, ensuring transit ability and clarity on mooring line movements to maximize fishing opportunities. During the construction phase, it is important to communicate broadly about the process, particularly for ultradeep waters, involving BOEM, U.S. Department of Energy, and developers. Clear communication should be maintained with fishermen, especially those using the same ports and transit ways, to ensure coordination and address any concerns.
- During operation and decommissioning, treat each wind farm as an experiment by collecting socio-economic data before and after construction. Hold annual or biannual meetings to discuss impacts on the fishing community, and consider ecotourism opportunities, engaging a diverse range of stakeholders beyond fisheries.

Table 11. Comments From Respondents on Engagement, Research, and Outreach

It will be important to engage with the fishing communities, Tribal nations, and other stakeholders early on to get their feedback on potential conflicts at these ultradeep sites and how fishing and offshore wind can coexist at those depths. It is recommended to collaborate with federal and other state agencies from the planning through the decommissioning phases of the projects, as early as appropriate, to maximize success and minimize impacts on environmental and anthropological resources.
Planning - adequate commercial and recreational spatial data to avoid fishing areas since co-existence in the same space is unlikely. Additionally, BOEM should consider how fisheries may shift northward, or deeper over time due to climate change to avoid future conflict of important fisheries.
Siting - Connecting fishermen with the engineers within wind farm companies to co-design a specific farm for transit ability as well as shared clarity on movement of mooring lines to promote the most fishing opportunity outside of the farm.
Construction - there is likely a broader need for many sectors, not just fishermen, to understand how the construction of floating offshore wind is completed - especially those in ultradeep waters. I recommend good communication campaigns on this from BOEM, DOE, and developers. Additionally, adequate communication with fishermen within fishing ports who may use the same ports and transit ways during construction activities.
Understanding of fisheries activity offshore and understanding of what efforts are already underway.
Engagement with communities and Tribes should be more thorough before wind call areas are designated. NOAA's National Centers for Coastal Ocean Science process for modeling suitability should be applied to large areas that genuinely allow for an understanding of relative conflicts and for truly narrowing down to suitable locations. Research needs to be targeted at priority questions and, given the challenges and expense, should not be expected to reduce all risk - there need for realistic expectations with some risks mitigated through pre-emptive mitigation and monitoring where risks are high. The public will consider this riskier than nearshore simply because there is more uncertainty around some of the environmental aspects - this requires good messaging around how those risks will be addressed and how deep sea areas can be adequately monitored and the equipment maintained.
Engagement with experts focused on deep-sea biology, geology, oceanography, mining and legal specialists to better understand the species, habitats, conditions, and regulations regarding potential sites for ultradeep offshore wind.
Engagement with regulators and researchers about environmental compliance and timeline/feasibility will be important.
Work with the fishing industry. Most in the fishing industry feel engagement is a ticked box and not a real co-design planning opportunity. Need to engage with the fishing industry on layout, spacing, mooring line and cable layout, depth, etc. Make sure every single stage includes discussion with stakeholders. A lot of times, people come in with set plans and inform the audience rather than working with them. It can be difficult to get people from the fishing community to engage because of bad history. So, perhaps talk with collectives/collaboratives and use the chairpersons who can then coordinate with their constituents.
The fishing industry can have a large part to play in the work. Huge opportunity for data collection using the fishing industry (reduce use). Pilot projects to take people out to the sites. Get fishing vessels up to spec to help with development and data collection at farms.

Important every wind farm is treated as an experiment. Needed to look at the before and after. Collect socioeconomic data before and after. Perhaps annual or biannual meetings to hear how this has impacted the fishing community (positive or negative).
There could be ecotourism impacts/opportunities. So should be multi-stakeholder outreach and engagement, not just fisheries.
Industry has been willing to talk and provide feedback. The uncertainty is challenging even for 'traditional' offshore wind let alone ultradeep.
There seems to be a bit of a black box regarding BOEMs decision making process. Always a challenge because it needs to be clear about responsibilities. Need information on where to put the leases and then the companies need to define what development means (COPS). BOEM can be more explicit about their role versus the lease holder's role. Being transparent and thorough research needs/objectives and then reporting out as you continue to site new areas. Iterative learning process.
Recommend connecting with the Pacific fisheries management council, RODA [Responsible Offshore Development Alliance], and other fisheries advocacy and organizational groups. They may already be compiling this data.

3.5 Additional Resources for Assessing Environmental and Co-Use Aspects of Ultradeep Floating Offshore Wind Energy

Respondents provided several resources to help understand vessel movement patterns, commercial fishing activities, and the state of the science on wind and environmental interactions:

- California Offshore Wind Energy Modeling Platform (EEMS Modeling)
- California Offshore Wind Energy Gateway
- Identifying Offshore Wind Areas off the CA Coast, Point Blue
- North Coast Fisheries Mapping Project
- Data Basin
- Tethys knowledge base
- Tracking elephant seals
- International seabed authority
- Pacific Fishery Management Council
- Pacific Fisheries Information Network
- Marine Traffic
- Navy Marine Species Density Database for U.S. Pacific and Gulf of Alaska
- Deep ocean stewardship initiative
- NOAA Fisheries Species Directory
- NOAA Fisheries Critical Habitat.

4 Anchors

This section provides a qualitative assessment of anchor suitability for floating offshore wind in ultradeep waters, focusing on seabed conditions and the performance of different anchor concepts. Seabed conditions are evaluated based on bathymetry, slope, soil type, and geohazards. Most slopes in ultradeep waters are gentle, with the majority of areas having slopes under 5°, although steeper slopes exist, particularly along continental margins. Soil conditions tend to become muddier with depth, and rock outcroppings pose challenges for anchor installation.

Anchor types are categorized and assessed for their compatibility with different seabed conditions, slopes, and mooring loads. The study highlights that certain anchor concepts, like vertical load anchors (VLAs), suction embedded plate anchors (SEPLAs), and torpedo anchors are well suited for ultradeep waters, while others like drag embedment anchors (DEAs) and deadweight anchors may not be feasible. Installation challenges, including equipment limitations and the impact of seabed slope on anchor performance, are also discussed.

This section emphasizes the importance of detailed geotechnical investigations for anchor design and notes that ongoing innovations in anchor technology and installation techniques could further enhance anchor suitability in these challenging environments. Anchor feasibility is closely tied to seabed conditions, requiring careful interlinked consideration during the design and installation phases.

4.1 Seabed Assessment

4.1.1 Bathymetry and Slopes

Seabed bathymetry was extracted from the ETOPO dataset (NOAA National Centers for Environmental Information 2022) to cover the entire U.S. west coast and extending out into water depths beyond 3,000 m. Using geographic analysis tools, the seabed slope was calculated from the bathymetry (shown in Figure 13), with the BOEM lease block area (BOEM n.d.) and the U.S. Exclusive Economic Zone.

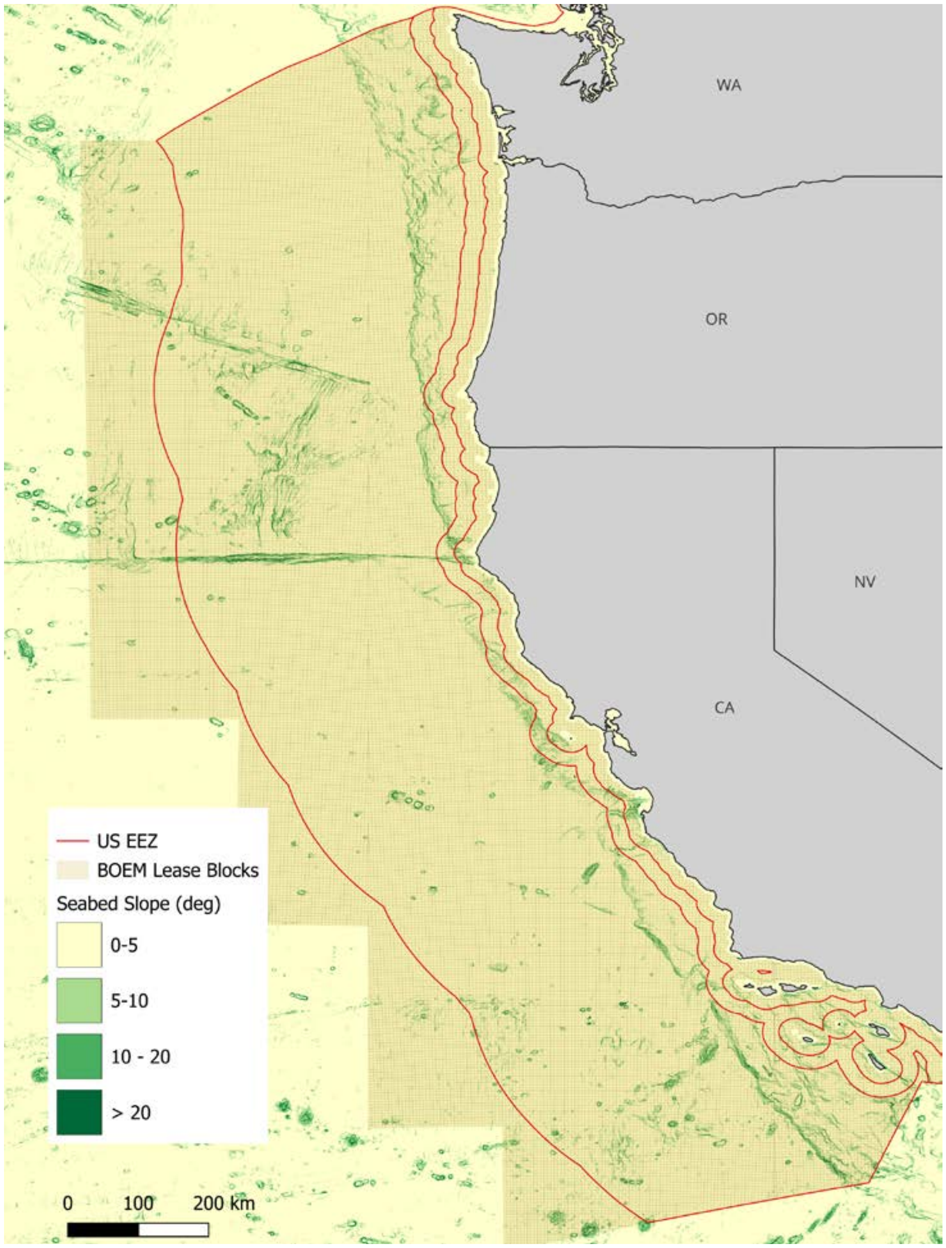


Figure 13. Seabed slopes along the U.S. west coast

Illustration by NREL

As seen in Figure 13, the seabed slopes within the U.S. Exclusive Economic Zone on the west coast are primarily between 0 and 5° (yellow shade), where steeper slopes above 5° only occur along the continental slope or in seismically active regions. A zoomed-in view of the seabed slopes with contours of water depth are shown in Figure 14.

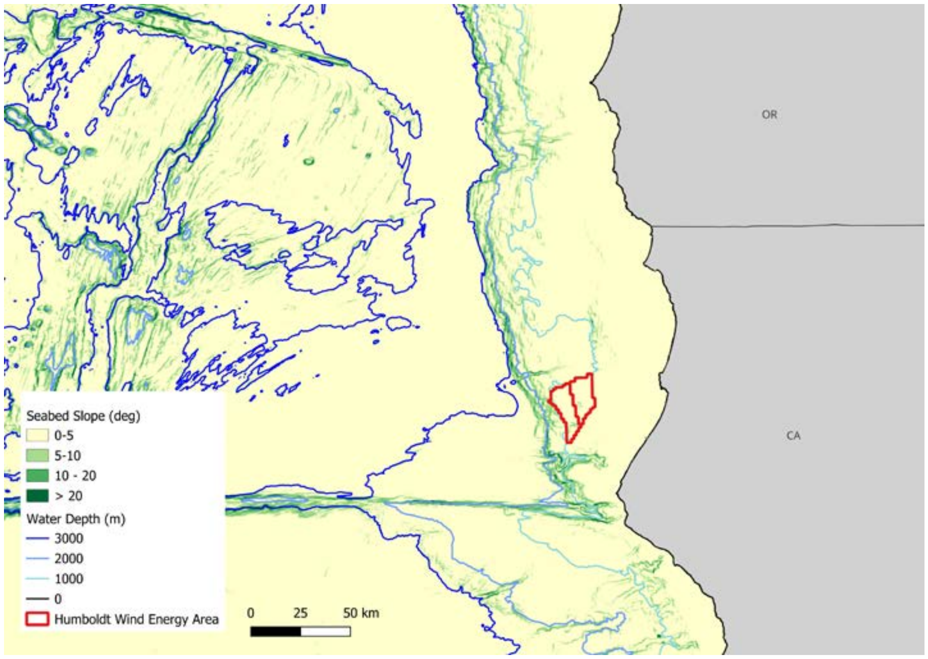


Figure 14. Zoomed-in example of the seabed slope analysis

Illustration by NREL

Using the water depth contours of Figure 14**,** ultradeep water first becomes prevalent at the upper edge of the continental slope on the west coast. Seabed slopes sharply increase along the continental slope, with some areas having slopes greater than 20°, but the majority of areas along the slope are much less than 20°. In areas below the continental slope, seabed slopes are less than 5° (yellow shade) in most areas except for areas with seismic activity, but those areas are far from shore.

The average seabed slope within each BOEM lease block of Figure 13 was calculated using the geospatial analysis program QGIS. The slopes were then distributed between different water depth groups to show which water depths had higher seabed slopes in general (Figure 15).

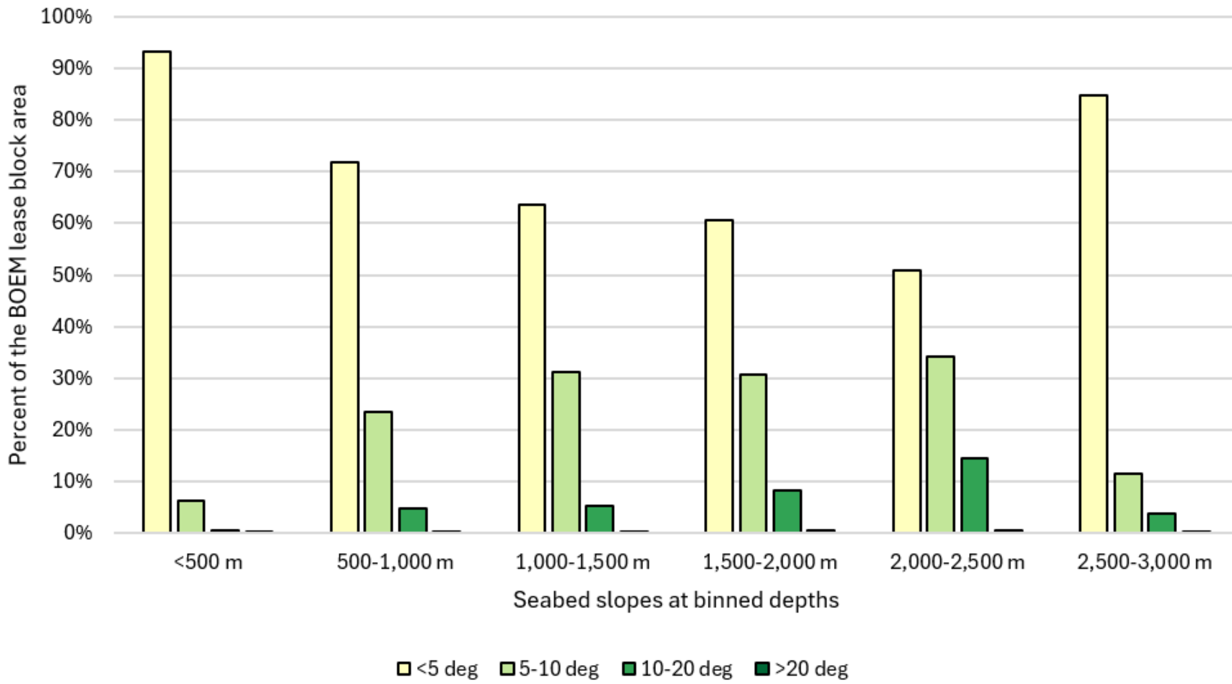


Figure 15. Seabed slopes in different water depth bins within U.S. Outer Continental Shelf blocks on the west coast

Shallower water depths on the west coast are relatively flat and have seabed slopes mostly under 5°. However, seabed slopes generally increase with water depth up to 2,500 m. Deeper than 2,500 m, the seabed slopes look similar to the flat, shallow waters of less than 500 m. Some of the increase in seabed slope can be attributed to the continental slope, as explained previously, but the data in Figure 15 represents the entire dataset of Figure 13 within the BOEM lease blocks, which includes other seabed irregularities farther from shore. This suggests that in general, the seabed slopes of this Pacific region increase as water depth increases, but only up to a certain point.

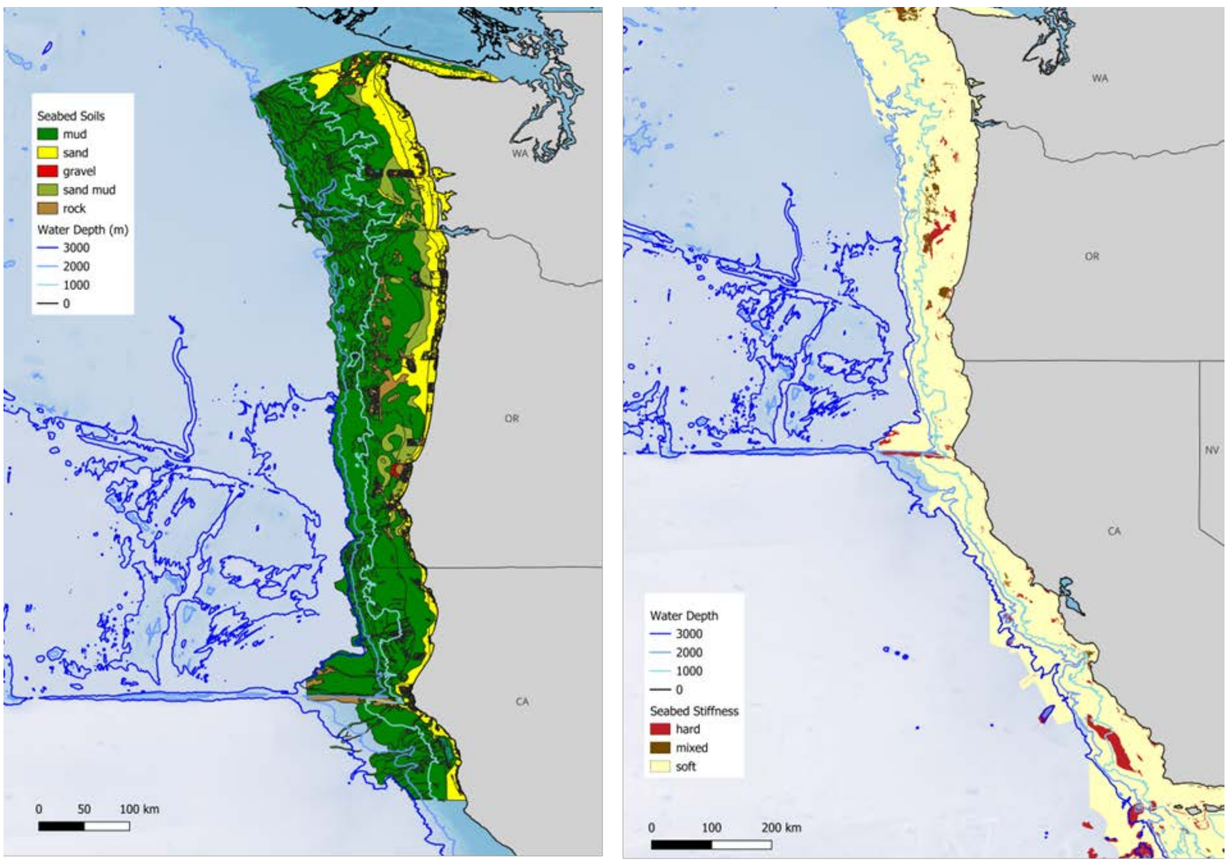
Seabed slopes in the Central Atlantic, where the continental shelf also quickly drops into ultradeep water depths, were considered in a separate analysis (Fisher et al. 2023). Similarly, the seabed slopes range from 2° to 5° on top of the continental shelf, increase to greater than 15° as water depth increases, and then flatten out to less than 2° at water depths around 3,000 m. Like the Pacific, the areas where the seabed slopes are the highest only occur for tens of kilometers laterally, meaning that most ultradeep water depths do not have significantly steep slopes—only on the drop from the continental shelf do slopes become a concern.

4.1.2 Ground Conditions

Deep-sea sediments often have characteristic geological properties. They typically feature fine-grained soils due to the lower sedimentation rate in the less energetic environment found in these locations, which tend to be distant from sediment sources near the shore. However, continental slopes often show evidence of mass movements, with mass transport deposits present on slopes and basin floors.

Due to their depositional environment, ultradeep sediments exhibit geotechnical properties that normally are characterized by low shear strength and high compressibility, influenced by the presence of microfossils and organic content. These soft marine clays demonstrate significant sample disturbance effects, consolidation behavior changes, and high sensitivity to disturbance. These factors are important to consider when designing deep-water anchor structures.

Limited seabed soil data are available in water depths past the continental slope of the Pacific region. A mapping of the seabed stretching from Washington to Northern California includes seabed soil data in water depths greater than 1,300 m (Goldfinger et al. 2014; Tajalli Bakhsh et al. 2020). Results from this report are mapped in Figure 16, showing both the soil type and soil stiffness classification (i.e., hard vs. soft).



(a) Seabed soil type (b) Seabed stiffness (hard vs. soft)

Figure 16. Seabed soil types at various water depths along the U.S. west coast.

Soil classifications from Goldfinger et al. (2014)

Figure 16 shows seabed soil data all the way down to the bottom of the continental slope at 3,000 m, encompassing ultradeep water. Along the shelf, it appears that the seabed primarily consists of soft mud from water depths of 1,000 m down to 3,000 m. Sand is prevalent along the northern Oregon coast and Washington coast, and rockier and gravelly soils are also above the continental slope in water depths less than 1,000 m. The same can be said for the soil stiffness, where harder soils are only found in water depths less than 1,000 m, outside of seismic areas.

Site-specific soil surveys are needed to accurately define soil types and consistencies for potential anchor embedment.

Rock outcrops along the U.S. west coast that may not have been captured in the data of Figure 16 present unique challenges. Installation of equipment such as anchors or cables will likely not be allowed in rocky areas for conservation purposes. The presence of rocky habitat needs to be well characterized and identified during geophysical and geotechnical survey campaigns.

Soil types in the ultradeep waters of the central Atlantic are mostly different than the soils above the continental slope (Fisher et al. 2023). It is reported that seabed soils above the continental slope primarily consist of sand, but at lower depths, below the continental shelf, the soils consist of a mixture of clay and silt (also referred to as mud).

4.1.3 Geohazards

Ultradeep water environments typically feature various geohazards which need to be identified and evaluated in detail. These geohazards may include:

- Excess pore water pressure: Soft sediments typically have high porosity and permeability, which are conducive to sedimentation that can lead to high pore water pressure, affecting the stability of the seabed and holding capacity of anchored structures.
- Gas hydrates and shallow gas: The combination of high pressure and low temperatures in soils with significant amounts of organic material creates ideal conditions for the formation and stability of gas hydrates. These can pose risks due to potential gas release (typically methane) and subsequent sediment disturbance caused by the volume expansion during the dissociation phase, leading to sudden changes in soil properties and affecting the anchor's performance. Gas hydrates have been identified in ultradeep regions of the U.S. Outer Continental Shelf (BOEM 2012; Merle et al. 2021).
- Shallow water flow and pockmarks: These features can indicate subsurface fluid movement. The presence of gas within the sediments can reduce the effective stress and increase the likelihood of fluid flow, while pockmarks are often formed by the seepage of gas from the underlying sediments to the seafloor. Soft sediments provide a conducive environment for gas accumulation and subsequent seepage.
- Mud volcanoes and salt domes: These structures can alter the seabed's geotechnical properties. Explosive eruptions are expected to be less violent than those onshore or at shallower water depths due to the dampening effect of the water and high water pressure. Nevertheless, they have the potential to deeply affect anchor point reliability.
- Seismic activity and faulting: Earthquakes and active faulting can trigger slope failures and tsunami generation with catastrophic impact on the integrity of anchored systems. This is an area that deserves more attention and dedicated studies.
- Slope instability: Understanding the mechanics of potential slides, including their triggers, dynamics and impact on subsea infrastructure, is crucial. Submarine slope instabilities can be activated by earthquakes, wave action, erosion by current or even slow material deposition (Dean 2009).

Any of these geohazards can shift soil layers and reduce the soil strength, which can significantly influence an anchor's performance. The shifting of soil layers can easily cause harder, rockier soils to emerge due to the displacement of the softer, lighter soils (Thompson and Beasley 2012).

Risks for anchors of floating offshore wind turbines are not well understood, so areas with potential for instability may be deemed unsuitable for anchor placement. If anchors are placed in potentially unstable areas, they must be designed to withstand forces from slides and ensure the stability of the mooring system. Several geohazard mitigation strategies are normally considered to reduce the risk to which these structures are exposed:

- Monitoring and assessment: Continuous monitoring of geohazard indicators, such as pore pressure and seismic activity, is essential for early detection and mitigation.
- Engineering solutions: Employing robust design principles that account for potential geohazards, including the use of flexible and redundant systems to withstand geotechnical challenges.
- Risk management: Developing comprehensive risk management plans that include emergency response protocols for geohazard-related incidents.

4.1.4 Geophysical and Geotechnical Implications

Geophysical and geotechnical survey campaigns in ultradeep water are more challenging than operations in typical water depth ranges. Advanced geotechnical and geophysical investigation techniques are required.

Geophysical data collection in ultradeep water relies on remote sensing and subsea robotics with enhanced abilities to survey and assess geohazards in these environments. High-resolution geophysical imaging aids in detailed mapping of widespread areas of seabed and are beneficial to characterize each anchor point location with sufficient accuracy.

For the geotechnical campaign, several aspects need to be considered. Remote in situ techniques need to be stretched to depths where they may have limited penetration ability. Soil sample quality may degrade due to stress relief when samples are brought to the surface, especially if dissolved gas is present in pore water. Additionally, determining the required soil parameters for an ultradeep water environment involves using both field and laboratory tests. Preliminary estimates can be made using soil index properties and specialized diagrams, with careful consideration of the unique geotechnical conditions and challenges present at such depths.

4.2 Anchor Technologies

Many anchor technologies exist that are applicable to floating wind applications in general. Their suitability to ultradeep water applications depends on their holding capacity characteristics, installation methods, and more. Anchors in ultradeep water can be expected to be larger in size to handle larger mooring loads—on the order of tens of meters—but exact dimensions cannot be provided without a geotechnical analysis of the site. The selection of anchor types we considered for ultradeep floating wind applications is shown in Figure 17. These range from well-established anchor types such as DEAs and suction piles, to newer concepts such as helical anchors and ring anchors. We discuss specific anchor types in more detail in the next sections.

The many anchor types can be broadly categorized as pile, plate, or deadweight anchors, based on their primary holding capacity mechanism. Deadweight anchors rely on the gravitational weight of the anchor to resist mooring loads, whereas the largest difference between pile and plate anchors is how they mobilize the surrounding soil to resist mooring loads (Cerfontaine et al. 2023). Piles primarily resist loads through the frictional component of soil shearing resistance, which is derived from the strength and friction of the soil in contact with the surface of the anchor. Plates primarily use the bearing resistance component of soil shearing resistance to resist loads, which is derived from the strength of the soil mass in the vicinity of the anchor. Other forms of resistance exist, such as suction, gravitational, structural, and inertial resistance (Aubeny 2019), but they are not as relevant for categorizing anchors in this report.

In addition to differentiating by holding capacity mechanism, some anchors are installed differently than other similar anchors for reasons such as differences in local soil conditions or installation costs and logistics. This prompts a second dimension to the anchor categorization, which is shown in Figure 17.

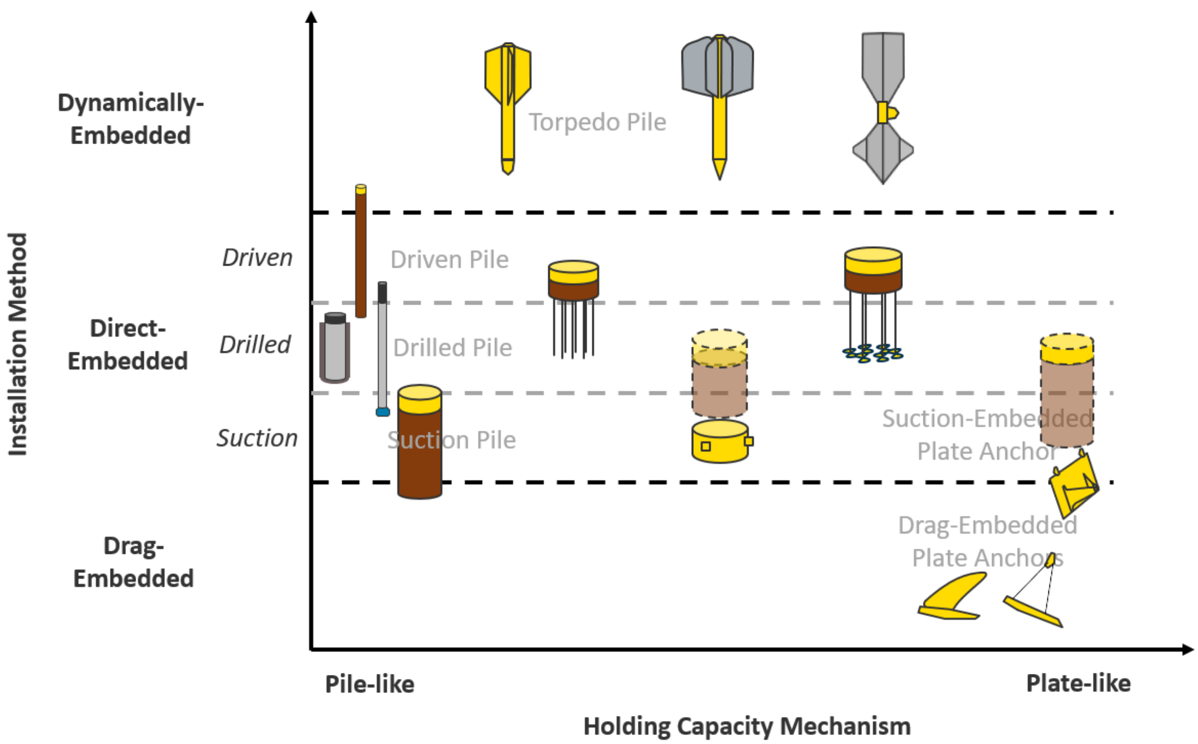


Figure 17. Anchor types overlayed on a two-dimensional categorization by capacity mechanism and installation method

Illustration by NREL

Figure 17 shows a categorization scheme of offshore anchors based on whether they are more “pile-like” or “plate-like” and the way they are installed in the seabed. For example, a driven pile, in this figure, refers to an anchor that is pile-like in that it primarily uses the frictional resistance of the surrounding soil and is directly embedded in the seabed, typically by means of a hydraulic or vibratory hammer. A dynamically embedded plate anchor, for example, is an anchor that primarily uses the bearing resistance of the surrounding soil and is installed dynamically, typically by free fall through the water column.

Various anchor concepts that fit different holding capacity mechanisms and installation methods are detailed in the following subsections and given an assessment for their suitability in ultradeep water. The assessment criteria are briefly explained here but are given more detail in Section 4.3. In ultradeep water depths, anchoring suitability is affected by four main factors:

- Slopes: The slope of the seabed can influence the holding capacity of the surrounding soil of the anchor, as well as increase the risk for geohazards. The exact slope of an anchor placement in ultradeep water is highly location-specific but should be minimized to avoid slope instabilities.
- Soils: The finer, softer soils of ultradeep water determine the holding capacity of the anchor and prescribe specific modes of failure of the anchor. Seabed soils are also highly location-specific and should be surveyed before designing anchors. Variation in the consistency of the soil with seabed depth is less known in ultradeep water, but also contributes to the performance of the anchor.
- Mooring loads: The magnitude of mooring loads in ultradeep water is likely to be larger than other locations given the increase in mooring system size and would likely be a more vertical load, which increases the need for anchors with higher vertical capacity. The cyclic nature of the load also influences the anchor, which is determined by the mooring system type and extreme loads on the platform.
- Installation: In ultradeep water, anchor positioning and embedment precision becomes more challenging, and space becomes limited for drag embedment due to the increase in depth-to-turbine-spacing ratio.

Given these design considerations, ideal anchors for floating offshore wind in ultradeep waters should have the following features:

- Able to resist sustained and cyclic vertical loads applied by the most likely mooring configurations
- Adaptable to seabed slopes (when deemed as suitable)
- Suitable in softer, finer seabed soils
- Compact and/or lightweight, to enable more anchors to be transported at once and minimize the number of transits from port to site during the installation process
- Easily and quickly installable, to minimize installation time on-site.

4.2.1 Established Anchor Concepts

Some established anchor concepts are suitable for ultradeep water. A brief overview of common anchor types used in industry is provided below.

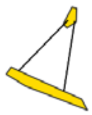
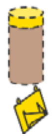
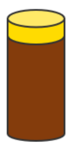
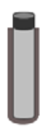
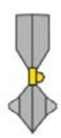
- DEAs are a common anchor type in the offshore industry that can support unidirectional horizontal loads, as seen in catenary and some semi-taut mooring systems. Conventional drag embedment by surface vessels is expected to be difficult and potentially infeasible in ultradeep water because of the large distance to the surface and potential lack of space for vessels to apply the required drag angles due to adjacent mooring lines already installed. However, embedment by using a second reaction anchor and a subsea tensioning device may be practical. In terms of mooring compatibility, DEAs would be limited to catenary or semi-taut mooring configurations, which are unlikely in ultradeep water due to the larger anchoring radii required for higher depths.
- VLAs and plate anchors use a similar concept as a DEA to resist mooring loads (based on the plate angle and surface area) but are well suited to support vertical loads and

horizontal loads that are relatively unidirectional, making them well suited to the expected taut mooring systems in ultradeep water. VLAs are installed similarly to DEAs (which may be challenging in ultradeep water), with the addition of a “keying” process to properly orient the plate in the seabed. Suction-embedded plate anchors use a suction pile for installation, which is practical in ultradeep water. Anchors that use suction embedment are well-suited to ultradeep water because suction embedment is done by subsea ROVs, which are already proven in deep water.

- Pile anchors typically consist of steel pipe and can have omnidirectional holding capacity. Suction piles, common for floating wind applications, have a sealed top and are embedded by pumping water out from their interior using ROV, making them practical for ultradeep water. Their proportions can be adjusted to suit different load directions and seabed conditions. Driven piles and drilled and grouted piles have more demanding installation processes and are therefore less practical for ultradeep water.
- Dynamically embedded anchors, or torpedo anchors, are released from a distance above the seabed and then use their own momentum to embed into the seabed. Their axisymmetric shape allows support for omnidirectional loads. They have especially low material and installation costs. Their positioning and embedment accuracy is lower than other anchor types but can be improved with innovations in telemetry and control. Dynamically embedded anchors are well-suited to ultradeep water because they are lowered from a vessel for installation, meaning there is minimal special equipment required to operate at depth, and they can be designed to have strong holding capacity in all load directions, making them suited for all mooring configurations.

Table 12 lists the suitability assigned to each established anchor type and a justification for its assessment.

Table 12. Established Anchor Technology Suitability for Ultradeep Water

Anchor Type	Suitability	Reasoning
DEA 	Not suitable	Even though they are relatively light in weight and are suitable for soft soils, they are not designed to withstand the sustained vertical loads expected in ultradeep water.
VLA 	Could be suitable	They share many attributes with DEAs, but VLAs are specifically designed for inclined and vertical loads. The complexity of drag embedment installations in ultradeep water limits their suitability for these depths.
SEPLA 	Suitable	They can perform well in soft soils, prefer inclined and vertical loads, and can be transported and installed in large quantities.
Suction pile 	Could be suitable	They can be suitable only if the mooring loads are not sustained, vertical loads (like a TLP) and their installation time and transport challenges can be minimized.
Driven pile 	Could be suitable	They would be suitable given their vertical load capacity and low dependence on seabed slopes but would need assurance on their installation capability and efficiency, as well as their compatibility with local soils.
Drilled and grouted pile 	Suitable, but only for weak rock	Only in weak, rockier seabed are drilled and grouted piles suitable, as their diameters tend to be larger. Pumping grout to ultradeep water depths can be very challenging.
Torpedo pile 	Suitable	They have significantly low installation times and can perform well in soft soils, with any reasonable seabed slope, under vertical loads. However, they would need assurance on embedment position.
Dynamically embedded plate anchors 	Suitable	Similar to torpedo anchors, dynamically embedded plate anchors would also have low installation times and perform well in any seabed slope under vertical loads but would also require assurance on embedment depth (Aubeny 2019; Zimmerman et al. 2009).
Deadweight 	Not suitable	Their large size and weight makes installation at large depths difficult, and would not perform well in softer seabed or slopes.

Viable anchors for ultradeep water are VLAs, SEPLAs, and torpedo anchors. Piles have conventionally been adverse for floating offshore wind because of installation noise and time but can be adapted for deeper waters with innovative installation processes or technology alterations for rocky seabeds, if they do not conflict with rocky seabed habitats. Suction piles can also be suitable, but only if they are not under sustained vertical loading and their installation processes can be made more efficient. DEAs and deadweight anchors are not suited for ultradeep water. These findings are also in agreement with other sources (Colliat 2012), which recommend torpedo anchors as suitable candidates for water depths up to 3,000 m, where VLAs and suction piles would also be suited for water depths up to 1,500 m. The established anchor types that have been deemed suitable for ultradeep water are shown in Figure 18. More detailed assessments of these anchor types are provided in Section 4.3.

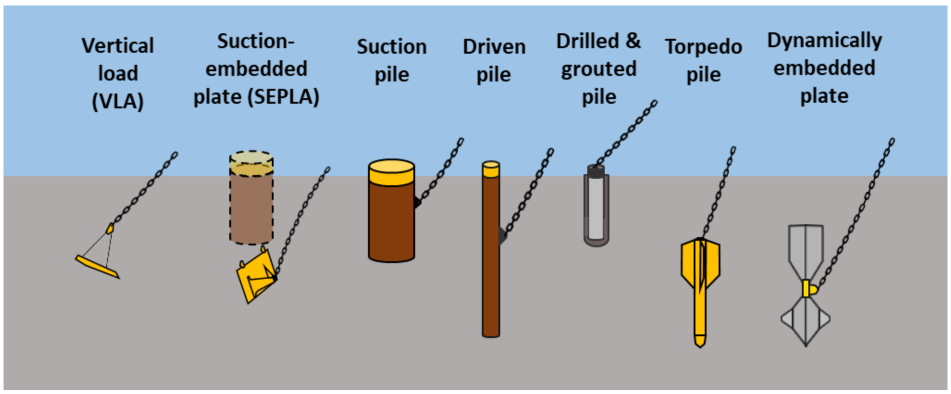


Figure 18. Established anchor types suitable for ultradeep water

Illustration by NREL

Improvements to these established anchor designs can increase suitability in ultradeep water, such as improving the drag embedment uncertainty in VLAs, the installation process of a driven pile anchor, or the weight efficiency of a torpedo anchor. Some of these uncertainties or disadvantages are addressed in other, less-established anchor designs.

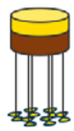
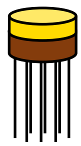
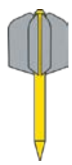
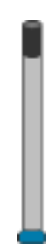
4.2.2 Innovative Anchor Concepts

Newer anchor technologies shown in Table 13 can help address some of the limitations of conventional anchors in ultradeep waters. The most promising anchor types that would be well suited for ultradeep water are helical piles, micropiles, torpedo piles printed in concrete, groutless piles, and ring anchors.

- **Helical** (or screw) piles are an improvement upon driven piles with more efficient installation methods and additional bearing capacity for more soil conditions. These anchors are directly embedded and use multiple long, slender piles with attached helices, which primarily use bearing capacity to resist loads (Harris 2019), making them act more like a large plate anchor rather than individual piles (Bradshaw, Cullen, and Miller 2022). **Micropiles** are a related concept, with multiple shafts but no screw ends, resulting in more pile-like behavior. These anchors are also directly embedded using a template to assist in installation. Both helical pile and micropile anchors may include a skirt on the seabed to increase horizontal capacity. Both anchors rely on specialized installation machinery operated by ROV, and they can both change their pile/screw diameters, lengths, and quantities to adapt to the local seabed conditions. This ROV installation method makes ultradeep installation practical, and the support for vertical loads is well suited for taut mooring configurations and tension leg platforms.

- **Concrete torpedo anchors** have been proposed as a lower-cost alternative to steel anchors. The concrete anchors are supported by a heavy metal booster that can be detached after they are dynamically embedded. Once embedded, this concept acts more like a plate anchor due to its large fins, making it closer to a dynamically embedded plate anchor (Zimmerman et al. 2009).
- **Groutless piles** are an anchor concept designed to maximize the load-bearing capacity of rock. The performance of this pile concept is ensured through the mechanical lock of the pile head into the rock. This makes the pile recoverable once the lock is reopened. Generally, this type of solution is only suitable for competent rocks, with an unconfined compressive strength equal or greater to 25 MPa. The use of groutless piles in non-cemented or weakly cemented carbonate sands and calcarenites presents significant limitations and is strongly discouraged.
- **Ring anchors** (also known as multi-line ring anchors) are suction-embedded ring-shaped anchors that use both frictional and bearing resistance (Lee and Aubeny 2020). They use a suction pile for installation, making them practical in ultradeep water. The anchor uses significantly less material than a conventional suction pile. Fins and flaps can be added to provide vertical capacity. They provide another alternative to SEPLAs, which have high geotechnical efficiency, can be used in many soil conditions, and have the capacity for out-of-plane loads and multiple mooring line attachments.

Table 13. Innovative Anchor Technology Suitability for Ultradeep Water

Anchor Type		Suitability	Reasoning
Helical pile		Suitable	They have high vertical load capacity, work in heterogeneous soils, and may be installed efficiently (Aubeny 2019; Harris 2019).
Micropile		Suitable	They have high vertical load capacity through the frictional resistance of piles. They are adaptable to all soil types and consistencies, including rock. They can be driven or drilled into the seabed at any depth, without the need for large installation vessels or equipment.
Concrete torpedo pile		Suitable	Similar technology to traditional torpedo piles but made in concrete with 3D printers and the potential to release the booster for further installations, leaving the fins embedded.
Groutless pile		Suitable, but only hard rock	Only in hard, rocky seabed are groutless piles suitable, as they need competent rock for the lock mechanism to hold on. In other seabed conditions they are less suitable.
Ring		Suitable	They have a high efficiency (ratio of holding capacity to anchor weight), can be used in many soil conditions, can be installed efficiently, and can be used as shared anchors (Lee and Aubeny 2020).

Each of these anchors would be well suited for ultradeep water. The following section details the criteria used to assess the suitability of each established anchor concept as well as some discussion on various innovative anchor concepts.

4.3 Anchor Assessment

Here, we provide a comparative assessment of the different anchor types for ultradeep waters considering seabed slope, ground conditions, transportation and installation, and mooring loads. More specifically, these anchor type assessments consider the following attributes of ultradeep water:

- Water depths between 1,300 m and 3,000 m
- Longer distances from shore (impacting installation times and cable lengths)
- Mooring loads that are likely to have higher vertical components to minimize the mooring system footprint and decrease mooring line material
- Seabed slopes of more than 10° along the continental slope in the Pacific, but only for a short lateral extent
- Seabed slopes below 4°, beyond the continental shelf
- Softer, finer, and muddier seabed soils farther from shore in deeper water.

Traditionally, the main driver for anchor technology performance (i.e., efficiency) has been the ratio of the steel material to holding capacity. Different seabed conditions and mooring loads have prompted different anchor designs and trade-offs between anchor performance and transportability while optimizing the cost to manufacture, transport and install. Many of these advancements occurred in the oil and gas industry, driven by incentives such as robustness, rapid deployment times and cost efficiency. Ultradeep water for floating offshore wind applications is yet another new environment where conventional anchor types may have drawbacks and new innovations to anchor technology can provide better performance or cost.

4.3.1 Slope Compatibility

An area of uncertainty for anchors in ultradeep water for floating offshore wind applications is their feasibility on steep seabed slopes. Steep seabed slopes can be found in ultradeep water, and features such as pockmarks can create localized areas of steep slopes within an otherwise flat region, so anchors may have to be placed on slopes in some cases. More extensive geotechnical surveys are required to characterize the soils along slopes since their properties will have a larger variability. Slope compatibility needs to be considered in the anchor design and selection process.

In general, seabed slope can affect anchor suitability in two ways:

- Direct influence on anchor holding capacity. Anchor installations, placements, and designs themselves need to be altered to adapt to slopes. Specific alterations vary with anchor type, but often, anchor size is increased on a slope to match the holding capacity that would be achieved on a flat seabed. There is also higher variability in soil geotechnical parameters on slopes and the anchor design and size will need to adapt to those changes in holding capacity.
- Risk of slope failure due to instability. Although anchors may perform well on a slope in ordinary conditions, events that shift soil layers can cause landslides or liquefaction (a reduction in soil strength in response to applied stresses) and displace or dislodge anchors. The risk of slope instability is higher in unconsolidated sediments (Tajalli Bakhsh et al. 2020).

All anchor types (or mooring system layouts) can be adapted to mitigate reductions in holding capacity and minimize the risk of failure from slope instability, but some anchors may be easier to adapt than others. In extreme instances, areas with unfeasible slopes will need to be avoided. In areas with localized steep slopes, anchor positions within floating offshore wind plant layouts can be adjusted to avoid areas with higher slopes.

As a simple measure, the effect of slope on anchors can be estimated geometrically. Because an anchor's holding capacity is a function of the embedded depth perpendicular to the seabed (Thompson and Beasley 2012), the holding capacity of an anchor embedded vertically in a slope scales with the cosine of the angle of the seabed (Figure 19). Downslopes can significantly reduce anchor capacity because the soil in a downslope must use shear strength to resist the gravitational forces from the soil above it, rather than use that shear strength to provide frictional or bearing resistance to the anchor. This can also be seen in Figure 19c, assuming that soil shear strength increases with depth perpendicular to the seabed slope. Slopes can also increase misalignments between the mooring line direction and the anchor attachment point during the installation process.

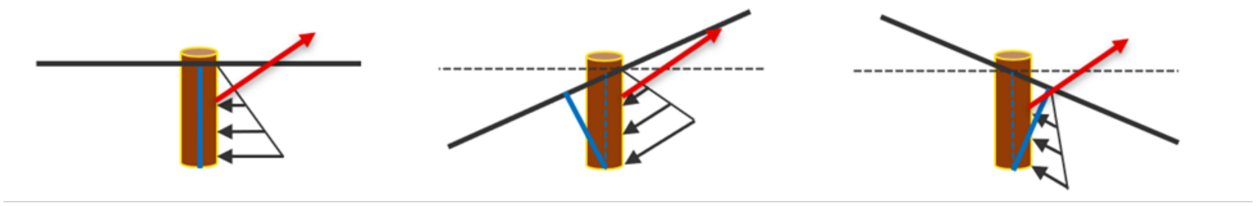


Figure 19. Anchor holding capacity effects in a sloped seabed

Illustration by NREL

Anchors can be embedded at an angle to maintain their position and orientation relative to the perpendicular of the seabed. They can also be planned for installation on an upward slope rather than a downward slope, as upward slopes provide higher resistance due to more soil being "above" the anchor. However, this technique is not fully practical for ultradeep waters since piles have more demanding installation requirements in deeper waters.

VLAs and SEPLAs achieve higher holding capacity with higher embedment depths. The dragging process in VLAs can be expected to decrease embedment depths on downslopes and potentially increase embedment depths on upslopes, if designed appropriately. SEPLAs are not influenced by slopes as much, even though they are also plate anchors, because they are suction-embedded and can be set to similar embedment depths regardless of seabed slope. Pile-like anchors would have different embedment depths on each side of the pile, which would increase the resistance in an upslope from the additional soil on the side of the anchor but would lose the same amount of resistance in a downslope from the reduced amount of soil on the side of the anchor. Given enough embedment depth, torpedo anchors and other dynamically embedded anchors would also not be influenced significantly by seabed slopes. Other innovative concepts like helical piles, micropiles, and ring anchors could be embedded enough to avoid any large reductions in holding capacity.

The feasibility of anchor installation on various seabed slopes—whether due to direct effects on holding capacity or potential slope instability—cannot be accurately determined through qualitative analysis alone. Few studies provide definitive maximum seabed slope angles for anchors. Some sources use 10° as a cutoff for evaluating anchor performance without providing complete justification (Thompson and Beasley 2012; Porter and Phillips 2020). Another study notes that at 10° slopes, rockier seabeds appear more frequently, suggesting soil instability and exposure of underlying bedrock, which would be unsuitable for conventional anchors (Goldfinger et al. 2014). Conversations with anchor experts indicate no defined upper limit for seabed slopes where anchors can be installed.

The risk of slope failure due to instability would least affect the anchors with the most embedment, as they would be less subject to change in installation. More detailed studies on the risks of individual anchor types to potential slope instabilities are needed.

4.3.2 Ground Compatibility

The seabed properties significantly influence the selection and design of an anchor for floating offshore wind applications. Anchors are designed to achieve holding capacities as a function of the properties of the surrounding soil. A qualitative assessment of different soil types as they apply to the performance of different anchor types is performed to determine which anchors are more or less suited for the soils of ultradeep water.

To evaluate anchor performance for different soil types, Figure 20 shows the compatibility of suitable established anchor types for ultradeep water relative to ground conditions, where the soil type ranges from clay soils with the smallest grain size to rocky materials that are naturally aggregated from a single or multi-mineral material. The qualitative data were gathered from a variety of sources (Aubeny 2019; Cerfontaine et al. 2023; Diaz et al. 2016; Thompson and Beasley 2012; Ma et al. 2019; ORE Catapult and ARUP 2024; Porter and Phillips 2020) and synthesized into a more visual figure. Quantitative anchor-soil curves similar to these could be derived based on calculating anchor capacities as a function of soil type and strength, but the qualitative representation in Figure 20 does not represent that level of detailed analysis.

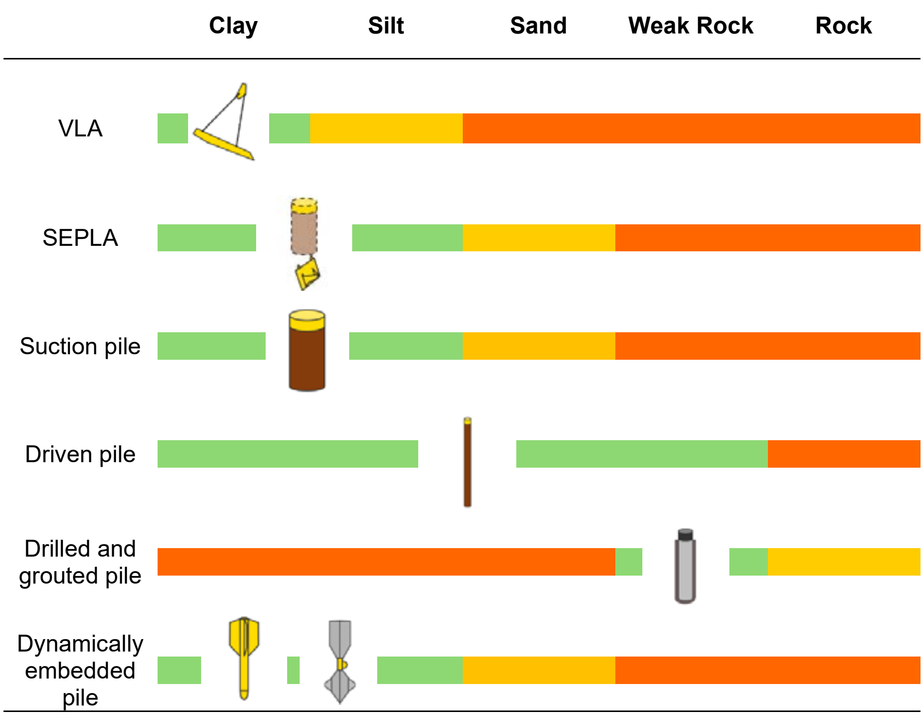


Figure 20. Ground compatibility for suitable established anchor types in ultradeep water.

Illustration by NREL; green = compatible, yellow = potentially compatible, red = not compatible

In general, at least one anchor type in Figure 20 is feasible to work in any soil condition. VLAs and SEPLAs favor the softer clays as opposed to stiffer sands. This is primarily because these anchors can be considered "plate" anchors, where their holding capacity increases as embedment depth increases. Softer clays allow for deeper embedment than stiffer sands. Suction piles are suited for most clay, silt, or sand soils, with some preference for softer clays over stiffer sands since the suction capacity is easier, or less costly, to achieve in softer clays. However, the suction pile design can be adjusted to work in any clay or sand. Ring anchors would likely behave similarly and could be designed for any clay or sand.

Driven piles are suitable for almost all soil conditions, except for hard rock. Soft clays are susceptible to liquefaction and disturbance during driven pile installation, which can significantly reduce the expected frictional resistance, but many oil and gas projects have installed driven piles in clay, proving their feasibility. Weak rock is categorized as having a maximum unconfined compressive strength of 5 MPa or less, while rock typically exhibits a higher unconfined compressive strength. Drilled piles are most suited for weak rock due to the resistance gained from the grout used to cement the anchor into the seabed. Groutless piles are more suited for harder rock. Micropiles can be drilled or driven, making them suitable for a wide range of soil conditions, and the piles of helical anchors can penetrate and operate in most clay or sand soils.

Torpedo anchors generally embed more deeply in softer soils than stiffer sands, but the trade-off between embedment depth and holding capacity may cancel out, as stiffer sands can provide higher capacities than softer soils (Aubeny 2019). Therefore, they are suitable in clays and sands but may slightly prefer softer clays for better initial embedment.

Based on ground compatibility, all these anchor types are feasible for ultradeep water for floating offshore wind. Some anchors prefer certain soils, but in general, the anchor design can be adapted to meet most soil conditions, with some change in cost. Innovative anchor technologies are becoming more adaptable to different soil types. For example, the number and size of piles in micropiles can be adapted for any seabed soil condition. Groutless piles have been designed to more efficiently anchor into harder, rocky seabeds. These newer designs address the seabed soil limitations of conventional anchors, making them more attractive for more seabed conditions.

Given these qualitative soil assessments, suitable anchors should be chosen for different offshore applications based on the local soil conditions. However, accurate soil samples that show attributes other than grain size, like soil strength or consistency, would be needed for a more accurate anchor evaluation. Comprehensive site investigations should be conducted in accordance with applicable standards.

4.3.3 Transport and Installation Compatibility

Another essential aspect to consider is the transportation and installation methods of anchors, specifically focused on ultradeep locations. Transporting anchors to ultradeep water sites presents significant logistical challenges, primarily due to the distance from ports and the limited availability of suitable weather windows. The long distances involved require careful planning and coordination to ensure the timely and efficient movement of anchors, which are often large and heavy, necessitating specialized vessels and equipment. This extended transit time increases the risk of encountering adverse weather conditions, which can delay operations and escalate costs. Additionally, the limited weather windows in deep-water environments constrain the periods during which safe and effective transportation and installation can occur. These constraints necessitate robust contingency planning, including the scheduling of operations to coincide with favorable weather forecasts and the potential for standby time, which further complicates logistics and adds to the overall project timeline and budget.

The size of each anchor is another important aspect of the transportation process, as the number of anchors that can fit on the deck of one installation vessel determines the total number of trips the vessel has to take for installation. Larger vessels can transport more anchors at a time, although the number of anchors that can fit on a vessel will depend on the size of the anchor. The same deck area can fit either 12 DEAs, 7 SEPLAs (including seven plate anchors and one suction-embedment tool), 4 driven piles, or 3 suction piles (Fulton 2022), as displayed in Figure 21. In another study, a typical vessel deck area can carry 12 VLAs, 4 suction piles, or 8 dynamically embedded plate anchors (Zimmerman et al. 2009).

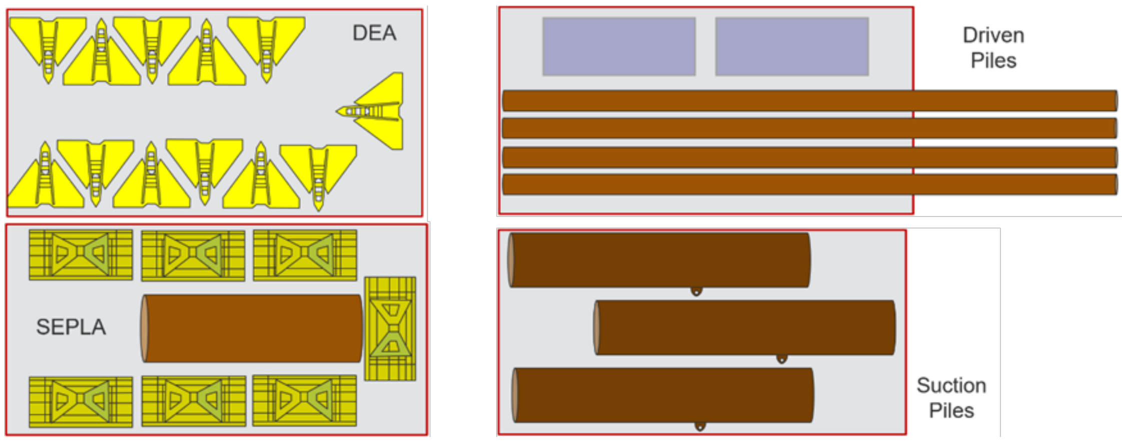


Figure 21. Typical installation vessel deck layout for anchors

Images adapted from Fulton (2022)

Vessel availability and capacity significantly influences anchor design and installation procedures. Specialized installation vessels are essential for efficiently transporting some anchor types. Larger vessels may be preferred for ultradeep sites to reduce the total number of transits. Conventional anchoring capabilities of vessels are generally limited to depths of less than 200 m, making dynamically positioned vessels more suitable for deep-water locations. These vessels are equipped with advanced positioning equipment, motion compensation and heave-compensated landing equipment. Additional equipment for hoisting anchors efficiently also enhances the installation process. The required bollard pull and horsepower of a vessel is often dictated by the proof load requirements of the anchor installation. The winch capacity is also dictated by the requirements to “key” an anchor (orient the plate anchor normal to the mooring load).

The penetration resistance of the soil determines the installation process of anchors, such as suction-embedment or driven-embedment. Soft sediments may offer less resistance, making installation easier, but may require deeper penetration to achieve the required holding capacity. Some direct embedment methods may have limitations based on water depth, such as current vibro-hammer technology, which may require further technological advancements, such as ROVs and subsea installation equipment to extend into ultradeep water. Rock conditions need special drilling equipment to allow for significant seabed penetration and to overcome the high hydrostatic pressures at greater depths, especially for grouted piles.

Each installation method (drag, direct, or dynamic embedment) varies in installation time, required equipment, positioning precision, embedment depth, seabed disturbance, and recoverability (the ability to retrieve/remove the anchor). Installation misalignments, including vertical tilts and planar twists, need to be discussed and agreed upon with the transport and installation contractor prior to the maneuvers, so these factors should be incorporated during the initial anchor design phase. The installation method attributes of the suitable, established anchors for ultradeep water are as follows:

- The transportability of an anchor is a function of the relative size of an anchor and how many can be transported on an installation vessel per trip. VLAs and SEPLAs are some of the most efficient anchors in terms of size and weight and many can be transported at once, whereas torpedo anchors are slightly larger in size, and drilled and grouted anchors may require more equipment on deck. Suction piles and driven piles will be the most difficult to transport due to their relative sizes.
- Dynamically embedded anchors (i.e., torpedo anchors) have the fastest installation time, driven and drilled pile anchors have the slowest installation time due to the required equipment, and all other anchors can be installed in a matter of hours but require some additional installation processes, such as keying, suctioning, or dragging.
- Most pile anchors and SEPLAs can be installed with high precision, whereas dynamically embedded anchors exhibit some level of uncertainty in their embedment position based on the depth at which it is dropped but can still be properly installed within tolerances.
- Driven piles, suction piles, and SEPLAs minimally disturb the seabed when installed, whereas drilled piles and torpedo anchors cause more disturbance. The area of seabed disturbance will depend on the size of the anchor and the resistance of the soil at a specific location but can be estimated to be roughly the same size of projected area of anchors that are direct-embedded and slightly larger than the projected area of dynamically embedded anchors.
- In terms of recoverability, suction piles are relatively easy to recover after short deployments but can be expensive to recover after long periods of time due to corrosion. Driven and drilled piles are difficult to recover as they use various methods to deeply embed into the seabed. SEPLAs, VLAs, and torpedo anchors can be recovered but may require additional steps, such as including specialized recovery ropes in the installation.

The method of anchor installation significantly influences its suitability for ultradeep offshore applications. Figure 22 provides a qualitative assessment of each general anchor type based on different attributes such as transportability, installation time, positioning precision, seabed disturbance, and recoverability.

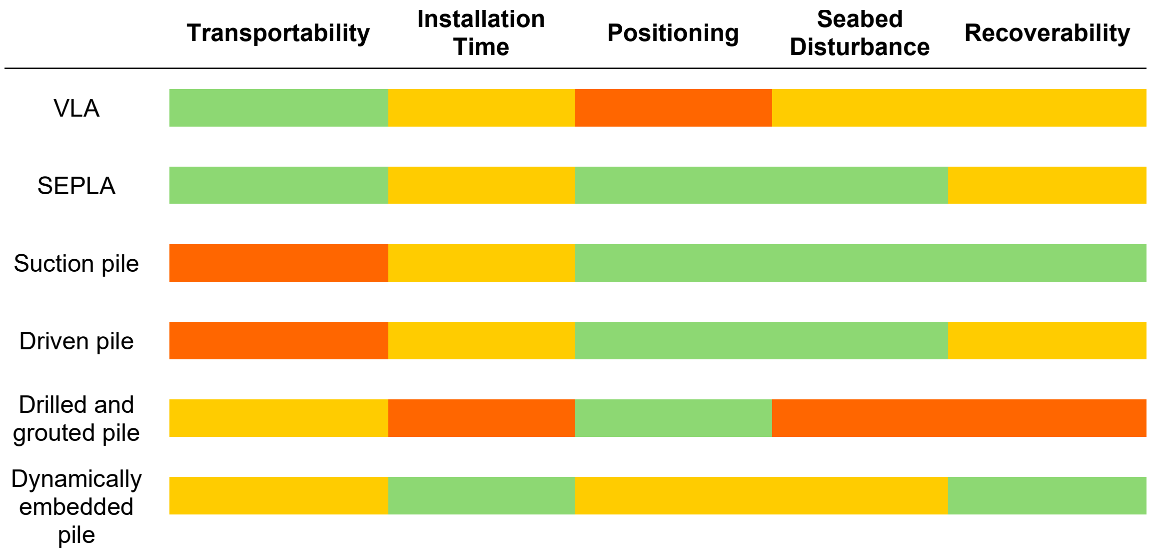


Figure 22. Summary of installation method attributes for each suitable established anchor type in ultradeep water.

Illustration by NREL; green = suitable, yellow = potentially suitable, red = not suitable

Innovative anchor concepts have been designed to address some of these transportation and installation limitations too. Helical piles and micropiles, for example, have been designed for precise positioning, efficient transportation, minimal seabed disturbance, and designed measures to retract, or unscrew, the piles.

4.3.4 Load Compatibility

Anchor types have been developed to resist different types of mooring loads. These mooring loads are the sum of forces that the mooring lines exert on anchors in response to the forces acting on a floating platform and the mooring system components themselves. Anchor holding capacities depend on the load characteristics, namely, load duration, the cyclic nature of the load, the load rate, the point of application, and the load direction (Aubeny 2019). These load characteristics need to be included in the anchor design and selection process for completeness. Figure 23 shows the different loading conditions an anchor is exposed during its lifetime.

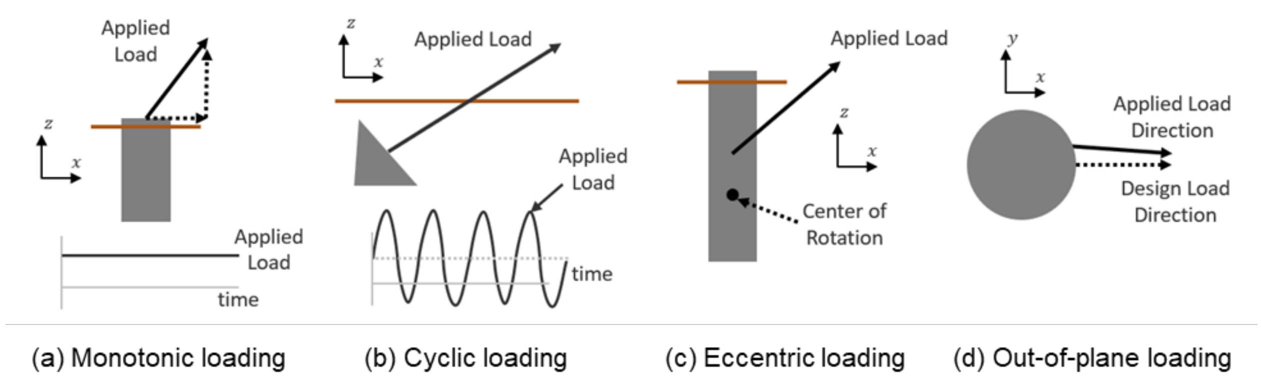


Figure 23. Depictions of loading conditions that an anchor can experience

Illustration by NREL

All anchors can be expected to undergo each of these loading conditions at some point in their design life. For the anchor types considered in Section 4.2, no loading conditions are prohibitive, but some conditions are more suited for some anchors over others.

These loading conditions, combined with the specific geotechnical properties of the surrounding soils, should be considered during the design phase to ensure the effectiveness and reliability of an anchor. For instance, anchors in soft soils under cyclic loading (Figure 23b) from environmental loads are subject to significant soil degradation coming from shear strength reduction, accumulation of pore pressure, soil fatigue, soil settlement, and soil deformation.

Suction piles are a clear example of pile anchors that do not perform well under sustained vertical loading (Figure 23a). Over time, the slow increase of pore water pressure in the soil reduces the overall passive suction resistance, thereby diminishing the vertical holding capacity. The vertical holding capacity of a suction pile is a function of the self-weight of the steel of the pile, the outer plate adhesion, and one of the following failure modes:

- Reverse end-bearing capacity relies on passive suction and is the maximum resistance value that can be mobilized
- Submerged weight of the soil plug
- Inner plate adhesion.

During sustained loading, the failure mode can shift from reverse end-bearing capacity to soil plug or inner friction, depending on the anchor embedment ratio (Aubeny 2019; Colliat 2002). In short-term cyclic loads, for example, these changes in pore water pressures do not develop.

Eccentric loading (Figure 23c) is a concern for pile anchors, which can significantly reduce the lateral holding capacity if the loading does not align with the center of rotation. Optimizing the padeye location, where the mooring line connects to the anchor, can mitigate these effects. On the other hand, plate anchors are not affected by eccentric loading because their shape and design allow them to align themselves with changes in the mooring load direction relative to the center of rotation.

For shared anchors, the loading interaction between different mooring lines can lead to partial compensation of horizontal forces since lines can counterbalance each other due to their different directions, reducing the net horizontal force acting on the anchor. However, the vertical and out-of-plane components of the load tend to build up, as the combined effect of multiple lines pulling in the same direction increases the vertical and torsional forces on the anchor. This buildup of forces can pose significant challenges. Careful design and analysis consideration are needed to ensure the anchor can withstand these compounded loads.

Other sources of out-of-plane loading (Figure 23d) include anchor installation misalignment or mooring system failure. These loadings can reduce load capacity for most anchors due to the extra resistance the soil has to provide to torsion. In order to avoid these issues, some anchors have designs that allow for out-of-plane loading, where the mooring line can swivel about a point on the anchor, making it "omnidirectional." Conventional plate anchors, however, will fail under out-of-plane loading (Yoon and Joung 2022), unless they can be "keyed" in the direction of the mooring load.

The anchor types considered for the ultradeep assessment are qualitatively assessed for their suitability toward mooring load directions and subsequently mooring system types (Figure 24), where the curves have been derived from qualitative data in number of sources (Aubeny 2019; Cerfontaine et al. 2023; Diaz et al. 2016; Ehlers et al. 2004; Thompson and Beasley 2012; Vryhof 2018).

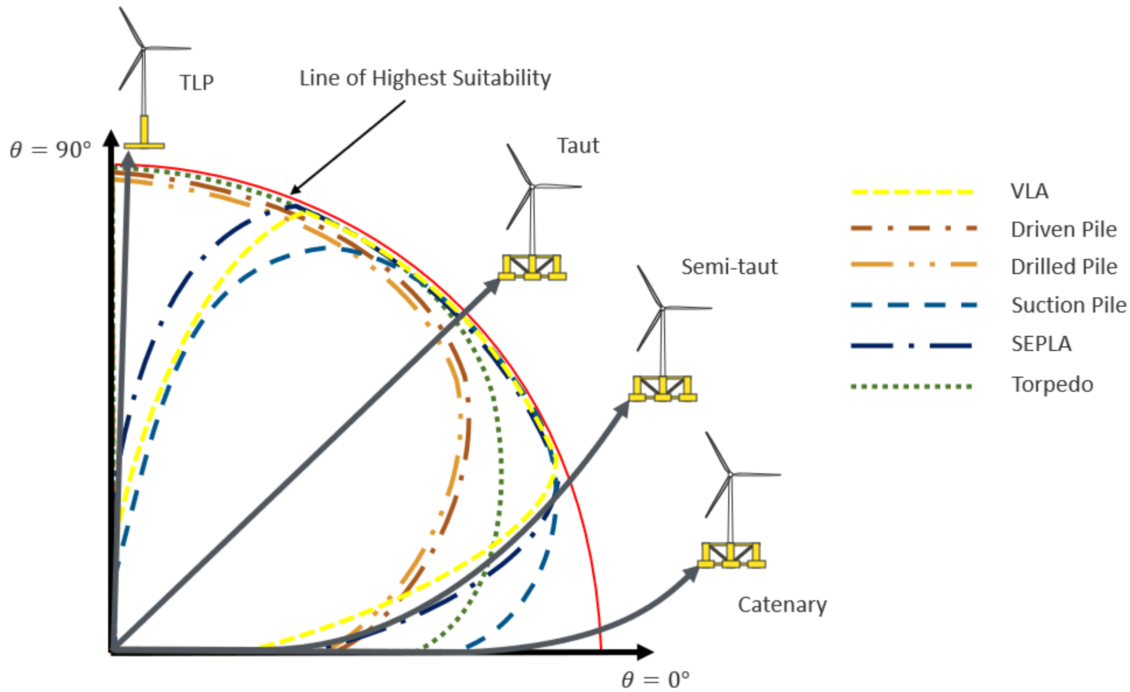


Figure 24. Mooring load direction relative suitability for different types of anchors

Illustration by NREL

In Figure 24, each anchor is represented by a shape that outlines the anchor's suitability to different mooring load directions, with the highest level of suitability along the edge of the red quarter-circle. These curves are only relative to themselves, meaning that the most suitable mooring load direction for a driven and a drilled anchor is likely to be 90° for both anchors, but we are not indicating which anchor is more suited for that load direction, only that both anchors will perform best at that load direction.

VLAs are installed similarly to DEAs but have a release mechanism that allows them to orient perpendicular to the mooring load direction. This allows them to resist inclined loads, though fully vertical loads are not recommended because the anchor can slide and lose embedment as load angles approach 90°. SEPLAs are also embedded by suction and can lose a very small amount of embedment depth during the keying process. When embedded deep enough, they can generate a large holding capacity in the vertical direction.

Suction piles have great inclined holding capacities due to their suction holding capacity mechanism, but as stated previously, they do not perform well in sustained vertical loading due to a loss in suction over time. Driven, drilled, and torpedo pile anchors are all suitable for most mooring load directions, with a slight preference for more vertical loads. Driven and drilled piles achieve their holding capacity from the bonding resistance along the sides of the pile between the steel and the rock by means of the grout, whereas their horizontal capacities are determined by their diameter-to-length ratios, which are usually small. Torpedo anchors can use both frictional resistance and bearing resistance depending on the specific design, and their large embedment depths can efficiently resist both horizontal and vertical loads but only if the release height is properly assessed for the installation phase.

4.3.5 Additional Considerations

Along with the previous defined anchor compatibilities, there are several aspects that are worth mentioning with respect to anchors for ultradeep water environments.

Scour, the process of sediment removal around submerged structures due to water flow, can reduce the anchor embedment depth. The rate of scour is influenced by the type of soil present. In soft soils, scour might be less significant compared to harder, more cohesive soils. Soft soils, such as fine silts and clays, tend to be more cohesive, which can reduce the rate at which they are eroded by water currents. The cohesive nature of these soils helps them resist detachment and transportation by flowing water. However, this does not mean that scour is entirely absent in soft soils; it can still occur, particularly in areas with strong currents or wave action. The key difference lies in the rate and extent of scour, which may be less pronounced in soft soils due to their inherent cohesiveness compared to non-cohesive sandy soils where scour can occur more rapidly and extensively (Sumer and Kirca 2022).

Trenching due to the movement of embedded mooring lines can present distinct challenges and dynamics. When mooring lines are subject to dynamic environmental forces such as currents, waves and wind, their oscillatory movements displace the soil and gradually form trenches in the seabed. In soft soils like fine silts and clays, this trenching effect can be more pronounced and severe due to the cohesive nature of the soil. In weaker soils, the soils of the trench can collapse. In ultradeep waters, the increased pressure can exacerbate the effect of cohesive soils by compacting the soil around the mooring lines, making the trenching process more gradual but persistent. The formation of these trenches can alter the anchor point performance by affecting the embedment depth and soil resistance distribution.

In ultradeep waters, marine growth and corrosion present different levels of challenges that require specific strategies to manage. Reduced light levels and lower temperatures result in slower growth rates and different species composition compared to shallow waters, making this aspect less problematic than in shallower waters. Corrosion is affected by the lower oxygen content, which can slow down certain types of corrosion but still poses risks, especially for mixed-metal assemblies and microbial-induced corrosion. To mitigate these issues, specialized antifouling and protective coatings are applied to underwater structures and anchors. These high-performance coatings are designed to withstand the harsh conditions of ultradeep waters, providing a barrier against marine growth and corrosion.

All these aspects necessitate careful monitoring and maintenance to ensure the anchor systems remain secure and effective. Additionally, the complex logistics of operating in ultradeep waters, including the deployment and inspection, require advanced equipment and techniques to manage the overall integrity of the mooring system. An example of this are periodic inspections and cleaning using ROVs, essential to manage biofouling and ensure the longevity and integrity of submerged structures

4.4 Conclusions

The ultradeep water market for floating offshore wind is still only in the feasibility stage of development. Floating offshore wind technology has not yet been demonstrated at 1,000-m depths, and we are extrapolating that technology to significantly deeper water. The anchor technologies discussed in this report and illustrated in Figure 25 represent our current assessment of the most suitable anchor types for ultradeep water floating wind applications. However, future technological innovations may lead to the development of even more effective solutions.

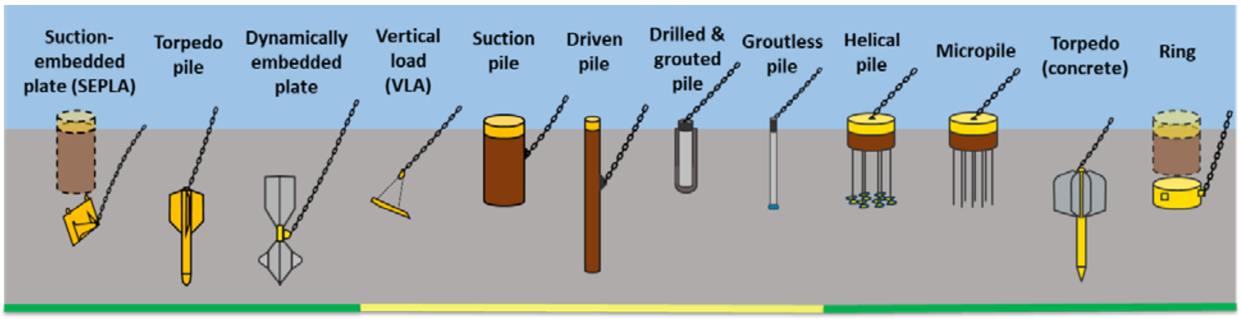


Figure 25. Suitable anchor types for ultradeep water applications

Illustration by NREL

General conclusions learned from this study include:

- Anchor design is relatively agnostic to water depth. Most conventional anchor types can be adapted for ultradeep water without changing the overall shape and function of the anchor.
- Anchor selection depends on site-specific conditions, and more data are needed to characterize soil types and geohazard risks present in ultradeep waters.
- Slope instability in ultradeep water depths may make some locations unsuitable for anchors. The potential for slope instability was not assessed in this report but should be accounted for in the mooring design process.
- The transport and installation of anchors in ultradeep waters will likely require more time and specialized vessels than in shallower waters.
- Ultradeep loading patterns influence how the soil around the anchor provides resistance. These patterns need to be included in the anchor design and selection process.

These conclusions, coupled with other findings from this project, can inform decision-making on anchor suitability for future offshore wind lease areas, guide anchor designers in considering ultradeep water conditions, and highlight areas requiring further research on ultradeep seabeds. These areas for further research are essential to advance the maturity level of the industry.

5 Modeling Tools

NREL has performed a qualitative review of its floating wind system modeling capabilities with respect to the unique needs of ultradeep waters (1,300–3,000 m). This review considers four tools used at NREL: MoorDyn, OrcaFlex, MoorPy, and a mooring line properties library. Based on the differences expected in ultradeep water, which are covered in Section 2, the existing modeling capabilities are deemed suitable for ultradeep applications with one possible exception: modeling of the elasticity of synthetic fiber rope mooring lines. The existing methods capture first-order behaviors but cannot represent more complex nonlinear viscoelastic responses that may have elevated importance to the loads of ultradeep mooring systems. A quantitative characterization of these limitations for ultradeep scenarios would help inform the most effective directions for model improvement, though lack of data is an ongoing challenge.

5.1 Model Capability Review

Ultradeep-water floating wind turbine systems are expected to involve the same design topologies and same driving physical phenomena as those of shallower water depths. Drawing from Section 2, the following is a brief summary of relevant phenomena changes (expected general trends to which there may be exceptions) in ultradeep water relative to shallower locations:

- Metocean conditions will have little change.
- Floating platform/substructure/turbine sizes will have little change.
- Mooring system configurations will tend toward taut or tension-leg options using synthetic fiber ropes or other non-steel materials.
- Mooring line lengths will be significantly longer, increasing the importance of mooring line elastic properties, and increasing sensitivity to drag loads from undersea currents.
- The range of applicable anchor technologies will have little change, though there may be increased preference for anchors that are more efficient to install, such as torpedo anchors.

With this summary in mind, we review the main mooring design analysis tools used at NREL for their applicability and potential shortcomings for ultradeep scenarios. Because significant changes in metocean conditions or floating platforms are not expected, the scope of review is focused on modeling the mooring lines. Modeling anchor behavior is not in the scope of these models, and ultradeep applications are not expected to have novel anchor modeling requirements.

MoorDyn is a lumped-mass mooring dynamics model developed by NREL that provides the core mooring functionality in the OpenFAST floating wind turbine simulator, as well as the WEC-Sim wave energy converter simulator. MoorDyn has been verified and validated in a number of studies and shown to accurately model the motions and loads of many mooring configurations and also common dynamic cable configurations. In 2021, capabilities for modeling sea current loads were added, meaning that it can model the effects of any subsea currents acting over long mooring line lengths. MoorDyn's modeling of mooring line elasticity has been expanded incrementally in recent years with three main features:

- Nonlinear tension-strain curve, supporting any user-specified static response

- Linear visco-elastic model, supporting the dynamic response from both slow- and fast-acting stiffness coefficients
- Mean-load-dependent dynamic stiffness coefficient, which adjusts the fast-acting stiffness based on the change in mean load.

These features provide first-order approximations of several complex behaviors that synthetic fiber ropes experience. However, there has been little opportunity or data availability for verification/validation studies. There are also known limitations of these methods, where more sophisticated methods exist[1] that can model the nonlinear viscoelastic behavior of different synthetic fiber rope materials.

The effects of vortex-induced vibrations on mooring lines are being added to the MoorDyn functionality over the course of 2024. Vortex-induced vibration effects are expected to be more prevalent in longer mooring lines in ultradeep waters, though it will require future study to understand their importance for floating wind applications. As with line elasticity, there are limited data available for verifying vortex-induced vibration behavior for mooring lines of offshore structures.

OrcaFlex is a commercial offshore systems simulation software with industry-leading modeling of mooring lines, cables, risers, and floating structures developed by Orcina. In recent years it has incorporated the AeroDyn model from NREL's OpenFAST code to be able to simulate complete floating wind turbines. OrcaFlex is very widely used in the offshore industry. Relative to OpenFAST, it provides more versatile and user-friendly simulation capabilities for subsea systems, although it is less capable in its wind turbine modeling. OrcaFlex is full-featured in modeling current and wave loads, without any known shortcomings applicable to ultradeep environmental loadings. To date, OrcaFlex includes only linear modeling of mooring line elasticity, putting it behind MoorDyn in this respect. However, the developers at Orcina indicate that nonlinear elastic modeling is under development. In addition, OrcaFlex allows use of external code for various model functions, and separate companies have developed proprietary add-ons that implement sophisticated fiber rope elasticity modeling. These add-ons are not publicly available, nor are their theoretical bases in the public domain.

MoorPy is a quasi-static mooring analysis tool developed by NREL used extensively in NREL's lower-order models for floating wind turbines and in design optimization workflows. The ability to model steady current drag forces was recently added to MoorPy, making it capable of modeling relevant ultradeep environmental loads. MoorPy uses only a linear stiffness coefficient for mooring line elasticity, but functions have recently been added to dynamically adjust this coefficient based on different conditions to provide a linear, quasi-static equivalent to the nonlinear dynamic elasticity modeling in MoorDyn. In this sense, MoorPy is well equipped to represent complex fiber rope elasticity behavior up to the extent that is practical for a quasi-static model.

[1] Although reviewing other mooring elasticity methods is outside the present scope, it is worth mentioning that detail on more sophisticated methods is available in academic papers (such as those reviewed here https://www.mdpi.com/2077-1312/11/1/193), and we have heard of proprietary methods from companies such as Dyneema.

NREL's mooring line property library is a recently created resource that can help researchers and designers determine reasonable mooring line property coefficients when sizing mooring systems. These values can then be put into models such as the three described above. The property coefficients are based on averages across published research papers and manufacturer specification sheets. The majority of included properties are straightforward and have coefficients with high levels of confidence. The area of greatest uncertainty is the elastic characteristics of fiber rope mooring lines. Coefficients are included that match the level of modeling detail currently in MoorDyn. However, there is a moderate degree of uncertainty in the coefficient values, and the set of coefficients neglects more complex rope elasticity phenomena.

5.2 Conclusion and Future Outlook

In summary, the models work well for all expected phenomena except for more complex rope elasticity phenomena, for which there are modeling limitations. These elasticity modeling limitations are pervasive among many offshore system simulation tools, though it is an active research area. The significance of those limitations is not well understood due to lack of study and lack of available comparison data. Given the elevated importance of rope elasticity in ultradeep waters, quantitatively characterizing the significance of these modeling limitations would indicate whether modeling improvements are needed. The creation of ultradeep references in Section 6 provides helpful design information with which to conduct the suggested characterization study. However, such a study would also need reliable data on the measured elasticity characteristics of synthetic fiber mooring ropes. These data are very rarely available in the public domain, posing an obstacle. Fiber rope elasticity is an active research area, and it is a topic in multiple active U.S. funding opportunities. Future research projects may provide pathways for realizing the public-domain data necessary for characterizing the rope elasticity modeling needs of ultradeep floating wind structures.

6 Reference Designs

This section presents conceptual design studies of two floating support structures that are well suited for ultradeep water: a semisubmersible with a taut mooring system, and a TLP. Designs for both configurations are made for water depths from 1,300 to 3,000 m, using engineering models to ensure the designs have adequate performance. These design studies provide greater insights on the feasibility and design drivers for floating support structures in ultradeep water. They also provide quantitative results about expected design dimensions and performance measures, which can be considered preliminary representative values for the floating wind systems that could be developed at these depths.

The goal for these two sets of reference designs is that they can be commonly used to investigate the feasibility of ultradeep water with realistic support structures, along with determining other important factors for floating wind farms, such as capacity density ranges and potential costs. Each design assumes a constant water depth without seabed slope or consideration of local seismic potential. This assumption is likely more significant for taut designs, whereas TLPs are less sensitive to changes in seabed conditions over the mooring system footprint.

The taut mooring system design study targets the most well-established mooring configuration for deep waters, as demonstrated in the oil and gas industry, using taut polyester ropes. As discussed in Section 2, a taut configuration is more likely than semi-taut or catenary mooring configurations because it avoids excessive system weight and ocean space use. We use the established VolturnUS-S semisubmersible platform design for the International Energy Agency Wind Technology Collaboration Programme (IEA Wind) 15-MW reference turbine since it can accommodate a wide variety of mooring systems, and we assume three mooring lines per turbine, consistent with most floating wind deployments to date. We also consider other rope materials for their suitability in the ultradeep range.

The TLP design study involves design of both the platform and the tendons. The platform has a single column and three pontoons, which aligns with more current mature TLP design concepts for floating wind. We assume six tendons (a pair per pontoon) to provide redundancy, since a single tendon failure would otherwise cause the platform to capsize. We use the 15-MW reference turbine with design constraints that ensure turbine loads will not exceed those on the VolturnUS-S platform. We considered a range of tendon material options before focusing on HMPE as the most established option that is suitable.

For both designs, we sized the components to withstand metocean conditions from the Humboldt Bay wind energy area off the coast of Northern California. This area is near a steep drop-off to ultradeep water depths and provides a well-characterized set of metocean assumptions to use for these general reference designs. Detailed site conditions at deeper water depths were not available at the time of this analysis. We focus on sizing the designs for design load case (DLC) 1.6, with the turbine operating at its rated wind speed under normal turbulence levels, combined with the most severe (50-year return period) sea state expected under these wind conditions. Wind, waves, and currents are assumed to be aligned to represent that most severe loading. We evaluate two orientations—one with mooring lines directly upwind and one with mooring lines directly downwind—to account for both the highest-tension and highest-motion cases, respectively. Table 14 lists the environmental parameters for DLC 1.6 for the Humboldt Bay wind lease area.

Table 14. Design Load Case 1.6 Environmental Parameters

Environmental Condition	Value
Wind speed (m/s)	10.59
Turbulence intensity (-)	0.06
Wind shear exponent (-)	0.14
Significant wave height (m)	10.5
Wave peak period (s)	18.7
Current speed (m/s)	0.92
Yaw misalignment (deg)	0
Turbine status	Operating

The resulting designs have similar detail as existing published reference designs and can therefore be added to the public reference design set, creating reference designs that can be used in ultradeep water for the first time. For both configurations, we developed the designs using design optimization tools based around lower-fidelity floating system models. These models include RAFT, a frequency-domain floating wind turbine simulator, and MoorPy, a quasi-static mooring system model. We verify the accuracy of the results by comparing with coupled time-domain simulations using OpenFAST, a widely used model that can directly check loads that are required by standards.

6.1 Taut Mooring System Design Study

Taut mooring systems are the most mature mooring solution for floating wind turbines in ultradeep water because they are compatible with existing floating wind turbine platform designs. Although TLPs are attractive for ultradeep water due to their low mooring system footprint, which allows the capacity density to be maximized, TLPs for floating offshore wind have not been demonstrated to the same level as semisubmersibles or spars, and they can face additional installation challenges and mooring system costs. In contrast, taut mooring systems can use similar polyester rope mooring lines as have been well established in the oil and gas industry, and these mooring lines do not face as stringent stiffness requirements as the TLP tendons discussed in Section 6.2.

6.1.1 Spread Mooring System Design Options

Previously, a preliminary mooring system sizing analysis was performed for catenary, taut, and semi-taut mooring system configurations across many anchoring radii and water depths up to 1,500 m (Cooperman et al. 2022). That analysis proposed trends for mooring system anchoring radii corresponding to different water depths. However, the water depths only went up to 1,500 m, leaving the majority of ultradeep water depths unexplored. We have now expanded on the previous study to include water depths up to 3,000 m for the three mooring system configurations, using some upgraded modeling assumptions. The costs of each mooring configuration were calculated using a similar design optimization process as Cooperman et al. (2022) that sized the line diameters and lengths to find the most cost-effective mooring system while meeting constraints. Since the results of the previous study, the mooring line type properties have been slightly updated (Hall et al. 2021), and the horizontal force on each mooring system design is taken to be the peak thrust force of the IEA Wind 15-MW wind turbine (Abbas et al. 2022) plus a steady current force based on extreme current conditions off of the U.S. west coast (Biglu et al. 2024), summing to 2.38 MN. The allowed mean offsets were limited to 100 m, as a reasonable value (sensitivity to this choice is explored later).

Figure 26 shows the results of the new analysis spanning water depths of 1,300 m to 3,000 m. Costs are indicated by the shading of the contour plots of Figure 26, where white space signifies that designs did not satisfy criteria. The mooring system costs include the material cost of the rope, the material cost of suction pile anchors, and assumed installation and decommissioning costs of each mooring line and anchor that come from industry recommendations (Hall et al. 2022). The white space in the contour plots signify combinations of parameters for which design criteria could not be satisfied by the optimization algorithm. These areas illustrate key feasibility challenges for certain mooring line materials in this depth range, subject to the selected design requirements.

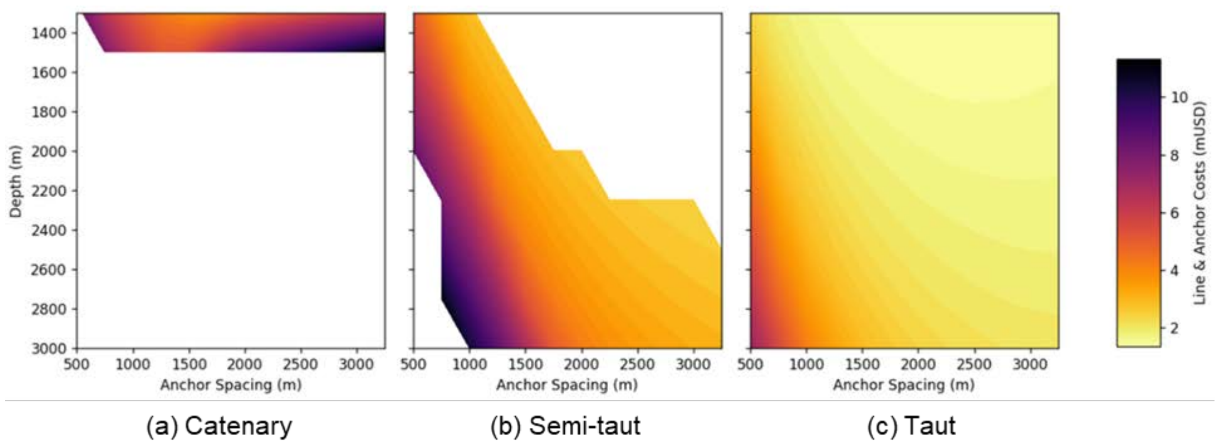


Figure 26. Mooring line and anchor costs as a function of ultradeep water depth and anchoring radius

Out of the three primary mooring system types—catenary, semi-taut, and taut—the taut mooring systems are able to satisfy design criteria across the widest range of ultradeep water depths and anchoring radii. The catenary configuration (Figure 26a) is modeled to consist of chain with a DEA, the semi-taut configuration (Figure 26b) is modeled to consist of chain and polyester rope and a DEA, and the taut configuration (Figure 26c) is modeled to consist of polyester rope and a suction pile. The catenary configuration is subject to constraints on the minimum amount of chain on the seabed and a maximum tension of the line. The semi-taut configuration is subject to constraints on the minimum amount of chain on the seabed, a minimum height of the rope off of the seabed, and maximum tensions of both mooring lines. The taut configuration is subject to a minimum height of the rope off of the seabed and a maximum tension of the line.

Each mooring system of Figure 26 is designed so that under this load, it has a mean displacement of 100 m from its equilibrium position, as well as an additional 10 m offset to account for extreme wave-induced motions, which is also in line with the previous work. This value of 110 m represents the maximum radius of the "watch circle," or the area in which the wind turbine can move on the water. However, for these mooring systems, this area is more triangular than circular due to the nonlinear restoring characteristics of the three mooring lines. Figure 27 gives a depiction of the watch circle area for an example taut polyester mooring system.

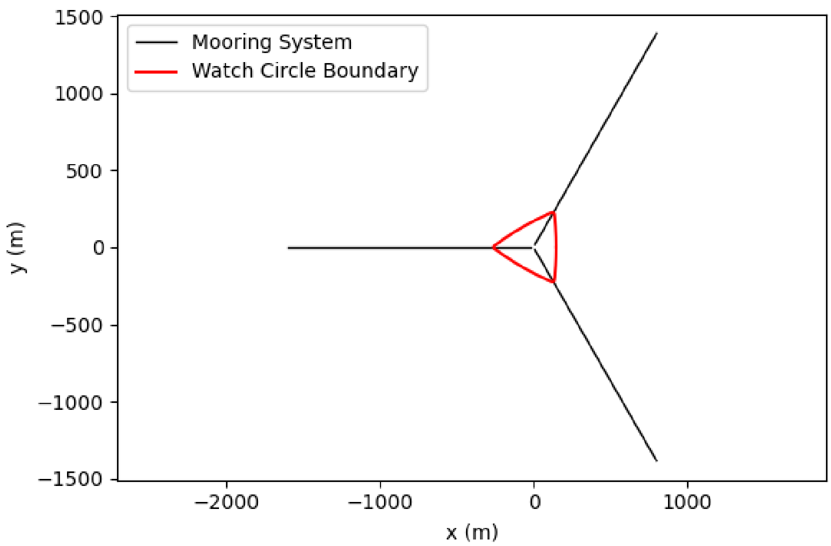


Figure 27. Watch circle area for an example taut polyester mooring system

When the wind turbine experiences loads coming from the negative *x*-axis of Figure 27, the primary mooring line to resist those loads is the one in line with the loading direction. However, when the wind turbine experiences loads coming from the positive *x*-axis of Figure 27, the loads are resisted by two mooring lines at 60° angles to the load. The one in-line mooring line provides greater resistance against the loads than the two 60° mooring lines, thus creating the triangular watch circle shape. The maximum watch circle radius of 110 m used in this study equates to the maximum distance from platform centerline to watch circle boundary.

Using these modeling techniques, we determined that the taut mooring system configuration is the most attractive for ultradeep water relative to other mooring configuration types (excluding TLPs). Referring back to Figure 26, no designs across the range of water depths or anchoring radii were infeasible for a taut design, whereas almost half of the semi-taut designs generated were infeasible, and almost all catenary designs were infeasible in ultradeep water. The high weight of chain in catenary mooring systems results in high tensions in the mooring line that cannot be alleviated by increasing chain diameter. The long chain segments of the semi-taut configurations had difficulty in meeting the lay length and tension requirements. This supports previous findings that DEAs (which would be used with catenary and some semi-taut mooring systems) are not suitable for ultradeep water. Higher anchoring radii may produce more feasible designs but would drastically increase mooring system footprints in ultradeep water, potentially limiting project capacities. Taut mooring systems could meet all design criteria and consist of much lighter mooring material, making them much more suitable for ultradeep water.

6.1.2 Taut Mooring System Designs

We developed a series of taut mooring system designs for the VolturnUS-S reference semisubmersible platform (Allen et al. 2020) with the IEA Wind 15-MW reference turbine (Gaertner et al. 2020) in water depths ranging from 1,300 to 3,000 m. For each water depth, we swept a range of anchoring radii and maximum allowable platform offsets to understand the design drivers for these types of systems and determine which designs could be used as reference designs. The diameter and length of each mooring line rope were sized using an optimization algorithm in the quasi-static modeling tool, MoorPy (Hall et al. 2021) to find the most cost-effective mooring system design within constraints, using the same process and assumptions as Figure 26c. To reduce computation time, these mooring line designs do not consider fatigue loading, neglect the small impact that chain would have on the upper and lower sections of the rope, and do not provide dimensions or capacities of anchors. They are based on quasi-static analysis of an extreme load condition.

The following sections showcase the design sweeps for three different line types: polyester, nylon, and HMPE. The mooring line costs and diameters for each rope are plotted as contour maps over the range of water depths, anchoring radii, and maximum offsets.

Two different lines are plotted on top of the contour maps to relate anchor spacing to water depth: one that is along the anchor spacing relation that gives the lowest-cost designs for each water depth (dashed black line), and one that follows a anchoring angle of 55°, which was chosen in a previous study (Cooperman et al. 2022) to give a good trade-off between cost and footprint. Theoretically, the ideal set of anchoring radii as a function of water depth could combine the objectives of minimizing cost, minimizing mooring system footprint, or minimizing line diameter based on manufacturing constraints. However, we determined that the 55° line from the previous study still provided a lower mooring system footprint without increasing mooring system cost significantly and would continue to be used for the taut mooring designs in ultradeep water.

Polyester

Figure 28 and Figure 29 show contour plots of mooring system cost and polyester line diameter, respectively, over the range of water depths and anchoring radii for various maximum offset limits. The least-cost and 55° lines are superimposed on each contour. The white space indicates water depth and anchoring radius values for which the model could not find design parameters that satisfied all design criteria.

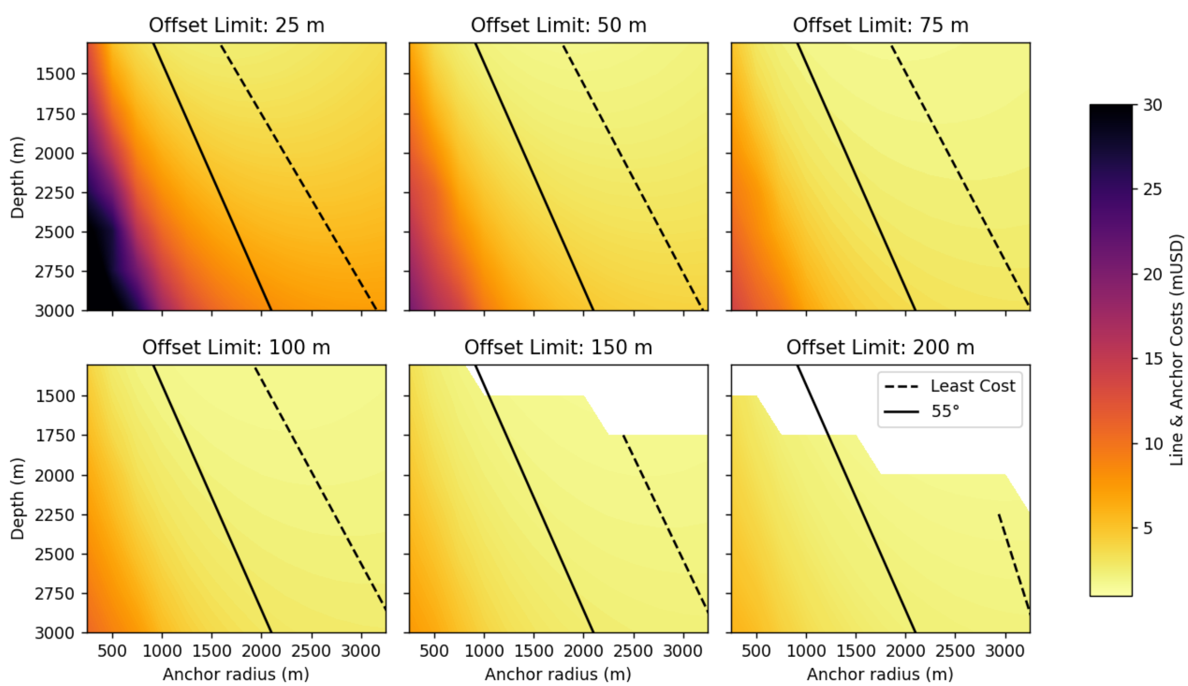


Figure 28. Polyester taut mooring system costs

In general, the costs for one polyester mooring line and anchor are within the range of $2–$6 million over most water depths and anchoring radii. Only at large water depths, small anchoring radii, and small offset limits do the costs significantly increase. As the maximum offset limit increases, the number of feasible designs over the range of water depths and anchoring radii decreases. This makes sense in that a design with larger lateral offsets produces higher tensions on the mooring line, which makes the maximum tension constraint harder to satisfy. To increase the minimum breaking load (MBL) of the line to help satisfy the maximum tension constraint, the optimizer increases the diameter of the mooring line. However, increasing the diameter of the polyester rope also increases its weight, which makes the line more susceptible to contacting the seabed. These two constraints conflict with each other for taut designs, especially at higher offset limits.

Additionally, as the maximum allowable offset increases, only the steeper mooring lines satisfy design criteria. This is likely because these steeper mooring configurations are much less susceptible to the rope contacting the seabed and can increase line diameter to meet the maximum tension requirements. More horizontal mooring system configurations are much more susceptible to seabed rope contact. However, these results and findings show that there could be potential to designing taut mooring systems with much lower mooring system footprints and larger offsets, as long as power cable designs are not as affected by these offsets, and other fishing or navigation constraints are considered.

The diameters of the taut polyester designs show similar trends as the cost results in that higher diameters are required for steeper designs with lower offset limits. However, they are still comparable at the larger offset limits. The blue lines in Figure 29 represent line diameters of 300 mm, where any designs to the left of this line require larger diameter rope than is currently manufactured. Most mooring line designs for offset limits above 25 m use diameters less than 300 mm, which are expected to be attainable.

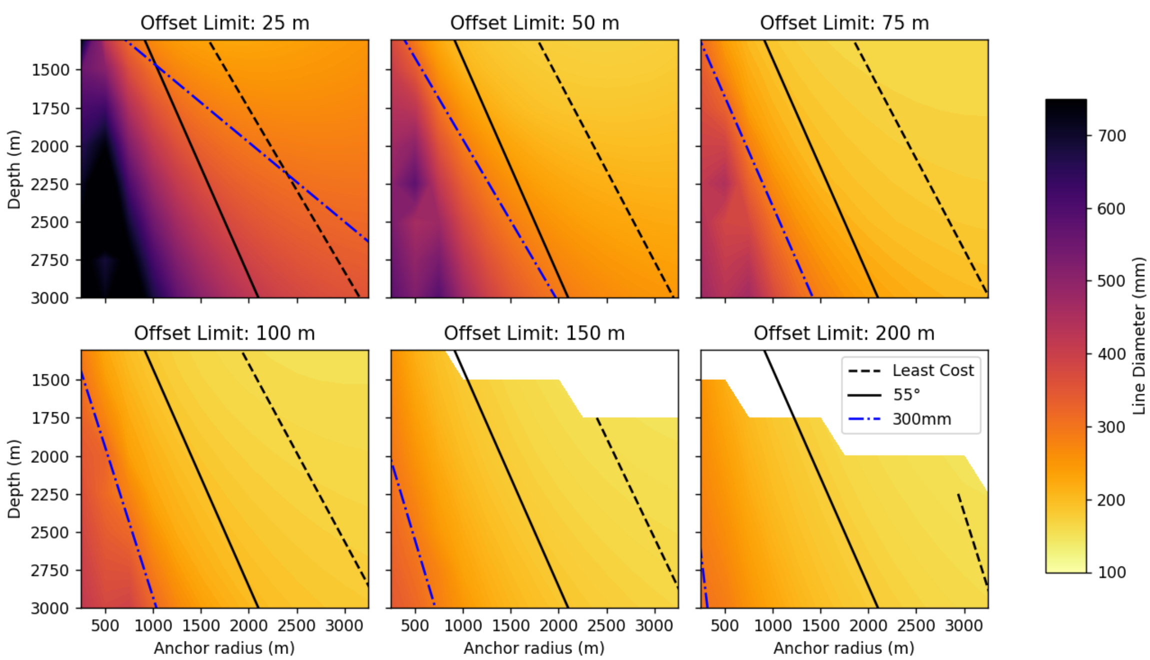


Figure 29. Polyester taut mooring system diameters

From these contour plots, we selected combinations of water depth, anchoring radius, and maximum offset limits to be reference taut designs to use in continuing ultradeep water studies. These designs are tabulated in Table 15. The solid black line used to represent mooring system designs that have a 55° anchoring angle was selected for the reference designs to balance objectives like cost, footprint, and diameter, which kept consistent with the results of previous studies. A balance between larger offset limits to minimize cost and smaller offset limits to avoid potential power cable, fishing, or navigational conflicts was made to select the reference design offset limits. The offset limit chosen to balance these factors was 100 m. The polyester rope diameters, lengths, and single-line pretensions along the 55° line at an offset limit of 100 m are tabulated in Table 15.

Table 15. Reference Taut Polyester Mooring System Designs With a Mean Offset of 100 m and Anchoring Angle of 55°

Water Depth (m)	Anchoring Radius (m)	Polyester Diameter (mm)	Polyester Length (m)	Polyester Pretension (kN)
1,300	910	186.5	1,539.7	808
1,400	980	185.3	1,656.4	1,045
1,500	1,050	184.8	1,774.0	1,286
1,600	1,120	185.9	1,895.0	1,478
1,700	1,190	186.3	2,012.7	1,638
1,800	1,260	186.7	2,130.0	1,767
1,900	1,330	188.2	2,251.1	1,912
2,000	1,400	189.3	2,369.3	2,034
2,100	1,470	190.2	2,488.2	2,139
2,200	1,540	191.3	2,607.2	2,244
2,300	1,610	192.6	2,727.1	2,357
2,400	1,680	193.6	2,846.1	2,458
2,500	1,750	194.4	2,963.0	2,538
2,600	1,820	195.9	3,084.0	2,660
2,700	1,890	197.2	3,203.0	2,763
2,800	1,960	198.5	3,321.2	2,863
2,900	2,030	199.8	3,439.8	2,982
3,000	2,100	201.3	3,558.7	3,094

The polyester diameters for each design are all between values of 184 and 202 mm, which are well within manufacturing capacities. The design at a water depth of 1,500 m had the lowest polyester diameter, despite not being the shallowest design. The deepest design does have the largest polyester diameter. Polyester lengths are generally proportional to the water depth and anchoring radius.

Nylon

Figure 30 and Figure 31 show contour plots of mooring system cost and nylon diameter, respectively, over the range of water depths and anchoring radii for various maximum offset limits. The least-cost line and 55° line can be seen over top of each contour.

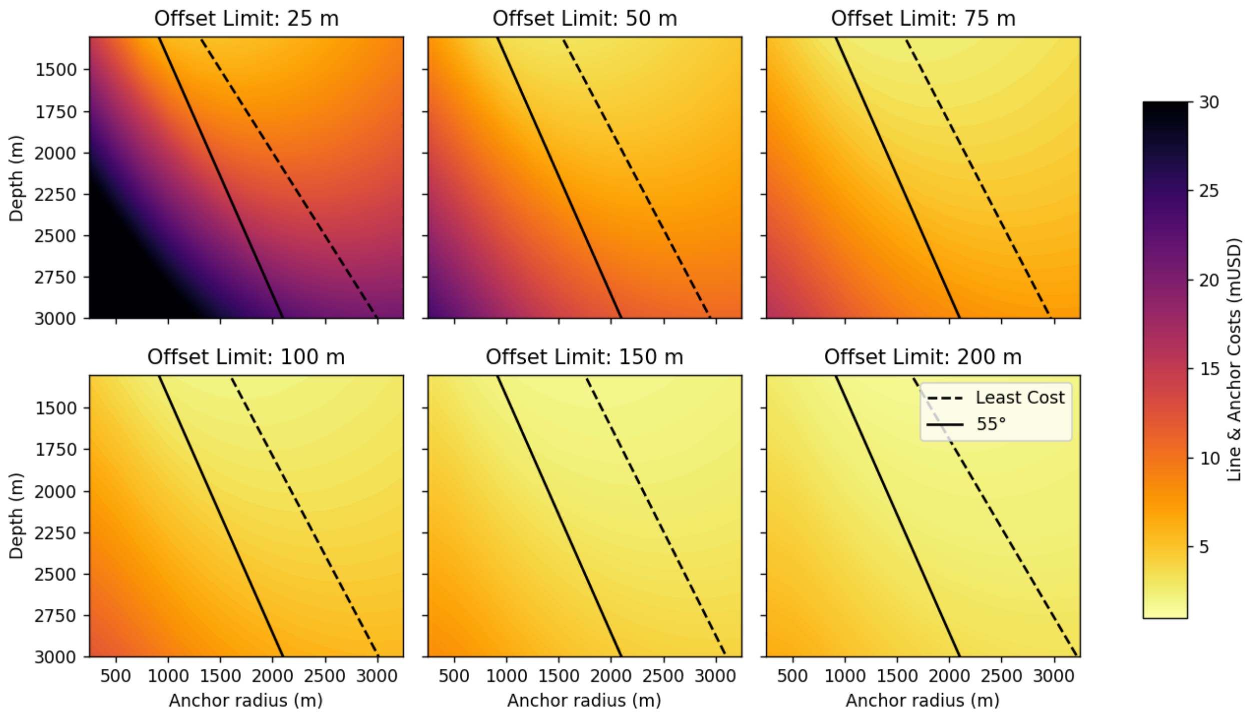


Figure 30. Nylon taut mooring system costs

The costs for a nylon mooring line and an anchor are slightly more expensive than polyester. For most water depths and anchoring radii, costs are \$3–\$7 million. Deeper water depths, small anchoring radii, and small offsets produce significantly more expensive designs. This is likely due to the lower stiffness (or higher compliance) of nylon material compared to polyester material in that larger diameters are needed to increase the MBL of the line to satisfy maximum tension constraints. The costs are also similar among the larger maximum offsets, showing that there are likely negligible cost savings in increasing the allowable offset.

All design points over the range of water depths, anchoring radii, and allowable offsets met constraints, likely because the lower stiffness of nylon produced smaller tensions in the line, making the maximum tension constraint easier to satisfy without the rope contacting the seabed.

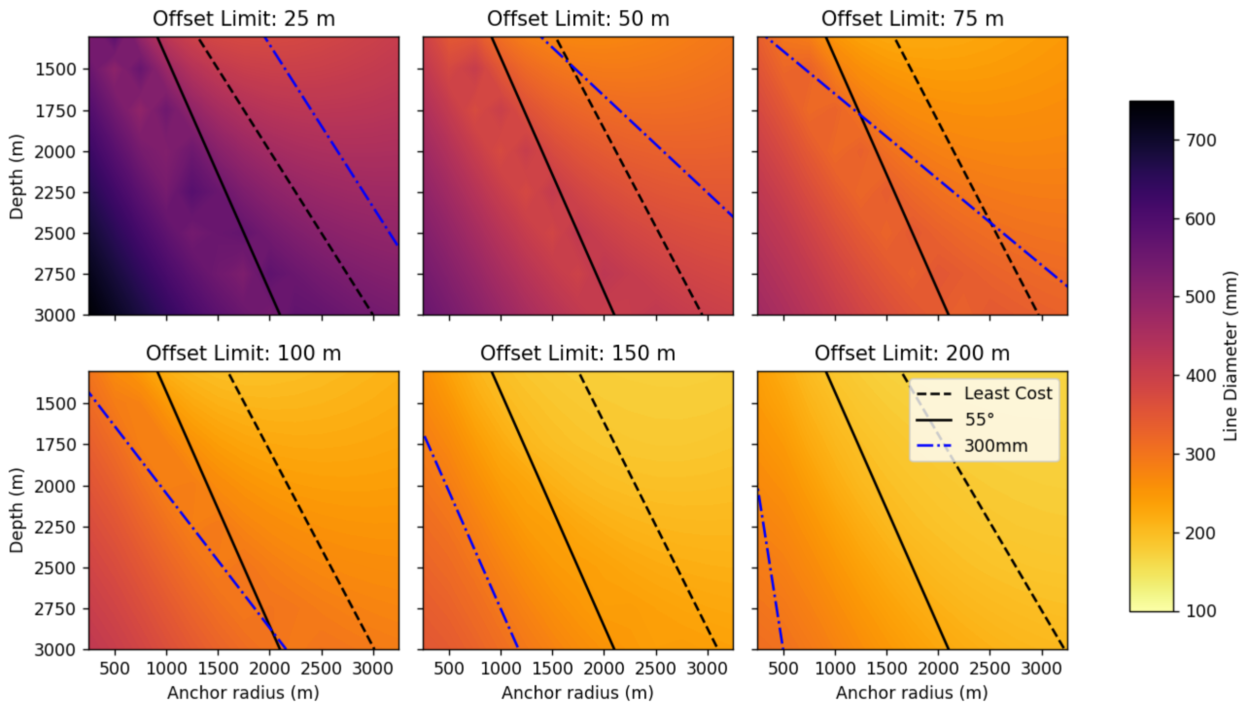


Figure 31. Nylon taut mooring system diameters

Similar to polyester, the diameters of the taut nylon ropes are larger for steeper designs with lower offset limits. Diameters at larger offsets continue to be comparable, again showing that there likely are not any cost or diameter savings at larger offsets. The required diameters are greater than the required diameters of polyester and can be up to 500–600 mm at a maximum offset of 25 m. For most designs though, the diameters are in the range of 200 to 350 mm. These diameters are larger because the optimizer can find larger nylon diameters to satisfy the maximum tension constraint without violating the seabed contact constraint in more water depth and anchoring radius combinations. The blue lines in Figure 31 represent line diameters of 300 mm, where any designs to the left of this line require larger diameter rope than is currently manufactured. Relative to smaller-diameter polyester, the larger diameters of nylon ropes may be more difficult to manufacture, but designs with larger allowable offsets are still expected to be attainable.

From these contour plots, we selected combinations of water depth, anchoring radius, and maximum offset limits to be reference taut designs to use in continuing ultradeep water studies. These designs are tabulated in Table 16. The solid black line used to represent mooring system designs that have a 55° anchoring angle was selected for the reference designs to balance objectives like cost, footprint, and diameter, which stay consistent with the results of previous studies. A balance between larger offset limits to minimize cost and smaller offset limits to avoid potential power cable, fishing, or navigational conflicts was made to select the reference design offset limits. These anchoring radii and offset limit amounts were taken to be the same as polyester for easier comparison. The nylon rope diameters and lengths along the 55° line at an offset limit of 100 m are tabulated in Table 16.

Table 16. Reference Taut Nylon Mooring System Designs With a Mean Offset of 100 m and Anchoring Angle of 55°

Water Depth (m)	Anchoring Radius (m)	Nylon Diameter (mm)	Nylon Length (m)	Nylon Pretension (MN)
1,300	910	224.7	1,490.0	2,507
1,400	980	231.7	1,608.8	2,557
1,500	1,050	240.0	1,729.3	2,612
1,600	1,120	248.3	1,851.2	2,739
1,700	1,190	255.1	1,970.3	2,814
1,800	1,260	260.9	2,088.5	2,893
1,900	1,330	268.4	2,209.9	3,034
2,000	1,400	274.8	2,328.9	3,132
2,100	1,470	278.4	2,442.0	3,474
2,200	1,540	285.7	2,564.7	3,455
2,300	1,610	287.9	2,670.9	4,085
2,400	1,680	290.8	2,780.5	4,552
2,500	1,750	299.7	2,911.3	4,160
2,600	1,820	296.2	2,993.0	5,635
2,700	1,890	296.9	3,091.4	6,460
2,800	1,960	300.3	3,199.7	6,892
2,900	2,030	299.7	3,287.5	7,948
3,000	2,100	296.9	3,360.3	9,422

The nylon diameters at each depth are larger than the diameters of the polyester designs, with values between 224 and 297 mm, which can still be considered within manufacturing capacities. The designs had increasing nylon diameters with increasing water depth, but only up to 2,500 m. Designs between 2,500 and 3,000 m had similar diameters. Nylon lengths scaled proportionally to the water depth and anchoring radius.

HMPE

Figure 32 and Figure 33 show the contour plots of mooring system cost and HMPE diameter, respectively, over the range of water depths and anchoring radii for various maximum offset limits. The least-cost line and 55° line can be seen over top of each contour.

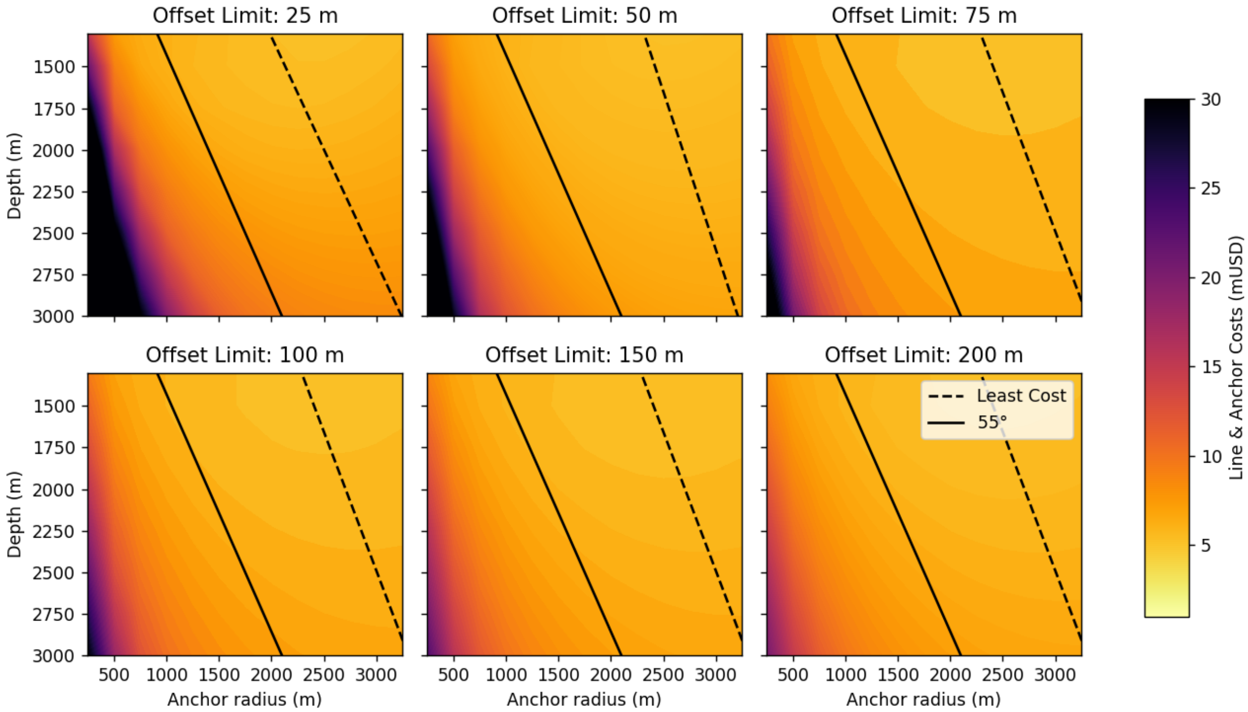


Figure 32. HMPE taut mooring system costs

An HMPE mooring line with an anchor is much more expensive than polyester or nylon. For most water depths and anchoring radii, costs are \$5–\$8 million. Deeper water depths, small anchoring radii, and small offsets produce significantly more expensive designs. HMPE is a much stiffer material than polyester or nylon and is buoyant in water. This means that the seabed contact constraint is rarely violated and the optimizer increases diameter to increase the MBL of the line to satisfy the maximum tension constraint. The stiffer material produces much higher tensions, which require larger diameters for increased MBL. The cost of HMPE is also assumed to be nearly an order of magnitude greater than polyester or nylon, hence the larger costs over the same water depths and anchoring radii. The costs are also similar among the larger maximum offsets, showing that there are likely negligible cost savings in increasing the allowable offset. The least-cost curves show little variation in the least-cost anchoring radius for each depth among the different offsets.

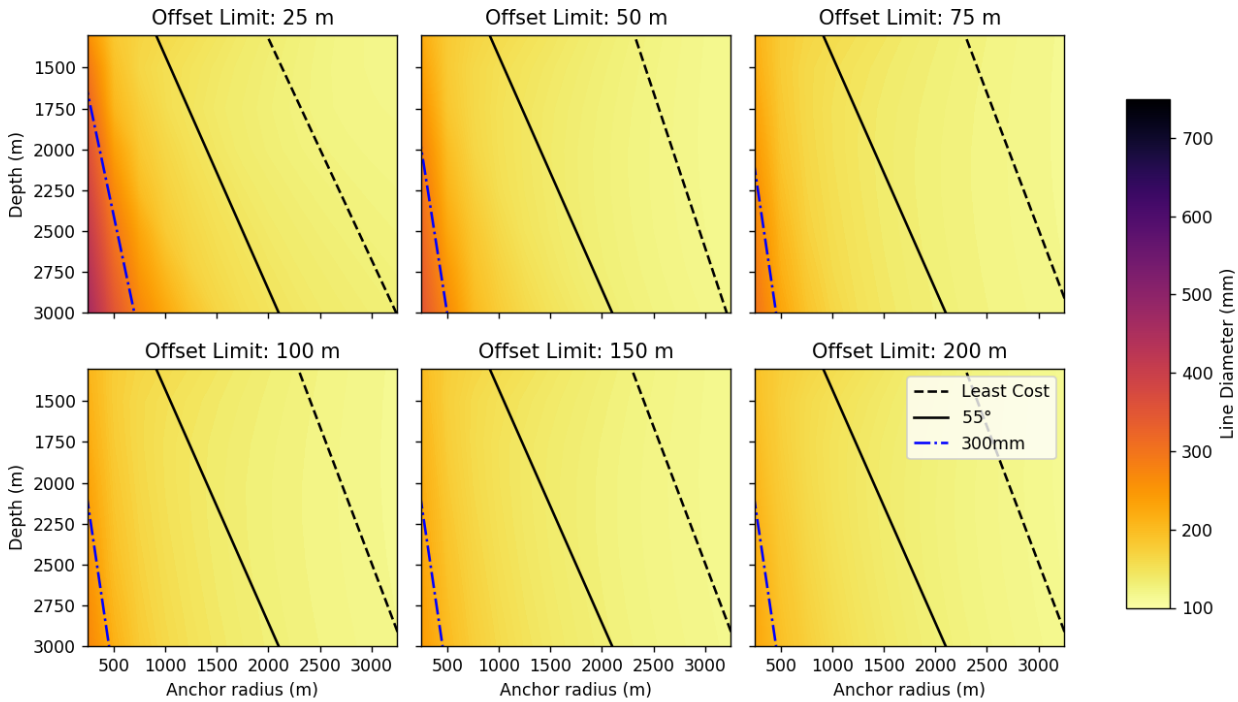


Figure 33. HMPE taut mooring system diameters

For nearly all depths and anchoring radii, HMPE line diameters could be kept below 150 mm. The minimum diameter seen across these scenarios is 114 mm. The changes in diameter show similar trends as the costs, as well as similar trends in the diameters of polyester and nylon. Again, there are few cost or diameter savings at larger offsets. Due to the significantly larger stiffness of HMPE, small changes in diameter result in large changes in MBL and tension, so to satisfy the maximum tension constraint in each design, the diameter does not need to change drastically. The blue lines of Figure 33 represent line diameters of 300 mm, but the HMPE diameters are not close to this potential rope manufacturing limit. HMPE rope construction for offshore structures is in a relatively nascent stage, so the limits on manufacturability are uncertain.

From these contour plots, we selected combinations of water depth, anchoring radius, and maximum offset limits to be reference taut designs to use in continuing ultradeep water studies. These designs are tabulated in Table 17. The anchoring radii and offset limit amounts across each water depth were taken to be the same as polyester and nylon for easier comparison. The HMPE rope diameters, lengths, and single-line pretensions along the 55° line at an offset limit of 100 m are tabulated in Table 17.

Table 17. Reference Taut HMPE Mooring System Designs With a Mean Offset of 100 m and Anchoring Angle of 55°

Water Depth (m)	Anchor Radius (m)	HMPE Diameter (mm)	HMPE Length (m)	HMPE Pretension (kN)
1,300	910	161.0	1,571.5	6.0
1,400	980	156.2	1,690.9	6.6
1,500	1,050	151.6	1,811.2	7.2
1,600	1,120	148.8	1,934.4	8.0
1,700	1,190	145.9	2,054.2	8.8
1,800	1,260	143.4	2,173.6	9.7
1,900	1,330	141.5	2,296.5	10.8
2,000	1,400	139.6	2,416.6	11.8
2,100	1,470	138.1	2,537.4	13.1
2,200	1,540	136.7	2,658.2	14.4
2,300	1,610	135.5	2,779.9	16.0
2,400	1,680	134.4	2,900.9	17.7
2,500	1,750	133.2	3,019.6	19.3
2,600	1,820	132.5	3,142.7	21.8
2,700	1,890	131.7	3,263.7	24.2
2,800	1,960	130.9	3,383.9	27.2
2,900	2,030	130.2	3,505.0	30.7
3,000	2,100	129.6	3,626.0	34.0

The HMPE diameters for each design are smaller than the diameters of the polyester or nylon designs. They all steadily decrease as water depth increases. HMPE lengths scaled proportionally to the water depth and anchoring radius.

6.2 Tension-Leg Platform Design Study

The defining characteristic of TLPs is their reliance on highly tensioned tendons that extend vertically from the substructure to the seabed and provide both stationkeeping and hydrostatic stability to the floating platform. TLPs were originally used in the oil and gas industry to minimize vertical motions of the floating platform. The concept has been applied to floating offshore wind platforms but has not been used in as many demonstration projects as other floating wind support structure types (Edwards et al. 2023). The vertical tendons provide a low mooring system seabed footprint, but the highly tensioned tendons and their anchors typically cost more than other mooring system types and are a more critical failure point because they provide platform stability. Additionally, because the tendons provide the primary source of stability (rather than ballast or buoyancy), typical TLP substructures are not naturally hydrostatically stable before they are moored, resulting in more difficult installation processes than other substructure types.

In ultradeep water, the key challenge with TLPs is that the water depth will entail very long tendons, and these lengths will make it difficult to achieve the necessary stiffness. According to conventional TLP design logic, a certain tendon stiffness is required to keep the platform's heave, pitch, and roll natural frequencies above the wave frequency range. Because the tendon stiffness scales with the inverse of the tendon length, especially stiff tendon materials or large tendon diameters are required. The following design study explores this tendon stiffness challenge while also accounting for other design changes that may be required as a result.

6.2.1 TLP Configuration Selection and Study Approach

Many TLP substructure concepts have been proposed for floating offshore wind, and developers have not yet converged on a preferred configuration. This work is intended to provide TLP support structure designs that can be easily used for ultradeep studies. As such, the TLP designs should be representative of the realistic and available TLP design shapes. Based on an inventory of all TLP design shapes used in previous studies and ones that are currently being developed or are deployed, we selected a representative TLP configuration with the following main characteristics:

- One central column
- Three cylindrical horizontal pontoons extending radially from the column to the tendons
- Two tendons at the end of each pontoon to provide redundancy.

To make the platform design more structurally feasible for the ultradeep scenarios considered, we also added three angled braces between the central column and the pontoons, and three vertical "cans" at the end of each pontoon (Figure 34). The pontoons provide buoyancy to the substructure as well as a proper moment arm to the mooring tendons to counteract environmental loads. The angled members primarily provide structural support to the pontoons to meet bending criteria. The end cans provide buoyancy at a location that directly resists the tendon tensions, reducing bending loads on the pontoons. They also help with hydrostatic stability when the tendons are not attached, allowing the platform to have a stable at-port and tow-out configuration with a reduced draft, simplifying assembly and installation processes.

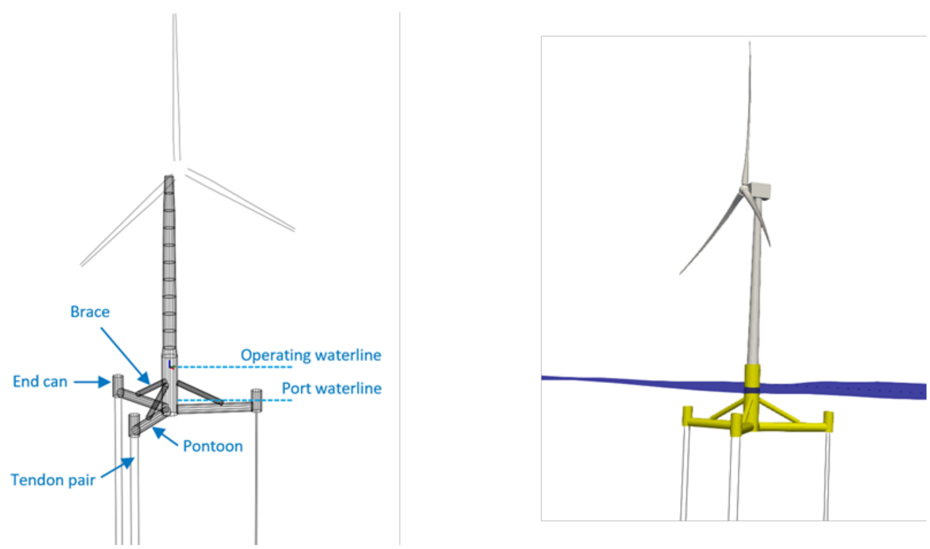


Figure 34. Selected TLP topology for reference design

Illustration by NREL

The mooring system tendons for this TLP were carefully chosen to provide a representative mooring system using available tendon materials. Six tendons were chosen (two connected to each pontoon) to distribute loads over a higher number of tendons and to add redundancy to ensure survivability in case one tendon fails. There is no ballast in the system, and the mooring tendons are assumed to extend straight down to the seabed from their fairlead positions. A pair of mooring tendons attach at the bottom of each end can, on opposite sides of the pontoon (Figure 35).

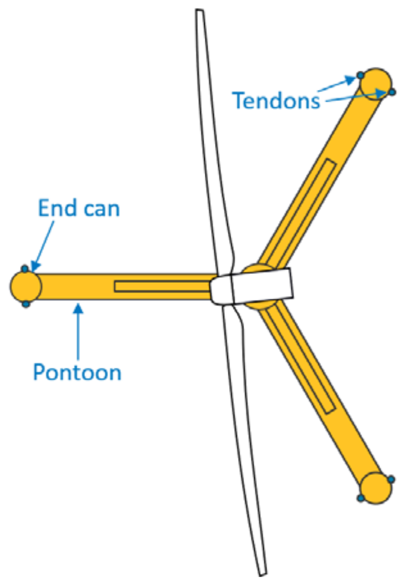


Figure 35. Top view of TLP showing tendon positions

Illustration by NREL

Previous TLP designs have used a number of tendon types. We investigated many different mooring tendon materials: studless chain, polyester, nylon, wire, HMPE, liquid-crystal polymer, carbon fiber, and steel pipe. After analyzing water depths in the range of 1,300–3,000 m, we found that conventional mooring material types like chain, polyester, and nylon could not be sized with the substructure to satisfy design criteria. Chain is not strong enough for its weight in these depths. Polyester and nylon do not provide enough stiffness. The remaining mooring materials produced working designs. With information gathered from more developed TLP concepts in industry, we determined that a mooring system consisting of HMPE mooring tendons would be the most representative and adaptable for ultradeep water, while minimizing overall material cost. HMPE is already in use for moorings, while the conventional option of steel pipe was identified as difficult to install for high-quantity floating wind applications.

Anchors were not considered as part of the design process because we do not expect them to have a significant effect on the other system parameters or on system cost trends. Anchor types such as driven piles or torpedo anchors that are able to resist vertical loads well would be the most suitable, but their specific design parameters are not included in this study.

To create suitable TLP design dimensions, we applied a sizing and optimization process using the RAFT model and explored the effects of a wide range of platform and tendon dimensions. The turbine used is the IEA Wind 15-MW reference wind turbine, which is described in Gaertner et al. (2020). Our design procedure aims to minimize the structure's steel mass (as a proxy for cost) while adhering to the following requirements:

- General hydrostatic stability, buoyancy, and pitch angle requirements
- Surge, sway, and yaw natural periods of greater than 25 s (to avoid wave frequencies)
- Heave, roll, and pitch natural periods less than 4 s (to avoid wave frequencies)
- Surge offsets less than 10% of water depth
- Tendon tensions stay between 100 kN and half of their minimum breaking load (safety factor of 2)
- Pontoon bending loads and deflections stay within safe values (safety factor of 2).

Among these constraints, the requirements for low natural periods and the structural constraints on the pontoon bending were the most dominant, requiring stiffer tendons and thicker pontoon structures, respectively. Platform pitch angles and surge offsets stayed well within the limits.

After exploring many design variations, we identified some design dimensions for which constant values are approximately optimal over the whole depth range, and we identified other parameters that should vary with depth. We then ran an optimization on those remaining parameters at each 100-m increment in water depth to create a series of TLP designs that cover the ultradeep water depth range. We detail those parameters and the resulting design characteristics next.

6.2.2 TLP Design Results

The TLP designs we generated over the range of ultradeep water depths involve three design parameters that are optimized as a function of depth:

- Tendon/anchoring radius: The distance of the tendons from the platform centerline has a large impact on the system's pitch stiffness.
- Pontoon wall thickness: The structural thickness of the pontoon members determines their strength to resist bending loads, which can change significantly over depth.
- Tendon diameter: The diameter of each tendon determines the tendon's strength and stiffness, and stiffness requirements change significantly with tendon length.

The number of pontoons (three), tendons (six), and all other platform geometric properties remain constant. The only other varied parameter is the tendon unstretched length; this is tuned automatically so that the platform sits at the intended height in the water. The platform and mooring characteristics that are set as constants, independent of depth, are tabulated in Table 18.

Table 18. Depth-Independent Platform and Mooring Tendon Parameters

Depth-Independent Parameter	Value
Freeboard (m)	15.0
Draft (m)	36.0
Column Diameter (m)	12.0
Column Thickness (mm)	50
Pontoon Diameter (m)	7.0
Angled Member Diameter (m)	4.0
Angled Member Length (m)	38.0
Angled Member Thickness (mm)	50
End Can Diameter (m)	8.0
End Can Length (m)	16.0
End Can Thickness (mm)	50

Each of these values were chosen following design exploration and optimization processes based on practical values aligned with minimizing the structural cost. The transition piece where the tower base begins is set at 15 m above the water surface—a standard value for the 15-MW reference turbine. The draft is set at 36 m, which is a compromise between stability in operating conditions and stability in a shallow-drafted port configuration. The center column diameter was set at 12 m to provide a slight increase relative to the tower diameter. The pontoon diameter was set at 7 m, which is large enough to provide enough strength for the tendon tensions, while avoiding excessive volume that would make it harder to maintain system natural frequencies in heave and pitch. The pontoon lengths and wall thicknesses varied with water depth. The angled brace members stay consistent over all depths. They attach along the tops of the pontoons at a distance of 40 m from the platform centerline, and on the side of the central column at 12 m below the waterline. The bottoms of the cans are at the same depth as the bottom of the central column, as well as the lowest depth of each pontoon, providing a flat bottom for ease of assembly and installation.

The platform and mooring characteristics that change over depth based on optimization results are tabulated in Table 19.

Table 19. Depth-Dependent Platform and Mooring Tendon Parameters

Water Depth (m)	Tendon and Anchoring Radius (m)	Pontoon Thickness (mm)	Tendon Diameter (mm)	Tendon Length (m)	Tendon Pretension (MN)
1,300	65.8	92	551	1,263	12.92
1,400	67.8	98	560	1,363	13.24
1,500	70.2	105	567	1,463	13.33
1,600	72.3	111	575	1,563	13.43
1,700	74.3	117	583	1,663	13.49
1,800	75.9	122	592	1,763	13.47
1,900	77.6	127	600	1,863	13.44
2,000	78.6	128	611	1,963	13.39
2,100	78.3	128	624	2,063	13.32
2,200	78.3	128	636	2,163	13.23
2,300	78.3	128	648	2,263	13.14
2,400	78.5	129	659	2,363	13.03
2,500	78.2	128	672	2,463	12.94
2,600	78.3	128	683	2,563	12.78
2,700	78.3	128	693	2,663	12.70
2,800	78.7	130	704	2,763	12.67
2,900	78.6	130	714	2,863	12.64
3,000	78.6	130	724	2,963	12.63

Considering the dimensions as a function of water depth, the overall tendon/anchoring radius and the pontoon wall thickness appear to stop increasing at depths greater than 2,000 m. Beyond these depths, while the platform dimensions stay constant and the tendon tensions also remain constant, the tendon diameter continues to increase. These values were varied to minimize the cost of each platform and mooring system while satisfying various design constraints, such as maximum heave and pitch natural periods, maximum and minimum mooring tendon tensions, maximum surge and pitch offsets, tower base bending moments, and nacelle accelerations.

The design parameters that changed between the shallowest and deepest TLP designs were tendon/anchoring radii, pontoon wall thicknesses, and the tendon diameters. The shallowest TLP design had tendon/anchoring radius of 65.8 m, a pontoon wall thickness of 92 mm, and a mooring tendon diameter of 551 mm. The deepest TLP design had a tendon/anchoring radius of 78.6 m, a pontoon wall thickness of 130 mm, and a mooring tendon diameter of 724 mm. Longer and thicker pontoons coupled with thicker mooring tendons are required to meet the heave and pitch natural frequency constraints for TLP designs in deeper waters.

The tendon diameters are significantly larger than currently manufactured rope sizes. The dominant driver of these tendon diameters is the minimum natural frequency constraints for platform heave and pitch motions, which conventionally are kept higher than the wave frequencies. The long tendon lengths require a large cross section to achieve the necessary stiffnesses for meeting these constraints. While the tendon stiffness is at the limit at these diameters, the tendon axial strength is many times greater than required. Accordingly, tendon materials that are stiffer could allow for smaller diameters and less material use. Significantly stiffer materials that are also lightweight, affordable, and easy to install are not yet commercially established. However, research and development in high-stiffness tendons for offshore applications are ongoing and could result in new commercially viable options in the years ahead. There is also potential to reduce tendon diameters by relaxing the natural frequency constraints and allowing more motions in heave and pitch. This deviation from typical TLP design assumptions could enable significantly smaller tendon diameters, but the technical feasibility and implications require additional study.

The characteristics of the TLP reference designs are generally similar to existing designs except for the tendon diameters. The platform topology uses already established elements and its dimensions are on the same order as TLP designs for shallower water depths. The identified tendon diameters, while much larger than current commercial rope sizes, are necessary to satisfy the design constraints we used, which are in alignment with floating wind TLP studies in the literature. There are few if any technical barriers to producing tendons at this scale. If these diameters were too large to manufacture, a larger number of smaller-diameter tendons could be used instead. Regardless, the commercial viability of this quantity of tendon material in terms of cost, supply chain, and installation vessel capacities could be a concern. This is an area warranting further techno-economic analysis.

6.2.3 TLP Design Dynamic Response and Verification

We analyzed aspects of the shallowest and deepest TLP designs in the OpenFAST simulation tool (discussed in Section 5) to verify that the performance predictions by the RAFT-based design approach were representative. The philosophy of this verification is to spot-check specific quantities of interest, which allows for modeling oversights to be identified and corrected. We show selected results from the final iteration of this verification process to demonstrate that the designs are within reasonable tolerances for the sake of this design study.

We first verified the natural periods of floating platform motions computed with RAFT against the natural periods obtained from OpenFAST numerical decay tests in calm water with no wind. Table 20 summarizes the resulting natural periods. There are moderate differences in the predicted natural periods that could arise from differences such as tower flexibility and hydrodynamic assumptions between the models, but these differences are small enough for the sake of verifying the general sizing approach. The natural periods of sway and roll are omitted because they are similar to the natural periods of surge and pitch, respectively, due to platform symmetry.

Table 20. Natural Periods Estimated by RAFT versus OpenFAST

	1,300-m water depth			3,000-m water depth		
	RAFT (s)	OpenFAST (s)	Diff. (%)	RAFT (s)	OpenFAST (s)	Diff (%)
Surge	104.6	109.4	-4%	175.5	195.1	-10%
Heave	2.81	2.88	-2%	3.42	3.62	-6%
Pitch	3.38	4.15	-19%	3.38	4.35	-22%
Yaw	62.9	68.2	-8%	106.4	131.8	-19%

We then performed RAFT and OpenFAST simulations for DLC 1.6 considering two different platform orientations with respect to the wind, wave, and current directions (which are aligned for DLC 1.6). In the upwind configuration, one pontoon faces into the wind, resulting in the largest loads on the pontoon and its tendons. In the downwind configuration, one pontoon is oriented downwind, resulting in the lowest loads on its tendons. It is important to check whether the tendons become slack in this less loaded orientation. These two orientations are illustrated in Figure 36.

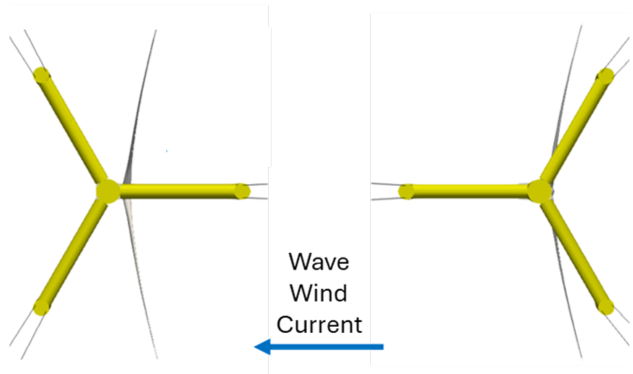


Figure 36. Platform configurations with the pontoon aligned with the wave, wind, and current in an upwind (left) and downwind (right) orientation, viewing from below

Illustration by NREL

Figure 37 presents the main statistics (mean, standard deviation, minimum, and maximum) for some quantities of interest computed with RAFT for water depths ranging from 1,300 m to 3,000 m. The results show that the mean surge displacement increases almost linearly with water depth, a consequence of reducing the surge stiffness due to the mooring system as the tendons get longer. Due to the large heave-surge coupling induced by the mooring system, the mean heave displacement also increases with water depth. The means of the other quantities of interest and the standard deviations of all quantities of interest are not significantly affected by water depth.

Figure 37 also includes the statistics computed from OpenFAST simulations (for a single wave and wind seed) for the 1,300-m and 3,000-m designs, showing a good general agreement with the RAFT results for the same water depths. From these results, the TLP system's performance is reasonable. The system has a mean pitch of 0.1° in both propagation directions, which is beneficial for power production and tower loads (smaller bending moment due to tower and RNA weight). The minimum tendon tensions are 8.76 MN or higher, meaning that the tendons do not become slack. All other simulation statistics are within reasonable values.

The OpenFAST results of the 1,300-m and 3,000-m designs give confidence that the adjusted designs through 3,000-m water depth will also behave as expected based on the lower-fidelity design tools they were developed with. Notably, all of these designs have offsets that are less than 125 m. These small watch circles demonstrate that TLPs benefit from very compact spatial footprints, even in ultradeep water.

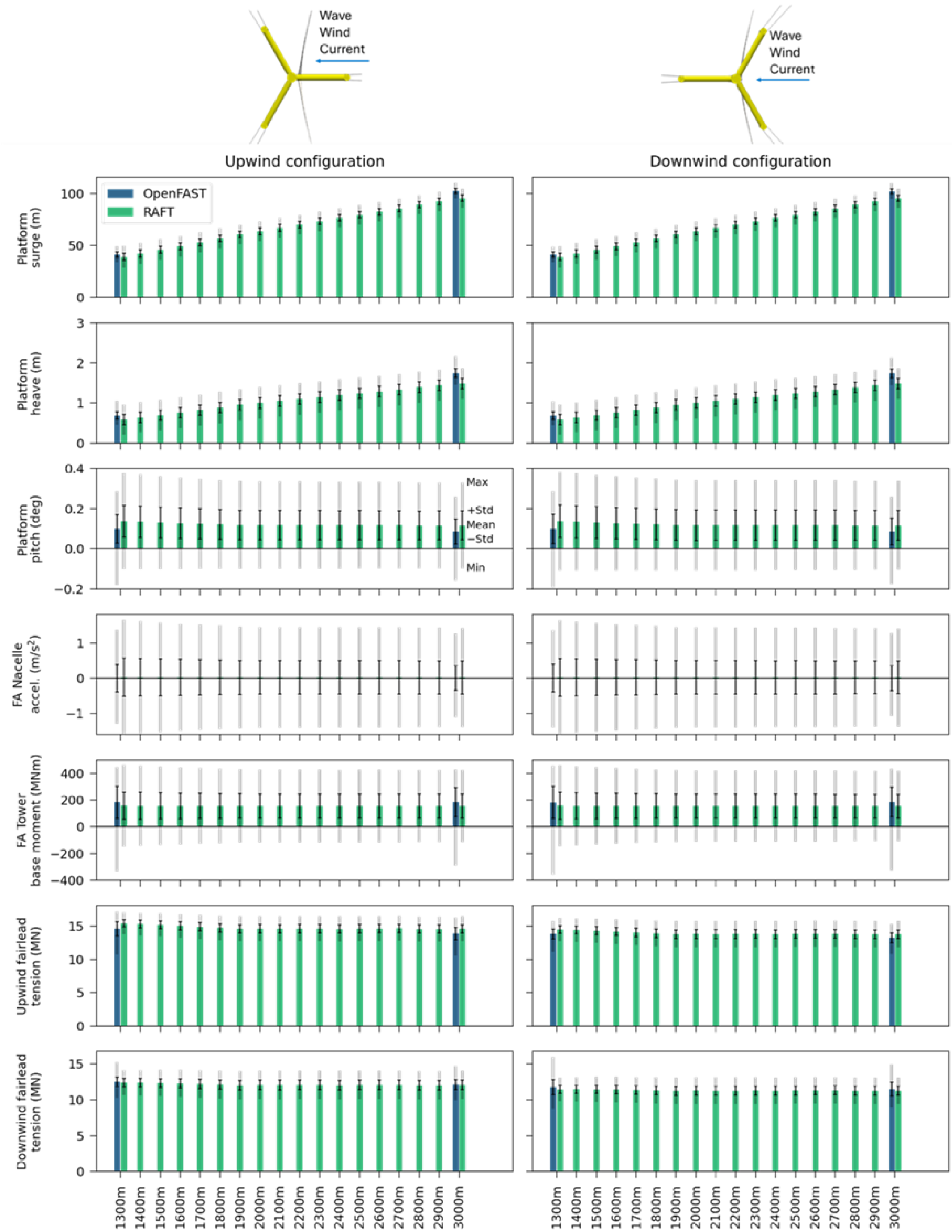


Figure 37. Statistics of main quantities of interest obtained with RAFT and OpenFAST for DLC 1.6 for two different pontoon alignments with respect to the waves, wind, and current

6.3 Conclusions

The designs developed for a TLP and a taut moored semisubmersible over ultradeep water depths demonstrate the feasibility of both support structure approaches at these depths. They also provide quantification of preliminary reasonable characteristics of such designs. The TLP reference design shows that TLPs can function in these depths with existing well-established rope materials (albeit very large tendon diameters) and reasonable platform sizes. The results with taut moorings show that many combinations of anchoring radius, allowable offset, and line type can produce workable mooring system designs for semisubmersibles in ultradeep water. For both support structure types, these technically viable examples provide a starting point that can then enable deeper analysis of aspects such as supply chain viability and commercial competitiveness.

Figure 38 provides a comparison of key metrics from each of the designs as a function of water depth. Those for the taut mooring systems are the designs with 100-m offset constraint, following the 55° relation for the anchoring radius versus water depth. This illustrates the key differences between the topologies, especially how the TLP offers minimal footprint but maximum line diameter.

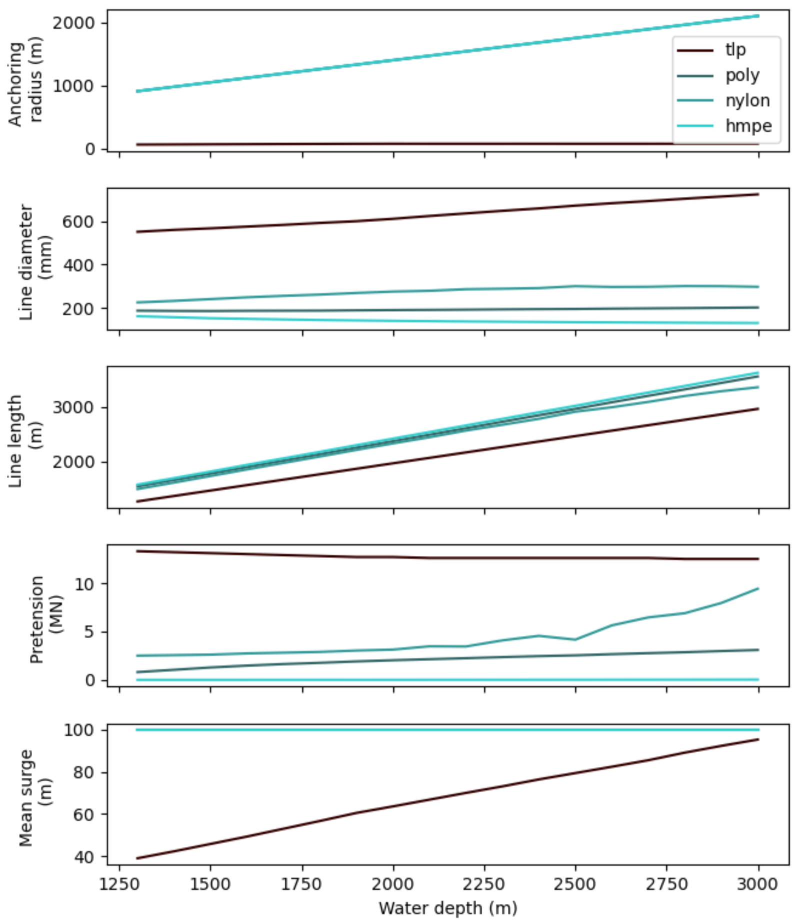


Figure 38. Key metrics from TLP and taut reference designs

To illustrate the geometric differences between TLP and taut mooring approaches, Figure 39 and Figure 40 show floating wind arrays using TLP and taut mooring systems, respectively.

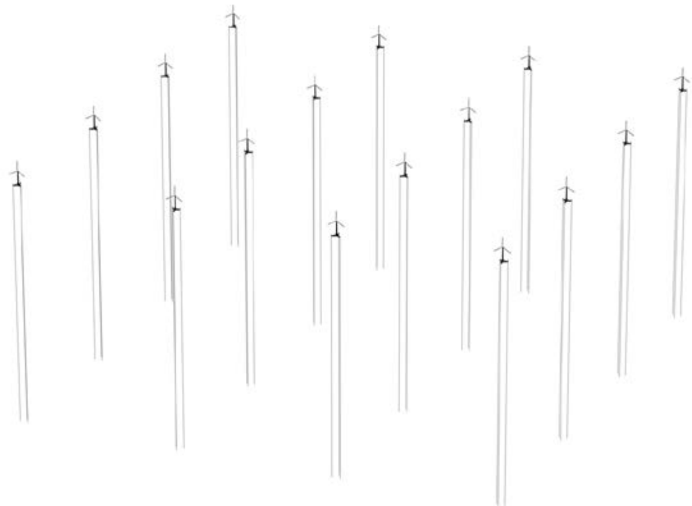


Figure 39. Array of reference TLPs at 3,000 m water depth

Illustration by NREL

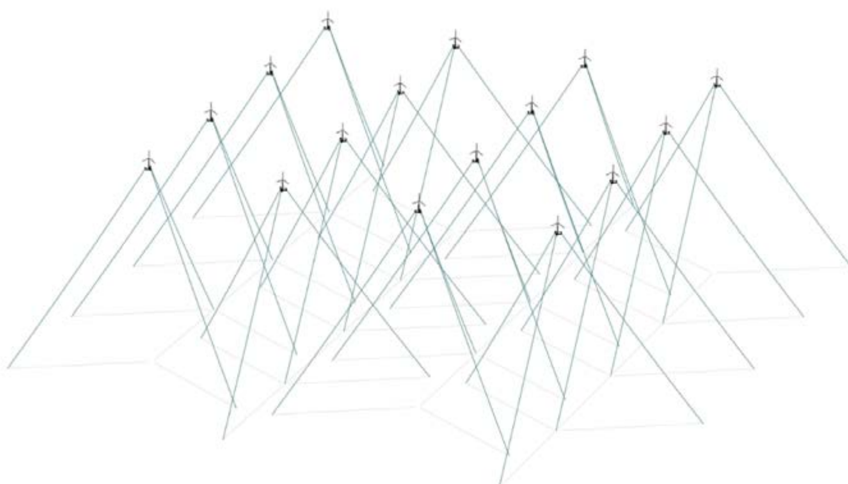


Figure 40. Array of semisubmersibles with reference taut polyester mooring systems at 3,000 m water depth

Illustration by NREL

Each floating wind array in these figures contains 16 wind turbines, spaced in a 4×4 grid layout with 2,100 m between turbines. The water depth across the entire farm is 3,000 m. The wind turbines, floating platforms, and mooring systems are drawn to scale. The reference taut mooring systems have an anchoring radius of 2,100 m, and because of this spread, the orientation of the taut mooring systems in every other row is reversed to avoid clashing of the mooring lines. The TLP mooring tendons, however, do not interact with other TLP systems. These systems could potentially be spaced closer together to increase capacity density, but other factors like wake effects, cable routing, or navigation would also impose constraints on the layout design. The potential advantages of a TLP design for this array would need to be balanced against the high cost of the TLP mooring tendons and the risk associated with adopting a new design.

7 Capacity Density

This section summarizes an analysis of drivers for floating offshore wind plant capacity density in ultradeep water and characterizes a range of potential capacity densities for ultradeep projects. We show that achieving capacity densities on par with fixed-bottom offshore wind development is possible for some mooring technologies in ultradeep waters.

Capacity density[2] describes the concentration of wind energy development in an area and is often specified in terms of megawatts per square kilometer. Understanding capacity density trends in wind energy projects helps to inform both energy system and spatial planning efforts. Borrman et al. (2018) and Mulas Hernando et al. (2023) analyze capacity density trends for fixed-bottom offshore wind farms in Europe and the United States, respectively, and Cooperman et al. (2022) explore how floating offshore wind mooring technology choices may impact wind plant layout through setbacks from lease area boundaries in waters up to 1,300 m deep. Technical challenges facing floating offshore wind development in ultradeep waters (beyond 1,300 m) could impact achievable capacity densities, with potential implications to marine spatial planning and project economics.

Mulas Hernando et al. (2023) group fixed-bottom offshore wind project capacity density drivers into three categories, which are applicable to floating offshore wind energy development:

- Physical project design drivers (including plant layout, turbine rating and rotor diameter, and internal wake effects or cluster wake effects from adjacent wind farms)
- Area utilization drivers (including soil conditions and geohazards constraining turbine placement, and lease area geometry stakeholder considerations)
- Economic and policy factors (including offtake agreements, prescribed turbine spacing, lease price, and state renewable energy procurement).

Just like for the fixed-bottom offshore wind energy industry, soil conditions, seabed slopes, geohazards, and coral and benthic habitats can restrict where components contacting the seabed can be placed, potentially limiting the number of turbines in a lease area. Unlike static fixed-bottom offshore wind turbines, turbines on floating substructures may naturally drift as wind, wave, and current forces interact with the mooring system design (e.g., orientation and stiffness). The water depth and mooring system type influence the diameter of the anchor radius—the horizontal distance from a wind turbine to an anchor—and therefore the area that is required for each turbine. Figure 3 qualitatively illustrates this potential anchor spread for TLP, taut, semi-taut, and catenary mooring line configurations. When compared to fixed-bottom commercial-scale wind farms, this unique feature of floating offshore wind systems can constrain capacity density in some circumstances.

In this section, we conduct an initial investigation of how taut mooring configurations may constrain floating offshore wind turbine placement and estimate capacity density for representative floating wind plants in generic lease areas (Section 7.3). In addition, we explore floating wind plant capacity density drivers in ultradeep waters by characterizing area utilization

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[2] Note that capacity density differs from a turbine's specific power (the ratio of a wind turbine's rotor-swept area to rated capacity, often specified in W/m^2).

for a range of lease area characteristics (Section 7.4). We focus the analysis on taut mooring systems because catenary and semi-taut mooring configurations are less desirable for ultradeep waters, and anchor radii are not the limiting constraint on turbine siting for TLP technologies.

7.1 Anchor Radii of Taut Mooring Systems in Ultradeep Water

Taut mooring system anchor radii may constrain achievable project capacity densities, especially as water depths increase. Section 6.1 outlines how steeper mooring lines (greater anchoring angles[3]) reduce anchor radius but result in greater line tensions. This increases costs due to the higher stiffness required to maintain stationkeeping effectiveness. We therefore use two relationships for how anchor radius varies with water depth to illustrate potential trade-offs between capacity density and mooring system cost.

Section 6.1 describes how anchor radius and system cost are calculated for different reference wind plant designs in ultradeep water. The best-fit equation for the anchor radius for the least-cost taut polyester configuration over a range of depths (corresponding to the dashed line in Figure 28) is provided in Table 21. This is compared to an anchor radius estimate for a taut mooring system with a 55° anchoring angle, which was chosen to balance cost and spacing considerations. Figure 41 illustrates these relationships over the range of depths for which they are derived. The figure also includes the potential anchor radius for a TLP (see Table 19) to underscore that it is unlikely to be a capacity density driver. A dashed gray line indicates 1 nautical mile (1.85 km) for reference since this wind turbine spacing was adopted by some fixed-bottom offshore wind projects on the U.S. east coast.

Table 21. Mooring System Anchor Radius (*r*) as a Function of Water Depth for Two Taut Mooring System Designs

55˚ Incline	Minimum Cost
r = 0.7 × depth	r = 0.91 × depth + 974

[3] Anchoring angle is the acute angle formed between the seabed and a straight line connecting the turbine to the anchor.

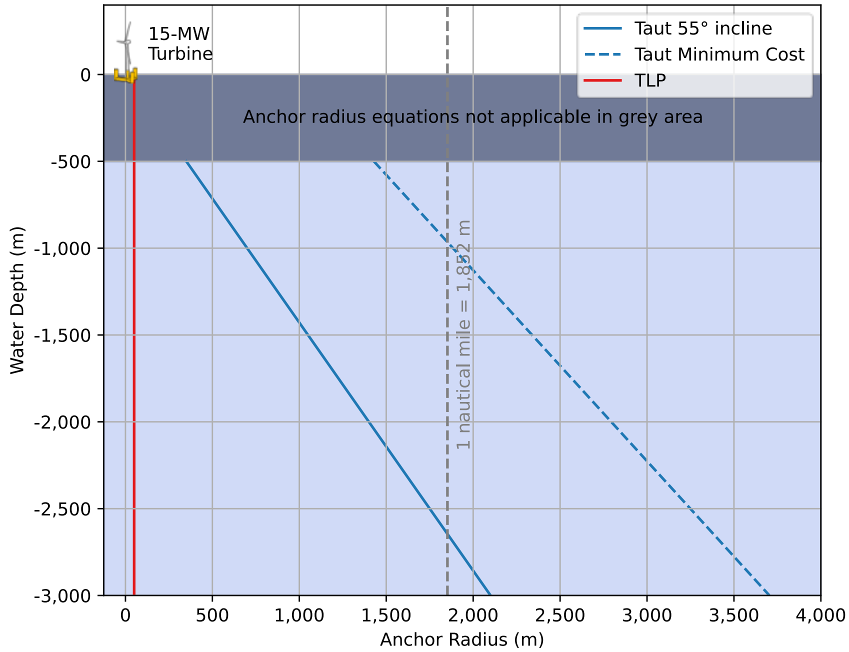


Figure 41. Illustration of anchor radii for TLP and taut mooring configurations

Figure 41 indicates that taut mooring systems designed for minimum cost in ultradeep waters have large anchor radii, likely greater than 1 nautical mile. Taut mooring systems with a 55° incline have smaller anchor radii of less than 1 nautical mile up to depths of approximately 2,600 m. The anchor radius impacts how far from a lease area boundary the floating turbine can be located, as depicted in Figure 42, and can also affect turbine spacing within a lease area.

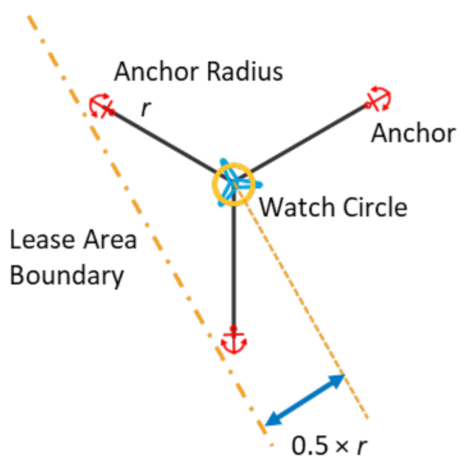


Figure 42. Depiction of minimum distance from wind turbine position to lease area boundary

Illustration by NREL

In addition to considering the mooring system cost, two financial factors that impact developers' thinking around capacity density include the cost of the subsea cables and impacts from wake losses (Lundquist et al. 2019). As minimum spacing increases, so can subsea electrical cable cost, which may encourage higher capacity densities. Note that the array cables represent a relatively small fraction of the total project capital expenditures, although ultradeep projects will have increased array cable costs if the cables go all the way to the seafloor (Section 8). Even so, energy production may play a larger role in wind plant layout optimization (Fleming et al. 2023; Stehly and Duffy 2022). This analysis does not consider mooring system designs that enable passive wake loss mitigation, or “wake dodging,” from the drift of floating platforms within their watch circles with changes in wind direction (Alkarem et al. 2024).

7.2 Wind Plant Layout

This section explores a range of potential relationships between anchor radius and wind plant layouts for projects with and without shared anchors (multiple turbines connecting to the same anchor). While floating offshore wind turbines may drift within their watch circle, for taut systems in ultradeep waters the anchor radius is 20–40 times larger than the watch circle radius. Therefore, we assume the watch circle radius is unlikely to drive capacity density in ultradeep waters. Instead of defining plant layout in terms of minimum turbine spacings (turbine-to-turbine distances)—which could be dynamic—we define minimum spacing in terms of the distance between watch circle centers (which are static points). This analysis considers the impact of anchor radius on the minimum spacing within the potential lease area. As water depths increase, the taut mooring system footprints grow with the anchor radius. Figure 43 summarizes the three layouts considered and the resulting minimum spacings, assuming that:

- Mooring lines do not cross, i.e., they do not intersect when viewed from above
- Mooring lines that do not share an anchor should be separated by a minimum distance (buffer, b)
- Mooring lines can intersect at a shared anchor.

Under these assumptions, the minimum spacing between watch circle centers for a taut mooring configuration is an anchor radius (r). The assumption that mooring lines cannot cross is conservative, as it does not account for vertical separation between adjacent lines. In theory, it is possible to space adjacent mooring lines and/or cables such that they cross from a bird’s-eye view but never collide in three dimensions. That minimum distance depends on the amount of movement those lines experience due to wind, wave, and current forces. More work needs to be done to understand if mooring lines could cross from a top-down perspective considering safety and maintenance standards and potential concerns from other ocean users.

The minimum spacing between watch circle centers for a shared anchor wind farm using a hexagonal layout is $r\sqrt{3}$ because this is the side length of the triangle enclosed (see Figure 43b). This decreases to r in the “double hexagonal” layout shown in Figure 43c, though it is important to note that placing an anchor beneath the watch circle of an adjacent turbine may pose challenges for maintenance.

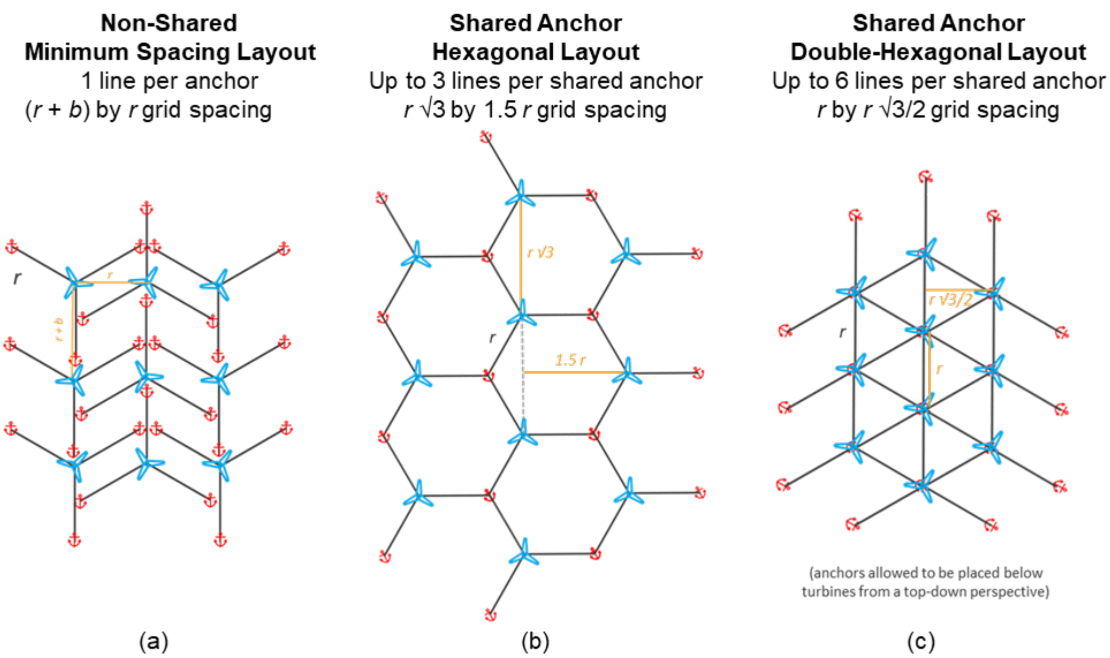


Figure 43. Minimum spacing between watch circle centers for wind plant layouts with (b, c) and without (a) shared anchors. Blue rotor icons indicate watch circle centers and red anchor icons indicate anchor positions.

Illustration by NREL

Table 22 presents equations for minimum boundary setbacks and minimum spacing between watch circle centers for taut and TLP mooring systems based on the range of layouts considered above. We use these relationships to examine impacts on capacity density for wind plants in ultradeep water.

Table 22. Minimum Spacing and Boundary Setback Equations for Different Mooring System Types

Metric	Depth Range (m)	Mooring System Type	
		Taut 55° Incline	Taut Least-Cost
Minimum boundary setback (m)	500–3,000	0.35 × depth	0.46 × depth + 487
Minimum spacing between watch circle centers (m)	500–3,000	0.7 × depth	0.91 × depth + 974

7.3 Capacity Density Estimates for Generalized Floating Wind Plants

In this section, we estimate capacity densities for generalized floating offshore wind plants with taut mooring systems in a square lease area of 15.6 km × 15.6 km (13 × 13 OCS lease blocks). This results in a total lease area of 243 km^2, similar in area to the Humboldt Bay lease areas. We make the following assumptions for generalized wind plants:

- Flat seabed with constant water depth
- 15-MW wind turbines on floating substructures with three taut mooring lines per turbine
- Wind turbine layout does not account for cable routing or offshore substation position(s)
- No excluded area from slopes, geohazards, soil types, obstructions, or other ocean users

- All anchors must be placed within the lease area boundary
- Water depths between 1,300 m and 3,000 m are considered.

These assumptions simplify the analysis to estimate capacity densities, but other efforts are starting to optimize floating offshore wind plant layouts considering factors like depth, slope, and soil variation (Hall et al. 2024).

Resulting capacity densities for taut systems with 55° inclines (a) and minimum costs (b) are presented in Figure 44 to show the range of potential outcomes. The figures include gray shading to indicate the range of capacity densities identified in early fixed-bottom offshore wind projects in the United States (Mulas Hernando et al. 2023).

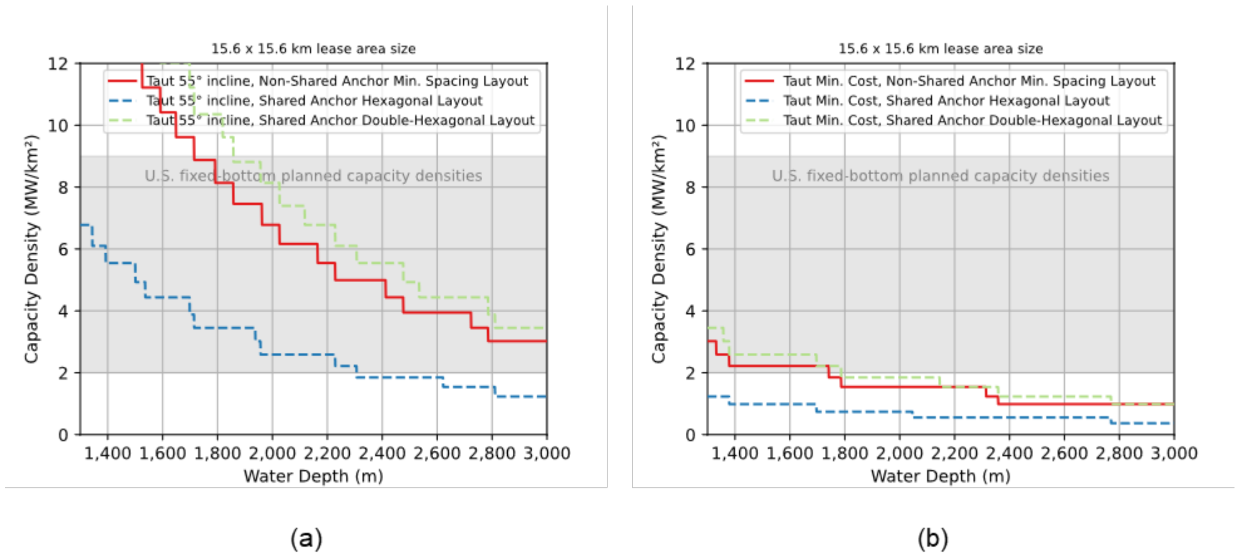


Figure 44. Maximum capacity density vs. water depth

Figure 44a indicates that, depending on the layout, taut mooring systems with a 55° incline can largely achieve capacity densities on par with fixed-bottom projects in the Unites States. The least-cost taut mooring configuration in Figure 44b constrains capacity densities mostly below 3 MW/km^2 for projects in ultradeep waters. The figure also indicates that shared anchor double-hexagonal layouts can achieve greater capacity densities than layouts without shared anchors and minimum spacing. The shared anchor single-hexagonal layouts exhibit considerably lower capacity densities than minimum spacing layouts without shared anchors.

Since capacity density also changes with turbine rating, we present a sensitivity of capacity density to turbine rating in Figure 45. We examine two constant relative turbine or watch circle center spacings (7 rotor diameter (D) by 7D spacing on a square grid and 10D by 4D spacing on a rectangular grid). The turbines considered are assumed to have a constant specific power (ratio of generator rating to rotor-swept area).

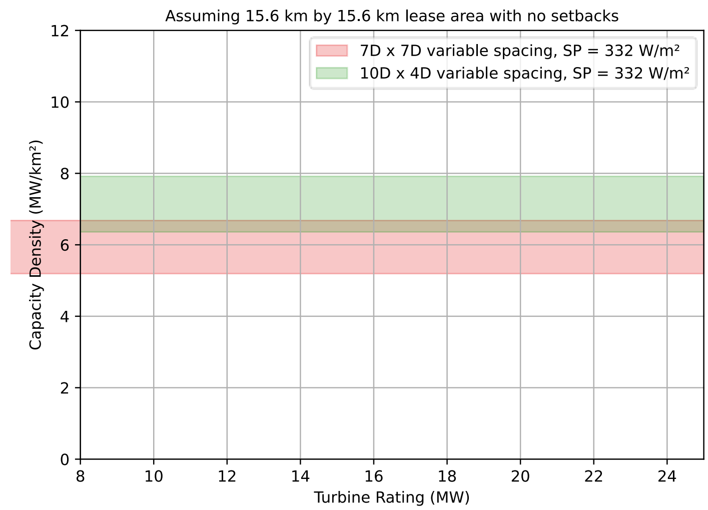


Figure 45. Sensitivity of capacity density to turbine rating for constant relative turbine spacings and constant turbine specific power (SP)

7.4 Area Utilization Estimates for Generic Floating Wind Plants with Taut Mooring Systems

The area within a lease that can be used to site turbines depends on the mooring technology, water depth, lease area size, and lease area shape. For taut technologies, we define the ratio of the usable area to the total lease area as the area utilization (see Figure 46). We then analyze area utilization for generic rectangular lease areas based on the two taut mooring configurations outlined in Table 21 considering mooring system setbacks illustrated in Figure 42. We consider rectangular lease areas for illustrative purposes, but the same concepts would apply to irregularly shaped leases.

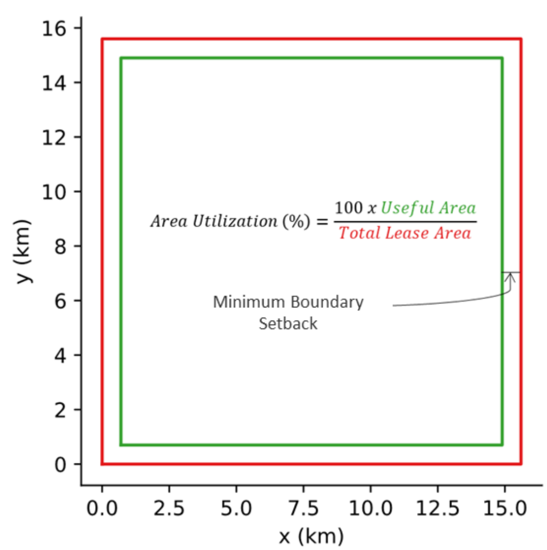
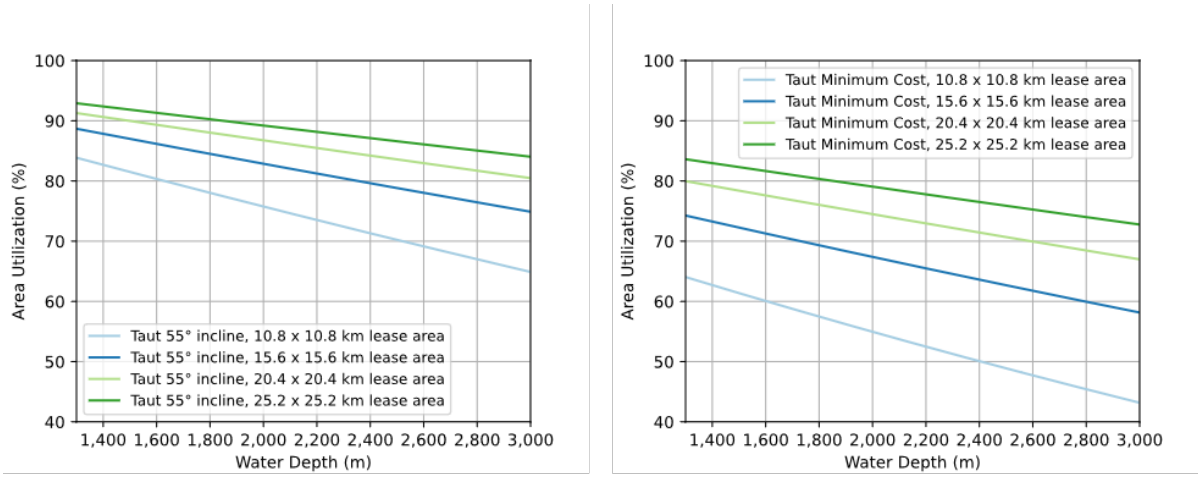


Figure 46. Area utilization formula

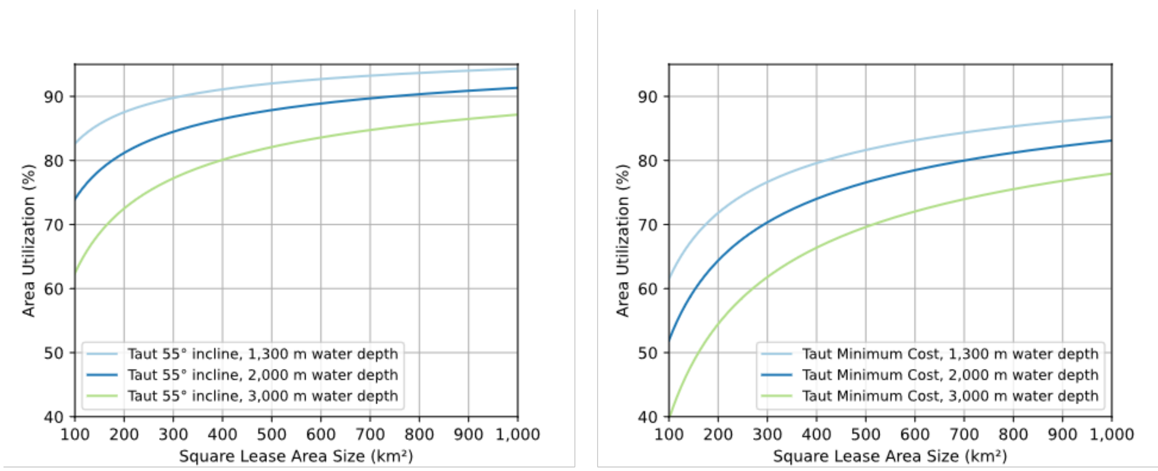
For taut mooring systems, area utilization decreases as water depth increases since the minimum boundary setback distance is driven by the anchor radius. This dynamic is captured in Figure 47 for several different lease area sizes. Comparing Figure 47a and Figure 47b indicates that a steeper anchoring angle allows for increased area utilization at a given depth.



(a) (b)

Figure 47. Area utilization vs. water depth based on taut mooring systems with (a) 55° incline and (b) minimum cost designs

Figure 48 illustrates that area utilization increases with lease area size since the boundary setback at a fixed depth represents a smaller fraction of the lease area side length. This relationship is presented at three different depths.



(a) (b)

Figure 48. Area utilization vs. total lease area based on taut mooring systems with (a) 55-degree incline, and (b) minimum cost designs at three depths

The shape of the lease also impacts area utilization. To assess this, we consider leases with constant areas but different aspect ratios (ratio of width to height) for the two taut mooring configurations and three different depths. The resulting area utilizations are presented in Figure

49. Square leases yield higher area utilization than narrow rectangular leases. Note that this matters most for narrow leases (aspect ratios below 0.2). Very narrow lease areas in ultradeep water could be infeasible for taut mooring systems if the width of a lease area were less than approximately two times the anchor radius.

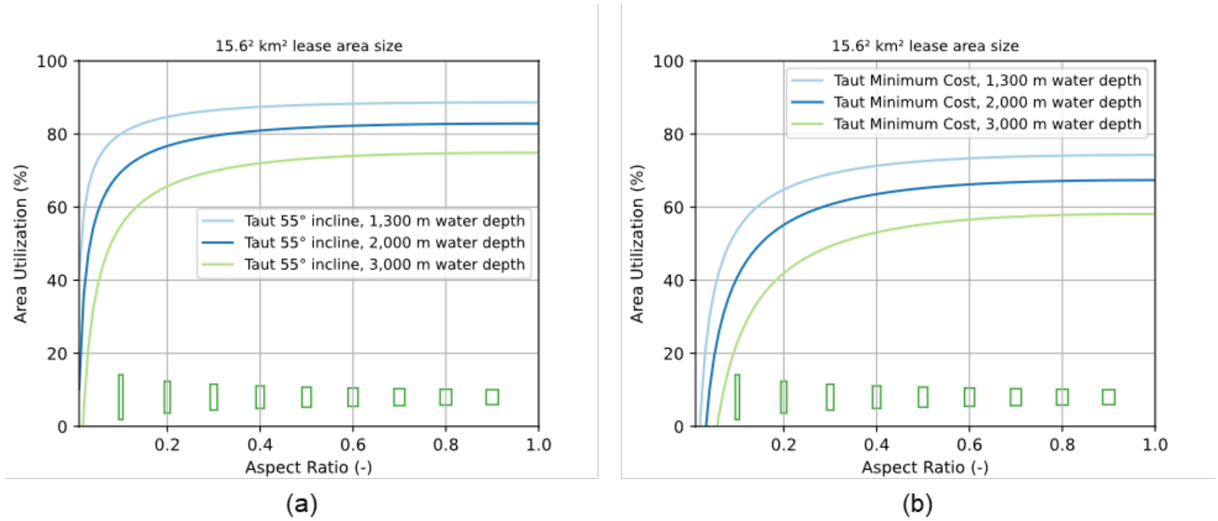


Figure 49. Area utilization vs. aspect ratio based on taut mooring systems with (a) 55° incline, and (b) minimum cost designs

7.5 Conclusion

The key conclusions from this analysis include the following:

- Anchor radii of TLP systems do not (significantly) limit floating wind plant capacity densities in ultradeep waters. Minimum spacing limits would be imposed by constraints other than the mooring system anchor radius.
- Capacity densities for taut mooring systems are constrained as water depth increases (assuming mooring lines cannot cross).
- Taut mooring systems with a 55° incline can largely achieve capacity densities on par with fixed-bottom projects in the United States. An alternative taut mooring configuration that minimizes mooring system cost is more limiting, with capacity densities mostly below 3 MW/km^2 for projects in ultradeep waters.
- Capacity densities for taut mooring systems with shared anchors can exceed those achieved by layouts without shared anchors but may pose installation and maintenance challenges.
- Area utilization decreases with water depth but increases with lease area size. It also depends on the shape of the lease area, with square leases yielding more usable area than narrow rectangular leases.
- A steeper anchoring angle allows for increased area utilization at a given depth.

8 Cost Assessment

This section provides an overview of the major capital cost drivers for floating offshore wind plants and how deployment in ultradeep water could affect capital expenditures (CapEx) for an offshore wind plant. The analysis focuses on comparing the CapEx of a 1-GW wind plant at two different water depths: 1,000 m, which is representative of existing lease area depths, and 3,000 m, which is the deepest depth considered in this study. Several cost elements are also examined at intermediate points between these depths.

A typical cost breakdown for a utility-scale floating offshore wind farm is shown in Figure 50. As wind plants are sited in deeper waters, including ultradeep depths, the most significant changes are to the balance of system (indicated with blue shading in Figure 50). The balance of system includes floating platforms, moorings, anchors, array and export cables, and offshore substation(s). Cost drivers for each category are discussed in the following sections.

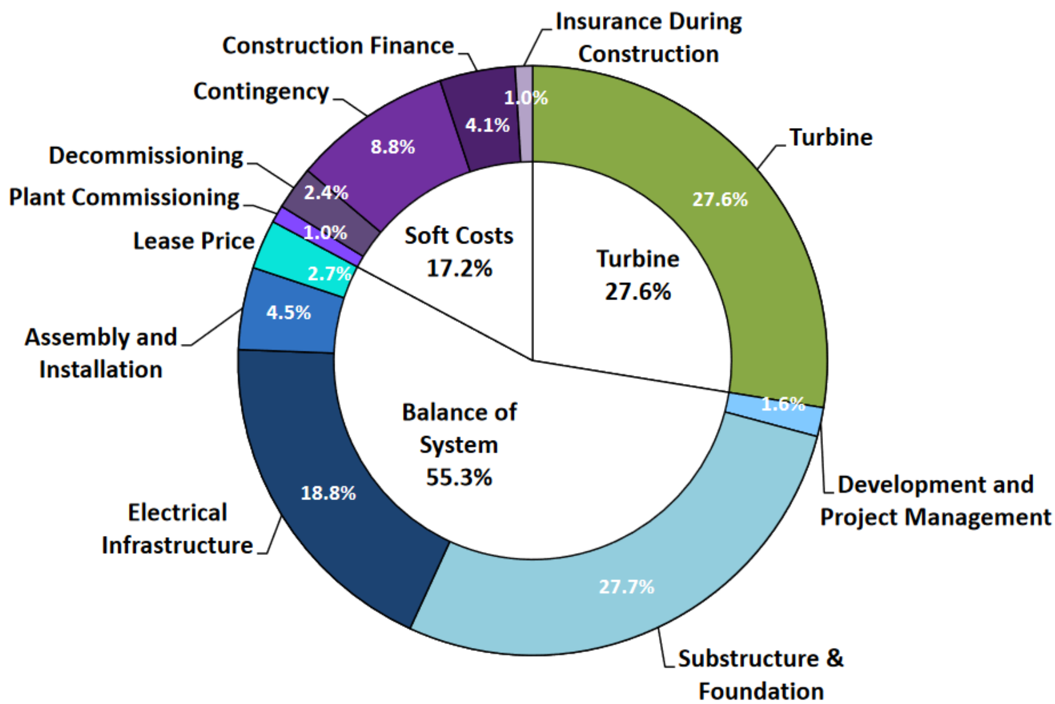


Figure 50. Floating offshore wind system CapEx component cost breakdown

Source: Stehly et al. (2023)

8.1 Cost Drivers

8.1.1 Wind Turbine Capital Expenditures

Wind turbine designs are not expected to change between water depths of 1,000 m and 3,000 m. We keep the cost of the turbine fixed at $1,700/kW (Stehly et al. 2023) throughout this study.

8.1.2 Development and Project Management

Development costs may be higher in ultradeep water because access to the site is more challenging. Survey vessels will need to spend more time in transit to more distant sites and will also require more time to deploy equipment to reach the seabed at deeper depths. Engineering and project management costs could also be affected by the longer timeline and complexity of operating in ultradeep water. We estimate a 30% increase in development and project management costs for a site at a depth of 3,000 m relative to a baseline value of $98/kW (Stehly et al. 2023) for a site at 1,000 m.

8.1.3 Substructure and Foundation

Substructure

Changes to the floating platform design depend on the type of platform. A platform that is stabilized primarily by buoyancy and/or ballast (semisubmersible, spar, and hybrids of those types) will most likely use taut moorings in ultradeep water. Because the synthetic ropes used in taut moorings are neutrally buoyant, the additional length of mooring lines does not require extra buoyancy from the platform to support their weight. Semisubmersible, spar, or hybrid platform designs will likely not differ significantly between ultradeep and non-ultradeep depths, and as a result, costs are assumed to remain the same.

Moorings and Anchors

The components most sensitive to changes in depth are the mooring lines, which must extend at least the distance from the seabed to the floating platform. Non-vertical moorings have additional length associated with the spread of the anchors away from the wind turbine location. If the mooring design remains the same, a wind farm in 3,000 m of water requires triple the length of moorings as a wind plant in 1,000 m of water. Mooring designs can be customized to the depth of a project to obtain a least-cost solution, using various combinations of chain, synthetic rope, wire, and anchor types to achieve the required stiffness, range of motion, and load-bearing capability.

For taut mooring systems, we consider designs developed in Section 6.1 for polyester lines with a maximum floating platform offset limit of 100 m. Each mooring system consists of three polyester ropes connected to suction pile anchors. Figure 51a reproduces the cost surface for taut polyester mooring system designs with different anchoring radii in water depths between 500 m and 3,000 m. The solid black line indicates the lowest-cost design at each depth, and the dashed line is for a taut mooring making a 55° angle with the waterline. The least-cost designs have anchoring angles between 20° and 40°, depending on the depth, which corresponds with larger anchor radii than the 55° designs. Although the shallower angles require longer line lengths, they also reduce tension in the lines, allowing for smaller diameter mooring lines and lighter anchors than the 55° case and resulting in lower mooring system costs.

The chart in Figure 51b shows the cost of a single rope and anchor for each design. Although the cost of the 55° inclined design is higher at every depth, the smaller anchor radius of this design enables closer spacing of turbines and shorter array cable lengths. Section 7 focused on the impacts of different mooring spacing on capacity density; in this section we discuss the cost trade-offs between the least-cost mooring system and the total wind plant CapEx.

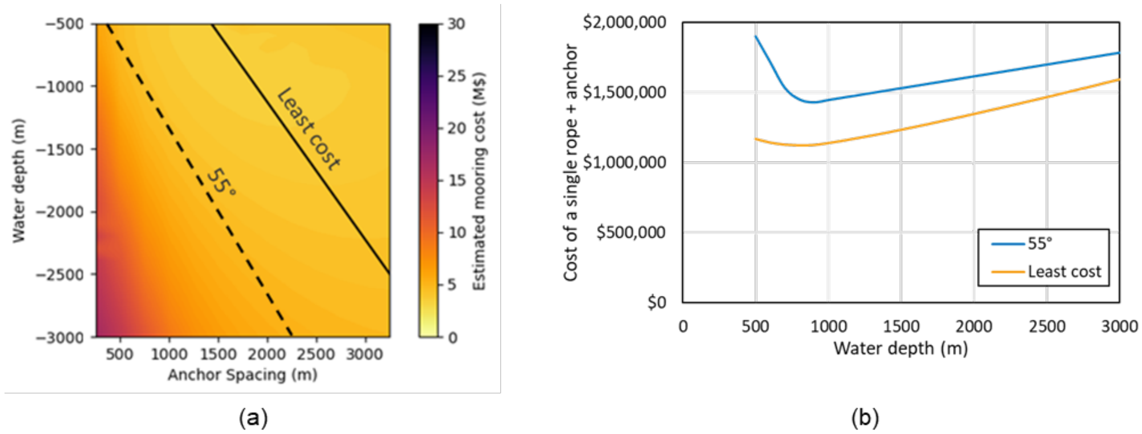


Figure 51. (a) Anchor radius vs. water depth for least-cost and 55° taut mooring designs; (b) cost of a single taut mooring line and anchor corresponding to the least-cost and 55° trendlines

8.1.4 Electrical Infrastructure

Array System

Regardless of water depth, floating offshore wind plants will require dynamic cables that are designed to withstand the motion they experience when hanging from a floating platform. We estimate a 20% cost premium for dynamic cables relative to static cables (used in fixed-bottom offshore wind plants) to account for the more robust cable design and the additional cable protection elements such as buoyancy modules and bend stiffeners.

Water depth has a significant effect on array cable costs if the cables are brought to the seabed between each turbine, because the cable sections will need to be much longer in ultradeep water. An alternative approach that could be used in both deep and ultradeep water is to suspend the array cables above the seabed. In this case, the length of the cables would depend on their depth below the surface, rather than the depth to the seabed. Floating offshore wind demonstration projects to date have brought cables to the seabed in depths up to 300 m; however, the array design strategy for deeper water remains uncertain. We model costs for both approaches in this study.

Offshore Substation

The cost of a floating offshore substation is not expected to change significantly between deep and ultradeep water. The majority of the costs associated with an offshore substation are for the floating platform and electrical equipment (e.g., converters and breakers for an HVDC system, transformers and switchgear for an HVAC system), which are independent of depth. The mooring system must be adapted to the appropriate depth, but it represents a small fraction of the total cost.

Export Cable

Two important factors influencing export cable costs in ultradeep water are the distance from shore and the increase in hydrostatic pressure with depth. Ultradeep waters tend to be located farther from shore, following the slope of the continental shelf. The extra distance increases the length of export cables and the associated cost. In addition, cables must be designed to withstand greater hydrostatic pressure at ultradeep depths to prevent water penetration.

8.1.5 Assembly and Installation

Details of the assembly and installation processes vary depending on technology selection; however, there are common elements that are similar for most floating offshore wind technologies. A key element is the staging and integration port, where the blades, nacelle, tower, and floating platform are integrated into a floating wind turbine generator before the system is towed out to the wind plant site. Other major components, such as mooring rope or chain, anchors, cables, and offshore substation, may be staged through the same port or from ports closer to where they are manufactured.

The port infrastructure for ultradeep projects is not expected to be substantially different than for projects in less deep water, although there may be more demand for quayside storage for some components. Longer mooring lines and cables will take up more space. They may also motivate a shift to large vessels to reduce the number of trips between the wind plant site and the port. Larger vessels require ports capable of accommodating their dimensions. For example, cable lay vessels with a carousel capacity of 7,000 t have a draft of 5.4 m and length up to 136 m, whereas a cable lay vessel designed for a carousel capacity of 17,000 t has a draft of 8.5 m and a length of 171 m (Prysmian Group 2021). Day rates for larger vessels are higher and the use of a larger vessel may also limit the selection of ports or require port upgrades.

Vessel costs are an important factor in the overall installation costs. These may be higher for ultradeep sites for several reasons: longer transit times to sites farther offshore, longer mooring lines and cables that require larger vessels or more trips back and forth, and more time spent onsite for operations such as lowering cables or anchors to deeper depths.

8.1.6 Lease Price

The amount paid to obtain a seabed lease is set in a competitive auction process that can result in very different prices depending on participants and market dynamics. For this study, we assume a fixed cost per square kilometer to model how a larger mooring footprint could lead to higher costs for a given plant capacity. Based on the winning bids in the 2022 California lease auction, we set a fixed cost of $600,000/km^2 for this analysis (Musial et al. 2023).

8.1.7 Soft Costs

There is not a direct relationship between soft costs and depth; however, many of the costs in this category are proportional to other costs that vary with depth. We calculate the various soft costs as a percentage of the total CapEx, installation cost, or system (procurement) cost, as shown in Table 23.

Table 23. Soft Costs

Cost Category	Value
Construction insurance	2% of total CapEx
Commissioning	1.15% of total CapEx
Decommissioning	17.25% of installation CapEx
Installation contingency	34.5% of installation CapEx
Procurement contingency	5.75% of system CapEx
	8% for a 2-year installation period
Construction finance factor	11% for a 3-year installation period
	14% for a 4-year installation period

8.2 Capital Expenditure Modeling

We use NREL's Offshore Renewables Balance-of-system Installation Tool (ORBIT)[4] to obtain estimates of CapEx and installation times for a representative wind plant in deep and ultradeep water.

The baseline wind plant studied in this analysis consists of 65 15-MW wind turbines (975 MW total capacity) on semisubmersible floating platforms. Each platform has three taut mooring lines oriented at 55° from the (horizontal) waterline, with no sharing of anchors. The turbines are arranged in a rectangular grid with a target spacing of 4D × 10D (960 m × 2.4 km). At 3,000 m, the anchoring radius is more than 4D, so we impose a wider grid spacing of 7.8D × 10D to prevent any mooring lines from crossing. This spacing constraint is a relatively simple representation of how depth may impact plant layouts, but it is not the result of a detailed floating array design process. Actual floating offshore wind plant layouts will likely arrive at different solutions as the industry moves from pilot projects to larger-scale arrays. Layouts—not to scale—are shown in Figure 52 for 1,000-m depth and Figure 53 for 3,000-m depth. Black dots indicate wind turbine positions, and the lines extending from turbines in the lower-left corner illustrate the mooring line spread.

[4] https://github.com/WISDEM/ORBIT

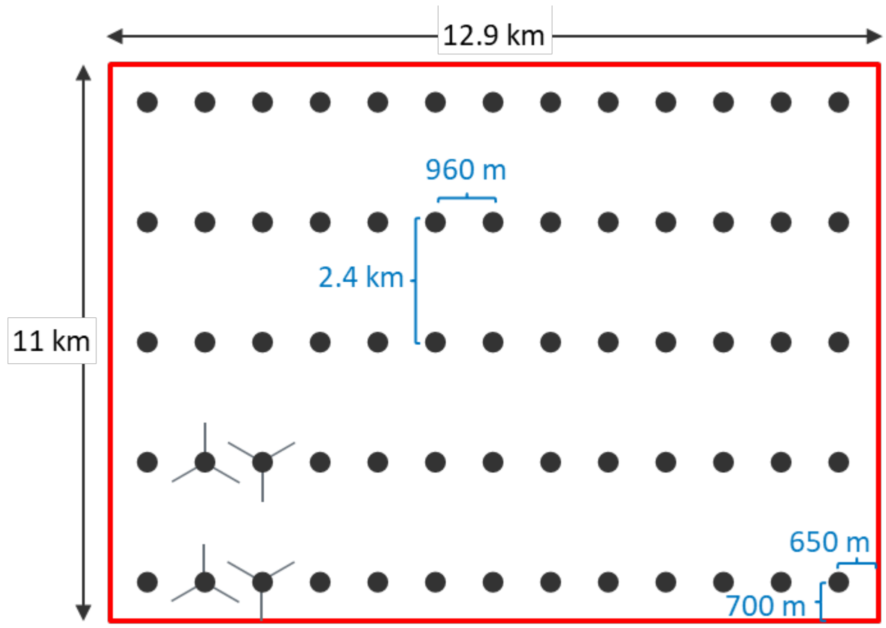


Figure 52. Baseline plant layout at 1,000-m water depth

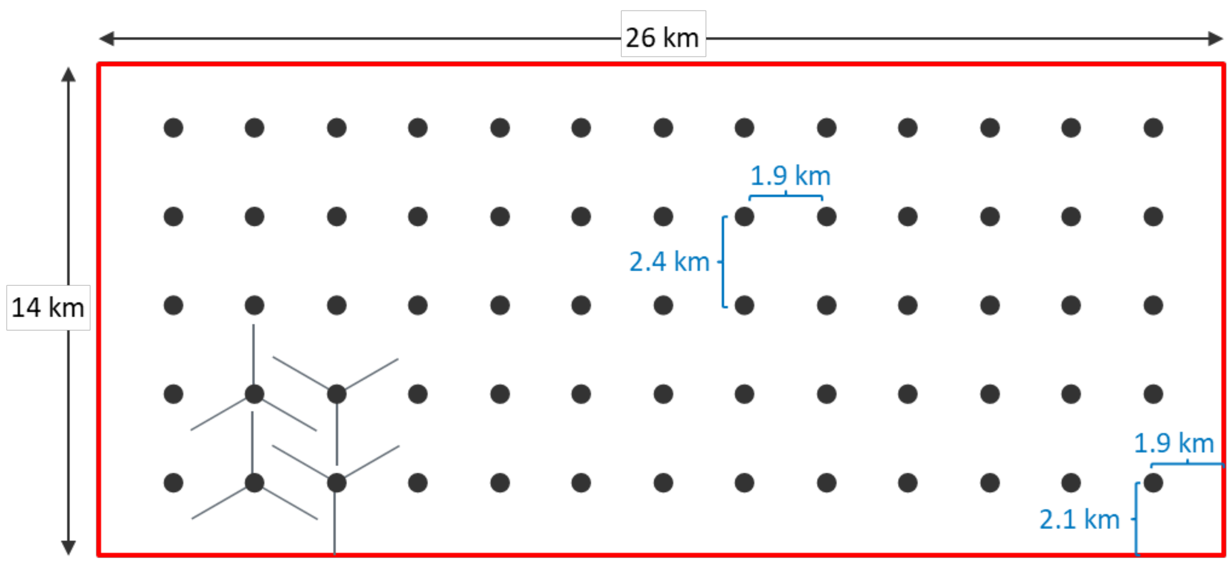


Figure 53. Baseline plant layout at 3,000-m water depth

Although this study focuses on the effect of water depth, we also account for the fact that ultradeep sites tend to be farther from shore than shallower areas. Taking the areas identified in California's AB 525 sea space study (California Energy Commission 2024a, 2024b) as representative of potential future offshore wind sites, we can extract a trendline relating distance from shore to depth (Figure 54). For this analysis, we assume that the 1,000-m depth site is located 41 km from shore and the 3,000-m site is 87 km from shore. The export cable route distance is assumed to be 50% longer (62 km and 131 km, respectively) to approximate the effect of non-straight-line routing to avoid obstacles and reach coastal points of interconnection.

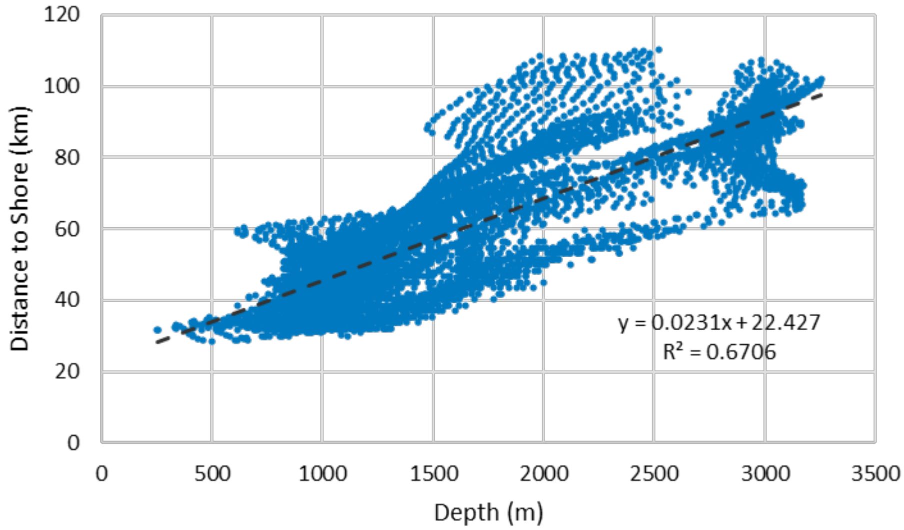


Figure 54. Depth and distance to shore of aliquots within AB525 sea space

Within the floating offshore wind array, turbines are connected to a floating substation with intra-array cables. We compare two options for the cable layout: suspended at a depth of 300 m below the water surface or extending the full depth to be laid on the seabed between turbines. In both cases, we use 66-kV dynamic cable that can carry power from up to five wind turbines in a string to deliver to the substation.

We prescribe the installation sequence using a combination of fixed dates and dependencies between phases. This sequence is intended to illustrate how depth affects installation timelines and may not be representative of actual installation plans. A historical weather reanalysis timeseries (Hersbach et al. 2020) was used to simulate operational delays based on wind and wave conditions in 2002–2005 in the northern California lease areas. For the baseline wind plant, installation begins with pre-lay of the anchors and mooring lines on May 1 in the first year of construction. Wind turbines begin to be integrated with floating platforms and towed out to site for hookup once mooring installation is 50% complete. Connection of the array cables starts when 25% of the floating platforms have been installed. The floating substation installation begins on May 1 in the second year of construction, followed immediately by the start of export cable installation.

8.3 Results

8.3.1 Baseline Wind Plant

Figure 55 presents the total CapEx, in dollars per kilowatt, for the baseline wind plant at 1,000 m and 3,000 m. Total CapEx is 25% higher for the ultradeep site than for the deep-water site. Costs for three major components—the wind turbine, floating platform, and offshore substation, with a total value close to $3,000/kW—do not change significantly. The remaining cost components are all higher for the 3,000-m site than for the 1,000-m site. Higher installation and soft costs represent more than 60% of the total increase in CapEx between the two sites. A significant factor in both of these costs is the installation time, which increases from 557 days for the 1,000-m site to 901 days for the 3,000-m site (Figure 56). During a longer installation period, more port and vessel costs are accrued, and these additional costs are subject to higher construction financing rates.

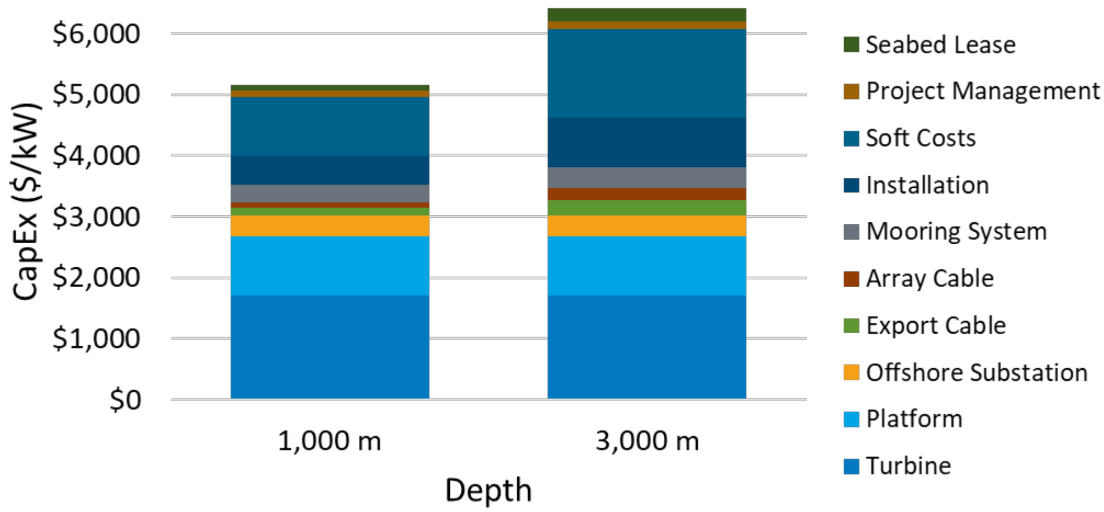


Figure 55. CapEx comparison for baseline wind plant at 1,000-m and 3,000-m depths

The export cable, array cable, mooring system, and seabed lease each contribute close to 10% of the increase in total CapEx from the deep site to the ultradeep site. These increases are all related to increased demand for materials (cable or mooring line) or space (lease area) at the ultradeep site. The mooring system, array and export cables all take significantly longer to install at the 3,000-m site than the 1,000-m site. Higher installation costs for these components are captured in the installation line item.

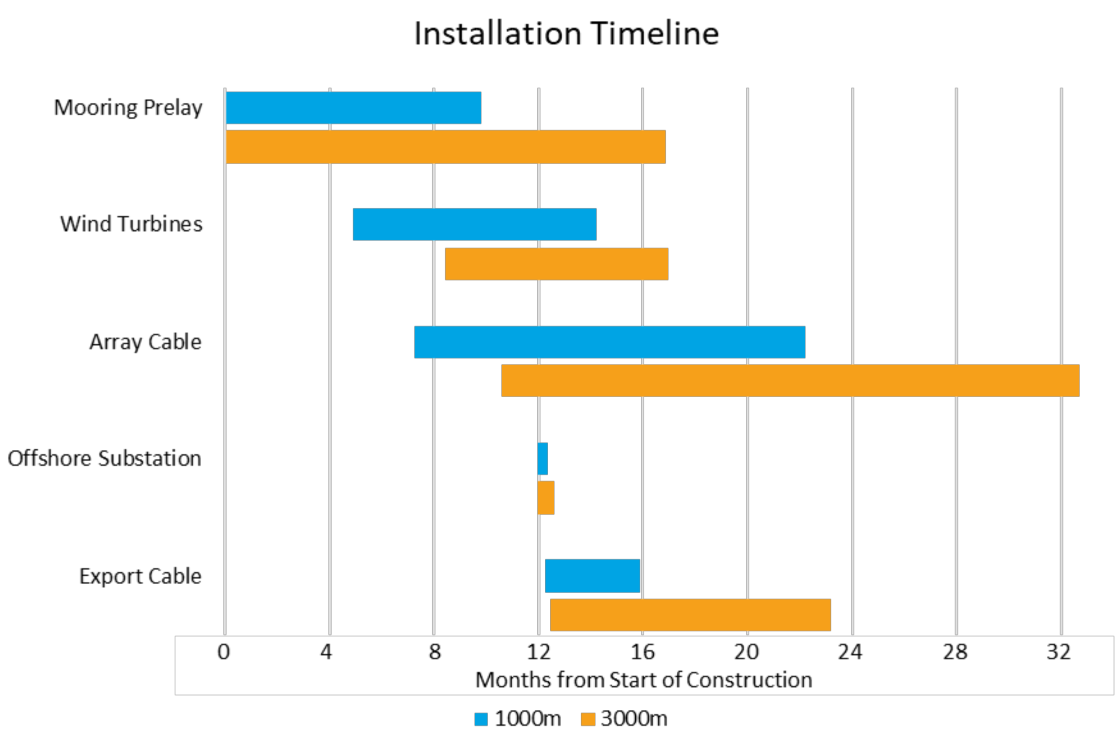


Figure 56. Installation timeline for baseline wind plant at 1000 m and 3000 m water depth.

Note: Activity durations include delays when weather conditions are outside operational limits.

The installation timelines shown in Figure 56 are useful illustrations of how schedules may lengthen in ultradeep water, but there are several limitations to the analysis that should be kept in mind. The ORBIT model assumes that the projects have uninterrupted supply chains and access to vessels when needed, without delays due to component or vessel availability. The model also assumes continuous, round-the-clock operations at sea except when wind speed or wave height limits are exceeded. We do not consider seasonal or nighttime operational limits that could be implemented. Wind and wave conditions offshore northern California are relatively challenging, and the impact to installation timelines could be smaller in regions with less extreme sea states. Installation schedules are not optimized; for example, changing the sequence of phases or the degree of overlap could shorten the overall timeline. Despite these caveats, the general trends are indicative of differences between deep and ultradeep water offshore wind projects.

8.3.2 Array Cable Configuration

In Figure 56, the array cable installation is the last phase to finish, lengthening the installation times for both the deep and ultradeep sites. At the ultradeep site, array cable installation extends nearly 10 months beyond the end of the previous phase, delaying operations and delivery of power. Suspending the array cables in the water column reduces the total length of cable and the time required for installation. Figure 57 shows installation timelines for the deep and ultradeep wind plants with array cables suspended 300 m below the surface. Compared to the seabed-laid array cables, installation of the suspended cables finishes approximately 5 months earlier at the deep site and 10 months earlier at the ultradeep site.

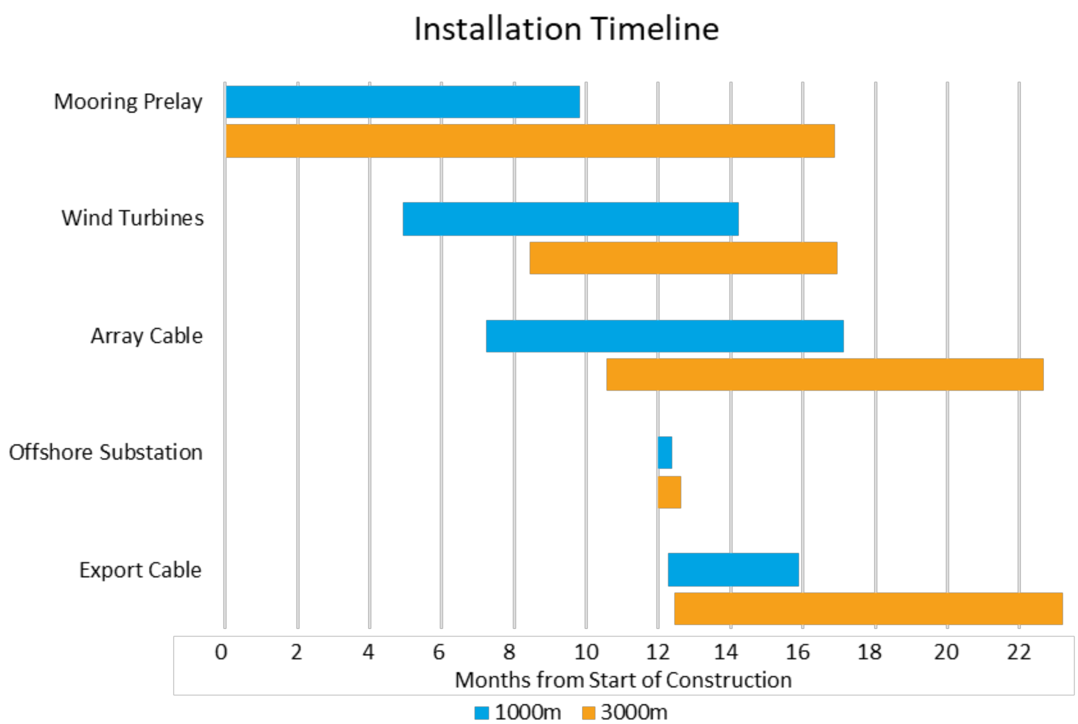


Figure 57. Installation timeline for wind plants at 1,000-m and 3,000-m water depth with floating array cables suspended 300 m below the surface.

Note: Activity durations include delays when weather conditions are outside operational limits.

Figure 58 compares the array system CapEx for suspended and seabed laid array cables for water depths between 600 m and 3,000 m. The cost of suspended cables is lower in all cases, and the cost differential increases with depth. Although the high-level trends appear reasonable, there are additional considerations that could affect the results in a more detailed analysis. We do not differentiate between the cost of cable accessories for seabed-laid cables (e.g., touchdown anchors) and suspended cables (e.g., additional buoyancy modules), applying the same dynamic cable cost in both cases. The choice of a suspension depth of 300 m is arbitrary, determination of an appropriate depth will require more detailed engineering design and consideration of potential impacts to other ocean users including marine life and vessel navigation. A different suspension level would change the magnitude of the cost estimate but would likely exhibit a similarly flat trend with depth.

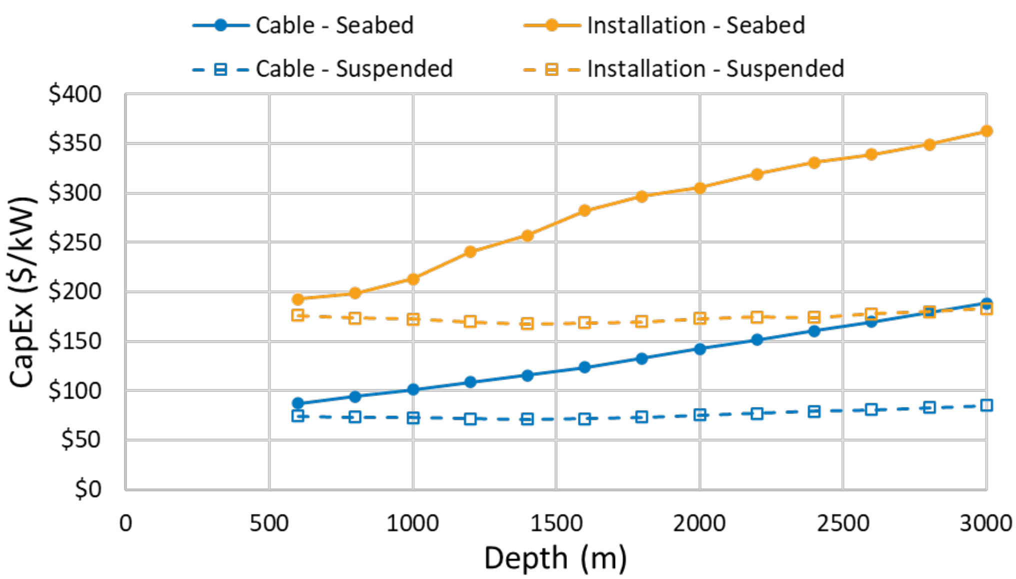


Figure 58. Array system CapEx for seabed laid and suspended cables at 300 m below surface

8.3.3 Mooring System Design

In the case of the electrical array system, selecting a less expensive array design reduces total CapEx for the offshore wind plant. For taut moorings, we compare two different designs: one that minimizes mooring cost and another that maintains a fixed mooring line angle over the full depth range. Because the mooring design impacts wind turbine spacing, the design change affects the lease, array system, and mooring system costs. Other CapEx components are not affected.

Lease areas for the 55° inclined system are illustrated in Figure 52 and Figure 53. The total areas are 140 km^2 (35,000 acres) at 1,000 m and 360 km^2 (90,000 acres) at 3,000 m. For the least-cost mooring system, the total areas are 300 km^2 (73,000 acres) at 1,000 m and 900 km^2 (220,000 acres) at 3,000 m. At the assumed cost of $600,000/$km^2$, these correspond to lease prices between $85 million and $537 million. Array cable lengths also increase for the wind plant with the least-cost mooring system relative to the 55° inclined system. At 3,000 m, the total array cable length goes from 512 km (320 miles) for the 55° inclined system to 625 km (390 miles) for the least-cost mooring system.

Figure 59 compares system CapEx for the affected components at 1,000-m and 3,000-m water depths for both mooring system designs. Although the least-cost mooring system is cheaper than the 55° inclined system, the extra array cable and lease area costs outweigh the benefits to the total CapEx. Although the least-cost mooring system appears disadvantageous from a CapEx perspective, wider spacing could potentially have other benefits such as reducing wake losses, which could improve energy production.

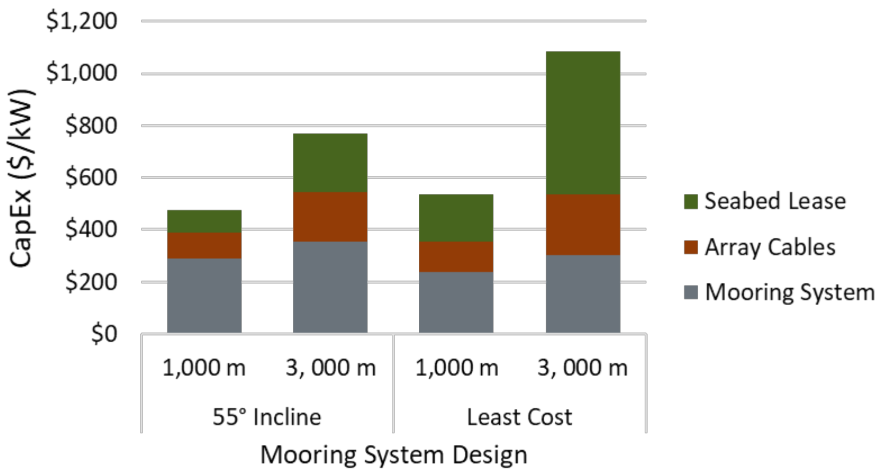


Figure 59. Lease, array and mooring system CapEx for offshore wind plants at 1,000-m and 3,000-m depths using 55° inclined taut moorings and least-cost taut moorings

8.4 Conclusions

Based on modeled CapEx for several different 975-MW wind plants in 1,000 m and 3,000 m of water (Figure 60), we observed CapEx increases of 15%–33% for the wind plant at the ultradeep site relative to same configuration at the deep site. This cost increase represents a significant challenge to the viability of ultradeep water offshore wind projects. Although operational expenses were not in the scope of this study, it is reasonable to assume that they would also increase to some degree due to the challenges of accessing ultradeep sites.

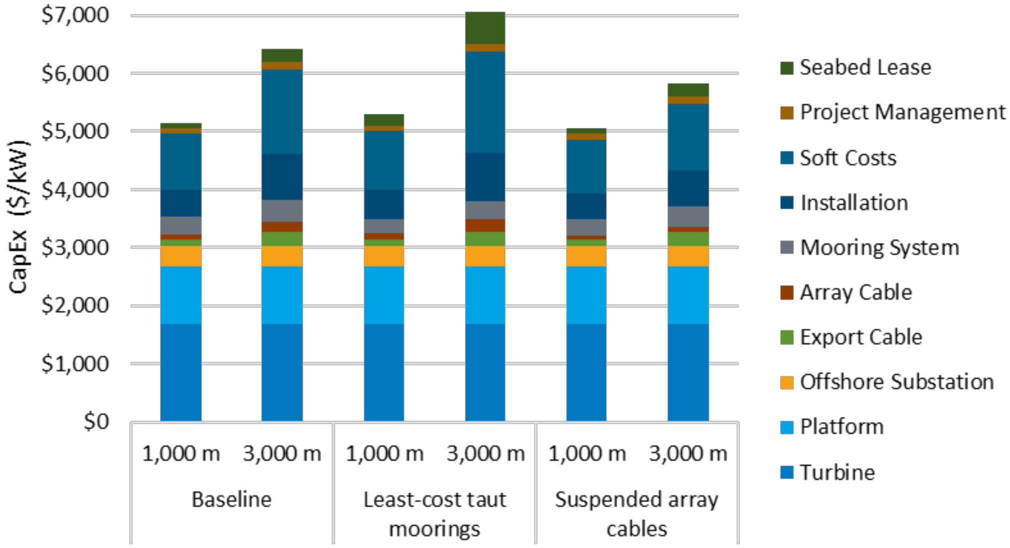


Figure 60. Summary of total CapEx for each scenario

The CapEx values reported here represent our best estimate of costs for floating offshore wind plants with access to a mature supply chain, adequate vessel availability, and supporting infrastructure such as ports and transmission. The floating offshore wind industry is in its infancy and gigawatt-scale projects have not been developed anywhere in the world. More experience with larger floating arrays and deployment in deep water will provide valuable learning on which to base new design and installation concepts and develop better estimates of the cost of ultradeep wind plants in the future.

9 Summary and Conclusions

In this report, we investigated potential challenges for the deployment of floating offshore wind energy in ultradeep water, defined here to include water depths between 1,300 m and 3,000 m. We considered technical, logistical, environmental, and cost factors that could pose challenges at these depths. In some of these areas, we were able to extrapolate from current technology to arrive at quantitative estimates of the effects of deeper water; otherwise, we provided a qualitative assessment. It is important to note that we limited our analysis to relatively "conventional" floating offshore wind technologies—which are themselves only in the early stages of commercial deployment—and did not analyze novel concepts that could be applied to ultradeep floating offshore wind in the future.

Our initial assessment of floating offshore wind technology in ultradeep water primarily identified potential challenges for underwater components: cables, mooring systems, and their installation. Systems above the waterline are generally not anticipated to undergo significant changes between deep and ultradeep sites. A specific challenge for electrical cables in ultradeep water is the need for reinforcement against increased hydrostatic pressure. Cable installation at these depths will require cable lay vessels that can maintain higher tension to support the weight of a longer cable hanging in the water column. The increased length of mooring lines in ultradeep water creates design challenges for each of the established mooring types. For catenary and semi-taut moorings, these challenges likely preclude their use in ultradeep water. Taut moorings remain feasible, but the growth of their footprint with depth may drive reductions in capacity density and increase cost. Tension-leg mooring configurations do not occupy significantly more space in ultradeep water, but alternative tendon materials may be needed to achieve sufficient mooring system stiffness. Both taut and TLP moorings apply vertical loads that affect anchor suitability. Additional data collection is needed to identify site-specific conditions and geohazards that also influence the selection of appropriate anchors. Although anchor design is relatively agnostic to water depth, the transport and installation of anchors in ultradeep waters will likely require more time and specialized vessels than in shallower waters.

Our investigation of environmental and co-use considerations for ultradeep floating offshore wind also focused on the underwater components. Although more data collection and analysis are needed to characterize any potential environmental impacts, key areas to consider include changes to oceanic dynamics due to energy removal and modifications, EMF, habitat alterations to benthic and pelagic fish and invertebrate species, underwater noise, structural impediments to wildlife, and changes to water quality. Fish and invertebrate species may be affected by EMF, whereas underwater noise and secondary entanglement are the primary concerns for marine mammals. Anchors and any other components that touch the seabed can increase sedimentation or create habitat that may alter the distribution of species. Accumulation of flora and fauna may also occur on floating offshore wind structures throughout the water column. Monitoring technologies can be adopted to address the need for data collection and provide input into the development of mitigation strategies. Although some general approaches can be proposed to reduce conflict with co-users, such as reducing the size of floating wind farm mooring line footprints, early engagement and coordination will be essential for the successful development of ultradeep floating offshore wind projects.

We focused on two main areas that represent economic considerations for floating offshore wind: capacity density and capital expenditures. Capacity densities for TLP systems are unlikely to be affected by water depth, but taut mooring systems may be constrained by their anchoring radius. Steeper taut mooring systems with smaller anchor radii can largely achieve capacity densities on par with fixed-bottom projects in the United States, whereas mooring systems with larger anchor radii limit the attainable capacity density in ultradeep water. The additional space required for taut mooring systems, as well as increased material demand and installation complexity lead to higher costs. We modeled CapEx increases of 15%–33% for different configurations of a 975-MW wind plant in 3,000 m of water relative to same configurations at 1,000-m depth. This cost increase represents a significant challenge to the viability of ultradeep water offshore wind projects. More experience with larger floating arrays and deployment in deep water will provide valuable learning on which to base new design concepts and develop better estimates of the cost of ultradeep wind plants in the future.

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