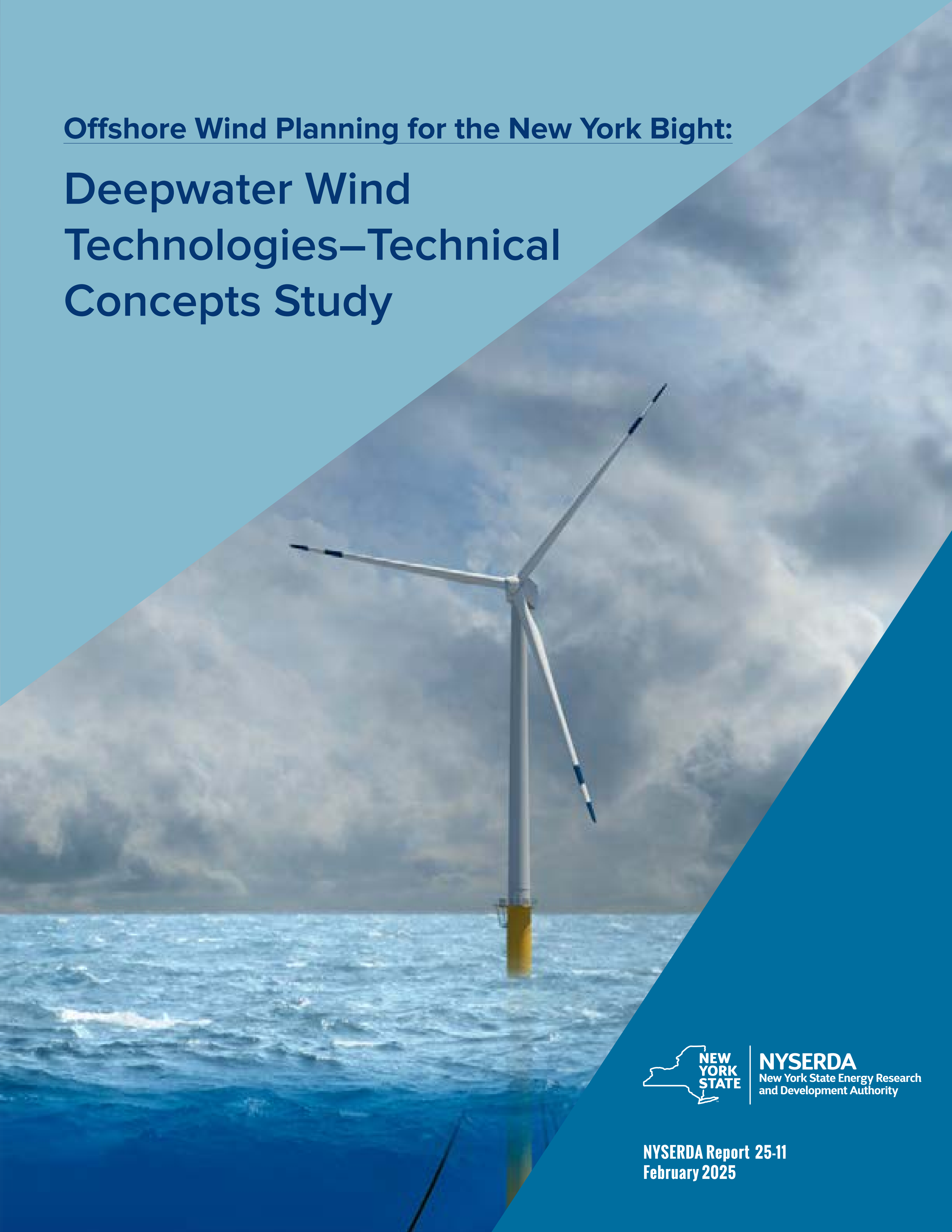
Offshore Wind Planning for the New York Bight:

Deepwater Wind Technologies–Technical Concepts Study



NEW YORK STATE

NYSERDA
New York State Energy Research and Development Authority

NYSERDA Report 25-11
February 2025

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NYSERDA provides resources, expertise, and objective information so New Yorkers can make confident, informed energy decisions.

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Advance clean energy innovation and investments to combat climate change, improving the health, resiliency, and prosperity of New Yorkers and delivering benefits equitably to all.

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Offshore Wind Planning in the New York Bight: Deepwater Wind Technologies–Technical Concepts Study

Final Report

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Abstract

This study compiles the existing information on deep water offshore wind (OSW) technology, next generation innovation, environmental impacts, and future considerations for the Area of Analysis (AoA) at or exceeding depths of 60 meters in the New York Bight. Technical specifications associated with deep water OSW turbines, moorings, anchoring, export and inter-array cables, substations, and risks for each are discussed along with a review of next generation technology. The overall design decisions start at the bottom with the anchors. Optionality for other components such as mooring lines and turbine platforms are highly dependent on anchor choice. Potential environmental impacts and considerations of deep water OSW infrastructure within the AoA, focus on physical and biological benthic constraints, oceanographic processes, and risks to marine resources and fisheries. The benthic seabed morphology and sediment type(s) determine the types of anchors that are feasible in an area, and therefore determine the OSW design. Results indicate that zone 1 is the most heavily fished with all anchor designs feasible in mud/clay areas, zone 2 has the highest density of sponges and corals with no ideal anchor due to its steep slopes and canyons, and zone 3 is the least fished with all anchor designs feasible in mud/clay areas. Future steps to support planning for deep water wind in the New York Bight region are identified to maximize energy output and minimize potential impacts to the environment and ocean users.

Keywords

offshore wind, fisheries, offshore wind technology, floating offshore wind technology, floating offshore wind environmental impacts

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Acronyms and Abbreviations

AC	Alternating Current
AoA	Area of Analysis
AUV	Autonomous underwater vehicles
BOEM	Bureau of Ocean Energy Management
Climate Act	Climate Leadership and Community Protection Act
DC	Direct current
DNV	Det Norske Veritas
EMF	Electro-Magnetic Field
FOSW	Floating Offshore Wind
GW	Gigawatt
GWh	Gigawatt Hours
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
kV	Kilovolt
kW	Kilowatt
MW	Megawatt
MWh	Megawatt-hour
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research Development Authority
OCS	Outer Continental Shelf
OCSLA	Outer Continental Shelf Lands Act
OSW	Offshore Wind
POI	Point Of Interconnection
ROV	Remotely Operated Vehicle
TLP	Tension Leg Platform
TWG	Technical Working Groups
VMS	Vessel Monitoring System
VTR	Vessel Trip Report
WEA	Wind Energy Area

Executive Summary

In 2019, New York's historic Climate Leadership and Community Protection Act (Climate Act) was signed into law, requiring the State to achieve 100% zero-emission electricity by 2040 and to reduce greenhouse gas emissions 85% below 1990 levels by 2050. The law specifically mandates the development of 9,000 megawatts (MW) of offshore wind energy by 2035, building upon its previous goal of 2,400 MW of offshore wind energy by 2030. The New York State Energy Research and Development Authority (NYSERDA) is charged with advancing these goals.

Since the early 2000s, offshore wind development off New York's coast has advanced in relatively shallow areas in the New York Bight, on the Outer Continental Shelf (OCS). As offshore wind (OSW) development continues to mature and offshore wind leases are developed in deeper waters, the size and type of the offshore wind components are likewise expected to grow, and the project footprint will change as the use of floating OSW technology begins to be deployed. This may result in changes in the types of potential effects and interactions seen to date for fixed-bottom offshore wind projects. NYSERDA is conducting studies to investigate the implications of developing floating offshore wind in deeper waters. Findings from the studies will be used to support the identification of areas that present the greatest opportunities and least risk for siting deepwater offshore wind projects, and other workstreams designed to help assure the continued responsible siting and development of offshore wind energy.

The Deepwater Wind Technologies–Technical Concepts Study examines offshore wind development in the identified Area of Analysis (AoA) at or exceeding depts of 60 meters in the New York Bight. Section 1 provides an overview of deepwater offshore wind (OSW). Section 2 describes the technical specifications associated with turbines, moorings, anchoring, export and inter-array cables, substations, and risks for each. Section 3 outlines the potential environmental impacts and considerations of deepwater OSW infrastructure within the AoA, focusing on physical and biological benthic constraints, oceanographic processes, and risks to marine resources and fisheries. Section 4 provides conclusions and future considerations for deepwater OSW development within the AoA.

Factors such as seabed morphology, water depth, and sediment type dictate the deepwater OSW structures that are feasible for use in a particular area, from the anchors to the turbines. The overall design decisions start at the bottom with the anchors. Optionality for other components such as mooring lines and turbine platforms are highly dependent on anchor choice. The physical seabed morphology and sediment type(s) determine the types of anchors that are feasible. Environmental considerations also inform technology and deepwater OSW farm design decisions. This study examines next generation technologies that may stretch the limits of what is currently deemed feasible in deep water and may help to mitigate impacts on some environmental factors. Efforts are being made to produce technology to implement deepwater OSW in a more cost-effective and environmentally responsible manner that minimizes impacts on ocean users and the marine environment. Innovative technology, infrastructure monitoring, accurate siting, and array designs could move the State closer to reaching its goals for developing clean energy in a responsible manner in the New York Bight.

Future steps to support planning for deepwater wind in the New York Bight region may include: pilot studies using next generation technologies, evaluation of shared anchor and mooring designs to minimize project footprints, and further review of design options for deepwater OSW farms that maximize energy output and minimize potential impacts to the environment and ocean users.

1 Introduction

For more than a decade, New York State has been conducting research, analysis, and outreach to evaluate the potential for offshore wind energy. New York State Energy Research and Development Authority (NYSERDA) led the development of the New York State Offshore Wind Master Plan (Master Plan), a comprehensive roadmap and suite of more than 20 studies for the first 2,400 megawatts (MW) of offshore wind energy. The Master Plan encourages the development of offshore wind in a manner that is sensitive to environmental, maritime, economic, and social issues while addressing market barriers and aiming to lower costs. The Master Plan included spatial studies to inform siting of offshore wind energy areas. Now, NYSERDA is undertaking new spatial studies to review the feasible potential for deepwater offshore wind development at or exceeding depths of 60 meters in the New York Bight.

Planning processes considering the development of offshore wind in the deepwater areas examined in each of NYSERDA's spatial studies must consider these studies in the context of one another. Decision making must additionally consider different stakeholders and uses, and will require further adjusted approaches and offshore wind technologies to ensure the best outcome. Globally, deepwater wind technology is less mature and primarily concentrated on floating designs at the depth ranges being assessed through these spatial studies, while deepwater fixed foundations are at their upper technical limit within the Area of Analysis (AoA). Therefore, floating designs were predominantly considered Since most, if not all, of the AoA would likely feature floating offshore wind (FOSW). NYSERDA, along with other state and federal agencies, is developing research and analysis necessary to take advantage of opportunities afforded by deepwater OSW energy by assessing available and emerging technologies and characterizing the cost drivers, benefits, and risks of FOSW. Findings from these studies and available datasets will be used to support the identification of areas that present the greatest opportunities and least risk for siting deepwater OSW projects. Offshore wind energy development is being introduced into a highly dynamic and human-influenced system. These reports seek to better understand the potential interaction of offshore wind development and marine wildlife and habitats; however, it is important to consider these within the broader context of climate change and existing land-based and marine activities.

1.1 Benefits and Cost-Reduction Pathways

The State's Master Plan analysis concluded that OSW development will enhance the State's job market, supply chain, and economy; reduce the use of fossil fuels; and provide other public health, environmental, and societal benefits. While the State plans to continue procuring offshore wind projects within the existing lease areas, the timing is right to build a better understanding of the opportunities and challenges of projects farther offshore. Cost is a critical consideration for the State in the development of offshore wind. A focused study on the cost landscape and technological readiness for deepwater offshore wind of 60 to 3,000 meters in water depths in the AoA was conducted to help the State understand how floating offshore wind may fit in New York's renewable energy portfolio. Additional discussion of costs and cost-reducing strategies focusing on State options for contracting related to deepwater OSW, job-training programs, and infrastructure investments will also be developed as part of future planning efforts. The State will continue to undertake research and engage its established Technical Working Groups (TWGs) on key subjects of fishing, maritime commerce, the environment, workforce, environmental justice, the supply chain, and the implications of floating offshore wind. The TWGs will continue to inject expert perspectives and the most recent information as an integral part of future decision making.

When combined, the information assembled in these studies will empower New York State and its partners to take the informed steps needed to continue to capitalize on the unique opportunity presented by offshore wind energy.

1.1.1 Spatial Studies to Inform Lease Siting

- Benthic Habitat Study
- Birds and Bats Study
- Deepwater Wind Technologies–Technical Concepts Study
- Environmental Sensitivity Analysis
- Fish and Fisheries Data Aggregation Study
- Marine Mammals and Sea Turtles Study
- Maritime Assessment–Commercial and Recreational Uses Study
- Offshore Wind Resource Assessment Study Zones 1 and 3
- Technology Assessment and Cost Considerations Study

Each of the studies was prepared in support of a larger planning effort and shared with relevant experts and stakeholders for feedback. The State addressed comments and incorporated feedback received into the studies. Feedback from these diverse groups helps to strengthen the studies, and also helps ensure that these work products will have broader applicability, and a comprehensive view Please note that assumptions have been made to estimate OSW potential and impacts in various methodologies across the studies. NYSERDA does not necessarily endorse any underlying assumptions in the studies regarding technology and geography, including but not limited to turbine location, turbine layout, project capacity, foundation type, and point of interconnection (POI).

The Energy Policy Act of 2005 amended Section 8 of the Outer Continental Shelf Lands Act (OCSLA) to give BOEM the authority to identify OSW development sites within the Outer Continental Shelf (OCS) and to issue leases on the OCS for activities that are not otherwise authorized by the OCSLA, including wind development. The State recognizes that all development in the OCS is subject to review processes and decision-making by BOEM and other federal and State agencies. This collection of spatial studies is not intended to replace the BOEM WEA identification process and does not commit the State or any other agency or entity to any specific course of action with respect to OSW energy development. Rather, the State's intent is to facilitate the principled planning of future offshore development off the New York coast, provide a resource for the various stakeholders, and encourage the achievement of the State's OSW energy goals.

1.1.2 Scope of Study

The spatial studies will evaluate potential areas for deepwater OSW development within a specific geographic AoA of approximately 35,670 square miles of ocean area extending from the coast of Cape Cod south to the southern end of New Jersey (refer to Figure 3). It includes three zones extending outward from the 60-meter depth contour, which ranges between 15 and 50 nautical miles from shore to the 3,000-meter contour, which ranges from 140 to 160 nautical miles from shore.

The eastern edge of the AoA avoids Nantucket Shoals and portions of Georges Bank, since those areas are well known to be biologically and ecologically important for fish and wildlife, fisheries, and maritime activity. The AoA does include other areas that are unlikely to be suitable for BOEM lease sites, such as the Hudson Canyon, which is under consideration to be designated as a National Marine Sanctuary. While OSW infrastructure will not be built across the entire AoA, the spatial studies analyze this broad expanse to provide a regional context for these resources and ocean uses.

- Zone 1 is closest to shore and includes a portion of the OCS. It extends from the 60-meter contour out to the continental shelf break (60 meters [197 feet] to 150 meters [492 feet] deep). Zone 1 is approximately 12,040 square miles.
- Zone 2 spans the steeply sloped continental shelf break, with unique canyon geology and habitats (150 meters [492 feet] to 2,000 meters [6,561 feet] deep). Zone 2 is approximately 6,830 square miles.
- Zone 3 extends from the continental shelf break out to 3,000 meters (9,842 feet) depth. Zone 3 is approximately 16,800 square miles.

Zone 2, stretching across the steeply sloped continental shelf break with its distinctive canyon geology and unique habitats, is unlikely to host OSW turbines, but is still likely to be impacted by OSW development activities through maritime traffic and/or cabling. Therefore, Zone 2 is included in this Deepwater Wind Technologies–Technical Concepts Study.

1.2 Deepwater Wind Technologies–Technical Concepts Study Introduction

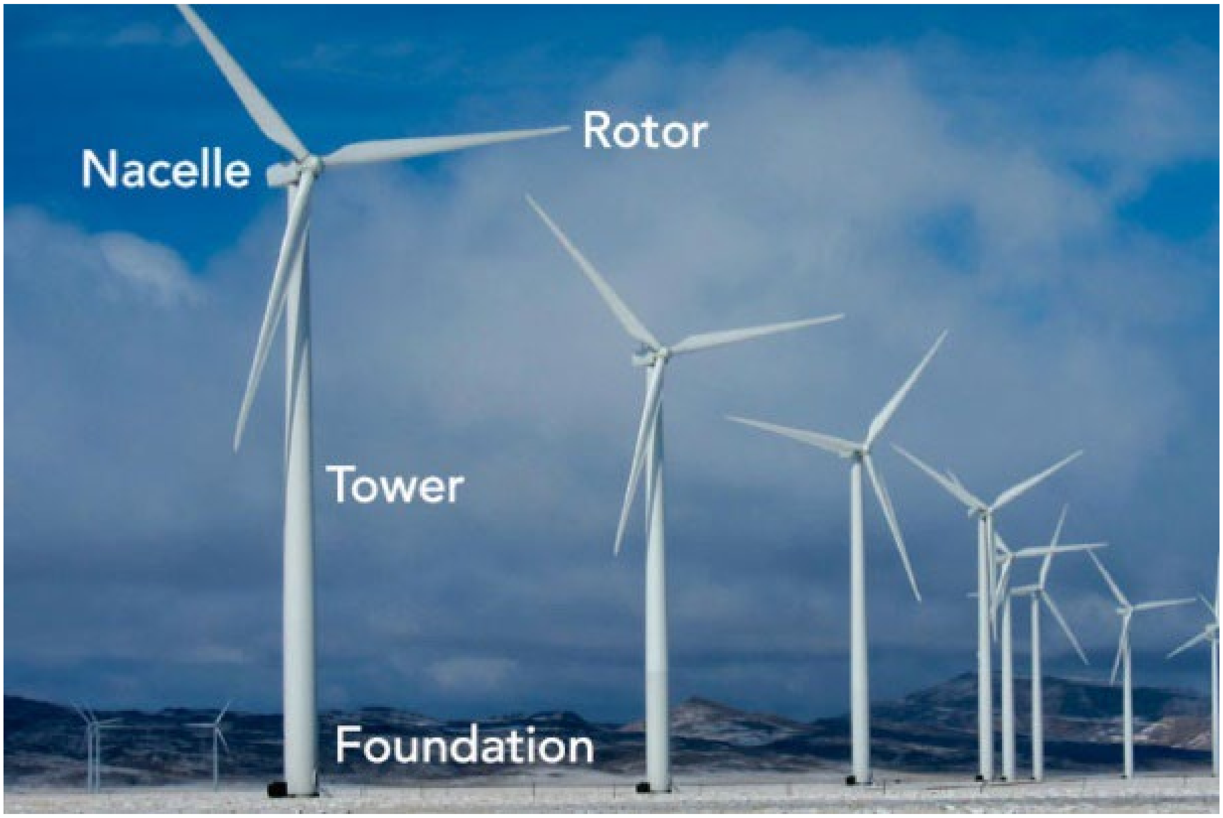
The purpose of the Deepwater Wind Technologies–Technical Concepts Study is to provide an overview of deepwater OSW technology that may be used to support OSW development off the coast of New York State in the AoA. It will also examine the potential risks to OSW infrastructure and to the environment and fisheries from deepwater OSW development. The study will also be used as a NYSERDA reference to inform stakeholders and assist with future discussions regarding siting for deepwater OSW in the region.

The following text describes some of the common OSW development terminology and definitions used in this Deepwater Wind Technologies–Technical Concepts Study (basic components seen in Figure 1):

- Deepwater Wind—Refers to OSW that is in 60 meters (197 feet) or greater water depth. As of report time there are no fixed foundation commercial scale projects deeper than 59 meters (194 feet).
- FOSW—OSW technology that includes a turbine supported by a buoyant floating foundation (also known as a “floater”) anchored to the seabed.
- Turbine—The power generator and its components, including the hub, blades, nacelle, tower, and foundation, either fixed or floating.
- Mooring system—The combination of anchors and mooring lines used for FOSW to hold the floating foundation in place.
- Inter-array cables—Cables between each OSW turbine in an array that tether the turbines together, and eventually feed terminal cables that lead to an offshore substation.
- Offshore substation—A structure often located inside a lease area that collects and stabilizes the power generated by the turbines, preparing it for transmission to shore.
- Export cable—A cable that sends power to an onshore substation at the POI.
- POI—Location where the OSW power is injected into the land-based power grid.
- Hub Height—Distance from the sea surface to the center of the wind turbine rotor, the rotor is made up of the blades and hub where the blades are connected.
- Rotor Thrust Forces—Forces exerted on the rotor due to the aerodynamic (wind) interaction with the turbine blades, which is compounded by movements of a floating platform.
- Air Draft—Distance between the waterline and the highest point of an object.
- Water Draft—Distance between the water line and the lowest point of an object.
- Nacelle—The “head” of the wind turbine mounted on top of the support tower. The rotor blade assembly is attached to the front of the nacelle.

Figure 1. Basic Components of a Wind Turbine

Source: Arcadia 2017



1.3 Offshore Wind Overview

OSW in the U.S. is predominantly made up of fixed-bottom foundations which are feasible in up to 60 meters of water depth, and most common along the U.S. East Coast within the shallow water depths provided by the wide continental shelf. Figure 2 details various fixed-bottom foundation designs (Riefolo et al. 2016). In the U.S., there are 20 leases contracted through BOEM along the Atlantic coast from New Jersey to Massachusetts as of [November] 2023 (Figure 3). The 2021 White House Executive Order 14008 (86 Fed. Reg. 7619) set a goal of reaching 30 gigawatts (GW) of OSW energy development in the U.S. by 2030. New York is among the leading states in contributing to this goal.

Figure 2. Types of Fixed-Bottom Foundation Offshore Wind Platform Designs

Source: EWEA 2013

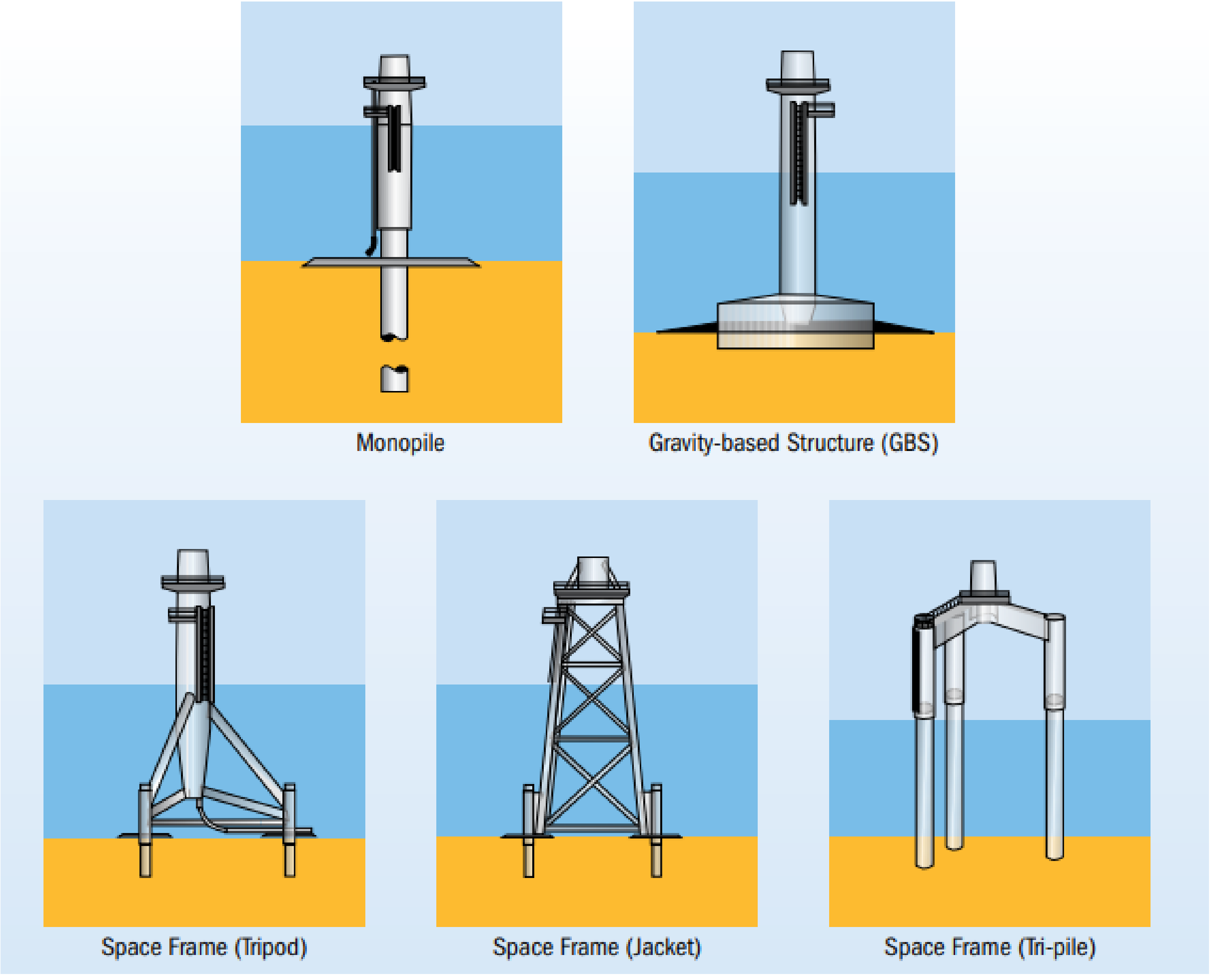
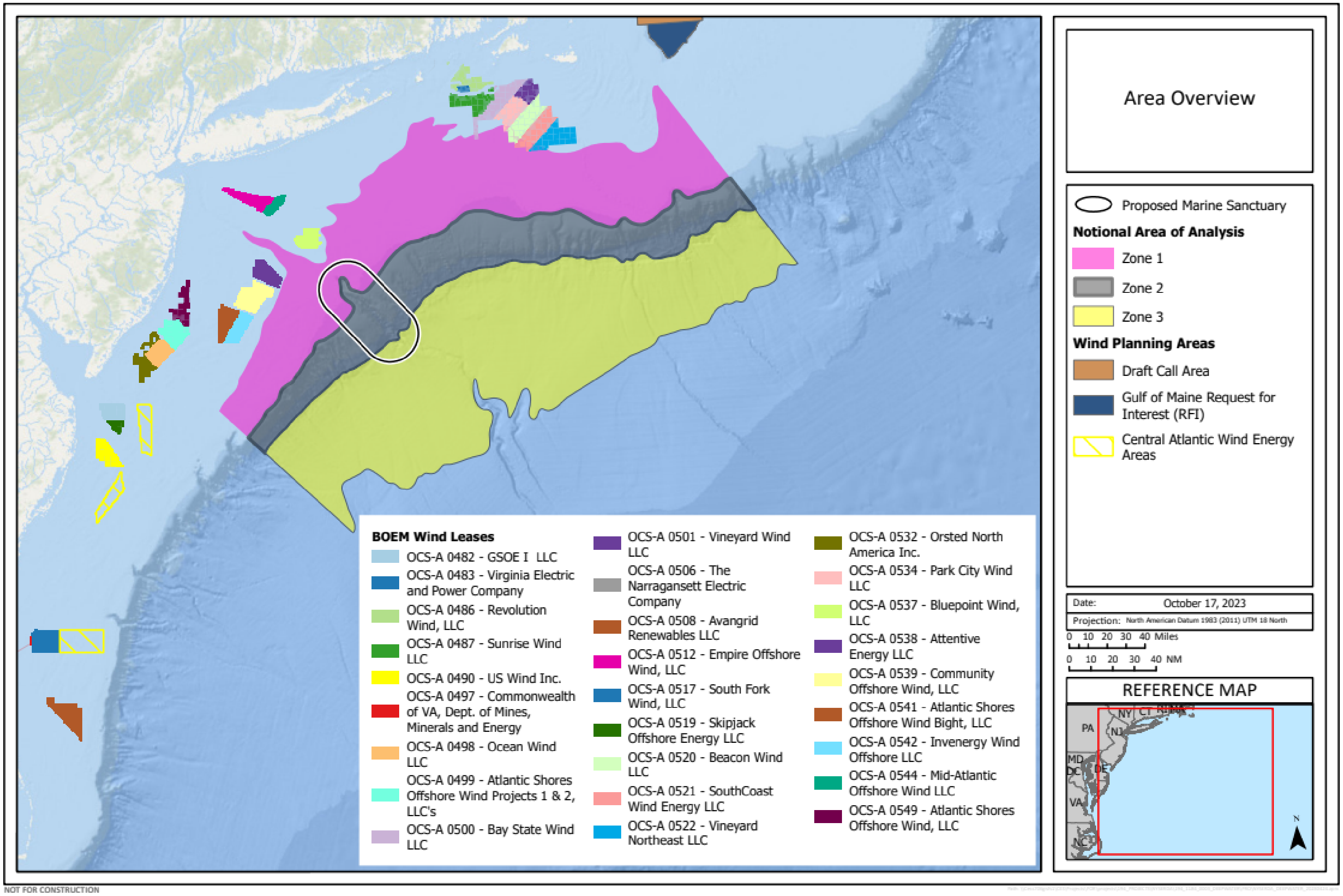


Figure 3 details the three zones in the AoA being assessed for deepwater wind beyond 60 meters (197 feet). The three zones stretch from New Jersey to the start of the Gulf of Maine offshore. As discussed in section 1.1.3, Zone 1 includes the continental shelf area that occurs beyond the existing New York Bight lease areas to the shelf break, including a depth range of 60–150 meters (197–492 feet). Zone 1 includes depths that currently serve as the transition zone between available technologies, since at the shallowest depths of this zone there may be the option to use fixed turbine foundation technologies in the near future. Zone 2 includes the continental shelf break, including a depth range of 150–2,300 meters (492–7,546 feet). Zone 3, the deepest zone, includes the abyssal plain with depths ranging from 2,300–3,000 meters (7,546-9,843 feet). This Deepwater Wind Technologies–Technical Concepts Study reviews the high-level technical concepts, limitations, and environmental impacts of deepwater OSW infrastructure and installation within the AoA.

Figure 3. Northeast Offshore Wind Projects, Planning Areas, and Three Zones within Areas of Analysis Considered

Courtesy NYSERDA



1.4 Deepwater Wind Overview

Worldwide, deepwater wind technology is primarily concentrated on floating designs, as deepwater fixed foundations have not been developed. The deepest fixed-bottom foundation farm, Seagreen in eastern Scotland, includes jacket foundations installed in depths of up to 59 meters (194 feet), is fully operational, and has a total installed capacity of 1,075 MW. In the U.S., floating technology is preferred for deepwater locations deeper than 60 meters (197 feet). Both floating and fixed technologies are included in this Deepwater Wind Technologies–Technical Concepts Study as relevant, with a case study describing the current technology used for the deepest fixed foundations and several next generation fixed and hybrid concepts, and both current and next generation technology for floating wind foundations.

Deepwater OSW projects are in their infancy. Fewer than 20 projects have been installed worldwide, and several of these were small demonstration projects that have since been decommissioned. For example, one single turbine 1:8 demonstration scale project (VolturnUS) was installed in Maine in 2013 and decommissioned the same year. This project used a concrete semi-submersible hull design with a spread mooring system.

The number of planned projects is over 40 and climbing, with planned projects set to benefit greatly from data and lessons learned through the demonstration and pre-commercial FOSW turbine and other deepwater wind projects. As an example, the New England Aqua Ventus I project is planned for installation in 2024 and will be a full-scale demonstration of 11 MW using the VolturnUS hull technology. The primary goals of this project are to demonstrate the design of the VolturnUS hull with a full-size OSW turbine and to work with local contractors to create jobs in Maine. Additional U.S. FOSW turbine projects are in various stages of planning in California, Maine, and Hawaii. The specific FOWS turbine technology planned for use in the proposed projects is undetermined as they are still in the early stages.

Despite technical challenges and immature industry, the demand for deepwater OSW in the U.S. persists due to the need to meet federal and state climate goals described in section 1.1, and to the many perceived advantages of developing OSW in deep water. For example, in many geographic locations wind energy potential is greater further offshore due to limited shallow water resources. The west coast of the U.S. has a narrow continental shelf (32 kilometers [20 miles] wide on the west coast versus 120 kilometers [75 miles] wide on the east coast) with steep drop-offs near the coast, making deeper sites the only option when weighing visual impacts and other nearshore ocean spatial use. Other spatial conflicts with OSW development, such as overlapping fisheries, are less likely in deeper waters further from shore. The overall available space in waters beyond 60 meters (197 feet) is vast. About two-thirds of the total potential ocean space area for OSW is located in deep water (NREL 2023). Expanding into deepwater areas is inevitable as OSW development progresses.

Although deep water is ideal for OSW in the numerous ways explained above, and further elaborated on in this Deepwater Wind Study, deepwater OSW technology is relatively new, which carries its own risks. Many of the first-generation deepwater designs rely on OSW components designed for shallow water or for floating oil and gas structures, neither of which is optimized for FOSW. Components designed for shallow water are too small and do not capture the scale or value of deepwater wind. Designs based on floating oil and gas structure are proven to operate in deeper waters but not for structures as tall or dynamic as wind turbines and mooring systems.

Turbine sizes will increase in deep water, thereby increasing materials cost. For scale, currently installed monopile foundations used in shallow water (< 60 meters [197 feet]) typically include turbines about 7.5 meters (25 feet) in diameter, and next generation turbine designs include monopiles around 13 meters (43 feet) in diameter. Fixed foundations in deep water will require even longer and wider monopiles to withstand the additional stress on the structure from more hydrostatic pressure and other physical forces that come with greater depths. Larger foundations create cost increases due to both the generally high and volatile price of steel (Myhr et al. 2014). It is for this reason that an analysis done by the National Renewable Energy Laboratory (NREL) found fixed-bottom foundations too costly when considering the compounding technical challenges presented in water depths greater than 50 meters (164 feet).

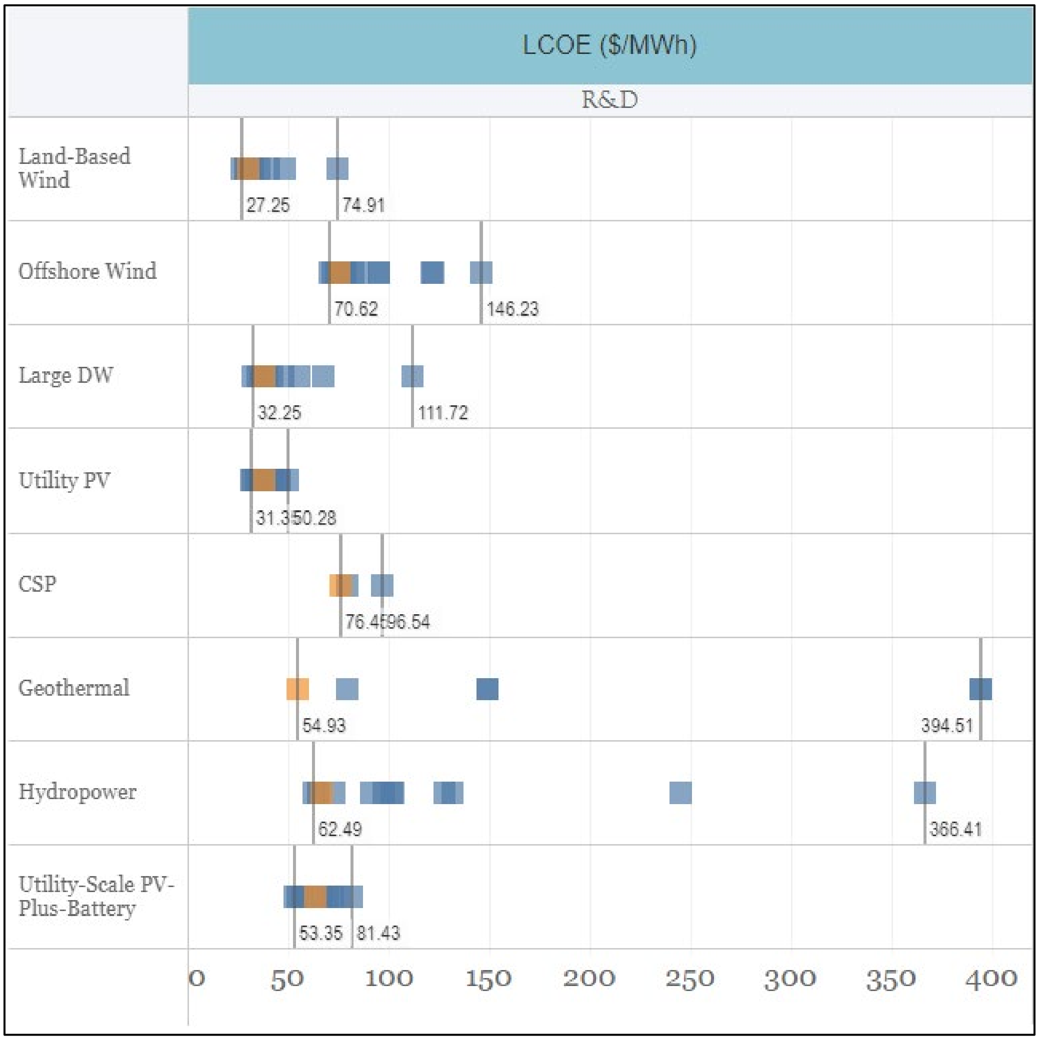
At commercial scale, a FOSW project is currently estimated to cost about 50 percent more than fixed-bottom foundation projects (NREL 2022a,b). At shallower water depths, fixed foundation technology for OSW is achievable at significantly lower cost compared to FOSW. To reduce costs for FOSW technology, an effort must be made to understand and achieve commercial scalability of foundation technologies. In support of this, the U.S. Department of Energy (DOE) introduced the Floating Offshore Wind Shot initiative in 2023, which seeks to reduce the cost of FOSW energy by more than 70 percent (to $45 per Megawatt-hour ((MWh)) by 2035 for deepwater sites. The initiative includes funding to research and improvement upon aspects of project development that are currently challenging and costly, such as (1) volatile material inputs for manufacturing, (2) limitations in a local U.S. based supply chain, (3) onshore grid upgrades, and (4) transmission integration (DOE 2023).

Addressing the overall cost of deepwater OSW projects will require a combination of innovations in technology with specific consideration to geography, site conditions, unique deepwater project design features, and installation methods (Garret et al. 2020). Figure 4 details the costs of energy for electricity-generating technologies. Innovations are needed to achieve broad efficiencies that result in reduced costs as seen in shallow water installations.

Figure 4. Levelized Cost of Energy for Electricity-Generating Technologies

Representative values for offshore wind include $70.62/MWh for a Class I fixed-bottom foundation installation, and $146.23/MWh for a Class 14 floating wind installation[1].

Source: NREL 2022c



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[1] PV = Photovoltaics, DW = Distributed Wind, and CSP =Concentrating Solar Power

2 Deepwater Offshore Wind Project Technical Specifications

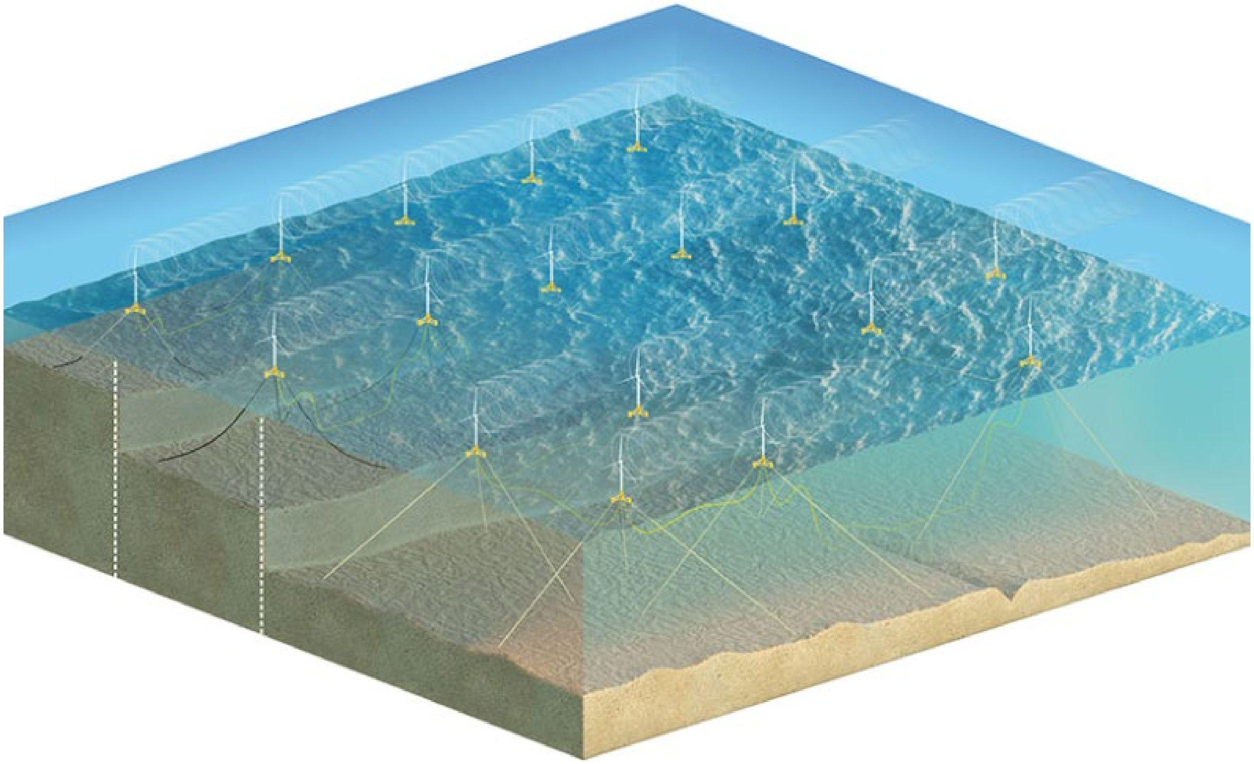
There are many design options contemplated for FOSW. As there are so few commercial deepwater installations currently in operation, marine engineers are continuing to model and test designs as well as build prototypes until a dominant technology or set of technologies emerges as most synergistic and capable of performing in a variety of different environmental conditions. To date, a blend of new and existing technologies used in other industries has produced multiple options for deepwater installations, With this push in innovation more options will continue to emerge in the coming stages of industry development.

Engineering and modeling efforts such as NREL's Floating Wind Array Design project will be integral to guide the design of large commercial scale deepwater OSW developments in the U.S. (Figure 5).

Figure 5. Example Array Design, Including Power Cables Anchoring to the Seafloor and Running between Turbines

One option for an array.

Source: NREL 2023



The sections below provide descriptions of the different primary components of deepwater OSW infrastructure, options for each component, and specifications, requirements, and capabilities of the readily available designs. The main focus of these sections is to provide an overview of the risk to deepwater wind infrastructure with case studies provided in section 2.7. Figure 6 includes an overview of multiple designs suitable for deep water and activities required for site assessment, construction, operations and maintenance, and decommissioning.

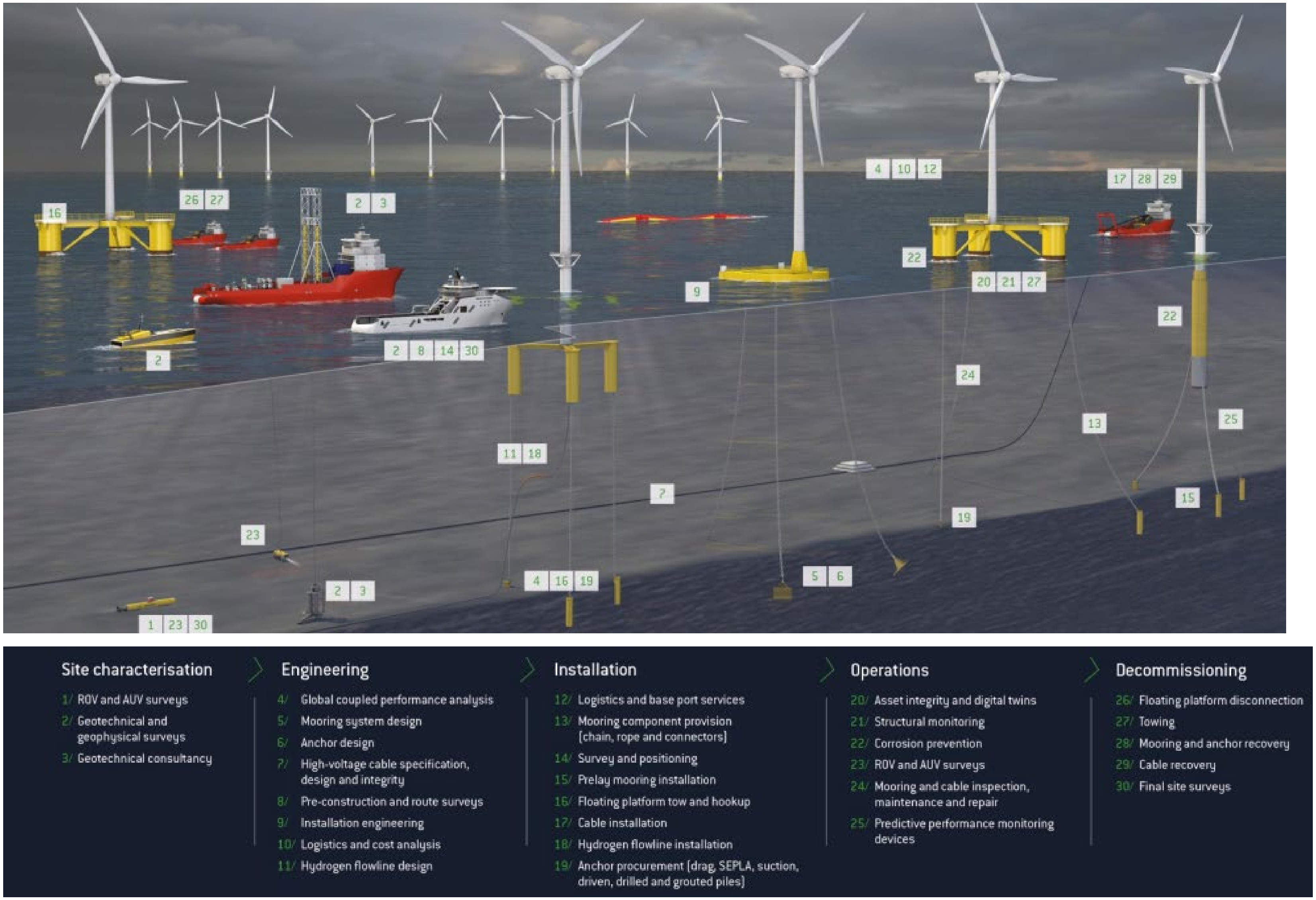
2.1 Turbine Types

2.1.1 Wind Turbine Generators

The preference for developers is to use the largest wind turbine generators commercially available to minimize the number of structures necessary for deployment, while still achieving the desired capacity. This minimizes the environmental impacts and reduces operations and maintenance costs (Musial et al. 2022). Similar to how the fixed-foundation OSW industry has assimilated lessons learned from onshore wind, FOSW can leverage lessons learned in fixed-foundation OSW to upscale and achieve commercial scale capacity (Orsted 2022). The size and capacity of OSW turbine generators has steadily increased over the last several decades, from 450 kilowatt (kW) in the first OSW farm installed off the coast of Denmark in 1991 (Shahan 2014), to a 16 MW prototype installed off the coast of China in June 2023 (Xin 2023). This trend is expected to continue, with sources predicting that commercially available wind turbine generators could reach a capacity of 20 MW or even as high as 30 MW by 2030 (Memija 2022; Proctor 2023). The wind turbine generators installed on floating platforms are the same as those installed for fixed OSW, with minor modifications to account for different forces acting on floating platforms (Carbon Trust 2022). The largest wind turbine generators currently installed offshore on fixed foundations are: (1) the Vestas V236-15.0 MW prototype off the coast of Denmark, which reached its 15 MW capacity for the first time in April 2023 and expects to receive its type certification in the third quarter of 2023 (Lewis 2023), and (2) the China Three Gorges Corporation's 16 MW wind turbine generator installed off the southeastern coast of China, which became fully operational in July 2023. Comparatively, the largest wind turbine generators deployed to date on a floating platform are the 9.525 MW Vestas V164 at the Kincardine OSW farm off the coast of Scotland. As the design of FOSW platforms matures, the size and capacity of the wind turbine generators will continue to be upscaled. The proposed New England Aqua Ventus I project off the coast of Maine, expected to be completed by the end of the decade, will use an 11 MW turbine (Nilson 2023). An Irish company, Gazelle, has announced a new floating wind platform that they claim could support turbines up to 20 MW (Blain 2023).

Figure 6. Examples of Deepwater Wind Designs and Required Activities for the Implementation of a Wind Farm

Source: Acteon Floating Renewables 2022



Site characterisation

1/ ROV and AUV surveys
2/ Geotechnical and geophysical surveys
3/ Geotechnical consultancy

Engineering

4/ Global coupled performance analysis
5/ Mooring system design
6/ Anchor design
7/ High-voltage cable specification, design and integrity
8/ Pre-construction and route surveys
9/ Installation engineering
10/ Logistics and cost analysis
11/ Hydrogen flowline design

Installation

12/ Logistics and base port services
13/ Mooring component provision [chain, rope and connectors]
14/ Survey and positioning
15/ Prelay mooring installation
16/ Floating platform tow and hookup
17/ Cable installation
18/ Hydrogen flowline installation
19/ Anchor procurement [drag, SEPLA, suction, driven, drilled and grouted piles]

Operations

20/ Asset integrity and digital twins
21/ Structural monitoring
22/ Corrosion prevention
23/ ROV and AUV surveys
24/ Mooring and cable inspection, maintenance and repair
25/ Predictive performance monitoring devices

Decommissioning

26/ Floating platform disconnection
27/ Towing
28/ Mooring and anchor recovery
29/ Cable recovery
30/ Final site surveys

2.1.2 Platforms

Deepwater wind turbine designs currently focus on floating platforms. Although next-generation fixed platform designs for deep water that are variations on shallow water designs are being explored (see section 2.1.3), deepwater fixed-bottom foundations are currently cost prohibitive.

There is no shortage of deepwater floating wind technology concepts and designs, with estimates of available commercial designs ranging into the hundreds (Buljan 2023). To date, there have only been approximately 50 deepwater floating wind platforms at either research or commercial scale commissioned worldwide (Whiting 2022; Sorlie n.d.). The majority of deepwater wind turbine type concepts have been adapted from fixed-bottom foundations and floating platforms used in oil and gas industry; however, additional considerations such as specifications of the tower and wind turbine generator type, operating conditions, scale, and volume can be unique to deepwater wind (Weller 2022). Additionally, unlike fixed OSW, due to the interface between wave and tidal motions exerted on the platform and the aerodynamic forces exerted on the tower and wind turbine generators for floating deepwater wind, parallel design of all components (controlled co-design) can be beneficial in optimizing FOSW design (Blain 2023). There are four main types of floating deepwater wind platforms categorized according to the mechanism used to attain hydrostatic equilibrium or static stability (Musial 2020): (1) barge, (2) semisubmersible, (3) spar leg platform, and (4) tension leg platform (TLP) (Figure 7). The dependencies and challenges of each of these main platforms are summarized in Table 1. In addition to the four main types of platforms, several new, hybrid, and multi-turbine floating substructure designs are under development, which are described in section 2.1.3.

Figure 7. Four Main Types of Floating Deepwater Wind Platforms

Source: Zhou et al. 2023

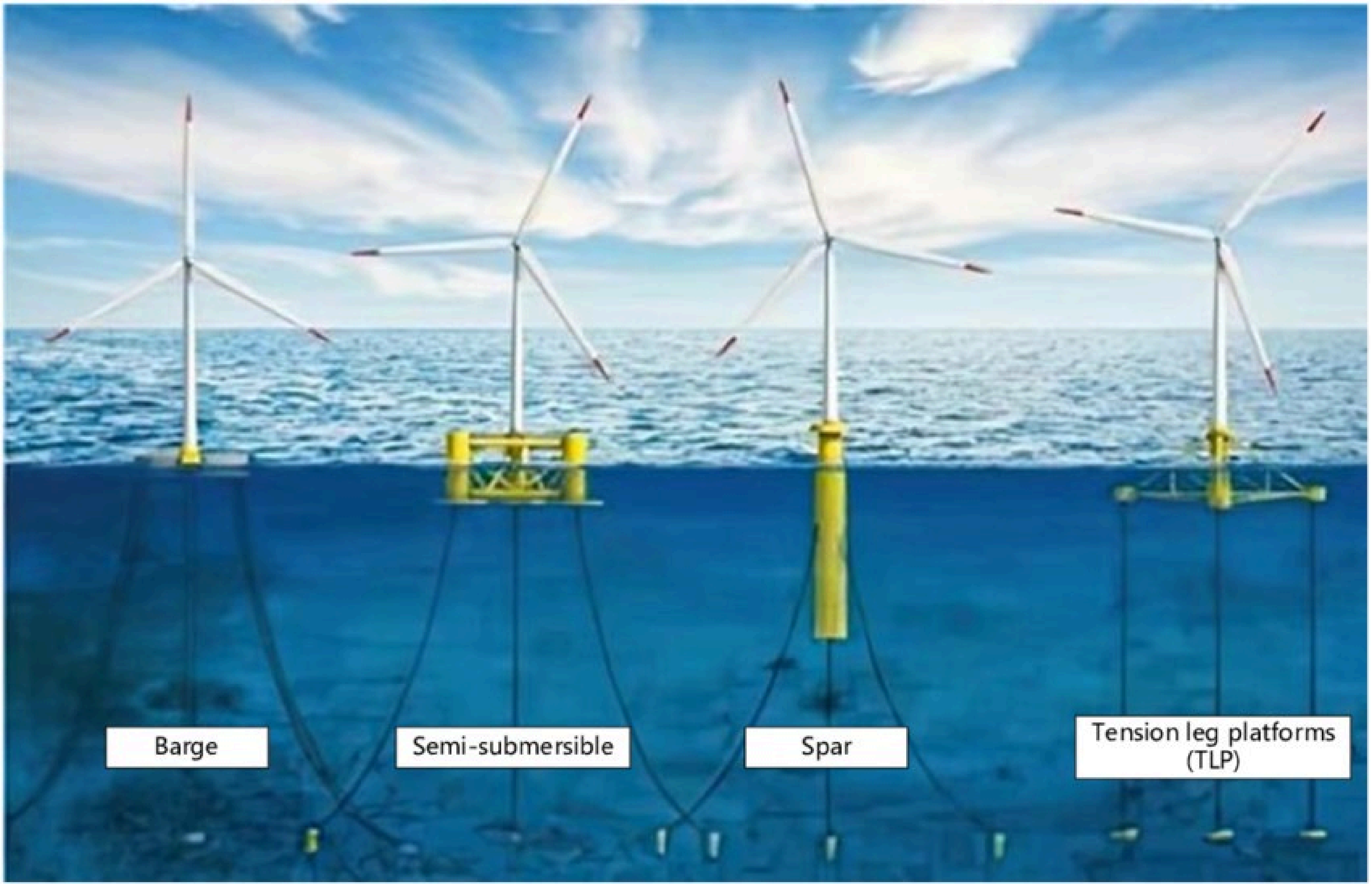


Table 1. Summary of Main Platform Types

Sources: Maxwell et al. 2022, Musial 2023, ABS 2013.

Platform Type	Equilibrium (Static Stability) Mechanism	Construction Needs	Dependencies and Challenges	Example Project(s)
Barge–One of the earliest design concepts composed of a large floatation system made of concrete and/or steel. Smallest draft requirement (20 meters [66 feet]).	Waterplane area	Staged in port then towed to deployment site.	• Larger proportion of platform surface above sea surface resulting in greater vulnerability to waves. • Requires port with no overhead restrictions. • Shallow draft hull enables use of shallower ports.	Floatgen (France; Floatgen n.d.)
Semi-submersible Platform–Currently dominant platform for floating offshore wind (FOSW), combines components of other platform types, typically composed of 3 to 4 columns with wind turbine generator installed on one of the columns.	Distribution of buoyancy widely at the water plane	Staged in port then towed to deployment site.	• Larger proportion of platform surface above sea surface resulting in greater vulnerability to waves. • Requires port with no overhead restrictions. • Comparatively large footprint at sea surface provides good stability. • Shallow draft hull enables use of shallower ports.	WindFloat Atlantic (Portugal; WindFloat Atlantic n.d.) Hibiki (Japan; Hibiki Wind Energy 2021) Kincardine (Scotland; Principle Power 2022)
Spar Platform–Cylindrical vertical platform with largest draft (120 meters [394 feet]).	Ballast weight installed below main buoyancy tank	Assembled in deepwater locations.	• Improves stability by increasing ballast in lower part of platform and lowering center of gravity. • Deep draft can limit access to shallow water ports.	Hywind (Scotland; Equinor 2023b) TetraSpar Demonstrator (Denmark; RWE 2023)
Tension Leg Platform–Vertically moored floating structure.	Tension in stiff mooring lines and submerged buoyancy tanks	Staged in port then towed to deployment site.	• Can be unstable during assembly. • Experiences high vertical load due to high tension on mooring lines; associated taught mooring. • Much smaller seafloor footprint. • Less risk of entanglement because mooring lines are vertical in the water.	X1 Wind (France; X1 Wind 2023) Provence Grand Large (under construction) (France; Prysmian Group 2023)

2.1.3 Next Generation Platforms

In addition to the four main floating deepwater wind platforms described above, there are numerous novel floating platform technologies currently under development including hybrid designs and multi-turbine platforms, and a few examples of fixed deepwater platform designs, one of which involves a hybrid floating and fixed platform technologies. Examples of hybrid and next generation fixed and floating platforms are described below.

The Irish company Gazelle has developed a hybrid platform that incorporates characteristics of both semi-submersible and TLPs, resulting in a smaller, lighter, less expensive platform that can be quickly deployed without specialized vessels and can support up to a 20 MW wind turbine generator. The unique dynamic mooring system (described further in section 2.2.2) is capable of balancing wave, tidal, and wind motions to reduce pitching and improve efficiency (Blain 2023) (see in Figure 8).

Figure 8. Gazelle Floating Platform

Source: Blain 2023

The Spanish company Esteyco is developing the Telewind® floating platform, which is a modified spar platform made of concrete, versus steel (Du 2021)—more commonly used for floating platforms (Figure 9). The platform is made up of two concrete rings nested inside each other. This platform requires a 16-foot (5 meters) draft clearance during assembly and towing, enabling the use of shallower water ports, removing the need to exclusively select ports with a deeper draft (Rivero 2023). A draft clearance determines the maximum permissible draft of a vessel to safely enter or leave a port. The draft of a vessel is the distance from the waterline to the lowest point of the hull, and it depends on the weight and distribution of the cargo, fuel, ballast, and other factors. After the platform is pulled out into the open ocean, the inner concrete ring is dropped to 50 meters (106 feet) below the surface and acts as a counterweight to stabilize the turbine (Rivero 2023).

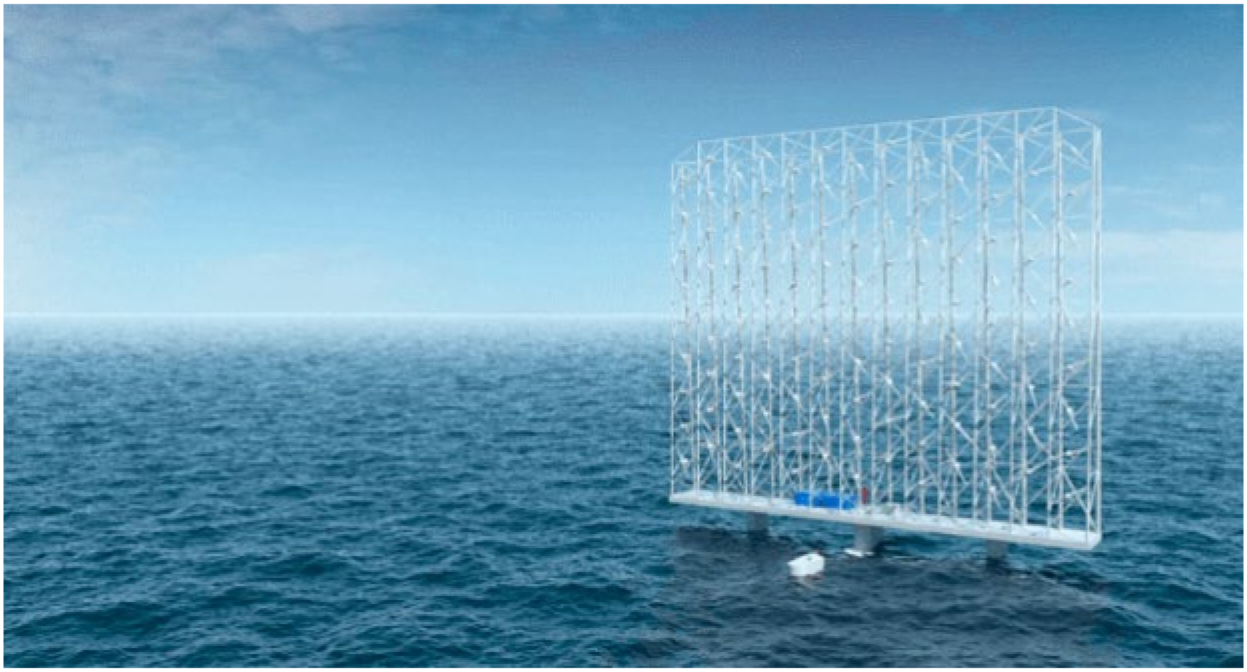
Figure 9. Esteyco Telewind® Floating Platform

Source: Esteyco 2023

Norwegian company Wind Catching Systems is developing the Windcatcher floating offshore power generator, which relies on numerous smaller turbines producing more rotations per minute than larger turbines generating more energy (Figure 10). The Windcatcher structure would have more than 100 rotors stacked vertically which could produce as much energy as five of the largest floating wind turbines in existence at half the cost (Hahn 2021). Wind Catching Systems has acquired a grant from Enova (an investment company owned by Norway’s Ministry of Climate and the Environment) and plans to install a turbine off the west coast of Norway for testing and certification in 2023 (The Maritime Executive 2022a).

Figure 10. Wind Catching Systems Windcatcher Multi-Turbine Platform

Source: Hahn 2021



Swedish based developer Hexicon has developed a multi-turbine platform called TwinWind™ that has two wind turbine generators mounted on one platform that is anchored to the seafloor with a single point mooring (Figure 11). The single point mooring allows the foundation to weathervane, or move, to align with the wind, as compared to the individual turbine nacelle moving to align with the wind in more traditional designs. (Hexicon Power 2022). This design allows for more turbines to be installed within a smaller area, which increases the energy yield, minimizes environmental impacts, and reduces costs associated with cables, steel, installation, and maintenance (Hexicon Power 2022). The design is compatible with major OSW turbine designs ranging from 3MW to 15+MW (Hexicon Group 2022a). Hexicon received a Statement of Feasibility from Det Norske Veritas (DNV) for the TwinWind™ platform in 2021 and received support from the United Kingdom government to deploy the first floating wind farm off of England and Wales in 2022. The 32 MW project is expected to be commissioned between 2025 and 2027 (Hexicon Group 2022b).

Figure 11. Hexicon TwinWind™ Multi-Turbine Platform

Source: Worley 2021

As stated above, deepwater fixed-bottom foundations are currently cost prohibitive; however, in recent years, several companies have proposed concepts for fixed-bottom foundations that can be installed in water depths of up to 100 meters (328 feet). The Barcelona based company Offshoretronic S.L. has presented a concept called TRIPOD "PLUS ©," a fixed platform composed of a tripod and monopile that they claim is fully scalable for wind turbine generators over 20 MW capacity that can be deployed in waters up to 90 meters (295 feet) (Figure 12). The platform can be installed in all types of seabed soils because it can be fixed to the seafloor via pre-piling, post-piling, suction buckets or a combination of small suction buckets and post piles (Durakovic 2021). Additionally, to support installation of the longer monopiles required for deepwater OSW, WinDecom, a wholly owned subsidiary of Offshoretronic, is developing a transportation and installation vessel with a tilting and lifting beam and roll-on concept (Figure 13), which is expected to reduce costs and installation timeframes as well as operational risks in port and during installation offshore without requiring crane lifts (Durakovic 2023).

Figure 12. Offshoretronic S.L TRIPOD “PLUS ©” Turbine Platform

Source: Durakovic 2021

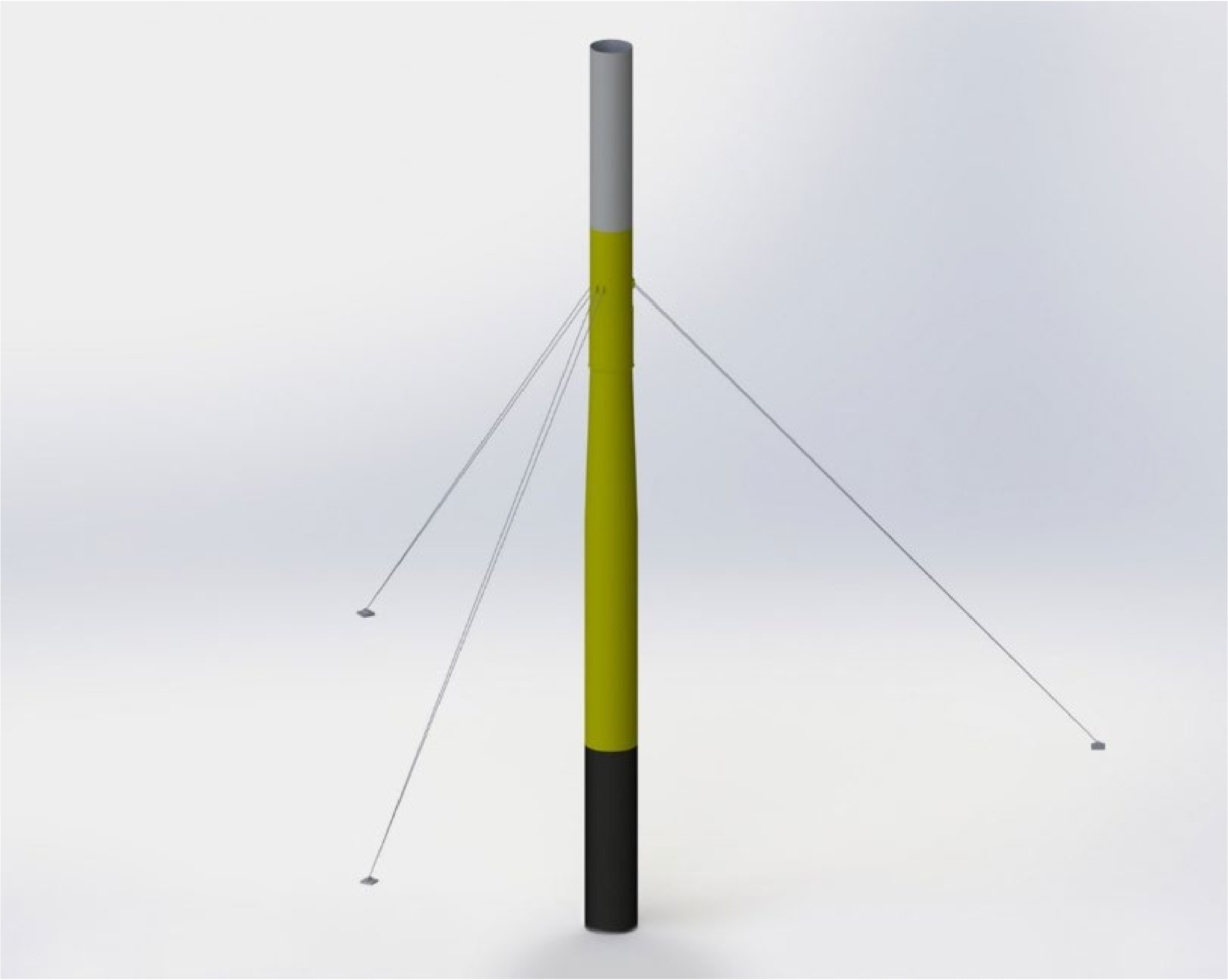
Figure 13. WinDecom Transportation and Installation Vessel

Source: Durakovic 2023

U.S. based company Entrion Wind recently received a statement of feasibility from DNV for its fully restrained platform which is a combination of fixed and floating platform technologies that enables the use of monopiles in up to 100-meter (328 feet) water depths as shown in Figure 14 (Memija 2023). The platform consists of a monopile, transition piece, and mooring system which can either be taught with pile anchors or with suction piles (Memija 2023). Feasibility studies are currently ongoing for the fully restrained platform concept, with a demonstration planned for 2024 and commercial operations are targeted for 2026 (Memija 2023).

Figure 14. Fully Restrained Platform Offshore Wind Foundation

Source: Durakovic 2022



2.2 Moorings

Each floating deepwater wind platform is typically stabilized by at least three mooring lines anchored to the seabed (Maxwell et al. 2022). Similar to floating platforms, mooring designs have been adapted from the oil and gas industry, as well as different types of buoys (e.g., navigation, metocean, etc.) that have been deployed for many years. However, there are additional design parameters to be considered for moorings used to support FOSW, including: tower configuration and flexibility, operational modes of the wind turbine generator, rotor thrust forces, hub height operating wind speed range, electrical cable layout, and wind farm configuration. Some of the key differences between the moorings used for FOSW and the moorings used in the oil and gas industry or for buoys are the use of new materials such as nylon ropes, the use of new configurations and combinations of chain and wire rope, and the application of chain and wire rope to the tension-leg platform (ABSG Consulting Inc. 2021).

2.2.1 Mooring Designs

The three primary types of mooring designs are catenary; taught (Tension-leg); and semi-taught (Figure 15). The type of mooring used will determine the amount of drift, or the watch circle, the area the platform will move within at the sea surface. The dependencies and challenges of each of these main platforms are summarized in Table 2.

Figure 15. Three Primary Types of Mooring Designs for Floating Deepwater Offshore Wind Platforms

Types: (A) Catenary, (B) Taught (Tension-leg), (C) Semi-taught.

Source: Yang et al. 2022

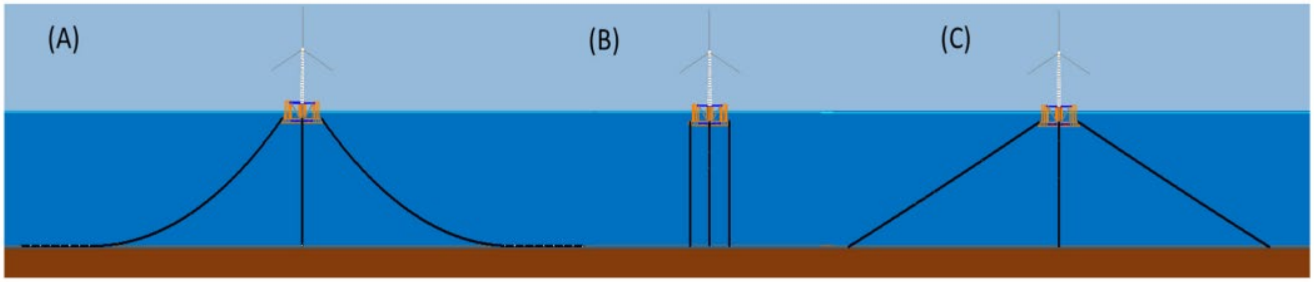


Table 2. Summary of Primary Mooring Systems

Source: Maxwell et al. 2022.

Mooring System	Description	Associated Platforms	Materials	Dependencies and Challenges	Example Project(s)
Catenary	Mooring lines form curve (catenary) shape; each line may be divided into upper, lighter, more flexible segments, and lower heavier segments; designed to be four times longer than water depth to account for wave action.	Spar, Semi-submersible, barge	Synthetic Rope, Chain	• Largest seabed footprint of the three primary mooring types. • Poses greatest entanglement risk to marine mammals due to the mooring lines being slack in the water column.	• Kincardine (Scotland; Principle Power 2022) • WindFloat Atlantic (Portugal; WindFloat Atlantic n.d.) • TetraSpar Demonstrator (Denmark; RWE 2023)
Taught (Tension-leg)	Mooring lines at 90-degree angle to seabed.	Tension-Leg	Synthetic and Wire Ropes	• Smallest seabed footprint of the three primary mooring types. • Doesn't allow for much vertical movement resulting in a significant amount of force on anchors due to wave action.	• Provence Grand Large (France; Prysmian Group 2023) • X30 Platform (PivotBuoy Project, Spain; Pivot Buoy n.d.)
Semi-Taught	Compromise between catenary and taught (tension-leg).	Semi-submersible	Synthetic Fibers, Chains, Wire Moorings	• Flexible enough to accommodate wave action without chain sweep that occur from catenary designs. • Trenching where chains reach seabed in vicinity of anchors concerns of impacts on benthic organisms.	• Hywind (Scotland; Equinor 2023b) • Floatgen (France; Floatgen n.d.) • Hibiki (Japan; Hibiki Wind Energy 2021)

2.2.2 Next Generation Mooring Designs

In addition to the three primary mooring designs described above, there are several next generation mooring designs currently under development including hybrid designs and multi-turbine mooring systems. Gazelle, the developer of one of the next generation platforms described above, has developed a dynamic mooring design wherein the two to three mooring cables come up over the platform and run over pivoting arms before dropping down in the center of the platform where a heavy counterweight is suspended (Figure 16). According to Gazelle, the mooring design puts 80 percent less load on the mooring lines than typical tension leg moorings, maintaining tilt under 1 degree while still allowing vertical movement (Blain 2023).

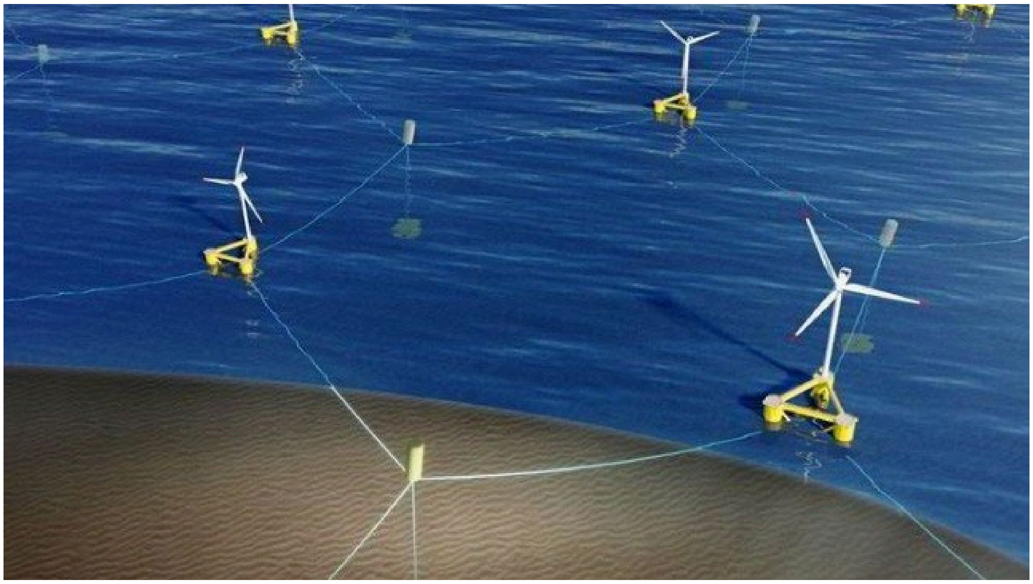
Figure 16. Gazelle Mooring System

Source: Blain 2023

TotalEnergies is developing a multi-turbine mooring design called Honeymooring that would connect three turbines to each mooring point in a honeycomb pattern, thus reducing installation costs and minimizing the seafloor footprint for future FOSW projects (Figure 17). However, the suspended components of the Honeymooring system would result in a larger total horizontal footprint within the water column than a single fixed platform, which could create significant navigational and operational conflicts with maritime uses such as shipping and fishing (Maritime Executive 2022b).

Figure 17. Total Energies Honeymooring, Mooring System

Source: Maritime Executive 2022b



2.3 Anchoring Mechanisms

All FOSW designs require an anchoring mechanism to secure the mooring system to the sea floor. Fixed-bottom foundation designs do not require anchoring, as the turbine foundation is embedded directly into the sea floor, and no additional support is needed. The anchorage systems typically proposed for use in FOSW include suction anchor, drag embedment anchor, anchor pile, and a relatively new design concept, shared anchor designs. These systems are explained in sections 2.3.1 to 2.3.4. The anchoring mechanism is part of the overall mooring system; this is highly impacted by seafloor characteristics in the installation area and the type of turbine platform used. The reliability of mooring and anchoring components and associated sub-systems (such as swivels or tensioners) can play a key role in the levelized cost of energy of a FOSW system, and therefore should be demonstrated to an acceptable confidence level for use in a commercial scale OSW farm (Weller 2022). For all types of anchors, the required minimum soil penetration depth should be verified at the site upon installation to ensure that design needs are met (ABS 2013; ABS 2020). The required minimum soil penetration depth will vary by the specific anchor being used and the geophysical, geological, and geotechnical characteristics of the anchoring location; an example of a final anchor penetration depth is 16 meters (52 feet) for a system that uses drag embedment anchors dragged a distance of 240 meters (787 feet) (ABS 2017). The needs and dependencies of the different anchoring mechanisms are summarized in Table 3 and each anchoring mechanism is described and pictured in the following sections. Next generation anchor designs are also discussed in section 2.3.5.

Table 3. Anchor Designs, Considerations, and Examples

Source: ABSG Consulting, Inc. 2021. ABS 2013.

Anchor Type	Construction Needs	Operations and Maintenance Needs	Dependencies and Challenges	Example Project
Suction Anchor	Installed as the first step in the process, along with the mooring lines. An ROV is used to complete the installation by pumping water out of the suction port.	For tension leg platform (TLP), taut and semi-taut floating concepts, the loads are transferred more vertically into the suction anchor caisson, parts of it as long term sustained loads. Periodic sub-sea inspections and maintenance is required using ROVs.	• Scour can be an issue. • Used with TLP systems because of their ability for high axial holding capacity. • High vertical loading capability. • Functions best in mud/clay, and only marginally in sand. Not recommended for hard substrate. • Sediment type determines the necessary shape profile. • Can be used with all of the major mooring and platform types.	• Hywind (Scotland; Equinor 2023b) • Hywind Tampen (shared design) (Norway; Equinor 2023c)
Drag Embedment Anchor	Can be installed using an Anchor Handling Tug and Supply (AHTS) vessel; installation of mooring and anchor system is less expensive as a result. On-site inspection of anchor placement is required to ensure proper installation.	Suitable for catenary moored systems because precise placement is not needed. Periodic sub-sea inspections and maintenance is required using ROVs.	• Soil liquefaction can be an issue (scour is not because they are completely embedded). • Functions best in mud/clay and sand, and only marginally in hard substrate. • Limited vertical load capability. • Limited ability to site anchors precisely. • Can be used with major mooring and platform types with the exception of tension leg and associated mooring.	• Hywind demonstration project (Norway; METCENTRE 2023) • Floatgen (France; Floatgen n.d.) • WindFloat Atlantic (Portugal; WindFloat Atlantic n.d.) • VolturnUS (US; University of Maine 2023)
Pile Anchor	Pile driven, either by a vibratory or impact hammer. Pile run is a risk that must be mitigated during installation.	Periodic sub-sea inspections and maintenance is required using ROVs, although pile anchors are very reliable. Small footprint.	• Can be used with TLP systems because of ability for high axial holding capacity. • High vertical loading capability. • Functions in all soil types and hard substrate; sand is the least preferred substrate. • Additional environmental assessment required for pile driving. • Can be sited precisely. • Can be used with all of the major mooring and platform types.	• No operational examples in deep water. Many oil and gas projects use pile anchors.
Shared Anchor Design	Phased construction to accommodate the integration of multiple turbines.	Periodic sub-sea inspections and maintenance is required using ROVs.	• Resisting significant and inconsistent loads from multiple directions. • If one anchor fails, multiple mooring lines can go adrift. • Substrate type is determined by individual anchor type (see descriptions above).	• Hywind Tampen (shared suction anchor) (Norway; Equinor 2023c).

2.3.1 Suction Anchor

The suction anchor, also known as the suction caisson or suction pile, is composed of a long steel cylinder topped with a pile top or cap (Figure 18). The top or cap is composed of valves used to assist with embedding the anchor into the substrate. The suction anchor penetrates about half of its length under its own weight, although this is dependent on soil conditions and the specifications of the anchor. The soil embedment is typically completed by suction, which can be achieved using a remotely operated vehicle (ROV) for precise installation (Figure 19). It is one of the most widely used anchor types for projects involving deepwater moorings and has been used extensively in the oil and gas industry for several decades, particularly for TLP platforms (Olson and Gilbert 2005). One of the large benefits of suction anchors is that they can be sited on the seafloor precisely. Suction anchors are often used with TLP and spar-type FOSW designs.

Figure 18. Suction Anchor Deployed at Hywind Tampen off the Coast of Norway

Source: Seamar AS 2022

Figure 19. Sequence of Events to Install Suction Anchor, including an Remotely Operated Vehicle for the Final Steps

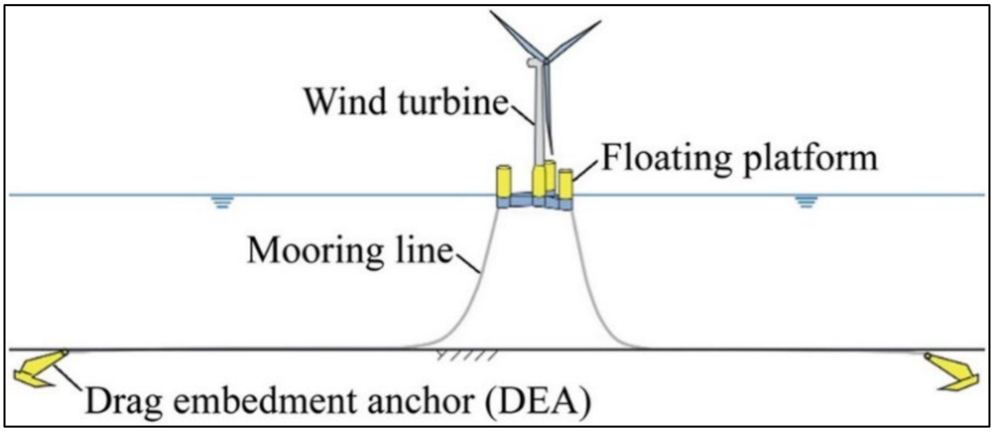
Source: Acteon Floating Renewables 2023

2.3.2 Drag Embedment Anchor

As the name implies, drag embedment anchors are installed by being dragged along the seafloor until the desired burial depth is achieved (Figure 20). This method of installation allows for an initial penetration depth that attains the desired holding capacity for the FOSW structure. For semi-submersible and spar-type FOSW turbines, drag embedment anchors are thought to be the optimum choice because they have a high-holding capacity against lateral loads (ABS 2017). One limitation of drag embedment anchors is the potential for liquefication issues (sinking in the liquefied soil), leading to failure. The structural integrity of the seabed soil may fail due to wave-induced or seismic-induced liquefication, thus leading to the anchor sinking in the liquefied soil (Sumer and Kirca 2022). Drag embedment anchors must be inspected upon installation to ensure that proper burial occurred, which adds to the installation time and cost. The potential for a drag embedment anchor to move in its lifetime depends heavily on the sediment structure and the hydrodynamic movements of the mooring line and floating platform. Movement of a drag embedment anchor could impact benthic communities. Visual inspection with an ROV is advised along with typical shipboard testing, as testing for anchor drag from shipboard alone may not indicate complete burial with certainty (Yoon and Joung 2022).

Figure 20. Schematic of FOSW Turbine Semi-Submersible System with Drag Embedment Anchors

Source: Sumer and Kirca 2022

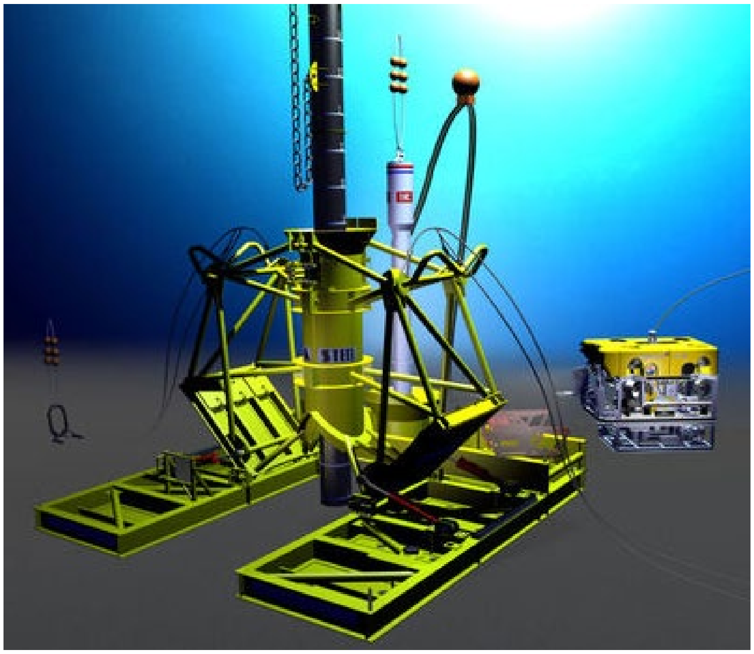


2.3.3 Pile Anchor

The pile anchor, also known as the driven pile anchor, is an anchor that can be precisely placed in a chosen location and is not likely to move over time (Figure 21). These anchors are driven into the soil using a vibratory or impact hammer. Due to the additional equipment required to drive the anchors, the anchors typically have a higher associated cost. Pile driving underwater noise and vibration have the potential to impact marine resources. Pile anchors have been used extensively in the oil and gas industry to hold offshore floating semi-submersible platforms in place due to their reliability. Conventional pile anchors are capable of withstanding uplift and lateral forces at the same time when the mooring line uplifting angle is 40 degrees or smaller (Weller 2022).

Figure 21. Pile Anchor and Installation Support Structures and Equipment

Source: Floating Wind Turbines 2023



2.3.4 Shared Anchor Design

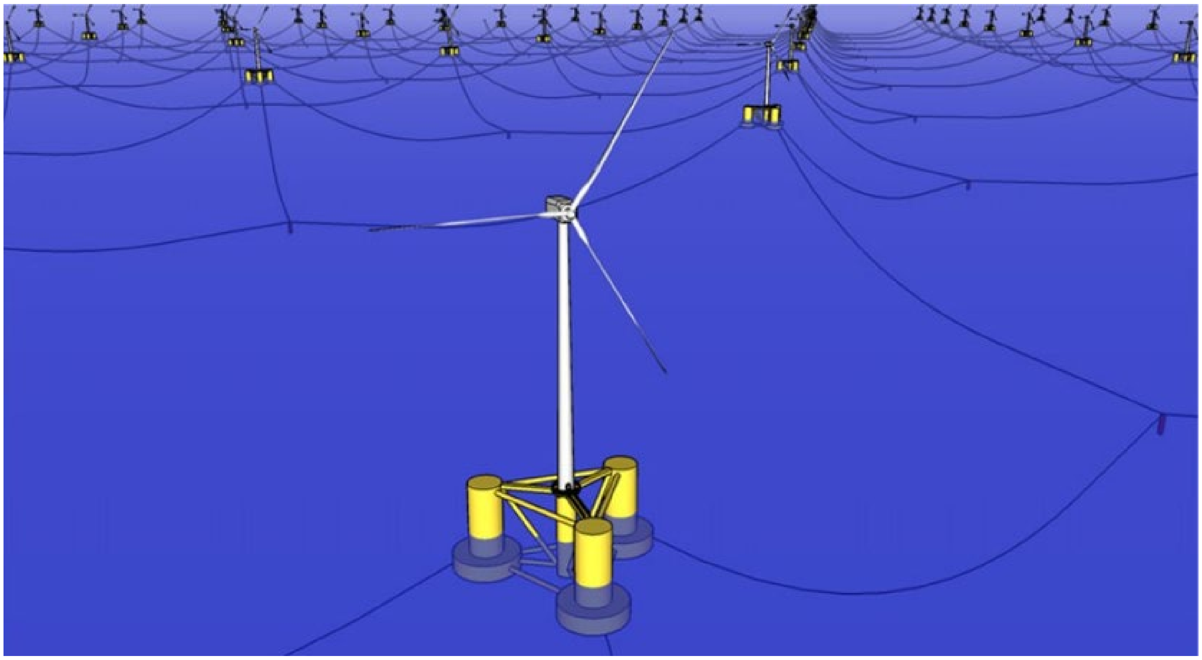
A shared anchor design involves multiple mooring lines sharing one anchor, which reduces the overall number of anchors required. The major advantages of this design include cost effectiveness and reduced seafloor footprint for the overall array when compared to other anchoring systems (Figure 22). The technical design aspects of this anchor design are complicated, and successful operation after installation is difficult to predict due, in part, to the hydrodynamic forces of multiple turbines in different directions on a single anchor. Each shared anchor must be strong enough structurally to handle loading from multiple directions simultaneously. Anchors designed with a directional preference in their holding position and capacity, such as drag embedment anchors, are generally not suited to support multi-line moorings (Diaz et al. 2016).

To date, a shared anchor design has been used for one full-scale OSW farm, Hywind Tampen. Nineteen anchors were used to support 11 turbines. As a comparison, for the Hywind Scotland project, 15 anchors were used to support 5 turbines.

The cost savings and decreased ecological footprint are reasons to continue to examine and develop shared anchor and/or mooring designs for commercial scale FOSW farms. A study published by NREL in 2022 considered a shared anchor and mooring design for a 10-turbine floating wind turbine array. Shared mooring lines tether floating platforms together and are connected to shared, multiline anchors. Cost reductions are accomplished with this shared design due to the need for fewer anchors and mooring lines, but the system design experiences compounding technical complexities (Hall et al. 2022).

Figure 22. Conceptual Shared Anchor System

Source: Fontana 2019

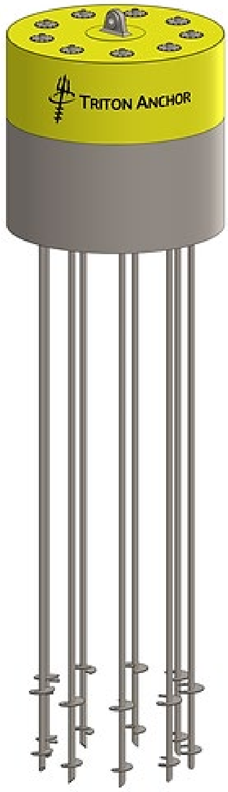


2.3.5 Next-Generation Anchor Designs

Although most of the anchor designs used in FOSW projects are based on technology developed for floating oil platforms (Amaechi et al. 2022), multiple designs have been proposed and tested that rely on innovative technology not seen previously in anchors. An example is an anchor designed by Triton, an American company. Triton's anchor design involves the use of helical piles that are installed with an ROV (Figure 23). The Triton anchor is effective in sand substrates and can be placed in precise locations on the seafloor. The footprint is similar to that of suction anchors, but the cost is lower due to the lower cost of materials required (fewer material is required) and lower installation costs associated with ROV installation. Additionally, Triton claims the design's inherently known as installed-load capacity removes the need for load testing after installation. The company is currently scaling the product from prototype to a general release and is supported by the Massachusetts Clean Energy Center and Department of Energy, among other organizations.

Figure 23. Triton Anchor

Source: Triton 2023



2.4 Export Cables and Inter-Array Cables

As depicted in Figure 24, all OSW grid designs include cables between each turbine (inter-array cables) that eventually feed terminal cables which lead to an offshore substation. From the offshore substation an export cable sends power to an onshore substation. When water depths allow, inter-array cables are typically buried and/or have a concrete mattress sheathing cover as they traverse the seabed. These cables transfer the electricity generated from each turbine and use burial depth and/or sheathing to decrease electro-magnetic field (EMF) emitted. Due to the water depth and floating mooring design, deep water

OSW developments will typically have inter-array cables that are suspended in the water column. These inter-array cables are exposed to wave action, currents, hydrostatic pressure, and the motion of the floating platform. These inter-array cables are commonly referred to as “umbilicals” (Rentschler et al. 2019, Rentschler et al. 2020). The needs and dependencies of the different cable mechanisms are summarized in Table 4. More detail on each cable mechanism is described and pictured in this section.

Figure 24. Power Transmission System of an Offshore Wind Farm from a Top View

Source: Rentschler et al. 2020

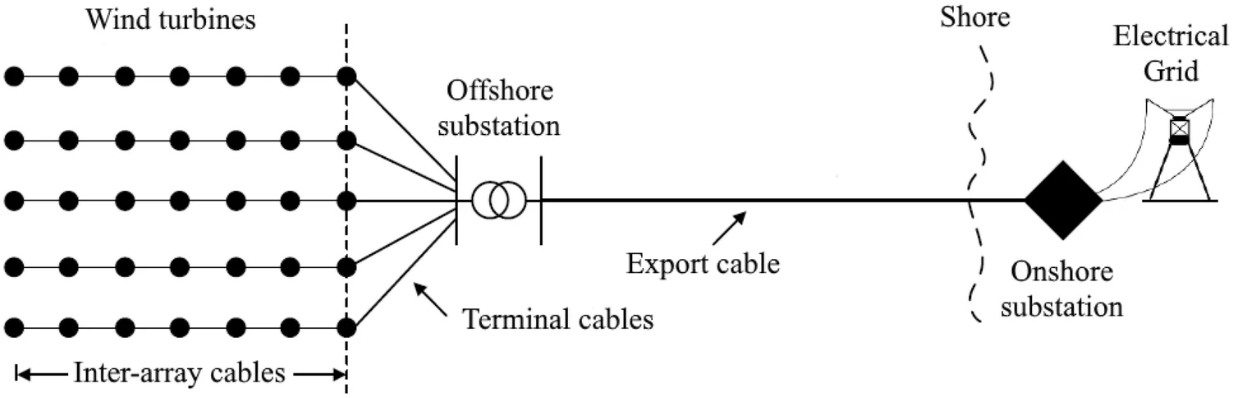


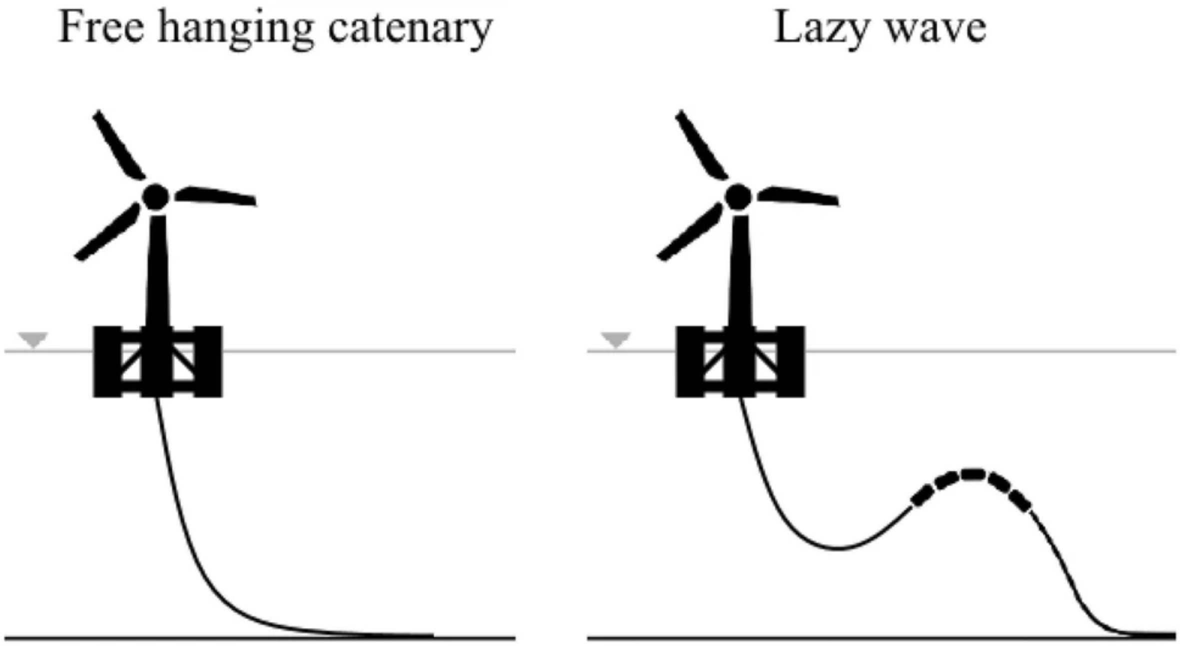
Table 4. Inter-Array Cable Designs, Considerations, and Examples

Cable Type	Construction Needs	Operations and Maintenance Needs	Dependencies and Challenges	Example Project(s)
Inter-array cables buried into seabed between turbines.	Vessel transit, then installed on/buried into seafloor.	Buried/covered cables need to be periodically monitored.	• Sediment substrate type determines burial feasibility or need for mattress sheathing. • Requires installation equipment that can operate in water depths >60 meters (197 feet; similar or adapted from tools already used in deep installation methods). • Dynamics of floating turbine, steep slope, hard or extremely soft substrate, and >60-meter (197 feet) water depths present significant challenges for being installed in AoA.	• No projects to date with buried inter-array cables between floating turbines.
Inter-array cables free floating within water column.	Vessel transit, then installed.	Need to be regularly monitored for cable failure, new growth, entangled debris and/or organisms.	• Currents, wave action, and dynamics of attached floating turbine load changes must be anticipated in cable and grid designs.	• Kincardine (Scotland; Principle Power 2022) • WindFloat Atlantic (Portugal; WindFloat Atlantic n.d.) • TetraSpar Demonstrator (Denmark; RWE 2023) • Hywind (Scotland; Equinor 2023b) • Floatgen (France; Floatgen n.d.) • Hibiki (Japan; Hibiki Wind Energy 2021)

The same inter-array technology for fixed foundations is also used in deepwater floating. Due to ocean currents and load shifts from floating platforms, buried inter-array cables may not be feasible connecting multiple floating platforms. To date, no commercial deepwater OSW developments use buried inter-array cables between floating platforms. Figure 25 details the free hanging catenary and lazy wave designs for umbilical cables. The lazy-wave design (also known as dynamic risers) includes an intermittent buoy(s) that lifts the cable up. Although dynamic riser cables have been field-tested by the offshore oil and gas industry for decades, there is still a lack of knowledge around the umbilical's efficiency and fatigue of being attached to floating platform dynamics (Carbon Trust 2018; Catapult 2015; Rentschler et al. 2019).

Figure 25. Catenary and Lazy-Wave Umbilical Designs

Source: Rentschler et al. 2020

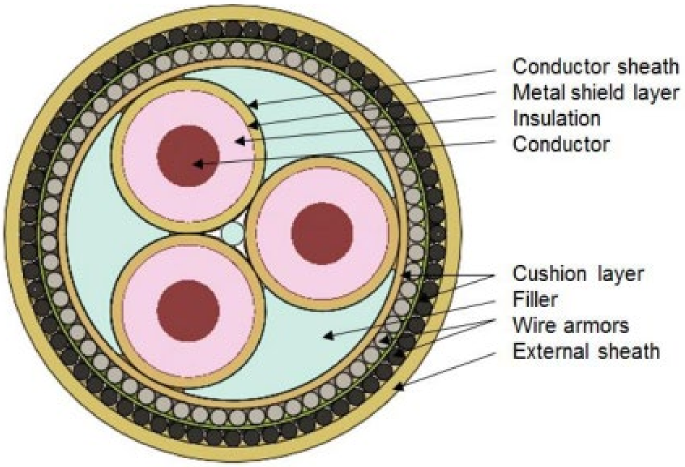


EMF emitted from the free-floating umbilicals has the potential to impact marine organisms within close proximity and alter their behavior or movement. Presently, a three-phase 33 kilovolt (kV) alternating current (AC) umbilical is the most common umbilical design and produces both magnetic and electric fields, though recent efforts are underway to develop a 66 kV and 230 kV AC umbilical (Gill et al. 2014; Copping et al. 2016; Rentschler et al. 2020; NYSERDA 2022). The umbilical is water sealed by a polymer sheath and electrically insulated to provide a water barrier as shown in Figure 26. Industry standards on sheathing will reduce EMF emitted into the water column (Rentschler et al. 2020; DNV 2022a). Twisted steel wires provide an armor that influences the umbilical's dynamic behavior (Rentschler et al. 2020). Deepwater wind will certainly require the use of high-voltage direct current

(HVDC) cables for longer transport distances and larger MW turbines, which typically emit higher intensity EMF (Gill et al. 2014). The use of HVDC cables could pose a feasibility issue due to the long distances to shore from the three zones of the AoA, If HVDC is not used then the farm will not require an offshore converter station. HVDC has been used in very deep water (1,600 meters [5,249 feet]) with lower MW power transmission (Hiachi n.d.), but no dynamic HVDC cable technology exists deeper than 60 meters (197 feet) at the power capacity needed for a deepwater OSW development. Current cable technology allows for a set of lower voltage cables, but not for a single export cable.

Figure 26. Cross-Section of an Umbilical

Source: Poirette et al. 2017



NYSERDA developed the “Offshore Wind Submarine Cable Overview,” which detailed the geophysical and geotechnical restraints on installing export cables, specifically steep slopes, hard substrates, and deep canyon morphology (NYSERDA 2021a). Zone 2 of the AoA includes the steep canyon continental shelf break that starts at 150 meters (492 feet) and ends at 2,300 meters (7,546 feet) (see Figure 37 in section 3.1). An inter-array cable drilled or buried in the seabed would not be feasible in Zone 2 or Zone 3. It is theoretically feasible for an inter-array cable suspended in the water column to go from Zone 3 past Zone 2 to and be buried in Zone 1, requiring in a very long suspended cable, which would be subject to forces that could make it difficult to engineer.

2.5 Offshore Substation Designs and Options

Both fixed-bottom and floating deepwater wind designs require the power generated from each turbine to be fed into an offshore substation and transmitted through an export cable to an onshore substation and connected to the grid, as shown in Figure 24. Offshore substations act as a multi-connector function as they receive power from multiple turbines (Robak and Raczkowski 2018). Substation platforms are designed similarly to oil and gas platforms to accommodate the switchgear, main and grounding transformers, and accessories necessary for HVAC or HVDC electrical systems (Erlich et al. 2013). Depending on the water depth, substations can be fixed (Figure 27) or floating (Figure 28). The needs and dependencies of the different substation mechanisms are summarized in Table 5 and each substation mechanism is described and pictured in the following sections. Next generation substation designs are also discussed.

2.5.1 Fixed Substation

Fixed substations are potentially feasible in offshore areas with up to 100 meters (328 feet) water depth and are anchored to the seabed similarly as fixed-bottom foundations (section 2.1; DNV 2022a). This water depth is similar to that seen in oil and gas fixed-bottom foundations. Technology allows for fixed substations (using a tall jacket foundation) to be economically viable (DNV 2022a). Offshore substations are typically 20 meters (66 feet) x 20 meters (66 feet) x 22 meters (72 feet) high. This is much smaller than the typical oil and gas Berkut production platform which measure 105 meters (344 feet) x 61 meters (200 feet) x 145 meters (476 feet) high (Marine Insight 2022). The foundation structure and substructure make up the support structure of a fixed substation, with the purpose of transferring the loads from the topside and support structure to the seabed (Robak and Raczkowski 2018; Figure 27). The topside structure and requirements of substations are discussed in the section below.

Figure 27. Offshore Fixed Substation

Source: Robak and Raczkowski 2018

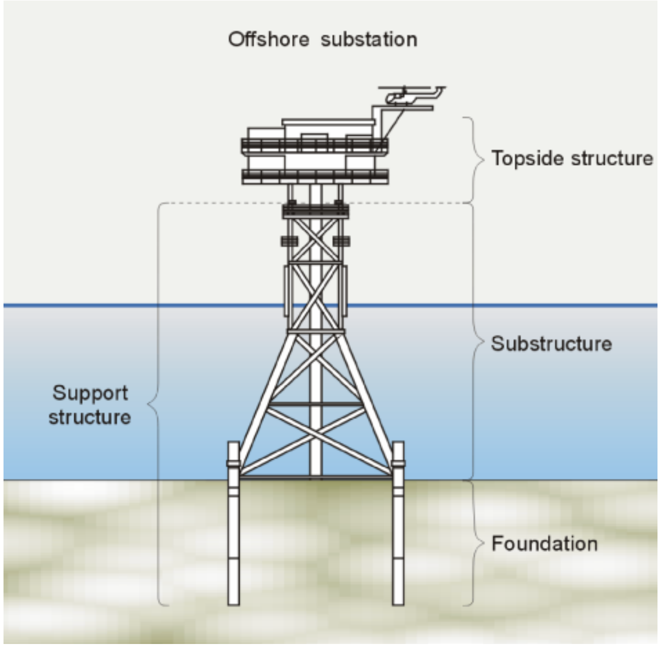


Figure 28. Barge Floating Offshore Substation

Source: DNV 2022b

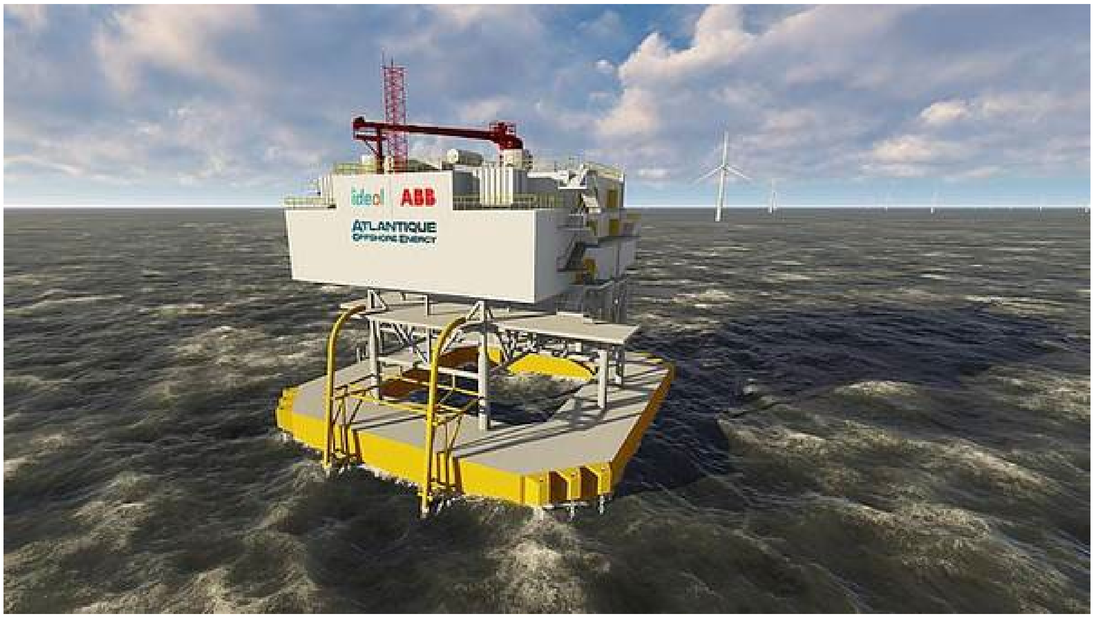


Table 5. Substation Designs, Considerations, and Examples

Substation Type	Construction Needs	Operations and Maintenance Needs	Dependencies and Challenges	Example Projects
Fixed	• Vessel transit, then drilled in the seafloor.	• Monitor topside structure for engineering procedures, stability, and upkeep. • Monitor underwater structure for engineering failures, upkeep, and scour.	• Similar constraints for fixed-bottom foundations include >60-meter (197 feet) water depth, sediment type, and slope. • Larger proportion of platform surface above sea surface resulting in greater vulnerability to waves. • Heavy load weight bearing for underwater structure.	• No projects to date with fixed substations in > 60-meter (197 feet) water depth. • Oil and gas fixed-bottom foundations are currently in operation up to 150 meters (492 feet). • Technology advances could make fixed substations economically viable up to 100 meters (328 feet).
Floating	• Spar platform type assembled in deepwater locations. • All other platform designs staged in port then towed to deployment site.	• Monitor topside structure for engineering procedures, stability, and upkeep. • Monitor underwater structures for new growth, debris entanglement, and engineering failures.	• Similar constraints for floating turbines. • Larger proportion of platform surface above sea surface resulting in greater vulnerability to waves. • Comparatively large footprint at sea surface provides good stability.	• Kincardine (Scotland; Principle Power 2022) • WindFloat Atlantic (Portugal; WindFloat Atlantic n.d.) • TetraSpar Demonstrator (Denmark; RWE 2023) • Hywind (Scotland; Equinor 2023b) • Floatgen (France; Floatgen n.d.) • Hibiki (Japan; Hibiki Wind Energy 2021)
Subsea	• Vessel transit, then installed onto seafloor.	• Little to no monitoring required.	• Seabed morphology, sediment type, and slope restrict areas feasible for installation. • Equipment must be pressure compensated. • Equipment must be monitored or made to withstand corrosion or biofouling.	• Aker subsea station (expected to be available in 2024) (US; Aker Solutions 2022) • ABB Energy Industries services substation and collector stations (in use in oil and gas industry) (Norway; ABB Energy Industries 2023b)

2.5.2 Floating Substation

Substations can be floating depending on the water depth, similar to floating platforms in the oil and gas industry. Floating substation’s substructure consists of mooring lines and anchors similar to floating turbines (sections 2.1 through 2.3). An offshore substation’s topside is typically a box-shaped structure, built primarily of steel, containing the electrical equipment for some or all the platform’s functions and is placed onto its substructure (CTC Global 2011; DNV 2021; Robak and Raczkowski 2018). Topsides for substations with HVDC are usually larger than high-voltage alternating current (HVAC) substations, due to the inclusion of an AC/direct current (DC) converter. Additional requirements for offshore substation topsides include (Robak and Raczkowski 2018):

- Electrical equipment operating conditions (cooling systems, isolating clearances, etc.).
- Personnel or services working conditions, if manned (rooms, air conditioning, kitchen, etc.).
- Navigational, safety, rescue and signaling systems (lighting systems, fire systems, etc.).

2.5.3 Next-Generation Subsea Substation Designs

Aker Solutions, a U.S. company, has developed a subsea substation (Figure 29), which would substantially reduce the footprint by eliminating the three additional topside requirements listed above. According to Aker the subsea substation design is feasible in up to 1,500-meter (4,921 feet) water depths, has a design life (the typical lifetime of an offshore structure before decommissioning) of 30 years, and is expected to be available for market in 2024 (Aker Solutions 2022; Cision 2021). This technology could have potential to incorporate a closed-cycle/loop cooling system for HVDC converter stations in the future. The conversion process of generating AC power from the OSW farm to DC power for the export cable generates heat. This requires the use of either once-through cooling or closed-cycle cooling. Once-through cooling withdraws cooling water from the ocean through an intake caisson that circulates through the cooling system; the heat generated from the HVDC conversion process is transferred via a non-contact heat-exchanger and that waste heat then increases the temperature of the once-through cooling water which is then discharged back to the ocean. Closed-cycle cooling operates on the same principle, but the water is recirculated several times through the system, and generally results in substantially lower volumes of cooling water used compared to once-through cooling, and consequently lower entrainment of planktonic organisms from the source water. Potential subsea substation benefits include:

- Reduced footprint
- Seawater could act as a non-contact/passive cooling system.
- Increased reliability from stable temperatures at-depth.
- Fewer components and no rotating parts.
- Less maintenance and reduced material use.

Figure 29. Aker Solutions Subsea Substation within a Floating Wind Farm Visualization

Source: 4 Coffshore 2021

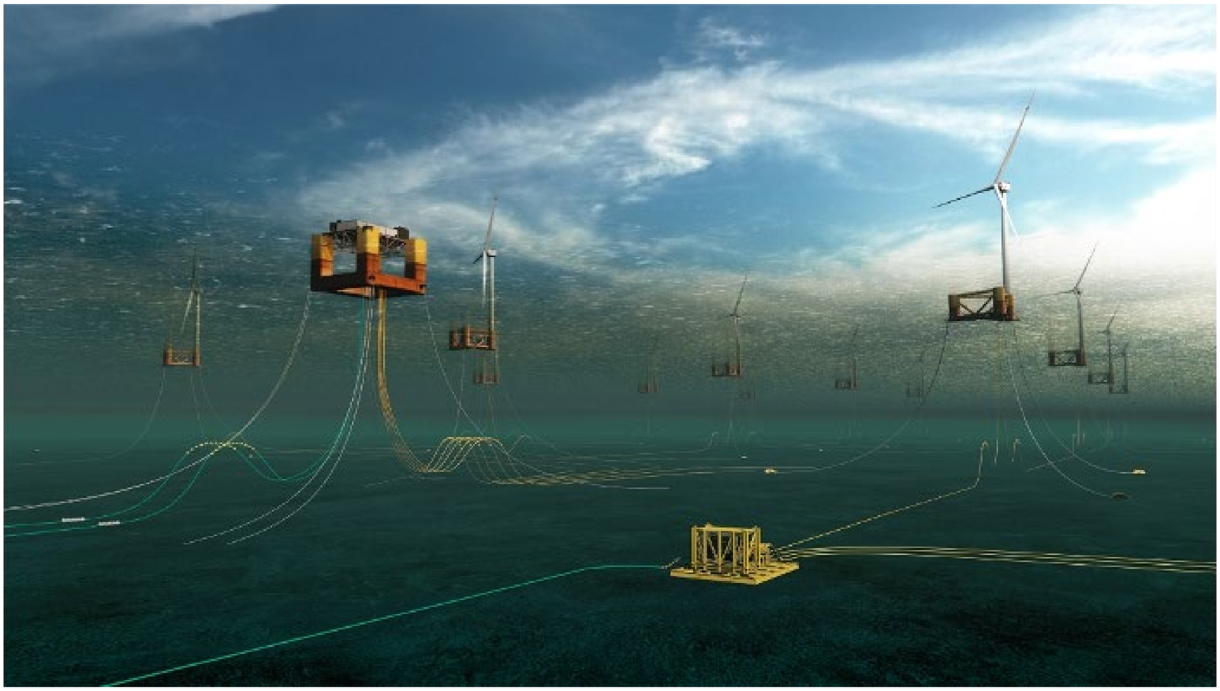
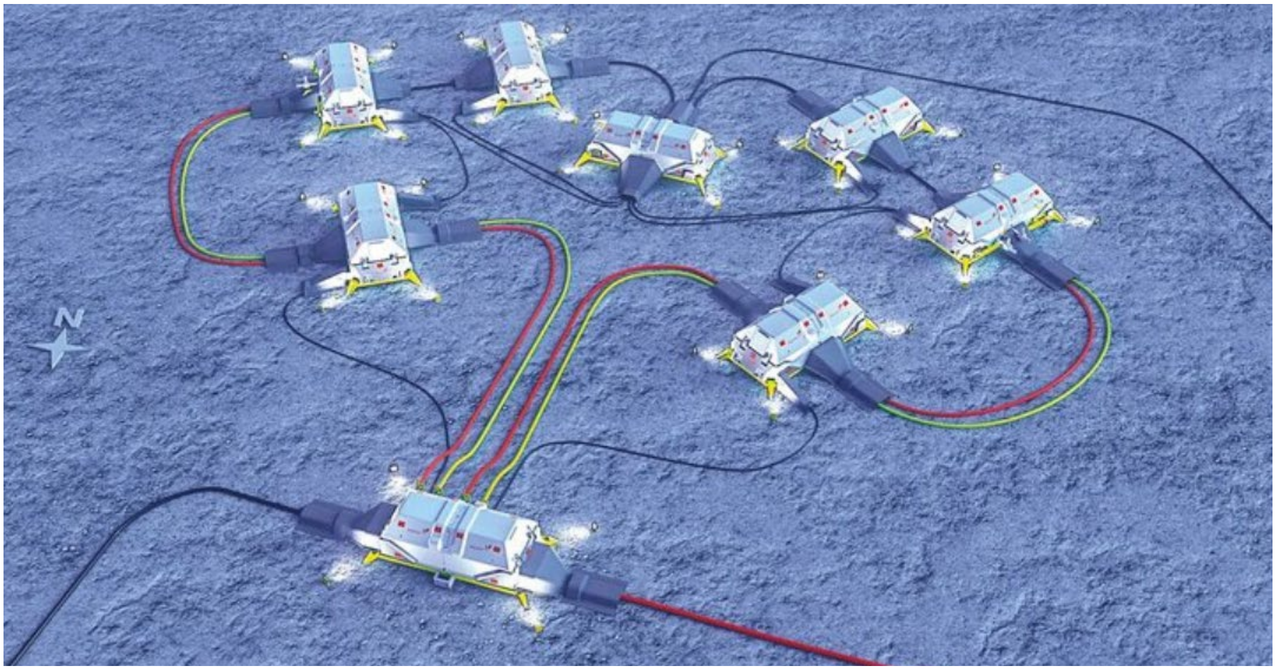


ABB Energy Industries has developed a "services substation and collector stations," which could replace the need for a floating substation. ABB tested this system almost 10 years ago for the oil and gas industry when they developed an electrification system for distribution, transmission, and conversion of power to subsea gas and pump compressors. This system (shown in Figure 30) had a peak capacity of 100 MW and was installed in up to 3,000-meter (9,843 feet) water depth for a lifetime of 30 years with little to no maintenance (Larson 2023). This type of equipment must be pressure compensated to withstand such water depths. To do this, ABB filled their subsea transformers with liquid, to eliminate all air and gas voids making the internal pressure similar to that of the outside water. This resulted in thinner walls of the equipment, reducing one-fifth of the steel needed in floating substations (Larson 2023).

Figure 30. Artist Rendition of ABB Energy Industry's Services Substation and Collector Stations

Source: ABB 2023a



2.6 Risks to Deepwater Offshore Wind Installations from Ocean Users and Oceanic and Atmospheric Conditions

Risks to deepwater wind installations include those that arise from extreme oceanographic and meteorological conditions and user conflicts, such as maritime and fisheries. Deeper waters are located in areas further from shore and are prone to more extreme weather events, such as storms and high winds that produce large waves. Ocean users like fishermen and the maritime industry may collide with above water components such as turbine towers or snag subsea components like inter-array cables. Table 6 includes some examples of risks for the different components of a deepwater wind installation, including risks that may lead to failure. These risks are summarized from Table 1–Table 5, with environmental risks further detailed in section 3.

Table 6. Risks to Deepwater Wind Infrastructure

Infrastructure	Technology	Risk(s)	Dependencies
Turbine Platform	Barge	• Force of motion of turbine and platform adds stress on tower and blades. • Vulnerable to excessive pitching in severe wave conditions.	• Mooring
	Semi-Submersible	• Large area at sea surface results in more vulnerability to waves.	• Mooring
	Spar	• Deep draft can limit access to shallow water ports.	• Mooring
	Tension Leg Platform	• Unstable during assembly. • High vertical load due to tension on mooring lines.	• Mooring
Mooring	Catenary	• Poses greatest risk for marine mammal secondary entanglement (section 3.2.5) due to slack in mooring lines.	• Platform • Anchor (tech type)
	Taught (Tension-Leg)	• Does not allow for much vertical movement resulting in a significant amount of force on anchors due to wave action.	• Platform • Anchor (tech type)
	Semi-Taught	• Trenching where chains reach seabed in vicinity of anchors concerns of impacts on benthic organisms.	• Platform • Anchor (tech type)
Anchor	Suction	• High demand on anchors from dynamic loading as a result of wind, waves and currents. • Anchor walls can buckle or soil plug can be failed if suction caisson size is too small.	• Soil type
	Drag Embedment	• Large uplifting angle due to rough oceanographic conditions. • Steep seafloors can lead to failure. • Deep waters reduce accuracy of siting.	• Soil type • Mooring line angles
	Pile	• High demand on anchors from dynamic loading as a result of wind, waves and currents. • Soft soil layer may result in pile run.	• Soil type • Water depth for pile driving.
	Shared	• Oceanographic conditions that complicate dynamics of multiple turbines sharing one anchor.	• Overall design must accommodate technical thresholds for a shared design.
Inter-Array Cables	Buried Inter-array	• Bottom contact fishing gear. • Dynamics of connected floating turbine. • Steep slopes.	• Soil type • Slope
	Floating Inter-Array	• Transit • User conflicts • New growth • Derelict debris entanglement. • Currents, wave excitation, and load changes.	• Distance from substation and energy transferring.
Substations	Fixed	• Weight load increased with water depth. • Installation along steep slopes or hard substrate.	• Water depth • Seabed morphology • Weight load
	Floating	• Large area at sea surface results in more vulnerability to waves. • Ocean users • Damage from fishing gear.	• Anchor • Mooring
	Subsea	• Damage from anchors. • Damage from fishing gear. • Water pressure. • Installation along steep slopes or hard substrate.	• Seabed Morphology • Sediment • Slope • Equipment must be pressure compensated.

2.7 Case Studies

2.7.1 Hywind Scotland

Hywind Scotland was the world's first commercial scale floating wind farm and has been in operation since 2017 (Figure 31). The design includes the floating Hywind spar-substructure and suction buoys. The installation includes five 6 MW turbines, with a rated capacity of 30 MW and is located in a water depth range of 95–120 meters (312–394 feet). The Hywind spar-type floating platform was developed by Equinor and a 2.3 MW demonstration was tested for two years off the coast of Norway. The test run demonstrated operational feasibility and set the stage for Hywind Scotland (Ramachandran et al. 2021).

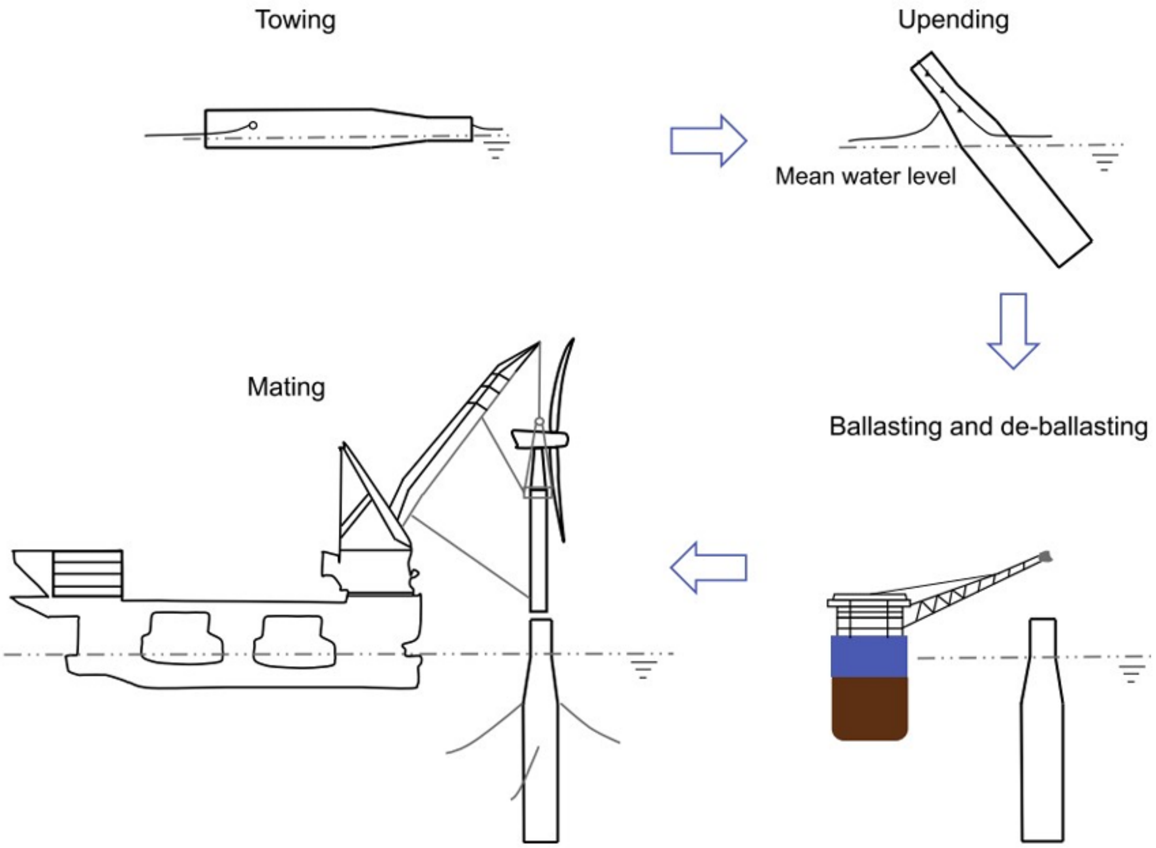
Figure 31. Image of the Hywind Scotland Wind Farm

Source: Equinor 2023a

Installation for the Hywind Scotland project occurred during the months of April to September to take advantage of suitable weather windows (wind and waves), which were determined by an assessment of metocean conditions during the previous year. The first marine component of installation included installation of suction anchors and mooring lines at the site. Inshore assembly of the turbines (upending, solid ballasting, and heavy lift) required waters deep enough to accommodate the deep draughts of the spar-type structures, and also required mild sea states. The spar structures were towed through the water out to the assembly site, upended using water ballast, ballasted again with solid ballast (magnetite), and mated to the tower and rotor assembly (Figure 32). Once assembled, the turbines were towed out to the wind farm installation location to be secured to the pre-installed mooring systems.

Figure 32. Installation Sequence of Turbines at Hywind Scotland

Source: Ramachandran et al. 2021



Over its 5 years of operation, Hywind Scotland has maintained high-safety standards with no lost time due to injuries despite occasionally harsh weather conditions of storms, wind gusts, and wave heights of 10 meters. Operations and maintenance of the topside components of Hywind Scotland is similar to fixed foundation OSW farms. Subsea maintenance includes ROV inspections of the mooring systems and suction anchor to monitor for scour. Due to its location, the project has required operations and maintenance methods that can withstand the periodic harsh sea states, such as a high-performance crew transfer vessel that can operate in non-standard transfer conditions. Mating the tower and rotor assembly with the spar structure required a heavy lift vessel (Saipem 7000), which is expensive and increased project costs. The invention of new technologies and vessels to address some of the technical challenges associated with installation and operations and maintenance would reduce costs for future spar-type and other FOSW turbine projects.

2.7.2 Kincardine Offshore Wind Farm Scotland

The Kincardine Offshore Wind Farm, commissioned in 2021 with a 50 MW capacity, is currently the world's largest floating wind farm (Figure 33). The five Vestas V164 9.5 MW wind turbine generators, which are the highest capacity wind turbine generators installed on floating platforms, and one Vestas V80 2 MW wind turbine generator are installed atop WindFloat semi-submersible platforms. These platforms are attached to the seabed with a catenary mooring system. The installation is located a little over 15 kilometers (8 nautical miles) off the coast of Aberdeen, Scotland in water depths ranging from 60 to 80 meters (197 to 262 feet). The WindFloat semi-submersible floating platform was developed by Principle Power and consists of three columns stabilized by "water trap plates" at the bottom of each column to create a static and dynamic ballast system (Edp 2022). Each side of the triangular shaped platform measures approximately 67 meters (220 feet), with a height of 12 meters (39 feet). The Kincardine Offshore Wind Farm was designed for a 25-year operational term.

Figure 33. Kincardine Offshore Wind Farm

Source: Principle Power 2022a

Installation of the Kincardine Offshore Wind Farm was performed in two phases starting in 2018 and was completed and fully operational by 2021. The WindFloat platform was towed to Edinburgh, where it was offloaded from the transport vessel then towed to Dundee for assembly and installation of the wind turbine generators. While the wind turbine generators were being installed, adjacent to the wharf the installation vessel transmitted to the offshore deployment location in order to begin installation of the anchors and moorings. Following installation of the wind turbine generators, the fully assembled platform was towed to the offshore deployment site and secured to the preinstalled moorings and power cables.

The Kincardine Offshore Wind Farm generates 218,000 MWh of electricity, providing enough energy to power 55,000 households (Power Technology 2023). Since commissioning in 2021, repairs have been needed on two of the wind turbine generators, one of which required towing the platform back to port for repairs (Penman 2023). The other four turbines remained operational during the repairs of the aformentioned turbines.

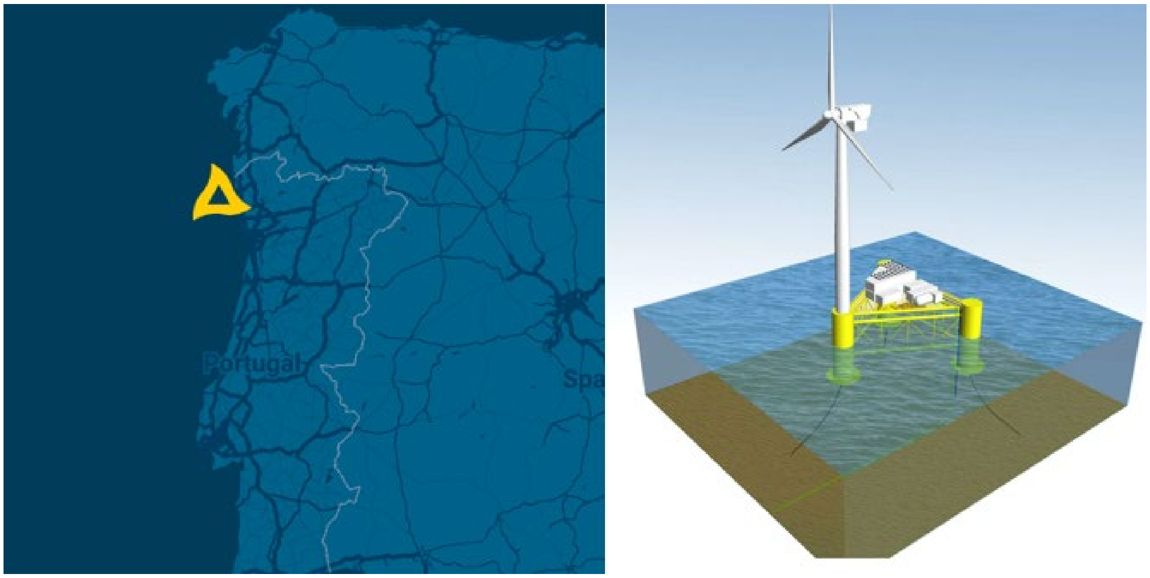
2.7.3 WindFoat Atlantic

WindFloat Atlantic off the coast of Viana do Castelo, Portugal, was connected to the grid in 2019 and commissioned in 2020. This is the world's first semi-submersible FOSW farm owned by Windplus S.A. and is located 20 kilometers (10 nautical miles) off the coast of Portugal in a maximum depth of 100 meters (328 feet). The wind farm consists of three wind turbines, supported by three semi-submersible floating structures (Figure 34). Each turbine has a capacity of 8.4 MW for a project total of 25 MW. The project will include 66 kV of dynamic cables for the collecting system.

The 25 MW wind farm is capable of generating 78 GWh of electricity annually, enough to power 25,000 homes (WindFloat Atlantic 2023). This is the first full-scale project to use semi-submersible technology and is the first floating farm in continental Europe (Principle Power 2022).

Figure 34. Location of the WindFloat Project off the Coast of Portugal (left) and an Installed WindFloat Foundation Illustration (right)

Source: Principle Power 2022b



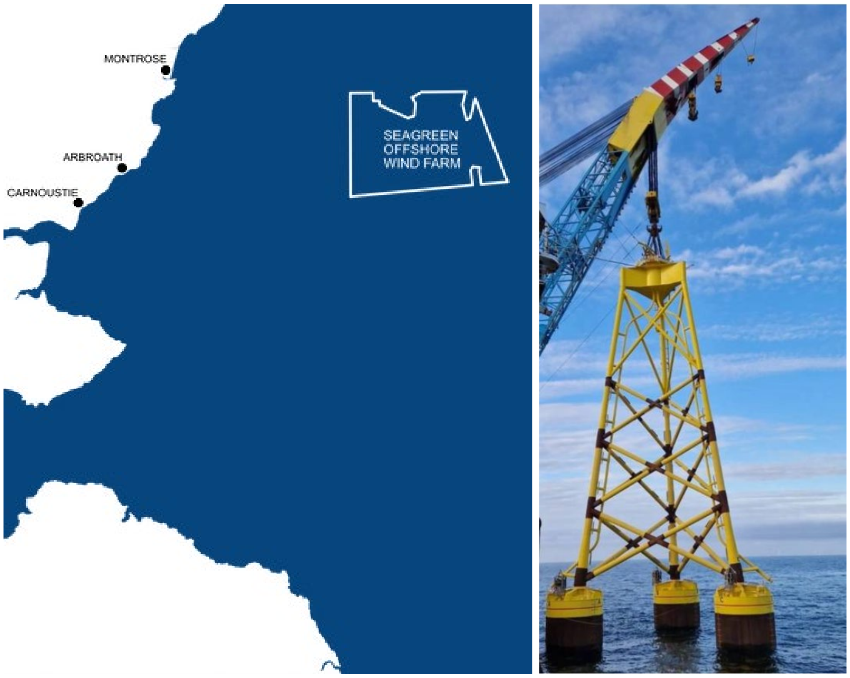
2.7.4 Seagreen Scotland

In April 2023, the final wind turbine foundation was installed at Seagreen, the world's deepest fixed-bottom foundation wind farm. The Seagreen project is owned by SSE Renewable and TotalEnergies and is located 27 kilometers (15 nautical miles) off the coast of Scotland in a maximum water depth of 59 meters (194 feet). The wind farm consists of 114 jacket foundations with suction caissons (Figure 35). Each jacket foundation will support a Vestas V164-10 MW turbine and the project will include 300 kilometers (186 miles) of inter-array cables. Inter-array cables will be buried to a minimum of 1 meter (3 feet) depth below the seabed when possible, and when burial is not possible the cables will be mechanically protected (Seagreen 2020).

When the project is complete, the 1.1 GW wind farm will be capable of generating approximately 5,000 GW hours (GWh) of electricity annually, enough to power more than 1.6 million United Kingdom households. Seagreen represents a project that is on the cusp of the maximum depth limit for fixed-bottom foundation and the minimum depth for floating platform installations. The technology used for this installation is not novel; the project's successful installation and operation has helped confirm that fixed-bottom foundations are logistically and economically feasible in water depths near 60 meters (197 feet).

Figure 35. Location of the Seagreen Project off the Coast of Scotland (left) and a Jacket Foundation Deployed with a Crane at Seagreen (right)

Source: Seagreen 2023



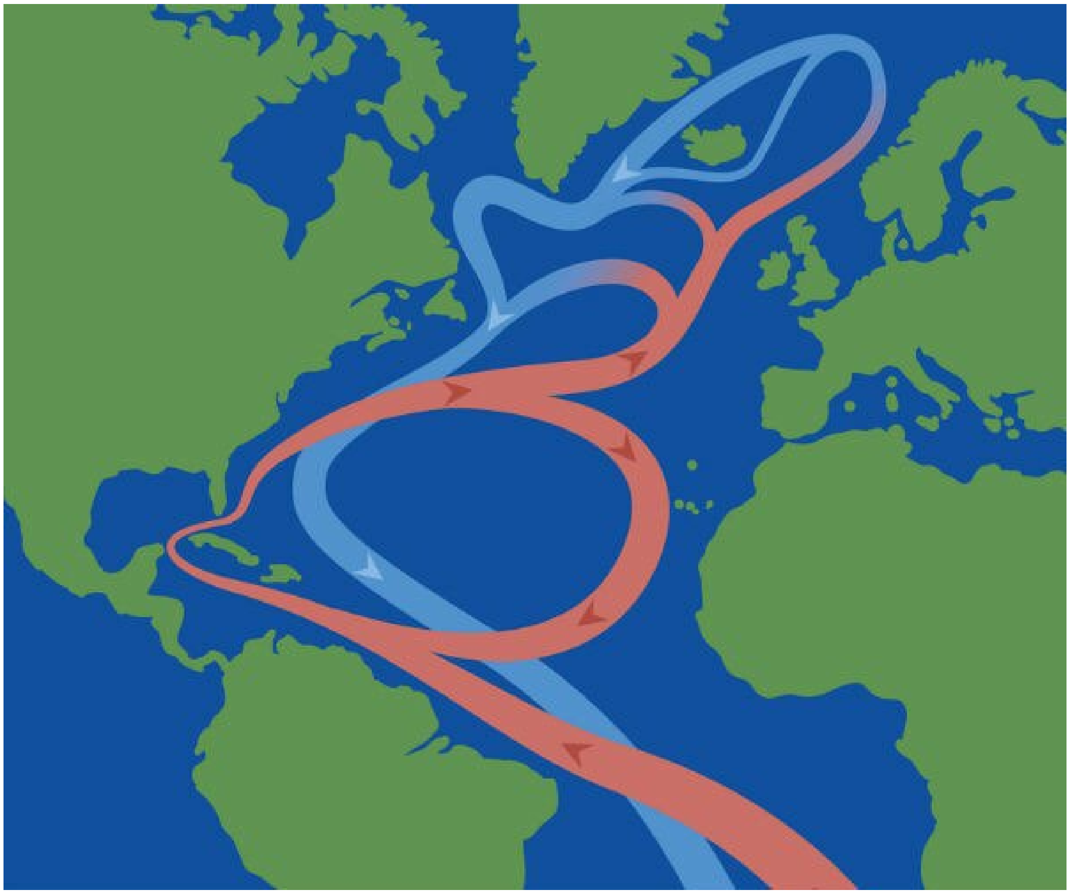
3 Environmental Impacts and Considerations

3.1 Environmental Factors of Oceanographic Characteristics

The North Atlantic Ocean is characterized by regional and global climate variability. The Gulf Stream moves warm tropical waters northward and is continued by the North Atlantic Current, known together as the Gulf Stream–North Atlantic Current. This current moves warm water to the Subpolar Gyre, creating the Atlantic Meridional Overturning Circulation that redistributes heat and drives Atlantic climate characteristics as depicted in Figure 36 (Yeager and Robson 2017). Marine primary productivity is a well-known driver of food-web dynamics, with high-primary productivity fueling the food web from the bottom up. Productivity drives animal distribution, with higher densities of predators generally found in areas with higher productivity. This region experiences a "Cold Pool," which is an annual band of cooler bottom water generated from thermal stratification that forms in the spring and breaks down in the fall and facilitates the distribution of many species (Lentz 2017, Friedland et al. 2020).

Figure 36. Visualization of the Gulf Stream-North Atlantic Current

Source: Newsmax 2018



The Hudson River discharges into the ocean and sediments and nutrients travel along the Hudson Shelf Valley in a southeastern direction. The Hudson Shelf Valley is a highly productive area, attracting bird and marine life. The Hudson Canyon is a submarine canyon seen indenting into the continental shelf (Figure 37). The continental shelf steeply slopes starting at approximately 100–200 meters (328-656 feet) down to the abyssal plain starting at 2,300 meters (7,546 feet) (Figure 37). New York State coastal waters have two major potential sources of nutrients: periodic upwelling from the deep eastern waters and the steadier input of nutrient-rich waters from the Hudson River that travel from land into shallow western waters and along the Hudson Shelf Valley. The highly productive waters along the Hudson Shelf Valley are particularly important for marine life and fisheries and are driven by upwelling dynamics from the Hudson Canyon. In June 2022, the National Oceanic and Atmospheric Administration's (NOAA) Office of National Marine Sanctuaries started its designation process to initiate a proposed national marine sanctuary of the Hudson Canyon area off the coast of New York and New Jersey (National Marine Sanctuaries n.d.).

Figure 37. Bathymetric Contours of the Areas of Analysis

Courtesy MARCO

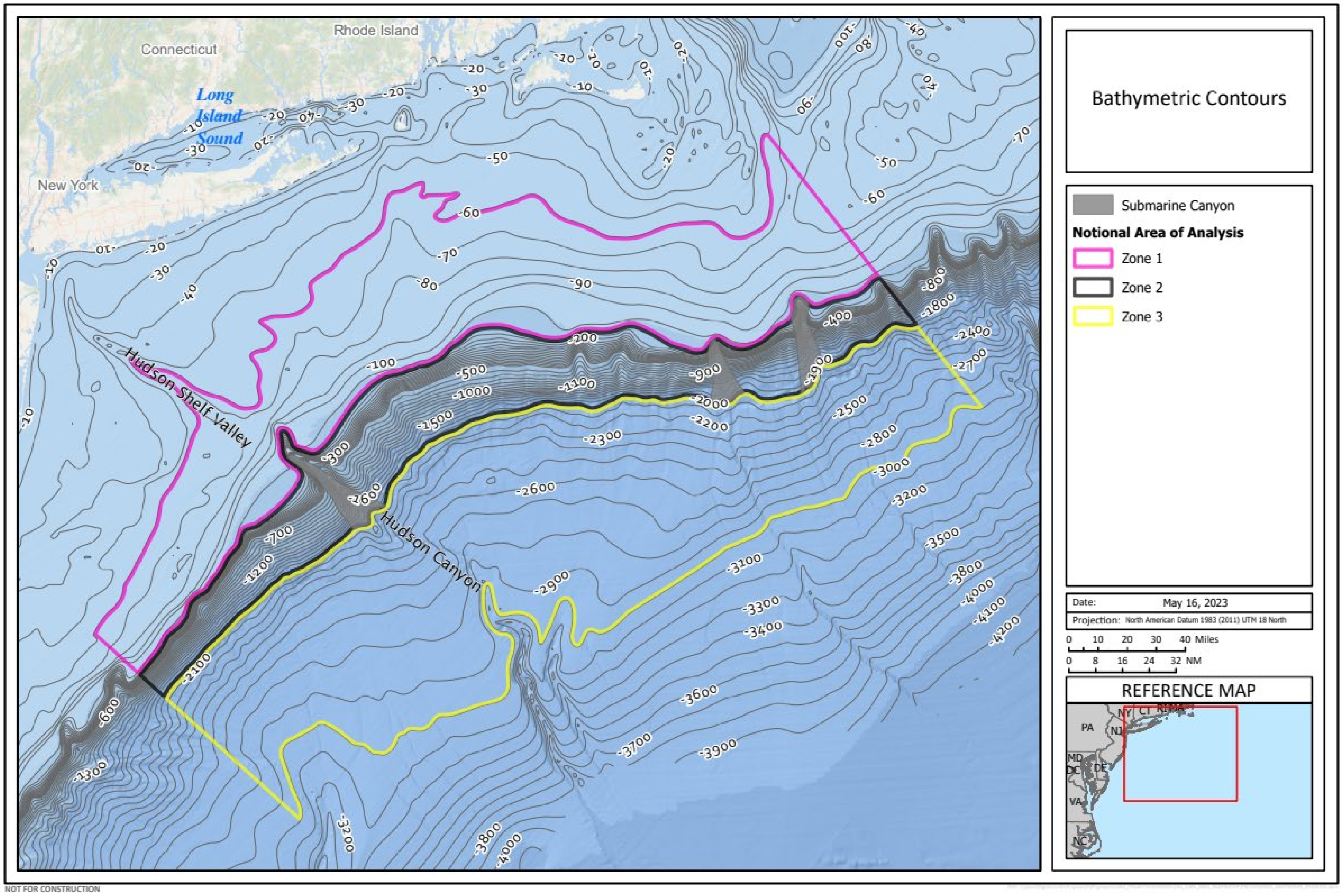
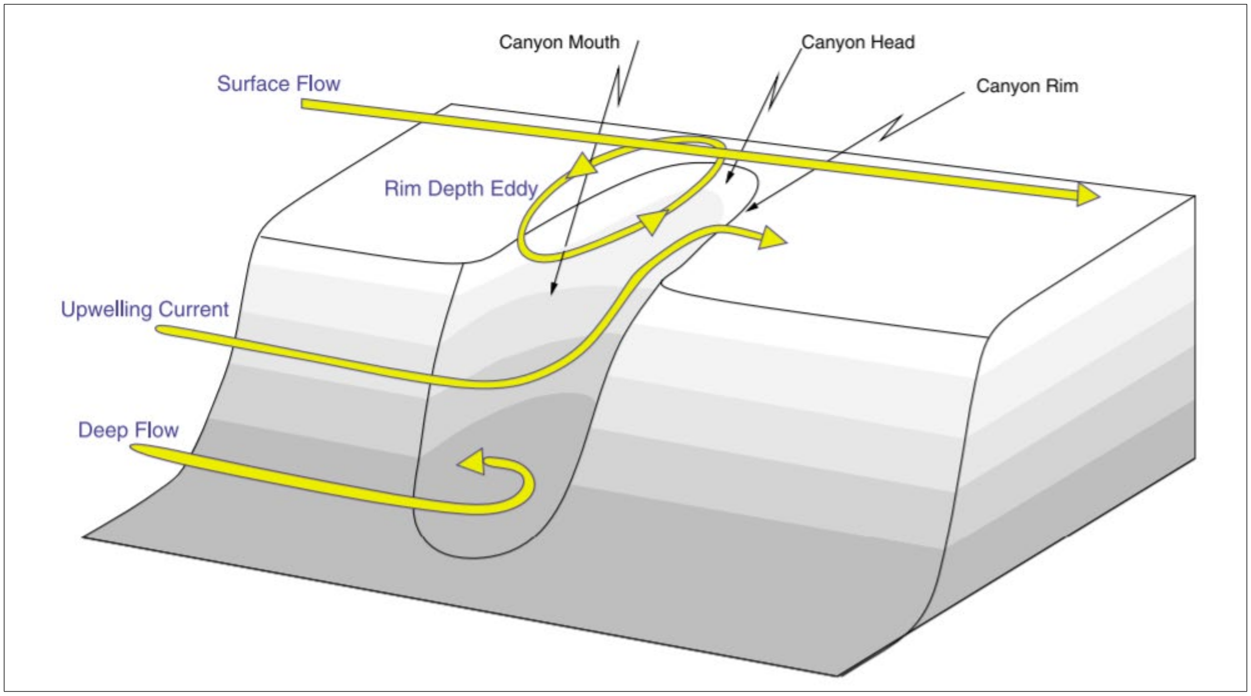


Figure 38 details the upwelling dynamics that occur over shelf break submarine canyons, including depiction of a rim depth eddy that concentrates nutrients locally (Allen and Hickey 2010). It is important to note that the hydrodynamics at the Hudson Canyon differ from that shown in Figure 38, with the North Atlantic deep currents moving the opposite direction from northward to southward. This image simply illustrates how influential submarine canyons are to local hydrodynamics.

Figure 38. Upwelling Dynamics of Submarine Canyon

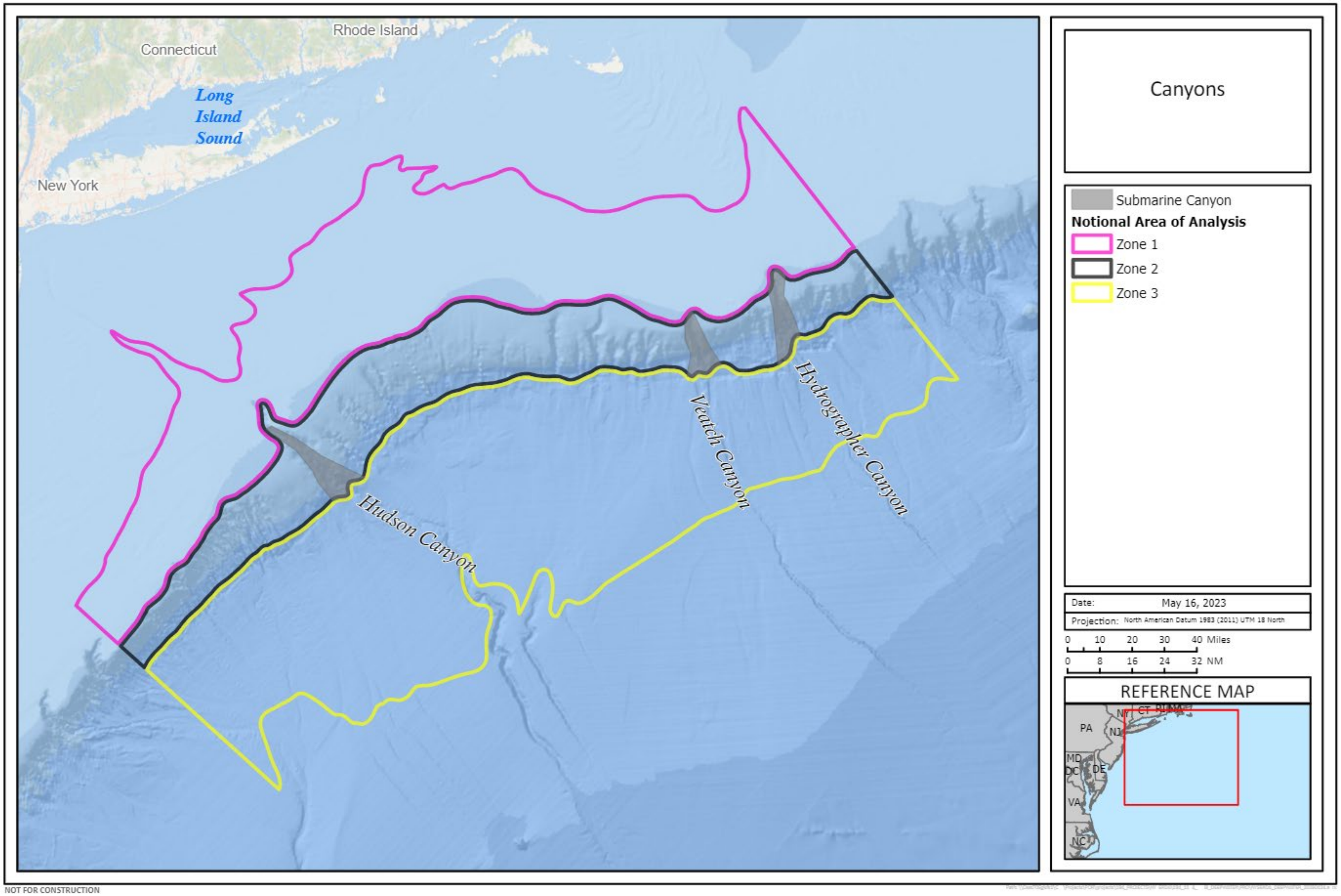
Source: Allen and Hickey 2010



The Hudson Canyon is the largest submarine canyon off the east coast and one of the largest in the world. Figure 39 details the Hudson, Veatch, and Hydrographer Canyons within Zone 2 of the AoA. Depending on each submarine canyon's size and water current direction, these submarine canyons could influence the net primary productivity waters on the continental shelf break. Computer simulations of both floating OSW in California and fixed-bottom foundations in the North Sea have shown some impacts on upwelling and stratification (Daewel et al. 2022; Integral 2022). To date, no computer simulations have been developed for the Northeast Atlantic looking at deepwater wind infrastructure or regions deeper than the continental shelf break.

Figure 39. Submarine Canyons within the Areas of Analysis

Courtesy Northeast Ocean Data Portal



3.2 Benthic Environmental Constraints

The benthic environment within the AoA holds a rich ecosystem of sponges and corals, which attract and house many other benthic species. The Hudson Canyon holds megabenthic assemblages across the canyon head and along the shelf break (Pierdomenico et al. 2017). This section details the accumulation of structures and sediments that determine the benthic environment in the AoA. A more in-depth investigation of the benthic environment is included in the Benthic Habitat Study (NYSERDA, 2025).

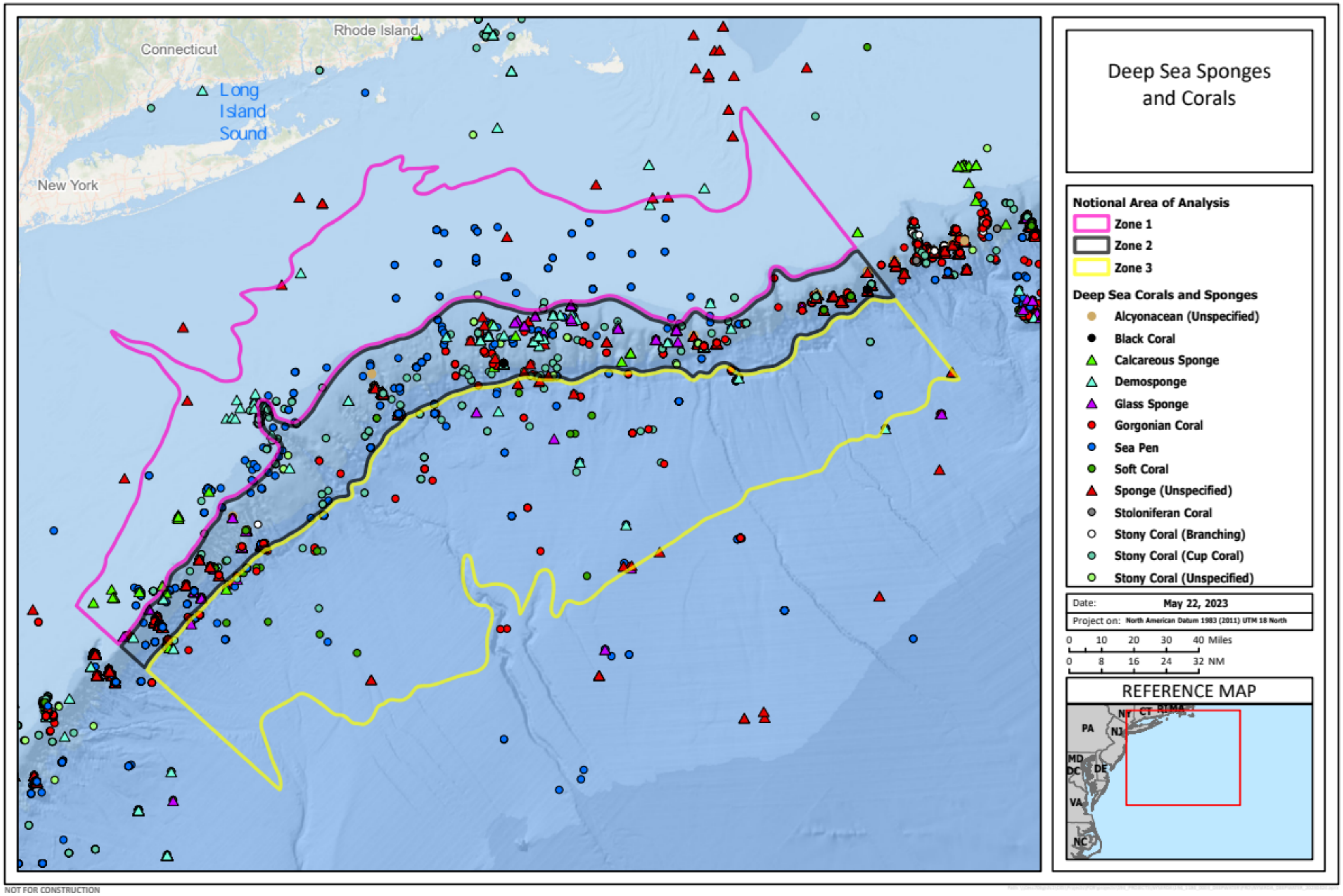
3.2.1 Deep Sea Sponges and Corals and Other Benthic Invertebrates

Deep sea sponges and corals are slow-growing and long-lived organisms, with individuals reaching over 100 years in age; forming biodiversity hot spots where they occur (Hogg et al. 2010). At greater water depths the complexity of food supply and surrounding geological substrate decline, further increasing the importance of benthic species on substrates (Buhl-Mortensen et al. 2010). The complex topography and the irregular hydrodynamic patterns along submarine canyons create habitat heterogeneity, a range of environmental conditions that differ from the adjacent continental shelf and slope sectors (Pierdomenico et al. 2017). Heterogeneous environments are predicted to support more diverse and complex biological assemblages (Tews et al. 2004). Submarine canyons generally harbor a substantially higher benthic biomass and biodiversity compared to the open slope (Rowe et al. 1982; Vetter et al. 2010; De Leo et al. 2010). The megabenthic assemblages found at the head of the Hudson Canyon and along the shelf break include sea stars, crabs, burrowing anemones, sea scallops, crangonid shrimps, sea pens, as well as the porifera (sponges) and zoanthids (cnidarians) found within reefs and deep sea (Pierdomenico et al. 2017). Sea pens play an especially important role by creating rich habitats for other fauna (De Clippele et al. 2015). They house large assemblages of mobile mollusks, invertebrates, crustaceans, and attached ophiuroids (Storm 1901; Stromgren 1971; Fujita and Ohta 1988; Buhl-Mortensen and Mortensen 2004; Baillon et al. 2014).

Figure 40 details the deep-sea sponges and corals within the three zones of the AoA. Deep sea sponges and corals are clustered at the shelf head of the Hudson Canyon, along the rim of the shelf break, and scattered throughout the Northeast and Southwest portions of Zone 1. In Zone 2, deep-sea sponges and corals are densely scattered throughout the shelf slope, and they are sparsely scattered in Zone 3.

Figure 40. Deep Sea Sponges and Corals within the Areas of Analysis

Courtesy MARCO



3.2.2 Seabed Morphology

The benthic environment differs greatly within the AoA. Benthic organisms are associated with specific sediment, slope, and morphology types. The morphology of the seabed determines the type of anchors that are feasible and the turbine grid spacing (section 2.3). The seabed morphology of Zone 1 is mainly low and flat with some upper flat/bank potions, Zone 2 is steep depression with multiple canyons, and Zone 3 has some areas of upper flat/bank in a mix of depressions (Figure 41). It is important to note that the abyssal plain in Zone 3 is not completely flat but has pockets of flat regions amongst many slopes and depressions (Figure 42).

3.2.3 Sediment

The soft sediment types determine anchor feasibility (section 2.3) and the types of organisms that inhabit an area. Zone 1 is composed of majority mud with some sand in the Northeast portion and majority sand with a small amount of mud and gravel in the Southwest portion, Zone 2 is majority mud and some sand and gravel, and Zone 3 is majority mud (Figure 42).

3.3 Broad Environmental Risks

Deepwater wind infrastructure has a larger footprint than fixed-bottom foundation wind farms and interacts with the marine environment differently. Table 7 details the high-level broad environmental risks posed from deepwater wind infrastructure and the potential mitigation measures available to minimize impacts. This section details the unique environmental impacts deepwater wind infrastructure could pose.

Figure 41. Seabed Forms within the Areas of Analysis

Courtesy MARCO

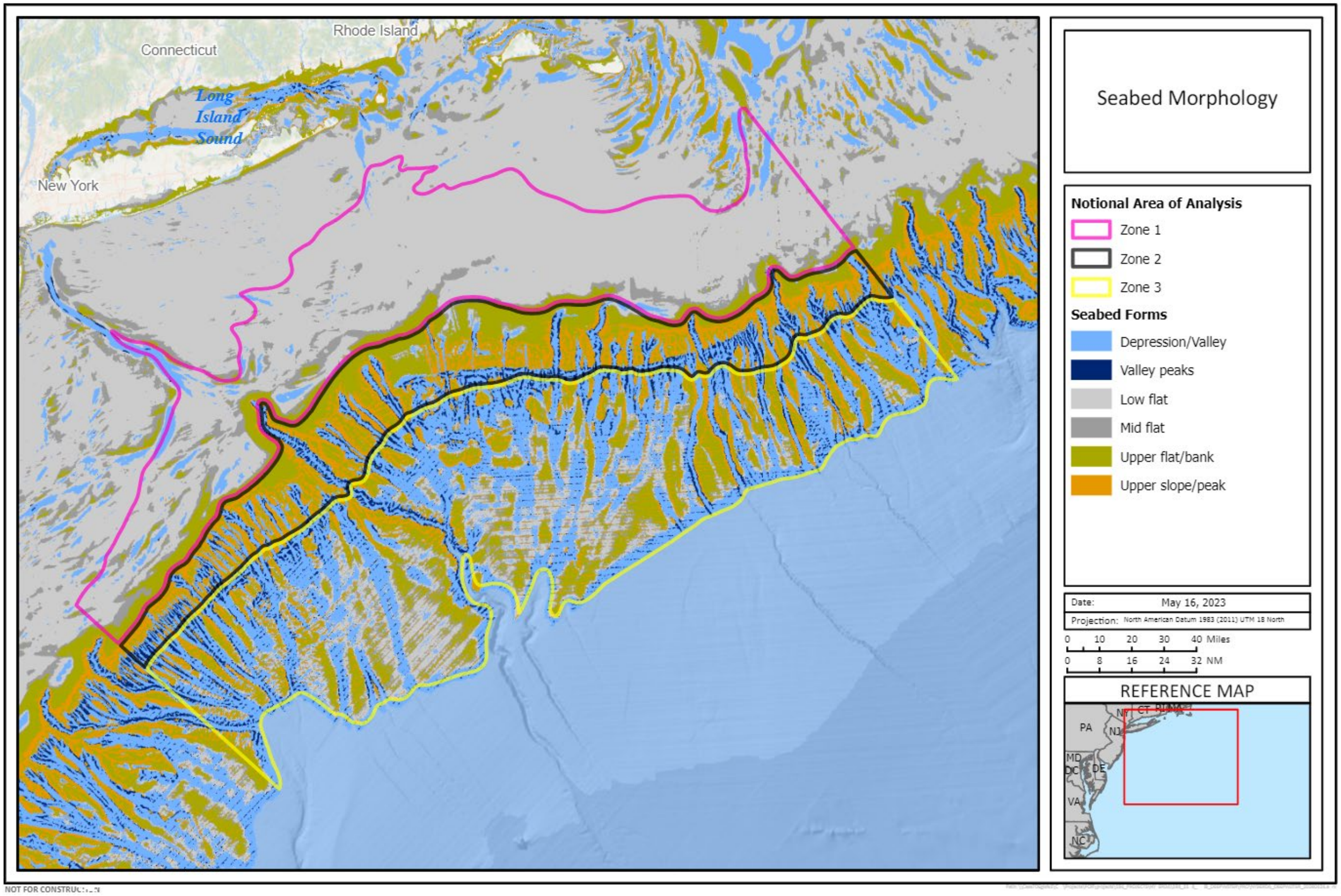


Figure 42. Sediment Types within the Areas of Analysis

Courtesy MARCO

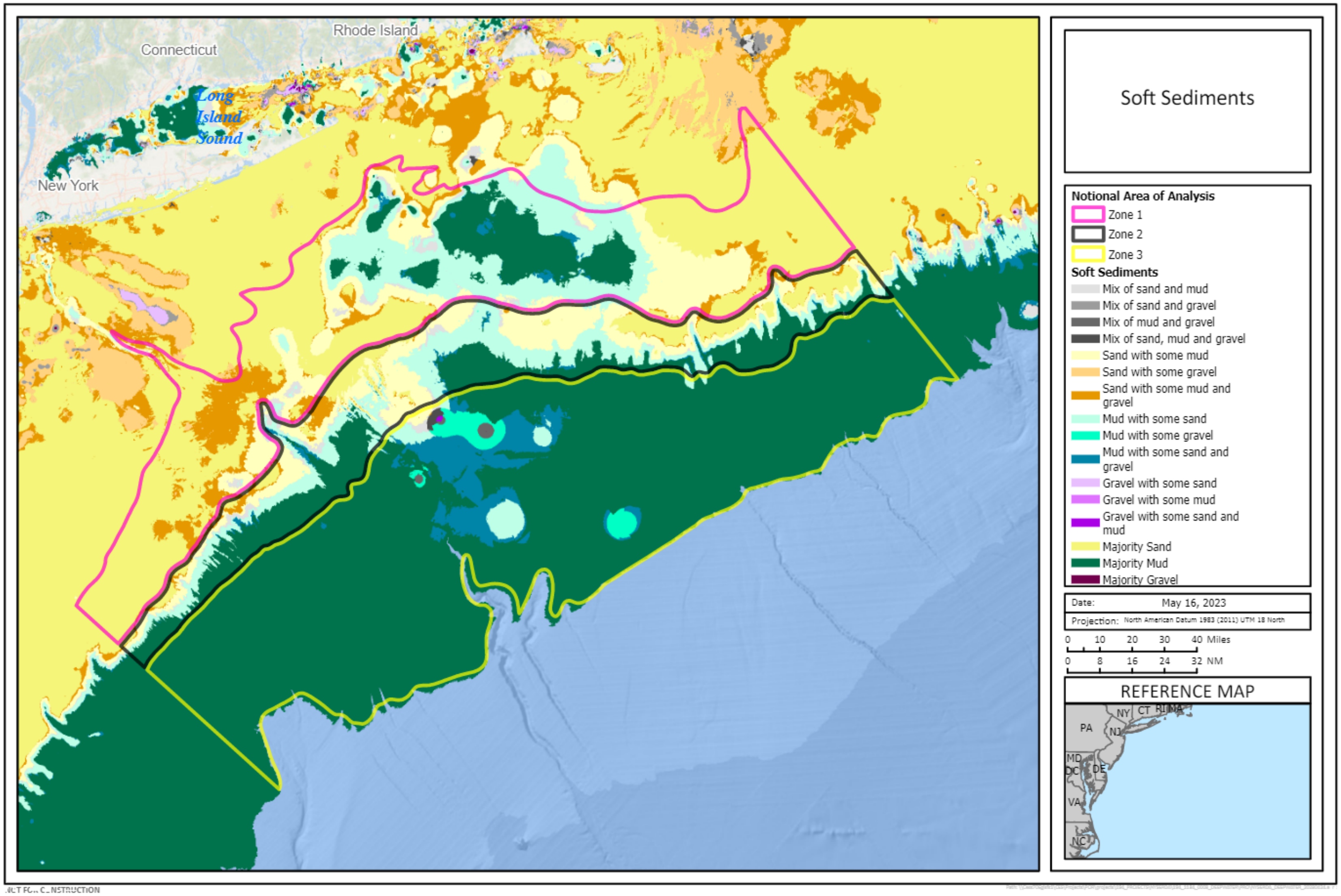


Table 7. Broad Environmental Risks and Mitigation Measures for Deepwater Wind Infrastructure

Deepwater Infrastructure	Environmental Risk(s)	Mitigation Measure(s)
Turbine Platform	Fish Aggregating Device	Expansion of "no take zone" within/around windfarms to further enhance the positive benefits for fish and invertebrate stocks and habitat.
	Habitat alteration	Creation of new habitat on and near structures to offset habitat fragmentation/modification (e.g., artificial reefs).
Inter-Array Cables	Electromagnetic frequency (EMF)	Use of proper electrical shielding on cables to minimize EMF, vibrations, and heat. Choices in current flow, cable configuration and orientation, and distances between cables.
	Secondary entanglement	Use of sensors, autonomous underwater vehicles (AUVs), and artificial intelligence (AI) to monitor lines for derelict debris.
	Turbidity/resuspension	Scouring protection and periodic routine inspections to ensure structural integrity. Scouring protection examples include boulders, gravel, and scour mats.
	Chemical pollutants	Plans for potential spills, contaminated sediments, and other project- or site-specific emergency protocols.
	Barrier effect	Use of proper electrical shielding on cables to minimize EMF, vibrations, and heat.
	Habitat alteration	Use of sensors, AUVs, and AI to monitor cables for organism settlements.
Mooring Lines	Upwelling	Model upwelling impacts from wind farm development and site accordingly to minimize hydrodynamic/upwelling impacts.
	Secondary entanglement	Use sensors, AUVs, and AI to monitor lines for derelict debris entanglement.
	Vibration	Use of taught mooring lines
	Barrier effect	Design turbine layouts to minimize contiguous barriers that could restrict normal migration routes.
	Habitat alteration	Use of sensors, AUVs, and AI to monitor lines for organism settlements.
Anchors	Seafloor disturbance	Scouring protection and periodic routine inspections to ensure structural integrity. Scouring protection examples include boulders, gravel, and scour mats. Avoid anchoring on sensitive seafloor habitats. Use mid-line floats on moored met buoys to minimize anchor sweep on the benthos ecosystems.
	Turbidity/resuspension	Scouring protection and periodic routine inspections to ensure structural integrity. Scouring protection examples include boulders, gravel, and scour mats.
	Habitat alteration	Creation of new habitat on and near structures to offset habitat fragmentation/modification (e.g., artificial reefs).
Substations	Seafloor disturbance	Avoid sensitive seafloor habitats. Scouring protection and periodic routine inspections to ensure structural integrity. Scouring protection examples include boulders, gravel, and scour mats. Avoid anchoring on sensitive seafloor habitats.
	Fish Aggregating Device	Expansion of "no take zone" within/around windfarms to further enhance the positive benefits for fish and invertebrate stocks and habitat.
	Larval entrainment	Design turbine layouts to minimize contiguous barriers that could restrict normal waterbody flow. Substations using cooling water would entrain fish eggs/larvae or other planktonic resources and/or interrupt larval transport.
	Habitat alteration	Creation of new habitat on and near structures to offset habitat fragmentation/modification.

3.3.1 Whale Entanglement and Underwater Monitoring

Primary entanglement is when marine wildlife become entangled with underwater infrastructure. This risk is very low for deepwater wind, since mooring lines and inter-array cables are a large diameter (approximately 0.7 meters [2.3 feet]) compared to a commercial longline (typically 1-4 millimeters [0.03-0.15 inches]) and are easy for marine mammals to detect. Additionally, the cables are more rigid with less curvature, decreasing loop creation (Bailey et al. 2014; Benjamins et al. 2014; Rentschler 2019). Secondary entanglement is the result of derelict debris floating in the water column becoming entangled on infrastructure, and marine wildlife becoming entangled in the debris on that infrastructure. Secondary entanglement is the most likely cause of marine wildlife entanglement. Tertiary entanglement is when marine wildlife become entangled in debris and later, the debris they are dragging becomes entangled in underwater infrastructure. To date, there is little evidence to indicate marine mammal collision or primary entanglement has ever been an issue with existing marine floating structures anywhere (Copping et al. 2020; Farr et al. 2021).

NOAA and the BOEM have a study to identify where derelict gear are in the water column in a computer simulation to assess secondary entanglement risk to whales from floating wind mooring lines (BOEM Pacific Region 2019). This study is focused on mooring lines, which take up a larger footprint of a deepwater OSW development, and not inter-array cables because it is more likely that secondary entanglement could occur on mooring lines. This study was completed in 2022, final findings have not been published on BOEM's Completed Environmental Studies website as of December 2023.

Limited research and technology advances have progressed with pingers, which are an acoustic deterrent and have been used to successfully and significantly reduce cetacean bycatch in some fisheries (Carretta et al. 2008). Effectiveness may be limited by habituation, especially amongst pinnipeds, and device maintenance and duration (Cox et al. 2001). Use of acoustic deterrent devices could add to noise pollution and attract certain animal groups, outweighing their benefits (Carretta and Barlow 2011; Findlay et al. 2018; Maxwell et al. 2022). It is important to note that the underwater footprint of a deepwater OSW development is significantly smaller than the marine area of the region. The likelihood of debris floating in the water column interacting with an individual OSW development is low considering the significantly small farm footprint (21.40 square miles for the OCS-A 0517 South Fork Wind lease) compared to the rest of the AoA (35,670 square miles). The BOEM Pacific Region (2019) study assumes debris gets entangled in underwater floating infrastructure with 100 percent probability, which does not reflect the natural probability of this occurrence. The best mitigation currently for entanglement is regular monitoring of underwater lines (Maxwell et al. 2022).

Deepwater wind brings new challenges and environmental parameters that will require infrastructure to be periodically monitored, such as hydrodynamic loading, platform motions, and fatigue. To mitigate environmental impacts in a cost-effective manner, many developers are looking to automated underwater vehicles (AUV), robotics, sensors, and artificial intelligence (AI) to perform infrastructure monitoring and maintenance (Rinaldo et al. 2021). Sensors and robotics are used in offshore energy today and can be adapted for deepwater wind structures. For example, BladeBUG (an inspect-and-repair robot) is able to crawl and walk on turbine blades, scan the area for failures, and perform repairs (BladeBUG n.d.; Rinaldo et al. 2021; Figure 43). The iFROG robot cleans and inspects monopiles up to 60-meter (197 feet) water depth (Figure 44). Fugro's Blue Essence uncrewed surface vessel with Blue Volta (an electrical ROV) completed the world's first fully remote inspection of the Aberdeen Offshore Wind farm in the North Sea (Robotics & Automation 2023).

Figure 43. BladeBUG Robotic

Source: Rinaldo et al. 2021

Figure 44. iFROG Robot

Source: OffshoreWIND.biz 2020

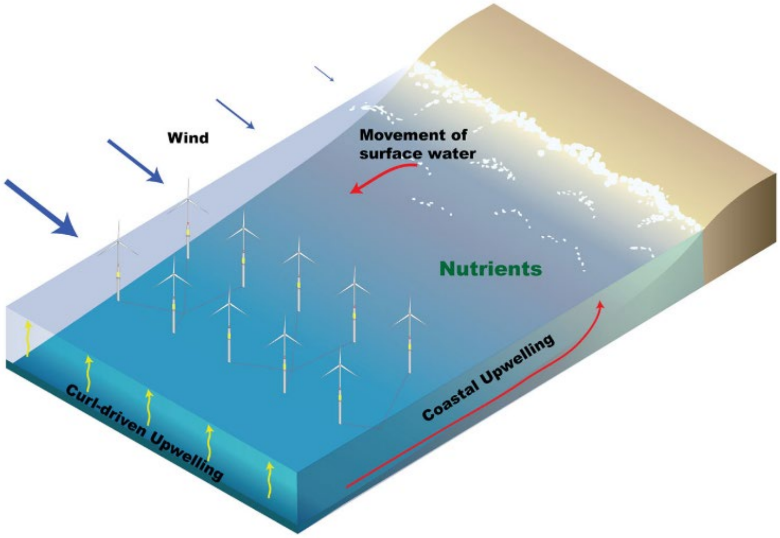
Deepwater wind will require inter-array cables and mooring line monitoring, which could detect entangled derelict debris. Robotics can be adapted from underwater monitoring systems used in offshore oil and gas to remove entangled debris (Yu et al. 2017). As the deepwater wind industry matures, sensors and AUVs will be tailored to monitor and repair cables and mooring lines in the water column. Monitoring technology engineers are anticipating an integration of subsea docking stations and control centers, where subsea and surface infrastructure is maintained by patrolling robotic platforms capable of inspection and repair.

3.3.2 Impacts to Upwelling

Wind-driven upwelling and hydrodynamics are responsible for the primary productivity that sustains the rich ecosystem of Northeast Atlantic coastal waters, as discussed in section 3.1. New York State coastal waters are unique due to upwelling that occurs from both the hydrodynamics at the Hudson Canyon and from coastal winds. Deepwater wind has the potential to impact both coastal wind and underwater current intensity with its infrastructure. Raghukumar et al. (2023) generated a model to indicate how deepwater wind development in California could impact cross-shore upwelling. Upwelling in California occurs from two processes: first, northwesterly winds drive transport near the coast, which produces upwelling of cool, nutrient-rich waters and coastal divergence and second, wind stress curl (horizontal gradients in the wind) drives divergent flow from the bottom and consequently, upwelling (Figure 45).

Figure 45. Cross-Shore Upwelling Processes of an Eastern Ocean Boundary

Source: Raghukumar et al. 2023



This study modeled the three (former) potential OSW site locations of Humboldt, Diablo Canyon, and Morro Bay. The study found that deepwater wind development changed the cross-shore structure of the wind-stress gradient, resulting in a reduction in the mean nearshore/offshore gradient in wind stress on the nearshore side of a wind farm and an enhancement on the offshore side of a wind farm (Raghukumar et al. 2023). No measurable change was observed within the highly productive 10 kilometer (6 mile) coastal upwelling zone at the three site locations. Since the net change in wind stress curl will be small across the wind farm wakes, little change in net upwelling is expected around wind farm wakes with topography and hydrodynamics similar to this model (Raghukumar et al. 2023). This model is unique to the cross-shore wind structure and upwelling in California and cannot be inferred for other geographic regions. Though these study findings cannot be inferred for the upwelling impacts in the New York Bight, it is helpful to see that deepwater wind infrastructure could interact with the complex upwelling and hydrodynamic systems within the three zones of the AoA, which could be studied in the future.

Many coastal fishes and invertebrates produce planktonic larvae that grow and develop in the waters over the continental shelf (Shanks et al. 2000). Afterward these late-stage larvae migrate to shore to complete their development and recruit into the adult population. Larvae are transported to shore following upwelling events (Roughgarden et al. 1991). The rich environment and productive fishing areas off New York State's coast rely on larvae being transported to shore for recruitment into adult populations.

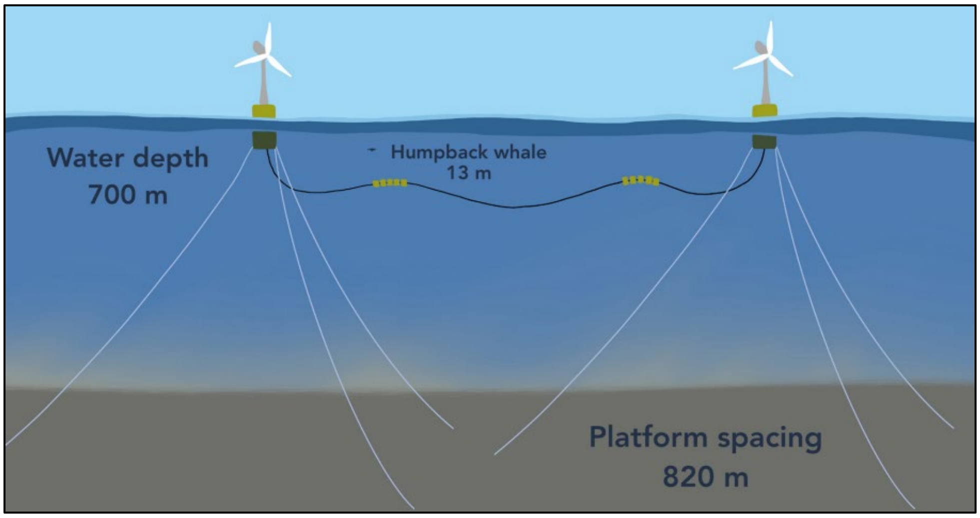
Marine deepwater wind infrastructure has the potential to alter currents that play a large role in hydrodynamic upwelling at the Hudson Canyon. Multiple mooring lines throughout the water column, depending on their placement, have the potential to impact deep and mid-line currents that are essential for upwelling (section 3.1). As of November of 2023, there has not been a model generated showing potential current impacts from marine deepwater wind infrastructure.

3.3.3 Mooring Line/Inter-Array Cable Barrier Effect

Barrier effect is when infrastructure presence can inhibit species from using the space. Barrier effect cancan occur if marine deepwater wind infrastructure causes collision risk or displacement of marine mammals. There are decades of literature on marine mammal interactions with marine floating structures, many of which use catenary or semi-taut mooring lines (section 2.2). To date, there is little evidence to indicate marine mammal collision or primary entanglement has ever been an issue with these existing floating structures, especially due to the large size of these structures (Copping et al. 2020; Farr et al. 2021). Displacement can lead to inaccessible areas and force foraging or migrating marine mammals to increase travel and use more energy to avoid a deepwater OSW development (Haberlin et al. 2022). It is important to note the sheer size of these underwater structures. Figure 46 shows an example scenario of deepwater wind turbines and midwater inter-array cables with a Humpback Whale (*Megaptera novaeangliae*) for scale reference. BOEM also developed a simulation of a humpback whale and floating wind infrastructure to visualize technology size and scale interacting with a Pacific species. When visualized to scale, there is presumably ample open water within a deepwater wind footprint for large marine species to coexist.

Figure 46. Size and Scale of Deepwater Wind Structures and a Humpback Whale

Source: Molly Grear, Pacific Northwest National Laboratory



3.4 Risks to Fisheries

Risks to fisheries from deepwater OSW developments include both temporary and potentially long-term impacts, similar to those identified for projects in shallower waters. Temporary impacts that may result from wind farm pre-construction surveys and construction activities include fish displacement from fishing grounds due to habitat alteration or construction noise, and increased vessel traffic in the region that may inhibit fishing or disturb fish in and near project areas. Permanent impacts from wind farm operations include the potential for complete or partial loss (exclusion) of fishing grounds for some fisheries if gear type is not compatible with deepwater wind infrastructure, potential for loss of gear due to entanglement in wind farm infrastructure, and the potential for navigation risk near and within wind farms which may preclude some types of fishing activities in the area entirely. Depending on the fishing gear type, complete/partial exclusion could occur within a lease area and also along the export cable route to shore. Some of these risks may be pronounced in deepwater FOSW installations due to the increased footprint of associated infrastructure both on the seafloor and in the water column (described in section 2) and will require further evaluation for individual OSW farms. The following section discusses risks to various types of fishing gear, a review of target species that may be impacted by deepwater wind installation infrastructure, and information about fishing practices that may occur in parallel with wind farm operations. A discussion of design measures to mitigate risk is also included.

3.4.1 Risks to Fishing Gear

Risks to fishing gear from deepwater wind projects will be dependent on project stage and specific project design. For example, during the cable laying phase of construction some fishing gear like traps and pots may not be safely deployed in or near cable corridors. Once construction is completed, cable corridors with buried cables may no longer pose risk to these gears unless cables become unburied, in which case re-burial is expected to occur. During operations, the main risk for many gear types is the loss of fishing grounds. Figure 47 displays the percent of seabed disturbed by fishing gear in the AoA, which provides an idea of areas where bottom contact gear would be most heavily impacted by the presence of deepwater wind infrastructure located on or near the seafloor. It is clear that bottom contact fishing activities in the deepest areas and those along the continental slope (the majority of Zones 2 and 3) would be least impacted by deepwater wind seafloor infrastructure, and that Zone 1 includes some areas (e.g., the eastern portion) that may be better suited from the perspective of reducing impacts on these fisheries.

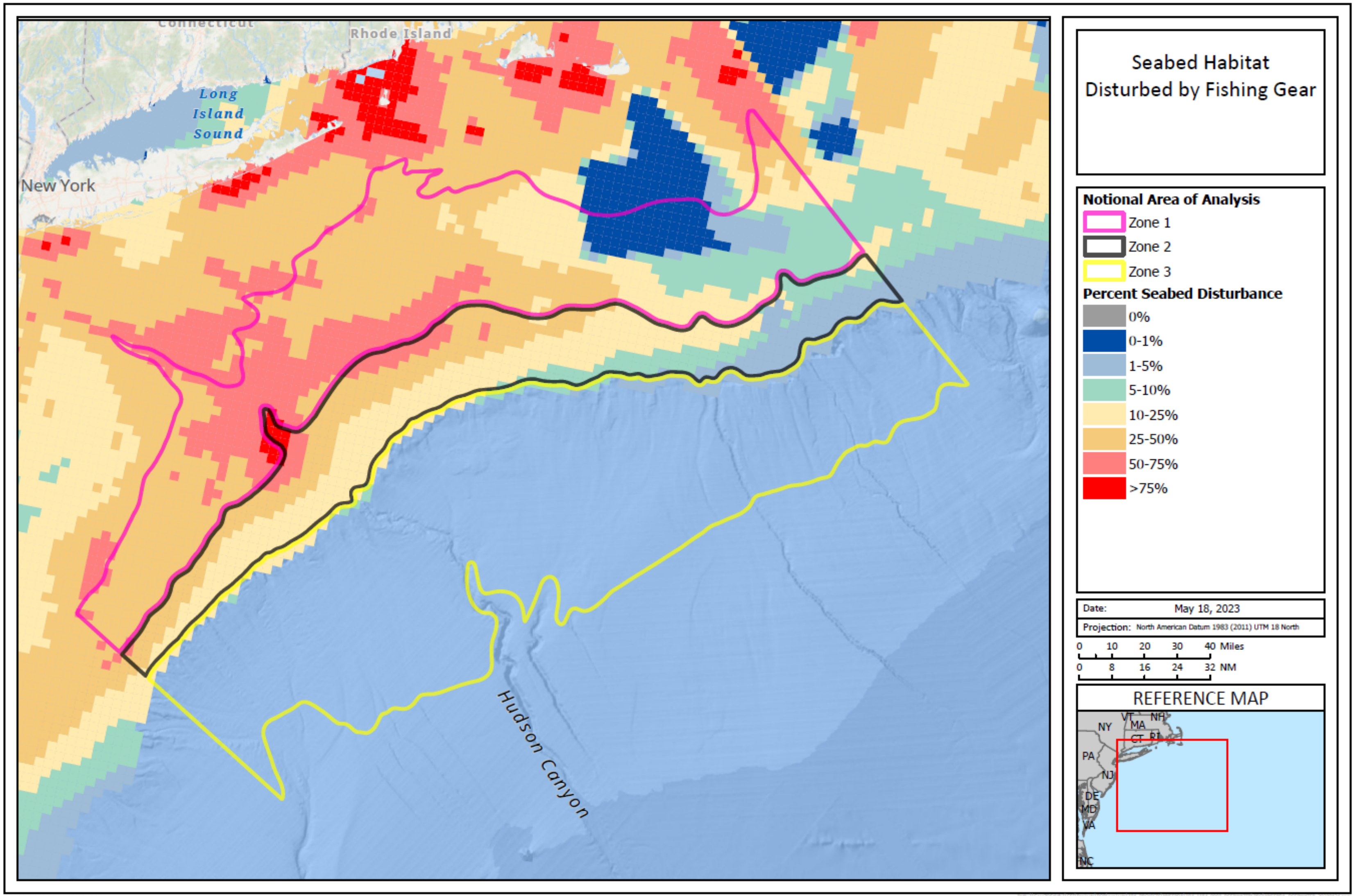
The following text includes a discussion of risk anticipated for some of the main gear types used in the AoA and surrounding region. Vessel Trip Report (VTR) and Vessel Monitoring System (VMS) data were reviewed for the analysis of the major gear types and fisheries required to use VMS to examine spatial trends; note that not all fishing activity is captured by VTR and VMS data, but general trends can be examined.

3.4.1.1 Bottom Trawling

Bottom trawling is likely to be impacted by OSW farms primarily due to loss of fishing grounds and potential loss of gear. In the New York Bight region bottom trawling occurs from near the shoreline out to the edge of the continental shelf where effort is particularly concentrated (Zone 2), and there are some VTR reports of trawling activity beyond the shelf slope (Zone 3). Bottom trawling effort is heavy in highly productive areas such as near the Hudson Canyon where nutrients are concentrated and food web dynamics yield an abundance of many species, including target fish species (e.g., monkfish, scallops, and a variety of groundfish species such as flounders and scup).

Figure 47. Percent of Seabed Habitat Disturbed by Bottom Contact Fishing Gear within the Areas of Analysis

Courtesy MARCO



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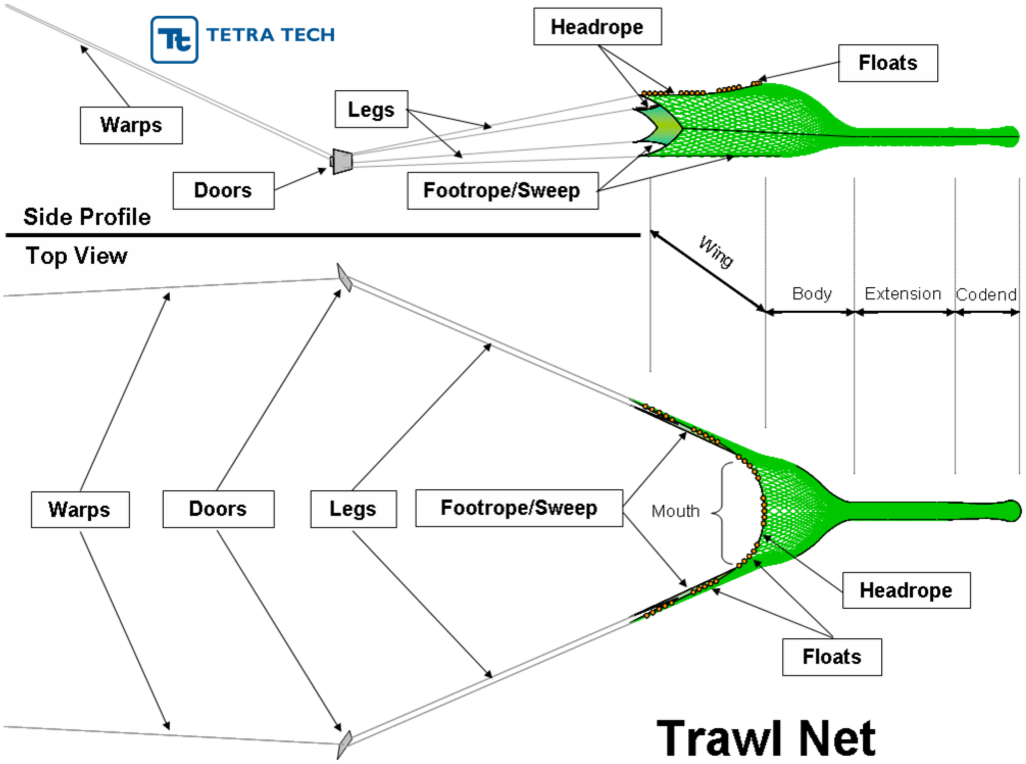
Bottom trawls are large and heavy pieces of equipment with multiple components that interact with the seafloor (Figure 48). Risks to bottom trawling activities include the following:

- Loss of fishing grounds within lease areas due to bottom infrastructure.
- Loss of fishing grounds along cable corridors if cable armoring at crossings impedes trawling.
- Potential loss of gear along cable corridors if cables become exposed and snag nets.
- Potential loss of gear if trawl nets snag at cable crossings.
- Potential loss of gear if trawl nets snag a mooring line.
- Potential loss of gear if trawl nets snag an inter-array cable during deployment or retrieval.

Figure 48. Schematic of a Typical Otter Trawl



3.4.1.2 Dredging

Similar to bottom trawling and other bottom contact mobile gear, risks to dredging are primarily from loss of fishing grounds and potential loss of gear. In the New York Bight region dredging occurs from near the shoreline to out over the majority of the continental shelf. Dredging does not occur near the edge of the continental shelf and into deeper waters of the slope or beyond and is primarily concentrated in depths between 40–80 meters (25–50 feet) in Zone 1. Within Zone 1, the majority of dredging occurs in the western portion; dredging east of the Hudson Shelf Valley is in shallower waters.

Industrial dredges are large and heavy pieces of equipment that have risk of hanging up on the benthic components of deepwater wind infrastructure (Figure 49 and Figure 50). The species primarily targeted by dredges in the New York Bight region include scallops, surfclam/ocean quahog, and monkfish. Risks to dredging activities are similar to trawling due to bottom contact and include the following:

- Loss of fishing grounds within lease areas due to bottom infrastructure.
- Loss of fishing grounds along cable corridors if cable armoring at crossings impedes dredging.
- Potential loss of gear along cable corridors if cables become exposed and snag dredge.
- Potential loss of gear if dredges snag at cable crossings.
- Potential loss of gear if dredges snag a mooring line.
- Potential loss of gear if dredges snag an inter-array cable during deployment or retrieval.

Figure 49. Depiction of Dredge Gear Used to Capture Sea Scallops

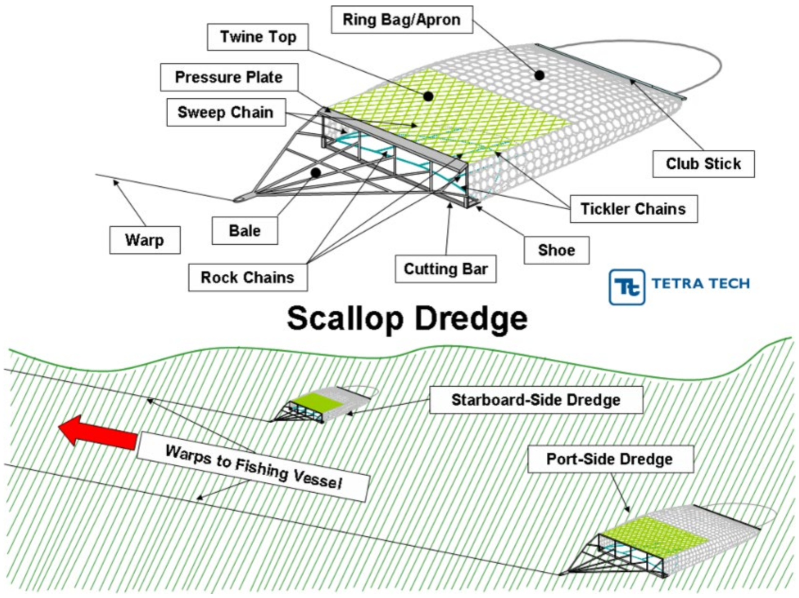
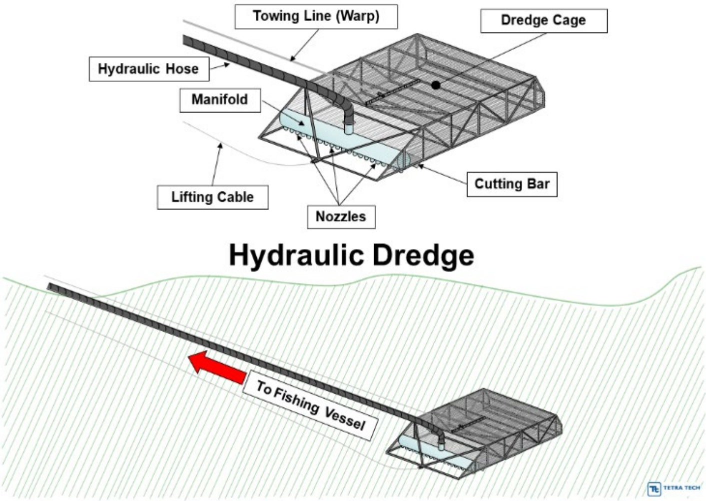


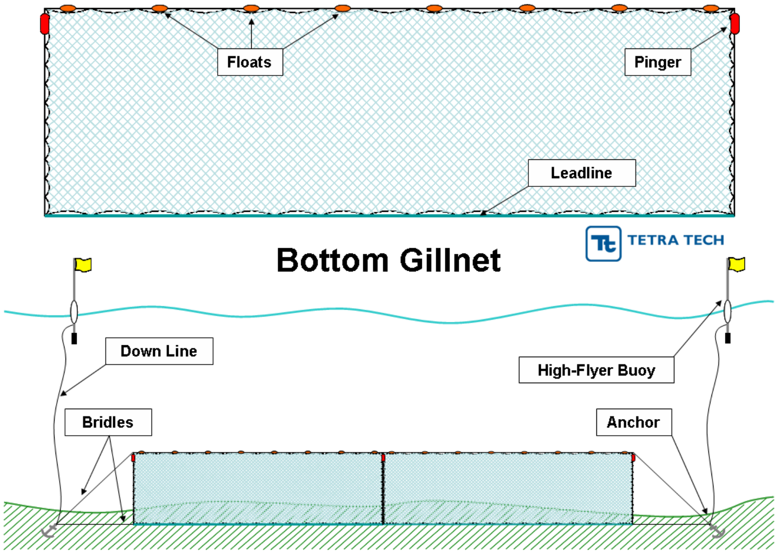
Figure 50. Depiction of a Typical Hydraulic Dredge Used in the New York Bight Region



3.4.1.3 Gill Netting

There are two types of gill nets used in the New York Bight region: set gill nets and drift gill nets. Set gill nets are considered bottom fishing gear and use anchors to keep them in place on the seafloor; as such they have components that may snag on exposed cables or other bottom infrastructure associated with deepwater OSW (Figure 51). Drift gill nets remain in the water column, attached to buoys and weights to fish midwater. In the New York Bight region, gill netting is primarily used over the continental shelf from the nearshore out to the continental slope, in the eastern portions of Zones 1 and 2.

Figure 51. Depiction of a Bottom Set Gill Net



Species often targeted by gill netting in the New York Bight region include groundfish (e.g., cod, haddock, spiny dogfish), mackerel and others. Risks to gill netting activities include the following:

- Loss of fishing grounds along cable corridors if cable armoring at crossings impedes gill netting.
- Loss of fishing grounds within lease areas due to bottom and/or water column infrastructure.
- Potential loss of gear along cable corridors if cables become exposed and snag gill nets.
- Potential loss of gear if gill nets snag at cable crossings.
- Potential loss of gear if gill nets snag a mooring line.
- Potential loss of gear if gill nets snag an inter-array cable during deployment or retrieval.

3.4.1.4 Longlining

Longlining gear is used on the bottom and in the water column throughout the New York Bight region (Figure 52). It is the only gear used extensively in the deepest waters of Zone 3 and is also used along the continental shelf and slope in deeper waters. Many longliners embark on multiple day trips and travel far from shore. An example is longlining for golden tilefish (Figure 53), which are most commonly fished between Hudson and Veatch Canyons and as far out as 100 miles from shore (NOAA Fisheries 2023a).

Figure 52. Depiction of a Bottom Set Longline

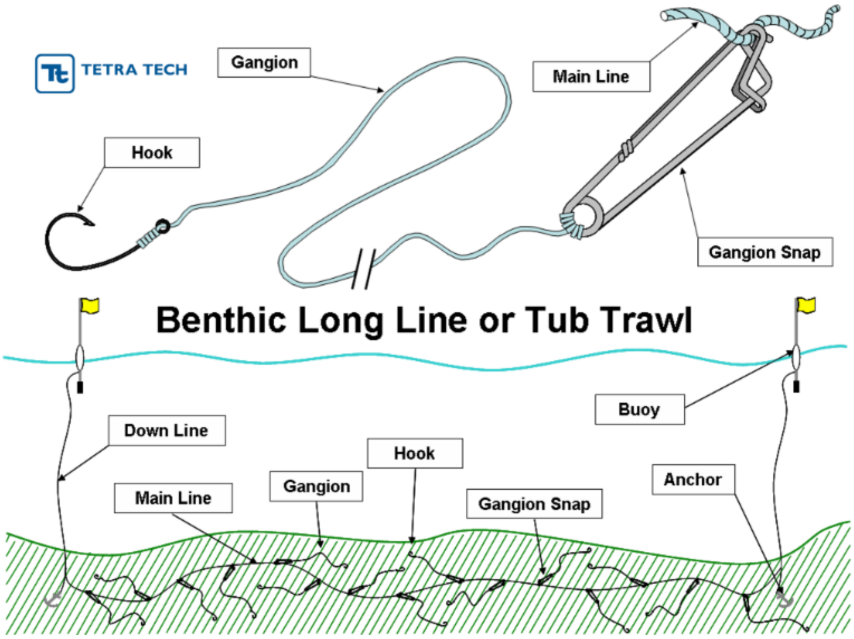


Figure 53. Golden Tilefish Caught 100 Miles off the Coast of Long Island

Source: NOAA Fisheries 2023b/Nichole Nigrin

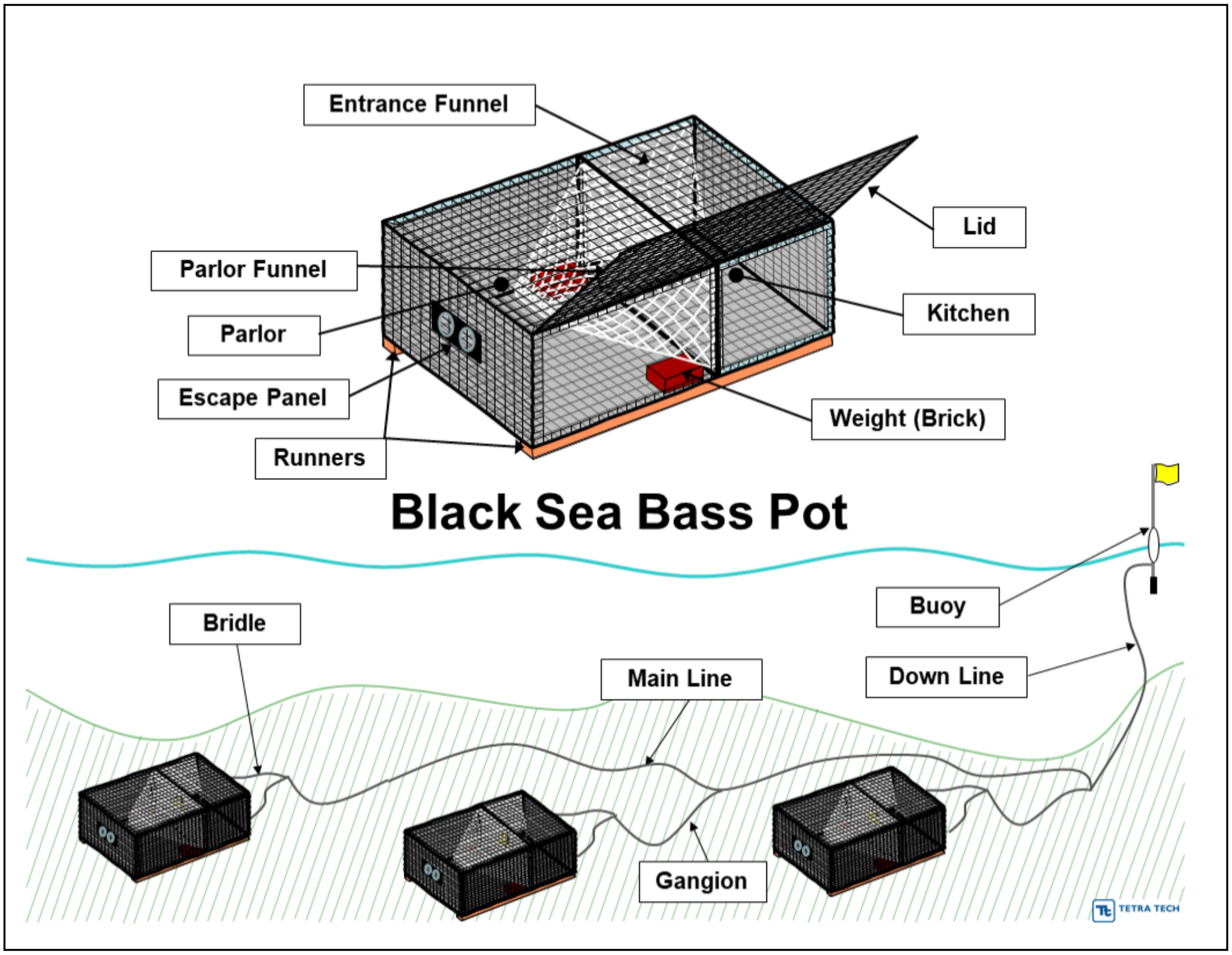
Other species often targeted by longlining in the New York Bight region include swordfish and tuna (by pelagic longline). Risks to longlining activities include the following:

- Loss of fishing grounds within lease areas due to bottom and/or water column infrastructure.
- Potential loss of gear along cable corridors if cables become exposed and snag bottom longlines.
- Potential loss of gear if longlines snag at cable crossings.
- Potential loss of gear if longlines snag a mooring line.
- Potential loss of gear if longlines snag an inter-array cable during deployment or retrieval.

3.4.1.5 Pots and Traps

Pots and traps are used on the seafloor and marked for retrieval with buoys on the sea surface throughout the New York Bight region (Figure 54). It is used extensively along the shelf slope of Zone 2 and is also used along the continental shelf from near the shoreline and into deeper waters (Zone 1).

Figure 54. Example Fish Pot



Species often targeted by pots and traps in the New York Bight region include scup, black sea bass (in shallowest zones), and various other species of groundfish. Risks to pots and traps gear include the following:

- Loss of fishing grounds within lease areas due to bottom and/or water column infrastructure.
- Potential loss of gear along cable corridors if cables become exposed and snag pots/traps.
- Potential loss of gear if pots/traps land on cable crossings.
- Potential loss of gear if pots/traps snag a mooring line.
- Potential loss of gear if pots/traps snag an inter-array cable during deployment or retrieval.

3.4.2 Fisheries Species Impacted by Deepwater Wind Development

This study includes a high-level review of the fisheries occurring in deepwater areas. The Fish and Fisheries Data Aggregation Study (NYSERDA, 2025) includes an in-depth analysis of fisheries in the AoA. We investigated the general spatial trends in fishing in the New York Bight region with a concentration on gear type (discussed in section 3.3.1). Some of the most common fisheries in the AoA include the following: groundfish (various species such as scup, monkfish, flounder species), shellfish such as Atlantic sea scallop, surf clam (shallowest areas), and ocean quahog, and pelagic species (various species such as squid, herring and large billfish). Based on VMS data, the vast majority of fishing in the AoA occurs nearshore and on the continental shelf (Zones 1 and 2). VMS fishing activity declines dramatically in areas below the continental slope in Zone 3, which is fished with longline gear for pelagics species such as swordfish, and tuna (section 3.3.1.4; Figure 55).

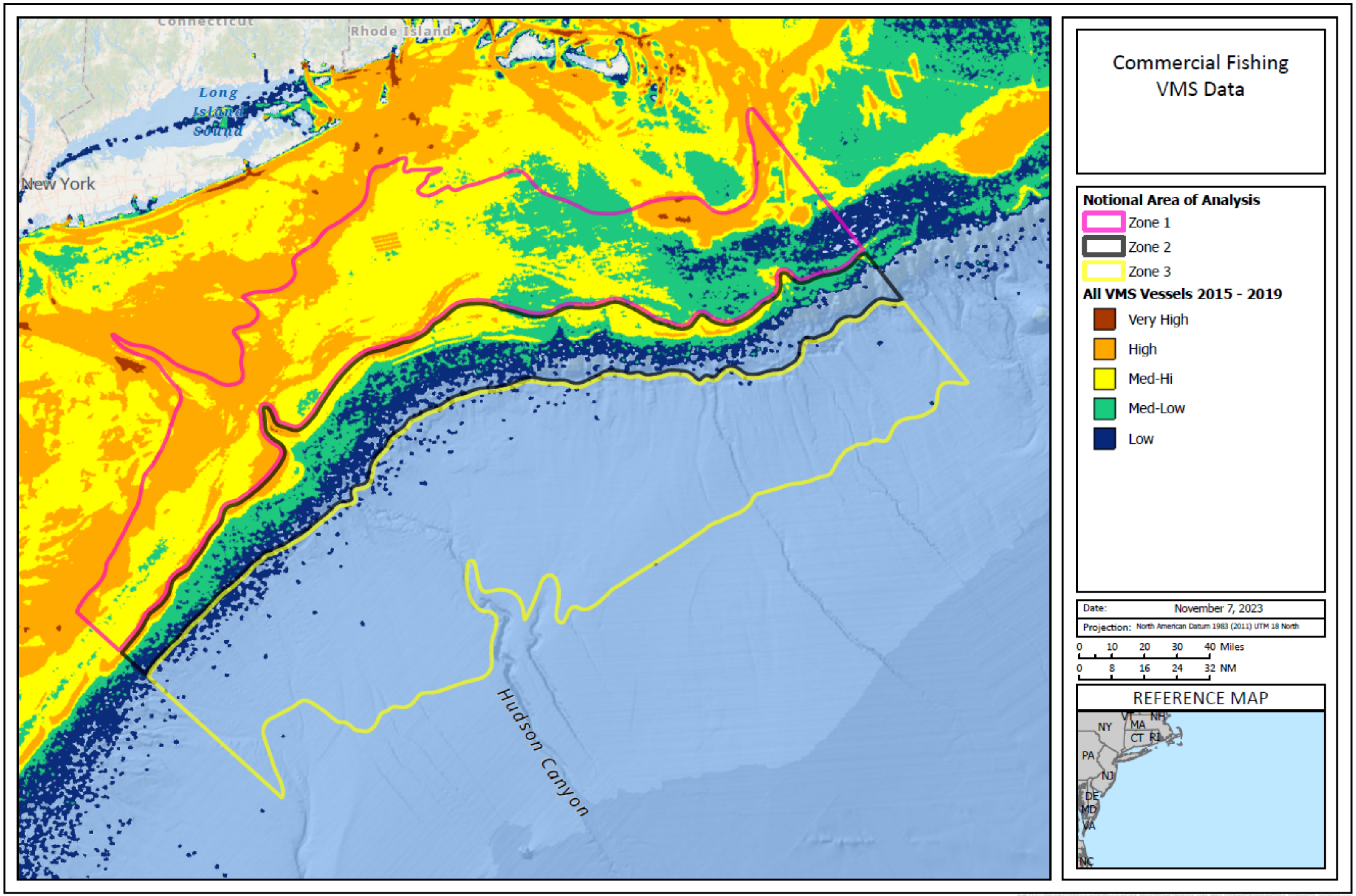
3.4.3 Design Considerations to Allow for Fishing in and Near Deepwater Wind Installations

During the construction and decommissioning phases of deepwater wind projects most fishing activities in the lease and cable corridor areas will be affected and some fishing methods will not be feasible in these areas (e.g., trawling and dredging). BOEM requirements for a Fisheries Communication Plan will help fishermen to plan for construction activities and to adjust their fishing activities accordingly. Frequent communication between each project Fisheries Liaison Officer and local fishermen will be necessary to minimize impacts on fishing during these phases.

Multiple studies have investigated the impacts of OSW farms on bottom contact mobile gear such as trawls and dredges and have concluded that the design of the wind farm greatly affects the outcome of fishing activity decline (e.g., Dunkley and Solandt 2022). OSW farms designed in one densely aggregated patch do not allow trawling to occur within a lease area, whereas those that are spaced more widely (greater than 1 mile between turbines for fixed turbine installations), or designed in multiple aggregated patches within a lease area, may allow trawling to occur safely between turbines or patches of turbines. However, closely spaced turbines would result in a smaller overall footprint. Similar implications exist for other gear types such as midwater mobile gear and traps/pots. Space between turbines or patches of turbines or other unique array designs may allow for safer fishing conditions and lower likelihood of gear loss or entanglement. Further analysis of the ideal turbine array design to coexist with fishing in the New York Bight area is warranted, and specific considerations for deepwater wind are discussed below.

Figure 55. All Vessel Monitoring System Vessels 2015–2019 within the Areas of Analysis

Source: MARCO



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For deepwater OSW there is an additional level of complication when assessing impacts, as the designs most likely to be used beyond 60 meters (197 feet) are floating, and the floating platform and mooring system used will determine the bottom footprint. For example, TLP designs with mooring lines that extend out at a small angle below the platform to anchors on the seafloor take up less space on the seafloor and in the water column than other designs that include mooring lines extending a greater distance/angle from the platform before connecting to anchors (e.g.: a spar platform with a catenary mooring design). Design considerations are one of the ways to substantially minimize the impacts OSW farms will have on fisheries and should be part of the early planning for deepwater OSW installations.

Important lessons can be learned from deepwater installations that are in operation regarding the potential for fishing in and near deepwater OSW farms. A recent effort was made to test the feasibility of use of different fishing gears within the Hywind Scotland floating wind farm in collaboration with Equinor and the Scottish government. Although the initial efforts were limited to three types of fishing gear (creels, fishtraps, and jigging lines), further trials with additional gear types are in the planning phases. The results will be useful when planning for deepwater wind in the waters of the New York Bight region and elsewhere.

4 Conclusion

Factors such as seabed morphology, water depth, and sediment type dictate the deepwater wind structures that are feasible for use in a particular area, from the anchors to the turbines. The overall design decisions start at the bottom with the anchors and optionality for other components such as mooring lines and turbine platforms are highly dependent on anchor choice. The physical seabed morphology and sediment type(s) determine the types of anchors that are feasible. Table 8 details the deepwater wind technical components and their functionality in each of the zones in the AoA. Table 9 (described by zones) includes a summary of the major environmental considerations for a deepwater wind installation in the New York Bight region. These environmental considerations also inform technology and deepwater OSW farm design decisions.

Table 8. Baseline Analysis of Technologies for Deepwater Wind in the Areas of Analysis

Deepwater Component	Technology Options	Zone 1	Zone 2	Zone 3
Anchors	• Suction • Drag Embedment • Pile • Shared	• In mud/clay areas, all anchor designs may be used. • In sand areas, best choice is drag embedment.	• No anchor is ideal due to steep slopes and canyons; drag embedment could be used, but cannot be sited precisely.	• In mud/clay areas, all anchor designs may be used.
Mooring Lines	• Catenary • Taught (Tension leg) • Semi-Taught	• Mooring line option dependent upon anchor selected above.	• Mooring line option dependent upon anchor selected above.	• Mooring line option dependent upon anchor selected above.
Turbine Platform	• Barge • Semi-Submersible • Spar • Tension Leg Platform	• Turbine platform option dependent upon anchor and mooring line selected above.	• Turbine platform option dependent upon anchor and mooring line selected above.	• Turbine platform option dependent upon anchor and mooring line selected above.
Cables	• Buried Inter-array • Floating Inter-array	• Buried Inter-array • Floating Inter-array	• Floating Inter-array	• Floating Inter-array
Substations	• Fixed • Floating • Subsea	• Fixed (in theory, with new technology) • Floating • Subsea	• Floating	• Floating • Subsea

Table 9. A Summary of the Major Environmental Considerations in the Areas of Analysis

Parameter	Zone 1	Zone 2	Zone 3
Seabed morphology	• Majority flat • Upper flat/bank	• Steep slopes and canyons	• Depressions/valval • Upper flat/bank
Deep sea sponges and corals	• Primarily sea pen in Northeast region. • Calcareous sponges in the Southwest portion. • Cluster of sea pen, soft coral, and demosponge at the head of the Hudson Canyon.	• Highest density of sponges and corals. • Clear density of sponges and corals Northeast and Southwest of the Hudson Canyon.	• Scattered sponges and corals. • Denser clusters of sponges and corals toward the base of Zone 2 in center portion.
Sediment Type	• Majority mud with some sand (Northeast portion). • Majority sand with a small amount of mud and gravel (Southwest portion).	• Majority mud and some sand and gravel.	• Majority mud
Water depth	• 60–150 meters	• 150–2,300 meters	• 2,300–3,000 meters
Fisheries Gear commonly Used	• Trawls • Dredging • Longlines • Pots and traps • Gill nets	• Trawls • Longlines • Pots and traps • Gill nets	• Longlines • Trawls
Common Fisheries	• Pelagics (e.g., squid, herring, and large billfish), surf clam/ocean quahog, scallop, groundfish (multispecies), monkfish	• Squid, scallop, groundfish (multispecies), monkfish, tilefish	• Pelagics (e.g., swordfish and tuna), tilefish

Identifying OSW lease areas in deepwater areas in the New York region will be required to reach federal and New York State targets for OSW in a timely manner. This study examined next generation technologies that may stretch the limits of what is currently deemed feasible in deep water and may help to mitigate impacts on some environmental factors. Large efforts are being made to produce technology to implement deepwater OSW in a more cost-effective and environmentally responsible manner that minimizes impacts on ocean users and the marine environment. A combination of these new technology development efforts and thoughtful siting and array designs will bring us closer to reaching federal and State goals for developing clean energy in a responsible manner.

Some suggestions for potential future considerations to support planning for deep water wind in the New York Bight region include the following:

- Pilot studies using next generation fixed-bottom foundation technologies in deep water.
- Concentrated efforts to develop shared anchor and mooring designs for FOSW to minimize project footprints, and in effect, potential impacts on benthic and pelagic environments.
- Concentrated efforts to further develop and test TLP platform designs in deep water to minimize individual turbine footprints in the water column, and in effect, impacts to the pelagic environment.
- Review of design options for turbine arrays that maximize energy output and minimize potential impacts to the environment and ocean users, such as fishermen.
- Further examination of the potential for the safe coexistence of ocean users and deepwater offshore wind farms.

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Appendix A. Deepwater Wind Research Studies

Table A-1. Completed and in Progress

Category	Study	Timeframe	Description	Principal Investigator/Funding Agency
Environmental Impacts	Floating Wind Power in Deep-Sea Area: Life Cycle Assessment of Environmental Impacts	2023	This project uses a life-cycle assessment method based on the Chinese core life-cycle database for 100 wind turbines. Many small-scale studies have been completed but none on this large of scale. This study accounts for the manufacturing, operation, and decommissioning carbon footprint.	Yuan, W. et al. / National Natural Science Foundation of China, the National Key Research and Development Program, Guangdong Natural Resources Foundation, Guangzhou Science and Technology Project, and Guangdong Provincial Key Laboratory Project.
	Identifying the Potential of Floating Artificial Benthic Ecosystems to Underpin Offshore Development	2022	Evaluates the ecosystem benefits of floating wind turbines in the open ocean developing	Komyakova, V. et al. / University of Tasmania
	Potential impacts of floating wind turbine technology for marine species and habitats	2022	Considers impacts on marine mammals, seabirds, fisheries, and benthic ecosystems. Examines entanglement and mitigation measures in particular. Recommends future studies and work for floating offshore wind farms.	Maxwell, S. et al. / University of Washington, Natural Resources Defense Council, Stony Brook University, Castalia Environmental, MarFishEco Fisheries Consultants, Heriot-Watt University
	Life Cycle Assessment of a Barge-Type Floating Wind Turbine and Comparison with Other Types of Wind Turbines	2021	Compares life-cycle assessment of floating foundations to fixed-bottom foundations and onshore wind turbines. Life cycle covers manufacturing, operations, disposal, and recycling.	Yildiz, N. et al / University of Birmingham
	Floating Offshore Wind: Environmental Interactions Roadmap: Public Summary Report	2022	Outlines activities required to ensure assessments are done with identifying key areas of work including aviation interaction, colocation and coexistence, cumulative impacts, electromagnetic fields, fisheries, Habitats Regulations Assessment (HRA), navigational risk, ornithology, skills gaps and underwater noise.	ORE Catapult, Xodus Group, Floating Offshore Wind Centre of Excellences

Table A-1 continued

Category	Study	Timeframe	Description	Principal Investigator/Funding Agency
Environmental Impacts (continued)	Potential environmental effects of deepwater floating offshore wind energy facilities	2021	A qualitative review to determine potential environmental effects of floating wind turbines addressing potential mitigation effects. The six categories of effects include changes to atmospheric and oceanic dynamics due to energy removal and modifications, electromagnetic field effects on marine species from power cables, habitat alterations to benthic and pelagic fish and invertebrate communities, underwater noise effects on marine species, structural impediments to wildlife, and changes to water quality. Uses appropriate analogs including fixed-bottom foundation wind farms, onshore wind, wave and tidal energy devices, and oil and gas platforms.	Farr et al. / California Polytechnic State University, San Luis Obispo, CA,
	Humpback Whale Encounter with Offshore Wind Mooring Lines and Inter-Array Cables	2018	Assesses and visualizes the likelihood and mechanisms of cetaceans may encounter from lines in a floating offshore wind array.	Copping, A. and Grear, M. / Pacific Northwest National Laboratory and Bureau of Ocean Energy Management
	Material consumption and environmental impact of wind turbines in the USA and globally	2022	Estimates the material demand for wind turbines and the carbon footprint changes.	Farina, A. and Anctil A. / Michigan State University
	Comparison of Environmental Effects from Different Offshore Wind Turbine Foundations	2020	Discusses types of foundation types, the conditions for each type, and their varying impacts.	ICF Inc. and Bureau of Ocean Energy Management
Turbines	Next Generation Floating Offshore Wind Turbine	2023	Discusses new technology designs for offshore wind turbines.	Miller, M. et al. / Institutes of Energy and the Environment (IEE) Seed Grant Program and Penn State University
	Floating offshore wind power: a milestone to boost renewables through innovation	2023	An overview of the floating offshore wind turbine platforms.	Iberdrola Renewables

Table A-1 continued

Category	Study	Timeframe	Description	Principal Investigator/Funding Agency
Mooring and Anchoring Systems	Novel and Efficient Seabed Ring Anchor for Omnidirectional Loading	2020-2023	This project will support a research team to develop models for the loading placed on multiline ring anchors subjected to wind, waves and other forces. A Multiline Ring Anchor (MRA) is a ring-shaped anchor designed to be deeply embedded in offshore soils for the purposes of anchoring multiple floating platforms.	University of California, Davis/NSF
Platform Designs (Floating Substructure)	Experimental Comparison of Three Floating Wind Turbine Concepts	2014	Explores three platform concepts via wave only performance, effect of wind global motions, nacelle acceleration.	Goupee, A. et al. / University of Maine, Technip USA Inc., Maine Maritime Academy
Wind Farm Design	Floating Offshore Wind Array Design	2022-2025	This project will develop and validate seabed, anchor and cable models, create an integrated floating wind array analysis tool, and develop an optimization framework for floating array designs and to guide future research.	NREL
Stakeholder Engagement	Addressing conflicts between fisheries and offshore wind energy industry-case-study of the WindFloat Atlantic project in Portugal	2020	A master's thesis case study project of fisheries stakeholder interactions and consultations in WindFloat Atlantic project area.	Braga, F./ Aalbord University
	Windfarms, fishing and benthic recovery: Overlaps, risks and opportunities	2022	Examines United Kingdom windfarm fisheries impacts and activities. Using Global Fishing Watch, the use of bottom-towed gear decreased post construction in 11 out of 12 wind farm sites. Examines stakeholder engagement in terms of offshore wind farms co-location and avoidance measures.	Dunkley, F. and Solandt, J./ Marine Conservation Society
Policy and Government Engagement	Floating Offshore Wind Shot	2023	A US Department of Energy program to reduce the costs of offshore floating wind	Wind Energy Technologies Office / US Department of Energy

Appendix B. Existing Deepwater Wind Projects Worldwide

Table B-1. Existing Deepwater Wind Projects Worldwide

Project Name	Year	Location	Water Depth (60 m or deeper)	Description and Technical Details	Turbine and Power	Mooring System	Designer	Development Stage and Current Status
Sakiyama	2015	Fukue Island, Japan	100 m	• Haenkaze, Toda Hybrid spar	• Hitachi, 2 MW	• Catenary mooring system	• Goto Floating Wind Power LLC	• Operational
Fukushima FORWARD	2013-2016	Fukushima, Japan	110-120 m	• 2013 Phase I (Substation): Fukushima Kizuna, Advanced Spar • 2013 Phase I: Fukushima Mira, compact semi- submersible • 2015 Phase 2: Fukushima Shimpuu, V-shape Semi-Submersible • 2016 Phase 2: Fukushima Hamakaze, Advanced Spar	• 2013 Phase I (Substation): 66kV, 25MVA • 2013 Phase I: Hitachi 2 MW • 2015 Phase 2: MHI 7 MW • 2016 Phase 2: Hitachi 5 MW	• All Phases: Catenary mooring system; drag embedment anchors	• All Phases: Fukushima Offshore Wind Consortium	• 2013 Phase I (Substation): Operational • 2013 Phase I: Being dismantled • 2015 Phase 2: Operational • 2016 Phase 2: Operational
WindFloat Atlantic (WFA)	2020	Viana do Castelo, Portugal	85-100 m	• WindFloat semi- submersible	• MHI Vestas 3×8.4 MW	• Catenary mooring system; Vryhof drag embedment anchors	• Principle Power	• Operational
Hywind Scotland	2017	Peterhead, Scotland, UK	95-120 m	• Hywind Spar	• Siemens 5×6 MW	• Semi-taught mooring system; suction anchors	• Equinor	• Operational
Kincardine	2020	Kincardineshire, Scotland, UK	60-80 m	• WindFloat semi- submersible	• MHI Vestas 2 MW (former WF1), MHI Vestas 5×9.5 MW	• Catenary mooring system	• Principle Power	• Pre-Commercial: WF1 relocated and operational in 2018, the five 9.5 MW turbines are under construction
New England Aqua Ventus I	2023	Monhegan Island in the Gulf of Maine, US	100 m	• VolturnUS, semi- submersible	• N/A, 12 MW	• Catenary mooring system; drag embedment anchors	• University of Maine	• Prototype demo, expected to be completed in 2023
TetraSpar	2021	Norway	200 m	• TetraSpar; tetrahedral structure assembled from tubular steel components	• Siemens, 3.6 MW	• Catenary mooring system	• Shell, RWE, TEPCO Renewable Power, and Stiesdal Offshore	• Demonstration Phase, Operational

m–meter; MHI–Mitsubishi Heavy Industries, Ltd; MW–Megawatt; N/A–not applicable

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