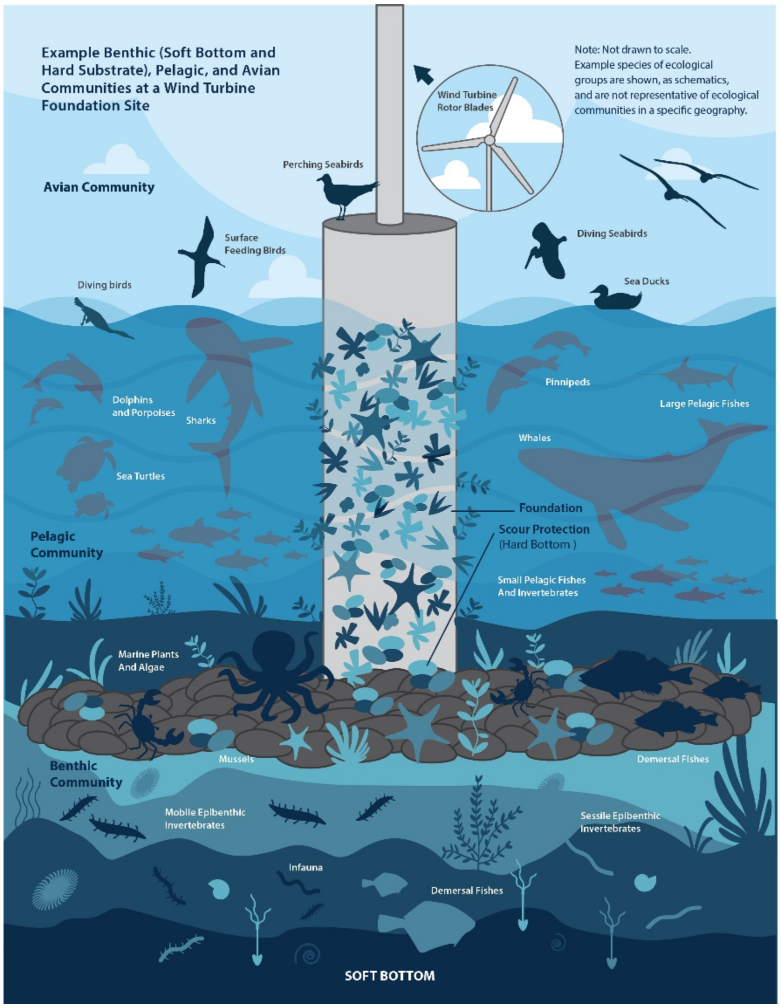
OCS Study
BOEM 2021-053

Comparison of Environmental Effects from Different Offshore Wind Turbine Foundations



U.S. Department of the Interior
Bureau of Ocean Energy Management
Office of Renewable Energy Programs

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Comparison of Environmental Effects from Different Offshore Wind Turbine Foundations

August 2021

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Prepared under Contract 140M0118A0004 by

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U.S. Department of the Interior
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Study concept, oversight, and funding were provided by the U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM), Office of Renewable Energy Programs, Washington, D.C., under Contract Number 140M0118A0004, BPA Call Order Number 140M0121F0021. This report has been technically reviewed by BOEM, and it has been approved for publication. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

REPORT AVAILABILITY

CITATION

ICF. 2021. *Comparison of Environmental Effects from Different Offshore Wind Turbine Foundations*. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Headquarters, Sterling, VA. OCS Study BOEM 2021-053. 48 pp.

ABOUT THE COVER

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Executive Summary

The development of the offshore wind industry along the Atlantic coast of the United States has raised concern from the public and throughout New England and the mid-Atlantic, about the potential effects of offshore wind foundations on the marine environment. This white paper provides a summary of currently available science that addresses potential effects of offshore wind foundations on the marine environment and provides a comparison of these effects for different foundation types. The white paper is not meant to identify a foundation preference as there are many considerations in the selection of a foundation. This summary has been developed to provide information to stakeholders who are concerned about the effect of foundations on marine resources and to explain which foundations are suitable to use under certain conditions. This white paper replaces the first version published in August 2020 (ICF 2020). Revisions to the white paper include updated information on several foundation types and adds an expanded description of acoustic effects.

Public concerns revolving around the potential effects of foundations in the marine environment associated with offshore wind development include:

- Differing degrees of impact depending on the foundation type.
- Direct effects on species from disturbance and/or loss of habitat during installation and operation.
- Alterations of physical processes, such as changes in hydrodynamics (i.e., the movement patterns of water, such as currents) and water quality (i.e., water chemistry, nutrient, and suspended sediment characteristics) that can result in changes in habitat suitability and indirect effects on species.

Some stakeholders recognize that offshore windfarm foundations and associated scour protection act like artificial reefs by providing habitat that supports marine life. The current state of knowledge on this topic is summarized below.

Types of Foundations

The offshore wind industry has adopted many of the foundation types that have proven successful in the oil and gas industry. Prototypes and early projects used simple caissons (monopiles), small steel truss jackets, and gravity structures in water depths less than 15 meters (m) (50 feet (ft)). As turbine locations moved into waters up to about 40 m (131 ft) deep, larger steel monopiles dominated. From 40 m to 60 m (131 ft to 197 ft) water depths, monopiles were joined by various space frame configurations (i.e., jackets, tripods, and tri-piles) as options for development. Beyond about the 60 m (197 ft) water depth, offshore wind projects are expected to transition from fixed-bottom structures to floating structures. Several floating offshore wind projects for deep water have now been deployed or are in advanced planning stages.

Monopiles and tri-piles are driven into the seabed and are not well-suited for geological conditions with shallow bedrock, boulders, or coarse gravel layers. Jackets, tripods, and some anchors for floating foundations require soil conditions in which piles or suction caissons can be embedded, but they can tolerate some obstructions better than monopiles. Gravity foundations and dead-weight anchors for floating foundations sit directly on the seabed and can therefore be located where foundation penetration into the seabed is not practical (Hammar et al. 2008). Table ES-1 summarizes the water depths and geological conditions suitable for various foundation types.

Wind turbine spacing is not dependent on the type of foundation selected. Regardless of the type of foundation, the cumulative areas of the wind turbine foundation footprints, including any scour protection, typically cover less than 1 percent of the area of an offshore wind project over which wind turbines are deployed (English et al. 2017). However, for some foundation types, a much larger area may be disturbed during installation. For example, seabed preparation for embedded gravity foundations may temporarily disturb an area several times larger than the foundation footprint itself.

Table ES-1: Site Conditions and Foundation Selection

Foundation Type	Maximum [1] Water Depths	Geological Conditions
Monopiles	50 m (160 ft)	- Sands and clays preferred. - Not suitable for shallow bedrock or strata with boulders, cobbles, or coarse gravel.
Jackets	60 m (200 ft)	With piles: - Stiff clays and medium to dense sands preferred. - Possible in softer silts and clay, and in very soft sediments overlying stiffer soils or bedrock. - Less well suited for locations with many boulders. With suction caissons: - Medium stiff clays and fine to medium sand preferred. - Not suitable for strata with cobbles, boulders, or coarse gravel layers or in very soft soils.
Tripods	50 m (160 ft)	- Same as jackets.
Tri-Piles	40 m (130 ft)	- Sands and clays preferred. - Not suitable for shallow bedrock or strata with boulders, cobbles, or coarse gravel.
Jack-Up	100 m (330 ft)	- Hard bottom conditions, stiff clays, and medium-to-dense sands preferred. - Possible in softer silts and clay, and in very soft sediments overlying stiffer soils or bedrock.
Suction Buckets	30 m (100 ft)	- Medium stiff clays and fine to medium sand preferred. - Not suitable for strata with cobbles, boulders, or coarse gravel layers or in very soft soils.
Gravity	40 m (131 ft)	- Sand, medium to stiff clays, bedrock, and strata with cobbles, boulders, or coarse gravel. - Not suitable for very soft soils or weak clays.
Floating	220 m (720 ft)	- Medium stiff clays, fine to medium sands, coarse sands, and gravel. - Less well suited for locations with many boulders.

[1] Maximum refers to the current or typical maximum water depth for currently constructed or planned offshore wind projects, not the technological limit for each foundation type.

Environmental Effects from Foundations

Ecological groups that were evaluated in this white paper and that could be affected by wind turbine foundations are:

- Benthic (i.e., bottom-dwelling organisms) soft-bottom and hard-bottom communities
- Pelagic (i.e., residing in open water) community, including fishes, invertebrates, marine mammals, and sea turtles
- Avian community, consisting of seabirds

Most changes to physical processes, including hydrodynamic processes (i.e., movement patterns of water) and sedimentary processes (i.e., alterations to seabed substrates by natural forces), that can affect species and habitats are localized and spatially limited, which means they occur in the vicinity of the foundation, within boundaries of the offshore wind project, or within the down-current extent of wakes generated by obstruction to prevailing currents. Most changes to physical processes are likely to occur for the duration that the offshore wind foundations are in place. After operations cease, structures are removed, although a scour pad around the footprint may remain if determined to be beneficial. Some changes are more temporary in nature and only occur during installation activities.

Activities such as dredging for site preparation of gravity foundations, or reverse-circular drilling for some monopiles, are expected to have greater seabed disturbance compared to methods that require low levels of bottom disturbance, like deadweight-anchored floating foundations and suction bucket foundations. Similarly, foundations that have smaller footprints, like jacket and floating foundations, are expected to result in relatively lower disturbances than structures with large footprints like gravity foundations. However, because of the temporary nature of the effects during installation, the small area directly affected by footprints in comparison to the overall offshore wind lease area, and possibility to reposition foundations (i.e., micrositing) to avoid sensitive features such as complex habitat, effects on benthic habitat are relatively minor overall. Additionally, baseline disturbance levels affecting benthic habitats, like rearrangement of the seabed due to severe storms or changes in sedimentary processes due to seasonal changes in ocean currents, may have relatively larger effects than foundation installations, depending on site-specific conditions and geographical locations. Similarly, wake and scour effects may vary across foundation types, but these effects are also localized and site-specific, and, given that any windfarm would be sited at least 12 miles offshore, scour at sites in the U.S. would be limited compared to windfarms sited in highly tidal zones, like in parts of Europe.

Beneficial effects from offshore wind project installation and operations include creating habitat comparable to artificial reefs, with increased biodiversity, abundance, and biomass, as well as providing enhanced foraging opportunities and refuge areas for many species of fishes, seabirds, sea turtles, and marine mammals.

Larger offshore wind projects take a longer time to install, extending the time period for effects to occur and increasing the risk of adverse interactions with sensitive ecological periods, such as spawning or migration periods. However, cumulative effects on physical processes from multiple turbines or adjacent wind projects are not expected to be perceptible because of wide spacing between individual turbines (at least 500 m [1,640 ft] in most cases). Cumulative, regional-scale beneficial artificial reef effects may occur when offshore wind projects are sited in proximity to each other, although such siting would also increase the cumulative risk of invasive species range expansion due to the “steppingstone” effect that could facilitate their spread across a region.

Conclusions

The type of offshore wind foundation utilized is highly dependent on the geological conditions and water depths of the windfarm site. The environmental effects of offshore wind turbine foundations are generally limited to the immediate vicinity of the foundations and the windfarm site area. The magnitude of the effect may vary among foundation types primarily due to each type’s underwater surface area, volume it occupies in the water column, and its footprint on the seabed.

Specific conclusions:

- Direct effects from the presence of the foundation structure on benthic species and habitats are typically greatest at monopile foundations and least at floating foundations. However, the effect across all foundation types is minimal, considering that typically less than 1 percent of the area of an offshore wind project site over which wind turbines are deployed is covered by structure footprints, including scour protection (English et al. 2017). However, seabed preparation for some gravity foundation designs may temporarily disturb areas several times larger than the foundation footprint itself.
- Foundations can act as artificial reef-like structures, which can have beneficial ecological effects for some species. Compared to monopiles, these beneficial effects could be larger with a jacket foundation, given the much greater surface area associated with its lattice structure, and may be

greater with some types of floating foundations depending on depth and surface area of the submerged structures.

- Risk of the spread of invasive species primarily varies with geographic location. For example, ocean current dynamics can influence transportation of invasive species to windfarm sites and presence of invasive species in the vicinity may increase the likelihood of spread to new structures. Risks are largest for gravity and floating foundations, compared to other foundation types, because they are generally towed to the site from ports, which increases the potential for the introduction of invasive species at the windfarm site.
- Wake effects, which include hydrodynamic changes, for example increased concentration of prey in wakes and changes to larval recruitment dynamics, would be similar across most foundation types. Compared to monopiles, smaller wake effects would be expected at jacket foundations, due to relatively less structure volume in the water column, and near the seabed at floating foundations, due to weaker currents at greater depths. Larger scour effects would be expected at gravity and suction bucket foundations compared to monopiles, due to the wider diameter of the base of gravity foundations near the seabed.
- Effects associated with the release of suspended sediment are mostly associated with installation activities. The smallest effects are expected for suction bucket foundations, which involve relatively little sediment disturbance during installation. The largest effects are expected for gravity foundations that require seabed preparation (e.g., dredging) and for monopiles if they use reverse circular drilling, both of which cause more extensive sediment disturbance than pile driving does during installation.
- Some species seek out wind turbine foundations for resting areas or enhanced feeding opportunities. However, this attraction could place them at increased risk of predation, collision with turbines, or interactions with fishing gear. For migratory species, there is concern that introduction of foundations in the otherwise featureless offshore environment could alter species' migration patterns by attracting them to linger at wind farm sites. This attraction effect is expected to be similar across foundation types, except for floating foundations, which have relatively less infrastructure extending through the entire water column.
- For species sensitive to visual or spatial disturbances, avoidance effects may result in effective loss of utilized habitat within, or species displacement from, an offshore wind project site, but typically an abundance of available surrounding habitat exists. Like the attraction effect, this avoidance effect is expected to be similar across most foundation types, but likely would be smaller at floating foundations, which are installed in deep water and have relatively less volume of infrastructure extending through the entire water column.
- Underwater noise, particularly noise caused by foundation installation activities, may cause mortality or injury to marine mammals, fishes, invertebrates, and sea turtles. Behavioral alterations from acoustic effects, such as startling, fleeing or hiding, may occur during foundation installation activities, such as pile driving. Impact pile driving during installation of some monopile, jacket, tri-pile, and tripod foundations produces acoustic effects that are anticipated to be relatively similar across foundation types, though the spatial extent of those effects would be smaller for jacket, tri-pile, and tripod foundations. Floating foundation anchors can also be installed by impact pile driving, with a smaller anticipated impact associated with smaller piles. Other installation methods or activities, such as dredging for site preparation of gravity foundations, vibratory pile driving, and reverse-circulation drilling, also produce noise. However, those activities would create lower noise levels that are not as impactful to organisms because of the nature of the sound wave, which is steady and continuous rather than impulsive like impact pile driving. The least noise-emitting activities occur during installation of suction bucket

foundations and floating foundations that use suction caissons, drag, dead-weight, or embedded anchors. Operational noise produced by wind turbine generators sitting atop the foundations may radiate through the foundation and into the water column and, in the case of fixed-bottom foundations, into the seafloor. This operational noise may result in behavioral effects on marine organisms. Such effects would be similar across fixed foundation types. Unlike fixed foundation noise, operational noise associated with floating foundations would not affect benthic species as the noise would not radiate into the seafloor and would result in a smaller spatial scale of effects for non-benthic species.

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Abbreviations and Acronyms

BOEM	Bureau of Ocean Energy Management
EIS	Environmental Impact Statement
ft	foot
GBS	gravity based structure
km	kilometer
m	meter
mm	millimeter
MW	megawatt
NEPA	National Environmental Policy Act
NM	nautical mile
OCS	Outer Continental Shelf
ROV	remotely operated vehicle
TLP	tension leg platform
U.S.	United States
WTGs	wind turbine generators

1 Introduction

Although the demand for offshore wind energy has never been greater, the United States (U.S.) currently has only one commercial offshore wind installation—the five-turbine, 30-megawatt (MW) Block Island Wind Farm built in Rhode Island state waters in 2016 – and a research project with two turbines located 26 miles east of Virginia Beach, VA that became operational in the summer of 2020. However, the last decade has seen marked increases in offshore leasing and project planning activities, driven in part by the Bureau of Ocean Energy Management (BOEM)'s robust offshore leasing program and state goals for offshore wind energy.

BOEM has issued offshore leases for wind energy, covering areas of the Atlantic Outer Continental Shelf (OCS) along Massachusetts, Rhode Island, New York, New Jersey, Delaware, Maryland, Virginia, and North Carolina. BOEM is also in the process of leasing areas off the coasts of New York, New Jersey, and the Carolinas. The water depth at these sites is usually less than 61 meters (m) (200 feet (ft)) and averages 30 m (100 ft), which makes them well-suited for fixed wind towers supported on the seabed. In contrast, water depths off the coasts of California and Hawaii, where BOEM has received lease requests, range from approximately 549 to 1,158 m (1,800 to 3,800 ft), which is far too deep for fixed turbines. Similar opportunities exist in the Gulf of Maine, where water is up to 366 m (1,200 ft) deep. Given the vast difference in depths at potential sites, it is critical to select the best type of foundation for a particular location.

Foundation types have different shapes, dimensions, footprints, and installation methods, as well as differing effects on the marine environment. Before selecting a foundation for their offshore wind energy installations, lessees must ask themselves a few questions:

- How deep is the water at the site?
- What is the seabed like? Is it sandy, or are there rocks?
- What is the *wind load* (i.e., wind pushing against the sides of the installation)?
- What is the *hydrodynamic load* (i.e., water flowing against and around the installation)?
- What will be the effects on the environment?

This white paper describes foundation alternatives that are currently in use or are likely to be used in the future and presents a comparison of their likely environmental effects on the OCS marine environment. The white paper is not meant to identify a foundation preference as there are many considerations in the selection of a foundation. This summary has been developed to provide information to stakeholders who are concerned about the effect of foundations on marine resources and to explain which foundations are suitable to use under certain conditions. This white paper replaces the first version published in August 2020 (ICF 2020). Revisions to the white paper include updated information on several foundation types and adds an expanded description of acoustic effects.

1.1 Stakeholder Concerns

During BOEM's outreach to stakeholders, commercial and recreational anglers, agencies, and members of the public raised concerns about the effects that installation of foundations could have on the marine environment. Their concerns include the direct effects on species from disturbance and/or loss of habitat during installation and operation, and alterations of physical processes, like changes in hydrodynamics and water quality, which can affect benthic species (i.e., species living in, on, or near the seabed). Stakeholders recognize that offshore windfarm foundations and associated scour protection create artificial reef-like structures that support marine life. Different foundation types will have differing degrees of environmental impact and a comparison of these impacts will help inform the public.

1.2 NEPA and the White Paper

The National Environmental Policy Act (NEPA), signed into law on January 1, 1970, requires that federal agencies assess the environmental effects of proposed actions prior to making decisions. NEPA established the Council on Environmental Quality to advise federal agencies about the environmental decision-making process and oversee and coordinate the development of federal environmental policy. Recently updated NEPA regulations (September 2020) require documents be concise and emphasizes a 150-page limit. Incorporating documents by reference is strongly encouraged.

This white paper is intended to be incorporated by reference in future NEPA documents and provides:

- An overview of the different foundation types.
- A description of the installation methodologies.
- A discussion of considerations by industry in foundation selection (e.g., cost, geology, availability).
- A description of environmental effects, both observed and anticipated, from the presence of different foundation types in the marine environment.

It also provides graphics and other means of communication that can be incorporated into the NEPA process and used for stakeholder outreach. The information included in this document reflects currently available science. BOEM updated the original white paper published in 2020 and will continue to update this white paper as new information becomes available and ongoing studies are completed. BOEM is required to use the best available science in all its documents and evaluations of activities authorized by the agency.

2 Types of Foundations

The early offshore wind industry developed foundations similar to those of the offshore oil and gas industry. Early shallow-water windfarms used gravity foundations (concrete or steel structures with a wide base filled with heavy ballast materials) or multi-leg, steel-truss "jacket"[1] structures anchored to the seabed with piles. Next came monopile support structures, which consist of a single, large-diameter "pole" that supports the entire structural load. When windfarming expanded into deeper waters (40 m or 131 ft), large steel monopiles began to dominate. As the industry continues to grow, offshore wind projects in deeper waters (60-m or 197-ft) will likely transition from using shallow, fixed-bottom structures to using floating structures. As shown in Table 1, when turbine sizes increase, so do rotor diameters, hub heights, wind forces on the turbine, and overturning moments.[2] Foundation designs must be adapted to accommodate these greater demands.

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[1] This type of platform is supported by a steel frame that consists of a structure supported by welded tubes and piled to the seafloor. The steel frame is called a *jacket*.

[2] *Overturning moment* is the effect of applied forces that try to rotate a structure about a fixed point, usually its base, i.e., to tilt it or to tip it over.

Table 1: Growth in offshore wind turbine sizes, 2000–2021

Offshore Wind Turbines	Year	Turbine MW	Rotor Diameter
Installed average parameters [1]	2000	2.0	65 m (213 ft)
Installed average parameters [1]	2005	3.0	90 m (295 ft)
Installed average parameters [1]	2010	3.1	95 m (312 ft)
Installed average parameters [1]	2015	4.5	120 m (394 ft)
Siemens Gamesa SG-8-0-167 [2]	2017	8.0	167 m (548 ft)
Vineyard Wind (project design envelope) [3]	2021	8.0–14.0	164–222 m (538-729 ft)
GE Haliade-X [4]	2020	12.0	220 m (722 ft)
Siemens Gamesa SG-14-222-DD [5]	2020	14.0	222 m (728 ft)
Vestas Wind Systems V236-15.0 MW [6]	2021	15.0	236 m (774 ft)

Sources: [1] Baring-Gould 2013; SMITH ET AL. 2015; [2] Siemens Gamesa 2017; [3] BOEM 2020; [4] GE 2019; [5] Siemens Gamesa 2020; [6] Vestas Wind Systems 2021.

In addition to gravity-based structures, monopiles, and multi-leg jackets, offshore wind foundation types include suction buckets, jack-up platforms, and anchoring systems for floating offshore wind turbines. Future floating turbine designs may include additional foundation types adapted from the oil and gas industry, such as deep-water spar and tension leg designs. Figure 1 shows examples of different types of offshore wind foundations.

Figure 1: Offshore wind foundation types

Left to right: Monopile, jacket, twisted tripod, floating semi-submersible, floating tension leg platform, and floating spar. (Illustration by Josh Bauer/NREL – Department of Energy)

The following sections provide overviews and descriptions of various foundation types. For each foundation type, descriptions include diagrams, typical dimensions, component materials, common water depths, depths of embedment below the seabed, and typical scour[3] protections for the foundation, if applicable. Descriptions also discuss installation methods and siting considerations, such as water depth and seabed geology.

Each foundation type is designed to support the portions of the wind turbine that are above sea level: the wind turbine tower, the nacelle[4] that contains the generator, the rotor hub, and the turbine blades. The foundation must be able to resist two types of stressors:

- ***Vertical loads*** from the weight of the wind turbine components
- ***Horizontal loads*** from the force of the winds, ocean currents, and waves

The foundation must resist the vertical loads to keep the wind turbine from sinking into the sea and must resist the horizontal loads to keep it from sliding on the seabed, tilting excessively, or being pushed over.

Another essential consideration when selecting a foundation type is how many turbines to site within a particular area. An effective windfarm utilizes as many as possible after considering the amount of energy generated versus the cost of the installation and making sure people are still able to enjoy ocean-based recreational activities. Appropriate turbine spacing helps balance energy generation with cost, while accommodating other maritime uses.

The spacing between turbines in a row is typically between 5 and 10 rotor diameters, which change according to the size of the turbine. The rows are typically spaced between 7 and 12 rotor diameters apart in the direction of the prevailing wind (Baring-Gould 2014). As a result, offshore wind turbines are spaced between 0.55 and 1.1 kilometers (km) (0.3 and 0.6 nautical mile[5]) apart, with the spacing expected to grow as turbine and rotor size increase (BOEM 2015).

The proposed Vineyard Wind project evaluated spacing options between wind turbine generators (WTGs) of approximately 1.4 to 1.9 kilometer (km) (0.75 to 1 NM). The U.S. Coast Guard recommends spacing offshore turbines on a 1-NM grid in the MA/RI Wind Energy Areas, where the project was located, to maintain maritime safety and ease of navigation MARIPARS 2020); Vineyard Wind has stated they will use this spacing. BOEM expects a 1-NM grid spacing for all other projects in the Rhode Island and Massachusetts lease areas. The type of foundation does not have a significant impact on the turbine spacing.

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[3] *Scour* is the removal of sediments from around moorings and piers caused by movement of water around hard structures. Scour holes compromise structural integrity and are one of the main causes of structure failures in water.

[4] A *nacelle* is a structure that holds engines, fuel, or equipment.

[5] One nautical mile = 1.1508 statute (land-measured) miles or 6,076 ft.

2.1 Monopile Foundations

2.1.1 Description

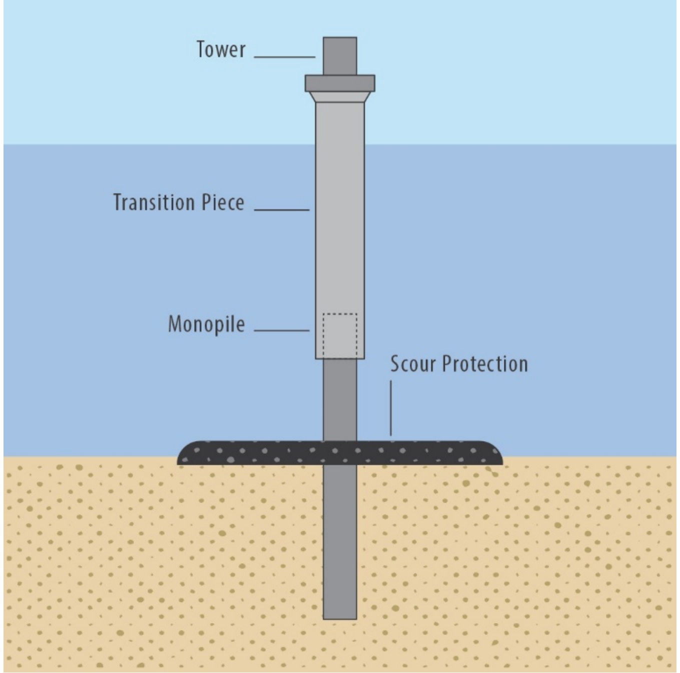

Figure 2: Monopile foundation

Worldwide, most offshore windfarms use monopile foundations, which consist of a single, large-diameter steel pipe, known as a *pile*, that is driven into the seabed to provide vertical and lateral support. Soil resistance at the end of the monopile and side friction between the pile and the soil combine to carry the vertical loads. The horizontal loads are carried by the monopile's resistance to bending and by the lateral resistance of the soil surrounding the embedded portion of the monopile.

The size of the monopile depends on the water depth, the strength of the seabed soils, the size and weight of the wind turbine, the area swept by the wind turbine blades, and the expected wind, wave, and current forces acting on the structure at the installation site. Table 2 provides information about monopile dimensions and project characteristics. Current designs include steel monopiles up to about 10 m (33 ft) in diameter. So far, monopiles have been used or proposed for use in water up to 50 m (164 ft) deep (BOEM 2020), but designers expect monopile technology will be feasible in waters up to 60 m (200 ft) deep (LEANWIND 2017).

Ocean currents around and past the monopile can remove or scour the natural seabed soils from around the monopile, creating a depression or void. Because a monopile depends on this soil for its lateral resistance, designers incorporate scour protection around the base of the monopile, typically a rock blanket, which is a layer created from stones that are large enough to resist scour. For a large monopile, a rock blanket may be about 50 m (164 ft) in diameter and 1–1.5 m (3–5 ft) thick.

For example, a turbine with a 150-m (492-ft) rotor diameter, a midrange turbine spacing of 7.5 rotor diameters (1.05 km or 3,690 ft) between turbines, and 9.5 rotor diameters (1.4 km or 4,674 ft) between rows would cover about 160 hectares (396 acres) of seabed per turbine. A 50-m (164-ft)-diameter rock blanket for scour protection would cover about 0.2 hectares (0.5 acre) or slightly more than 0.1 percent of the seabed within that turbine spacing.

After analyzing the scour-protection footprints for offshore windfarm plans submitted to BOEM, it was determined that the scour protection for a 12 MW monopile would disturb 0.34 hectares (0.85 acres) (BOEM 2020), which would equal 0.1 percent of the seabed within a windfarm site's total area based on a 1-NM turbine grid spacing.

2.1.2 Installation

Monopiles are typically prefabricated and transported to the site as a single structure. The depth of embedment below the seabed is comparable to the water depth, so the length of a monopile can exceed 80 m (260 ft). A 9-m (30-ft)-diameter pile could have a wall thickness of about 100 millimeters (mm) (4 inches) and weigh more than 1,750 metric tons (1,900 short tons).

Large cranes mounted on specialty installation vessels are necessary for handling these large, heavy monopile structures. The piles must be carefully positioned at the planned location, maneuvered to a vertical position, and lowered to the seabed. The seabed does not require any advance preparation. The monopiles initially sink into the seabed under their own weight but must then be hammered or vibrated to their design depth. The pile driving can deform or distort the top of the pile, so a separate, roughly cylindrical transition piece is often slipped over the top of the monopile and permanently fixed with a cement grout (Hammar et al. 2008).

Marine sediments that consist primarily of sands and clays are most suitable for monopile installation with pile-driving hammers or vibratory methods. Monopiles are less practical and may not be an economical foundation alternative at sites containing shallow bedrock or strata containing boulders, cobbles, or coarse gravel that can prevent the pile from reaching its design depth during driving.

In difficult soil conditions, monopiles can be drilled instead of driven. In the United Kingdom, the company LDD provided specialty relief drilling services at the Gwynt y Môr windfarm off the coast of North Wales from 2012 to 2014 to help install monopiles up to 6 m (20 ft) in diameter. The reverse-circulation drilling system is capable of handling piles up to 8 m (26 ft) in diameter (LDD 2020). Drilled monopile installation is also being explored for concrete monopiles (Desemberg 2014).

Monopile installation used to require carefully coordinated anchoring configurations to maintain station-keeping for the installation vessels during pile driving. Newer specialty installation vessels use dynamic positioning, which eliminates complex anchor-handling operations and allows the installation of even a large monopile in just a few hours.

Table 2: Sample offshore wind projects with monopile foundations

Project	Turbine MW	Water Depths	Monopile Diameter
North Hoyle	2	7–11m (23–36 ft)	4.2 m (14 ft)
Utgrunden I	1.5	--	3 m (10 ft)
Utgrunden II	3.0	20 m (66 ft)	5.4 m (18 ft)
Borkum Riffgrund, Germany	4.5	30 m (98 ft)	6 m (20 ft)
Monopile foundations installed before 2007	--	--	3–4 m (10–13 ft)
New 8 MW (as of 2017) turbines	8.0	--	7 m (23 ft)
Horns Rev 1	--	6–14 m (20–46 ft)	4 m (13 ft)
Vineyard Wind I, Massachusetts (permitted)	9.5	37–49.5 m (121–162 ft)	7.5–10.3m (25–34 ft)

Sources: BOEM 2017; BOEM 2020; Hammar et al. 2008; and Zucco 2006

2.2 Jacket Foundations

2.2.1 Description

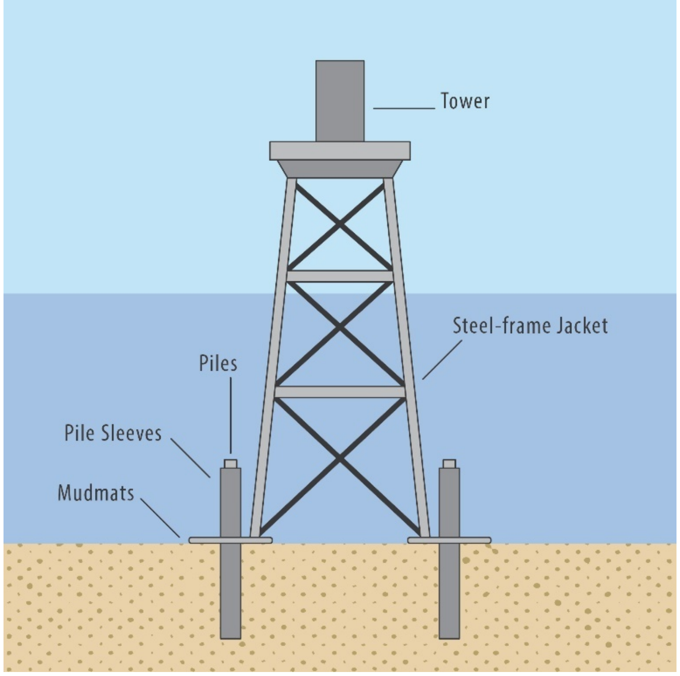

Figure 3: Jacket foundation

Jacket foundations are lattice-truss structures similar to the designs of many offshore oil platforms. The jackets are usually four-legged, with tubular legs at the corners and smaller-diameter horizontal cross pieces and diagonal struts welded between the legs to provide rigidity. The diameters of the tubular steel members that form the legs, often 1 to 3 m (3.3 to 10 ft), are much smaller than those of monopiles.

Above the waterline, a steel transition piece distributes the weight of the turbine tower and turbine to the jacket. The jackets are normally fixed in place using pipe piles or suction caissons, which transfer the vertical loads to the seabed. Horizontal forces create an overturning moment, which the piles counteract by a combination of compression and tension in the piles or suction caissons. The weight of the jacket and of the wind turbine also resist the overturning forces.

Table 3 provides data on jacket-foundation dimensions and project characteristics. Jacket foundations for offshore wind turbines have been used in waters from less than 5 m (for demonstration projects) but are most applicable for water depths between 30 to 60 m (100 to 200 ft) (Musial et al. 2006). In the oil and gas industry, which has a tremendous amount of experience with jacket foundations, larger jacket platforms have as many as 12 legs and have been used in waters over 400 m (1,300 ft) deep. The first commercial offshore windfarm in the U.S., the Block Island Wind Farm, uses jacket foundations.

Table 4 provides data on suction bucket jacket foundations.

2.2.2 Installation

Jacket foundations are typically built in a shipyard or other shoreside facility, and then transported to the site on a flat-top barge or specialty transport vessel. Jackets can also be floated and towed to the site. At the site, the jacket must be upended into a vertical position with large cranes or by controlled sinking, and then carefully lowered to the seabed.

Piles may be driven before placement of the jacket using a template on the seabed to precisely position the piles. The jacket is then lowered onto the piles and grouted in place. The jacket may alternatively be positioned on the seabed before pile driving, but that may require steel mudmats or footings on the pile legs to limit penetration into soft sediments. Pipe piles are then either driven through the hollow, tubular jacket legs or installed as skirt piles through external pile guides at the toe of the jacket. After driving, the piles are then grouted into place. The piles are much smaller in diameter than monopiles and can be installed with smaller driving equipment. (Energinet.dk 2015)

Jacket-foundation piles are well suited for stiff clays and medium-to-dense sands that can help generate the necessary friction along the length of the driven piles. They also work well in softer soils, such as silts and clay, but may require longer lengths to develop enough friction resistance. These piles are also effective where very soft sediments overlay stiffer soils or bedrock, provided the piles can develop sufficient tensile resistance. Piles are not well suited for locations with boulders.

Jackets may also be anchored to the seabed using suction caissons, which are open-bottomed cylinders attached to the jacket legs. Suction caissons are similar to large-diameter pipe piles, but instead of being hammered or vibrated into position, they are forced into the seabed by reducing the pressure within the caisson and leveraging the pressure of the ocean to force the caissons into the soil. The suction caissons transfer the loads to the seabed soils similarly to piles, but the caissons are larger in diameter and shorter in length. Jacket foundations with suction caissons are sometimes called suction bucket jackets.

Table 3: Sample offshore wind projects with piled jacket foundations

Project	Turbine MW	Water Depths	Pile or Leg Diameter	Base Dimension
Tamra	3	4–9 m (13–30 ft)	--	--
Utgrunden II (Baltic Sea)	3	20 m (66 ft)	1.5 m (5 ft)	--
Beatrice (North Sea)	5	48 m (157 ft)	1.8 m (6 ft)	20 m x 20 m (66 ft x 66 ft)
Block Island	6	23–28 m (75–92 ft)	1.8 m (6 ft)	18 m x 18 m (60 ft x 60 ft)
Alpha Ventus	5	28–30 m (92–98 ft)	2.5 m (8 ft)	--

Sources: Smith et al. 2015, 2017; English et al. 2017; Hammar et al. 2008; Sif 2020; Zucco 2006.

Table 4: Sample offshore wind projects with suction bucket jacket foundations

Project	Turbine MW	Water Depths	Bucket Diameter	Bucket Height
Yangxi Shaba Phase I, China	5.5 MW	26-30 m (85-98 ft)	7 m (23 ft)	8 m (26 ft)
Changle Waihai, China	8-10 MW	37-45 m (121-148 ft)		
Aberdeen Offshore Wind Farm	8.4 – 8.8	19 – 32 m (62 – 105 ft)	9.5-10.5 m (31-34 ft)	7-12.5 m (23-41 ft)
Borkum Riffgrund I	4	24.4 m (80 ft)	8 m (26 ft)	

Sources: 4C Offshore; Dekker 2018; Shonberg et al. 2017

2.3 Tripod Foundations

2.3.1 Description

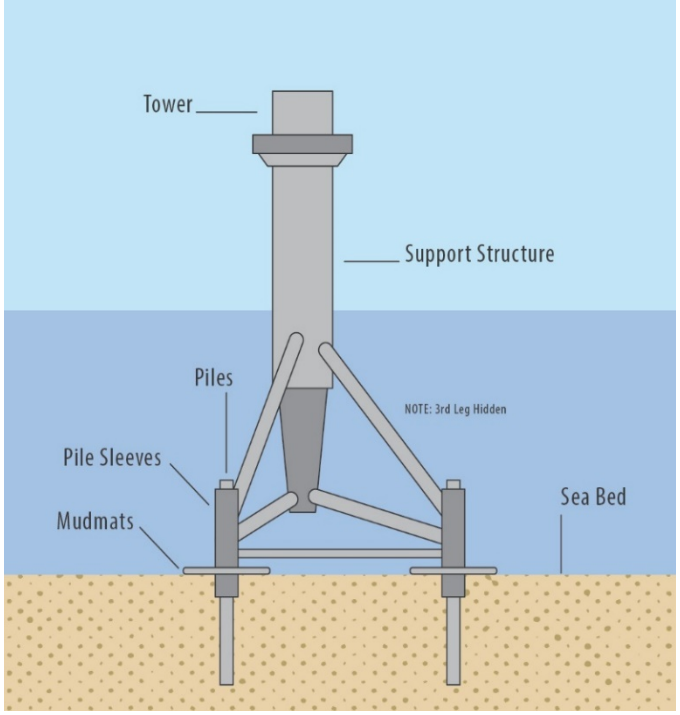

Figure 4: Tripod foundation

A tripod foundation adopts some characteristics of a jacket foundation and some of a monopile. It has a tetrahedral (pyramid-shaped) space frame constructed from tubular steel members. Like a jacket foundation, piles or suction caissons at the corners of the triangular base anchor the foundation to the seabed. The legs are typically 20 m (66 ft) to 40 m (131 ft) apart (Desemberg 2014), and a diagonal brace connects each leg to a cylindrical central column that is similar to a monopile, except that the central column does not enter the seabed. Additional tubular structural members connect the three legs together and provide additional support for the central column, which rises above the waterline to provide a base for the turbine tower.

The three-legged tripod base transfers the vertical loads to the seabed through the piles or suction caissons. As in a jacket foundation, horizontal forces create an overturning moment, which is resisted by a combination of compression and tension forces carried from the piles or caissons to the seabed soils. The bracing that connects the central column and the legs allows the central column to be smaller in diameter than a monopile.

2.3.2 Installation

The construction sequence for a tripod is similar to that of a jacket foundation. The tripod base and the central column would be constructed onshore as a single unit, transported to the site, oriented vertically, and lowered to the seabed. The piles are then driven through the pile sleeves. The seabed does not require any advance preparation prior to installation.

As with jacket installation, tripods fixed with piles are well suited for sites with stiff clays and medium-to-dense sands and could be used in softer soils, but they are not well suited for locations with boulders. Tripods may also be anchored to the seabed using suction caissons in suitable soils. Scour protection may be required around the base of the tripod in areas with high bottom currents or easily erodible sediment.

Table 5: Sample offshore wind projects with tripod foundations

Project	Turbine MW	Water Depths	Pile or Leg Diameter	Base Dimension
Design Estimate	3	20 m (66 ft)	--	--
Design Estimate	--	40 m (131 ft)	--	--
Alpha Ventus	5	28–30 m (92–98 ft)	2.6 m (8.5 ft)	--
Global Tech 1	5	38–41 m (125–135 ft)	2.5 m (8.2 ft)	--
Borkum West II	5	33 m (108 ft)	2.5 m (8.2 ft)	--

Sources: Hammar et al. 2008; BOEM 2017; English et al. 2017.

2.4 Tri-pile Foundations

2.4.1 Description

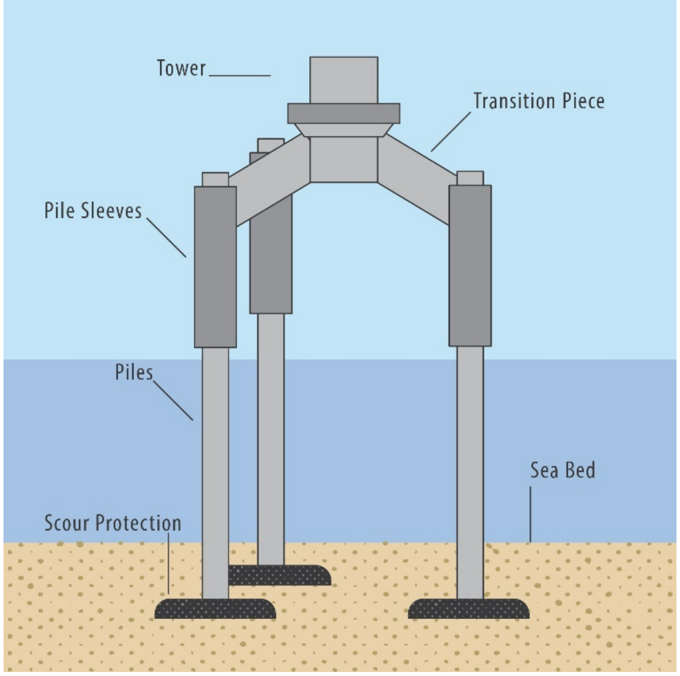

Figure 5: Tri-pile foundation

A tri-pile foundation consists of three cylindrical pile legs that connect to a transition piece above the waterline, forming a space frame that supports the wind turbine tower and turbine. The transition piece could also connect the three piles below the waterline to support a tower that rises above the water surface. Tri-pile foundations incorporate some of the features of a monopile foundation and some of a tripod foundation. The legs are similar to monopiles, but smaller, typically about 3 m (10 ft) in diameter. The three legs distribute the load over a larger footprint, similar to the base of a tripod foundation.

The three piles transfer the vertical loads to the seabed. As with a tripod foundation, horizontal forces create an overturning moment that is resisted by a combination of compression and tension forces carried by the piles to the seabed soils and by the stiffness of the three piles.

The footprint of the tri-pile foundation depends on the water depth, the wind and hydrodynamic loads, the geological conditions, the pile diameters, and the depth of pule embedment. Tri-pile foundations have been used in waters from 25 to 40 m (80 to 130 ft)-deep (Sánchez et al. 2019).

2.4.2 Installation

The foundation piles and the transition piece are fabricated as separate components for transport to the offshore turbine site. The piles are lifted from the transport vessel by crane, but the required crane size to lift and position the piles is much smaller than the size required for a monopile, due to the smaller pile diameter and lower weight. Similarly, smaller pile-driving equipment is required. As the three foundation piles are hammered or vibrated into the seabed, a guide frame maintains the proper alignment so that the transition piece fits atop the piles. The piles are connected by the transition piece, which is grouted into place.

In areas with high bottom currents or easily erodible sediment, scour protection may be required around the legs of the tri-pile foundation.

Table 6: Sample offshore wind projects with tri-pile foundations

Project	Turbine MW	Water Depths	Pile or Leg Diameter	Base Dimension
Hooksiel	5	2–8 m (7–26 ft)	3.4 m (11 ft)	--
BARD Offshore I	5	40 m (130 ft)	3.4 m (11 ft)	--
Veja Mate	6	39–42 m (128–138 ft)	--	20 m (66 ft)
Clearcamp	5	29–33 m (95–108 ft)	--	--

Sources: Buck et al. 2017; OSPAR 2018; Sif 2020

2.5 Jack-Up Foundations

2.5.1 Description

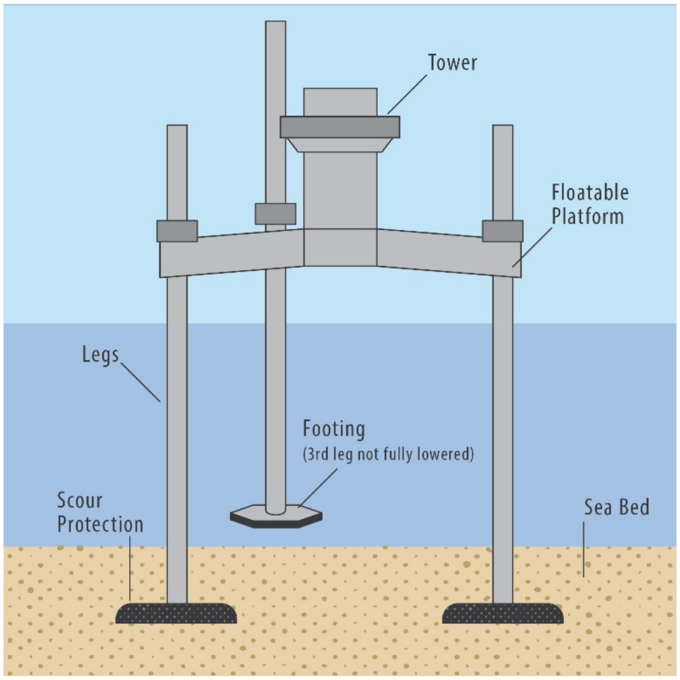

Figure 6: Jack-up foundation

Jack-up foundations are similar to jack-up drilling rigs and platforms that have been used in the offshore oil and gas industry for decades and now have been proposed for offshore wind projects. A jack-up foundation consists of a floatable platform with three or four legs that can be raised and lowered relative to the platform. When lowered, the jack-up legs pierce the seabed under the weight of the structure, plus the weight of any additional temporary ballast water. Footings or spud cans on the legs help to distribute the loads from the legs to the soil. Once the legs are set, ballast water is drained and the hull is jacked-up above the water surface to its operational height (Lafferty 2011).

As with tri-pile foundations, the spacing of the legs on jack-up foundations contributes to the platform's stability against overturning forces. Jack-up foundations for offshore wind have been proposed for water depths up to 100 m (330 ft) (OWPST 2020).

2.5.2 Installation

Jack-up platforms are constructed in port as floatable hulls. The turbine tower, rotor, and blades are installed on the hulls before deployment. Because they float, the entire assembly can be towed to the windfarm site by oceangoing tugs.

One of the benefits of jack-up platforms is that installation does not require any heavy-lift vessels or specialized installation vessels at the site. The legs are jacked into the seabed until they find enough resistance to raise the platform above the water level without the need for pile driving. To accommodate different types of soil or uneven seabed conditions, the extension of each leg can be controlled independently to maintain a level platform. When the platform reaches its design height, the legs are locked into place. Unlike other fixed-bottom designs, jack-up platforms can be decommissioned simply by "jacking up" the legs and towing the platform away (Lafferty 2011).

Jack-up foundation piles are well suited for hard bottom-conditions and stiff clays and medium-to-dense sands that can easily support the weight of the structure. They can also work in softer soils, such as silts and softer clays, but may require longer leg lengths and deeper penetration into the seabed to develop enough resistance.

In areas with high bottom currents or easily erodible sediment, scour protection may be required around the legs of the jack-up foundation.

Currently, there are no commercial wind turbines that use this type of foundation, but a jack-up platform was used for the foundation of a meteorological mast for an offshore wind farm in the Baltic Sea in 2012 (Dominion 2013).

2.6 Suction Bucket Foundations

2.6.1 Description

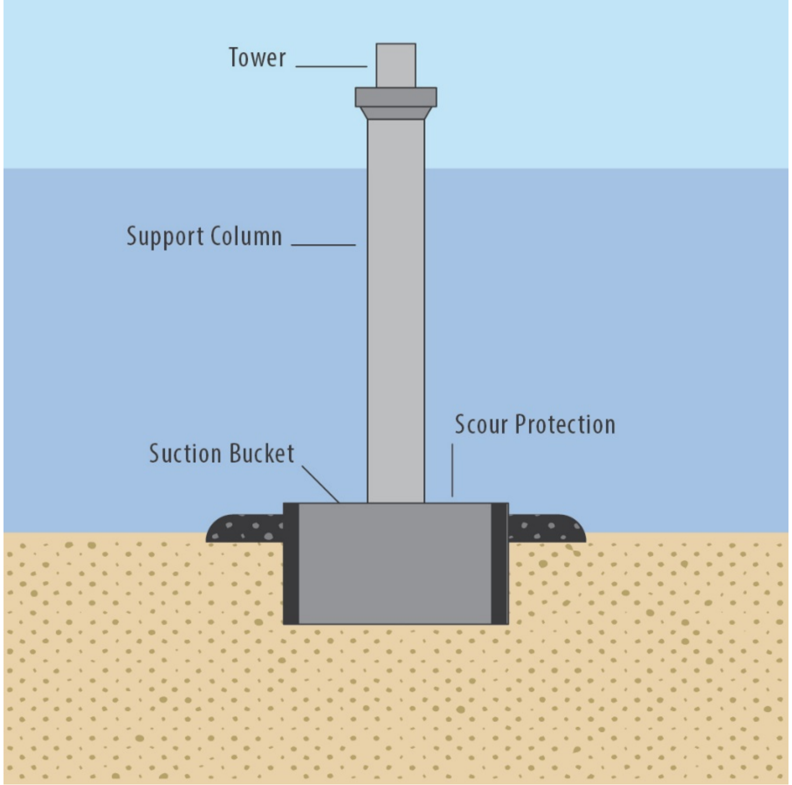

Figure 7: Suction bucket foundation

Suction bucket foundations - also called mono-bucket foundations or monopods - are essentially very large-diameter suction caissons. Unlike a suction bucket jacket foundation in which multiple suction caissons may be used instead of piles, a suction bucket foundation acts as a single, integral base for the entire foundation. In its simplest form, a suction bucket foundation is a cylinder with an open bottom and a closed top with a wide enough diameter and sufficient embedment depth to resist the overturning moments applied to the structure.

As with suction caissons, suction bucket foundations are forced below the seabed by pumping out water to reduce the pressure within the base and allowing the hydrostatic pressure of the ocean to force the suction bucket into the soil. The suction bucket resists vertical loads primarily by frictional resistance between the caisson walls and the soil. The overturning moments are resisted by the wide footprint of the base and frictional resistance along the walls.

Suction bucket foundations can create a wide, solid obstruction to current flow, leading to scour around the perimeter of the bucket, especially in sandy strata or where current wind speeds are high. Loss of soil reduces the frictional resistance of the foundation. Scour can also shorten the effective length of the flow path between the inside and outside of the bucket, weakening the ability to develop suction. To be effective, the design of suction bucket foundations must account for scour potential and include adequate scour protection, usually a rock blanket around the foundation and extending beyond the perimeter skirt.

2.6.2 Installation

Suction bucket foundations can be transported to the site on flat-top barges or vessels, but they can also be designed to be floated and towed. At the site, the foundations are maneuvered to an upright position and carefully lowered to the seabed through controlled flooding and using control lines. Once the rim of the suction bucket begins to penetrate the seabed under its own weight, subsea pumps on remotely operated vehicles (ROVs) create a pressure differential by pumping water out of the suction bucket and forcing it deeper into the seabed. Suction bucket foundations are best suited for sediments like medium-stiff clays and fine-to-medium sand. Cobbles, boulders, or coarse gravel layers can interfere with the suction, and very soft soils may not provide enough resistance for stability.

Until 2017, there were no commercial offshore wind facilities that used this type of foundation although several meteorological masts and wind turbine prototypes had been installed. Two Chinese projects, Xiangshui in 2017 and Dafeng in 2019 (Mathern 2021), successfully installed steel and concrete suction bucket foundations for full scale turbines. Other recent project proposals have included suction buckets within their design envelope as a foundation option (see Table 7).

Table 7: Sample offshore wind projects with suction bucket foundations

Project	Turbine MW	Water Depths	Bucket Diameter	Bucket Height
Frederikshavn, Denmark	3 MW	1-4 m (3-13 ft)	12 m (39 ft)	6 m (20 ft)
Wilhelmshaven, Germany	4.5 MW	18 m (59 ft)	16 m (52 ft)	15 m (49 ft)
Horns Rev 2, Denmark	Met mast	9-17 m (30-56 ft)	12 m (39 ft)	6 m (20 ft)
Dogger Bank, UK	Met mast	18 m (59 ft)	14 m (46 ft)	8 m (26 ft)
Qidong City, China (nearshore test facility)	2.5 MW	15 m (49 ft)	30 m (98 ft)	7.2 m (23.6 ft)
Xiangshui, China	3 MW	8-12 m (26-39 ft)	30 m (98 ft)	12 m (39 ft)
Dafeng, China	3.45-6.45 MW			
East Anglia One North (design envelope)	12-19 MW	33-59 m (98-194 ft)	25-35 m (82-115 ft)	

Sources: Mathern et al. 2021; Ding et al. 2020, Scottish Power Renewables 2017

2.7 Gravity Foundations

2.7.1 Description

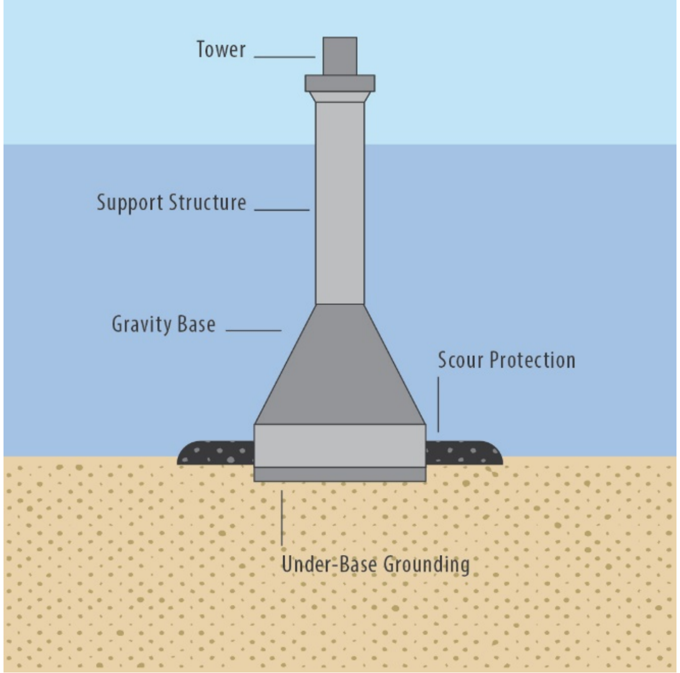

Figure 8: Gravity foundation

Gravity foundations, also known as gravity based structures (GBS), are structures with wide, heavy bases that sit on the seafloor and support the cylindrical central column that rises above the waterline. The base is most commonly made of reinforced concrete, but steel designs are also used. The gravity base supports the vertical loads of the wind turbine by direct contact pressure with the seabed and therefore require soils with a high bearing capacity. The overturning moment created by horizontal forces is counteracted by the weight of the base and the rest of the turbine structure.

The dimensions of a gravity foundation depend on the water depth and the expected wind, wave, and current forces acting on the structure. As rotor diameter, turbine hub height, and water depth increase, overturning forces and moments rise substantially, so gravity foundations had generally been limited to smaller turbines in shallow to medium waters (less than 20 m or 65 ft deep). More recently, gravity foundations have been used in or being proposed for waters up to about 40 m (131 ft) deep (Desemberg 2014, EDF Renewables 2020, Tetra Tech 2021). Conceptual gravity-based designs for offshore wind turbine foundations are being developed for water depths up to 100 m (328 ft) (Mathern et al. 2020).

Because of the wide, solid base that interrupts current flow, scour protection is needed around the gravity base if the foundation soils are erodible. At the Lillgrund Wind Farm, off the coast of Sweden, scour protection consisted of a rock blanket with up to 350-mm (14-inch)-diameter stones extending up to 8 m (26 ft) beyond the gravity base (Hammar et al. 2008).

2.7.2 Installation

Gravity bases often require seabed preparation to create a flat and level area for the base. Seabed preparation my involve dredging or the buildup of a level gravel pad. A site may be dredged several meters below the mudline to remove weak soils or to provide additional resistance through embedment (Esteban et al. 2015). Embedment can also be enhanced by including a perimeter steel or concrete skirt as part of the gravity base if the seabed soils allow penetration of the skirt. Skirted gravity bases often do not need seabed preparation in advance of installation. Any void between the seabed and the foundation within the skirt can be filled with concrete (Mathern et al. 2021). Gravity bases can also be used in locations not suitable for pile foundations, like sites with shallow bedrock or boulders. A gravel pad may be built up on the seabed to provide a uniform foundation before positioning the base.

For Thornton Bank Offshore Wind Farm, Phase I, the turbine grid spacing—500 m (1,640 ft) along a row and 700 m (2,300 ft) between rows—gives an area of seabed per turbine of 35 hectares (86 acres). The foundation pits for the 23.5-m (77-ft)-diameter gravity bases were dredged 7 m (23 ft) below the seabed and, including the pit side slopes, covered an area 192 m (630 ft) by 120 m (394 ft), or 2.3 hectares (5.7 acres), disturbing nearly 7 percent of the seabed within the windfarm area (Peire et al. 2009).

The design envelope for the Blyth Offshore Demonstrator Project Phase I considered an average seabed footprint size of 0.7 hectares (1.7 acres) and average dredge depths of about 1.6 m (5 ft) for the five Array 2 turbines (EDF Renewables 2020). The design envelope for the Empire Wind project estimates the footprint for each GBS foundation would cover 3.7 hectares (9.1 acres), including the scour protection. With the minimum design spacing of 1.2 km (0.65 nm), the maximum seabed disturbance from the turbine foundations would be about 2.5% of the windfarm area. (Tetra Tech 2021).

Gravity bases are built onshore, often at a drydock. Before they are ballasted, the bases are buoyant enough to float, which allows them to be towed to the site and eliminates the need for a large transport vessel and heavy lift cranes. The bases are sunk via controlled flooding and maintained at near neutral buoyancy until set in place. The gravity base is then ballasted with sand, stones, concrete, or iron ore. The central column, typically about 5 m (16.4 ft) in diameter, may also be ballasted to increase the overall weight and stability of the structure. Grout may be injected below the gravity base to further increase the stability of the foundation. The foundation pit is then backfilled, and the scour protection placed around the foundation.

Table 8: Sample offshore wind projects with gravity foundations

Project	Turbine MW	Water Depths	Base Diameter
Vindeby	0.45	2–4 m (7–13 ft)	--
Tuno Knob	5	3-6 m (10-20 ft)	--
Middelgrunden	2	4–9 m (13–30 ft)	16.5–19 m (54–62 ft)
Lillgrund	2.3	4–9 m (13–30 ft)	16.5–19 m (54–62 ft)
Nysted I (Rodsand I)	2.3	6–9 m (20–30 ft)	11 m (36 ft)
Nysted II (Rodsand II)	2.3	6–12 m (20–40 ft)	--
Thornton Bank OWF I	5	20–26m (66–85 ft)	23.5 m (77 ft)
Blyth Offshore Demonstrator Project Phase I	8.3	39 m (128 ft)	30 m (98 ft)
Fécamp Offshore Wind Farm	Met mast	30 m (98 ft)	23 m (75 ft)
Fécamp Offshore Wind Farm	7	25-30 m (82-98 ft)	--
Kårehamn	3	6-20 m (20-66 ft)	--
Empire Wind (design envelope)	10-18	23-41 m (75-135 ft)	55 m (180 ft)

Sources: Baring-Gould 2014; English et al. 2017; Hammar et al. 2008; Peire et al. 2009; van Wijngaarden 2017; EDF Renewables 2020; Esteban et al. 2019, Tetra Tech 2021.

2.8 Floating Foundations

2.8.1 Description

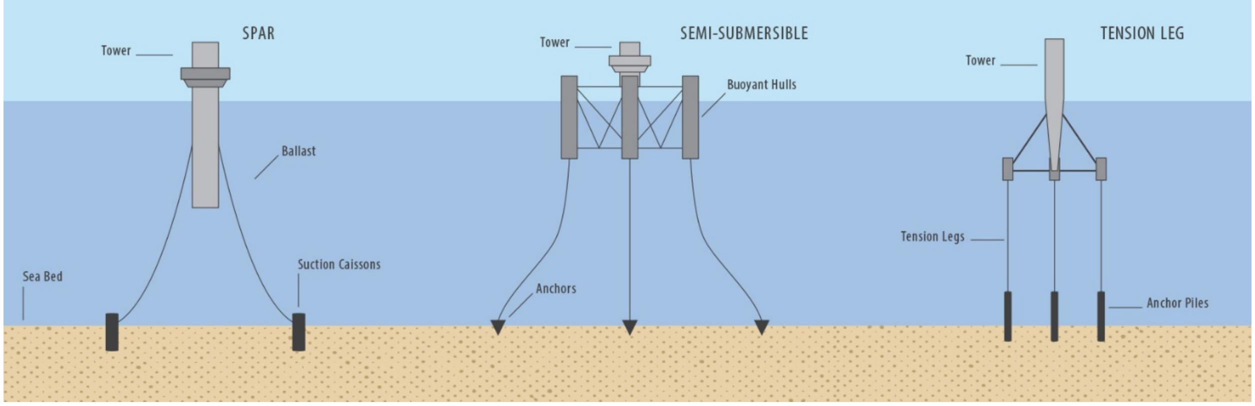

Figure 9: Floating foundations

As developers push into locations with higher winds and deeper waters, the costs for fixed offshore wind turbines rise dramatically. As in the oil and gas industry, the offshore wind industry has moved toward floating foundations for deeper waters. A few floating offshore wind projects have been built or proposed for waters from 40 m to 60 m (130 ft to 200 ft) deep but are expected to have a much greater use in waters deeper than 60 m (200 ft). Feasibility studies suggest floating technologies may be used in waters up to 700 m (2,300 ft) deep (Zountouridou et al. 2015; Desemberg 2014).

Floating turbine technology borrows designs from the offshore oil and gas industry. The three leading contenders for floating offshore wind foundations are spars, semi-submersibles, and tension leg platforms (TLPs). Spars (also called *spar buoys*) have a single ballasted cylinder that supports the tower and extends well below the waterline. The submerged ballast keeps the structure upright. Semi-submersibles have multiple submerged columns or hulls attached together with connecting braces. The hulls have sufficient buoyancy to cause the structure to float and resist overturning. TLPs are buoyant multihull steel floating platforms vertically moored to the seafloor by a group of tendons to minimize vertical movement of the structure. TLPs add an additional downward and stabilizing force by tension forces developed in the tendons.

A key component of all floating designs is the anchoring system. For spars and semi-submersibles, the main function of the anchors is station keeping. The tension developed by TLP anchors also provide both station keeping and stability to the floating structure. Anchors are available for any geological seabed condition.

Spars and semi-submersibles use catenary mooring systems[6] with mooring lines at low tension to keep the floating wind turbine on station. The mooring lines are connected to anchors, which can take the form of deadweight anchors that sit on the seabed, drag anchors that are set by pulling them through the soil, dynamically embedded anchors, driven piles, or suction caissons. Among the anchor types, deadweight anchors, made of concrete or steel, have the greatest mass and the largest footprint. Drag anchors are made of steel and once set, lie largely or entirely below the seafloor. Setting the anchor may temporarily disturb the seafloor as the anchor is pulled into and through the soil. Dynamically embedded anchors use various systems to force the holding surfaces of the anchor deep into the seabed to increase its holding power. The installation device is typically withdrawn, leaving the anchor behind, and

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[6] The *catenary mooring system,* the most commonly used system in shallow water, is named for the shape of the free hanging line as its configuration changes due to vessel or wave motions. At the seabed, the mooring line lies horizontally, so the mooring line has to be longer than the water depth.

creating little to no footprint on the seabed. The mooring lines for spars and semi-submersibles may also be anchored with piles and suction caissons.

Regardless of the type of anchor, it is common practice to attach a length of heavy ground chain (or *rode*) to the anchor. The rode increases the tension on the mooring line as it is lifted from the seabed and reduces the shock in the line. The movement of the rode may disturb the seabed during operation. Offshore mooring chains used in the oil and gas industry can have individual links that are up to 0.9 m (3 ft) long, and the chain can weigh 500 kg/m (336 lb/ft). The horizontal distance between an anchor and its surface connection point is 4 to 8 times the water depth.

TLPs use tendons that maintain tension against the buoyancy of the wind turbine platform, most often utilizing piles or suction caissons for their greater and more reliable pullout resistance; also, unlike drag anchors, they are precisely positioned during installation. The TLP anchors do not have rodes, so there is negligible seabed disturbance after installation, and the uppermost parts of piles and suction caissons can remain above the seafloor after installation.

Unlike turbines with fixed-bottom foundations, floating turbines may have inter-array cables suspended within the water column, instead of along the seabed.

2.8.2 Installation

Among the advantages of floating offshore wind turbine designs is the simplicity of installation and the elimination of the need for heavy lift or specialty installation vessels. Construction of the turbine platforms, including the installation of the turbine tower, rotor, and blades, is completed at a port. Because it floats, the entire assembly is deployed to the windfarm site by oceangoing tugs. At the site, installation involves adjusting the ballast in spars and semi-submersibles to achieve the design flotation level and connection to the mooring lines. In the case of TLPs, the buoyant hulls are flooded to partially sink the TLP platform for connection to the tendons. After the ballast water is pumped from the hulls, the buoyancy of the hulls maintains tension in the tendons.

Table 9: Sample offshore wind projects with floating foundations

Project	Turbine MW	Water Depths	Type	Anchor System
Hywind – Demo	2.3	220 m (720 ft)	Spar	Suction Caissons
Hywind Scotland Pilot Park	6	100 m (330 ft)	Spar	Suction Caissons (3 per turbine)
Fukushima Floating Offshore Wind Farm Demo Phase 1	2	120 m (390 ft)	Semi-submersible	--
Fukushima Floating Offshore Wind Farm Demo Phase 2	5	120 m (390 ft)	Semi-submersible	--
Sakiyama 2-MW Floating Wind Turbine	2	100 m (330 ft)	Semi-submersible	--
Kinkardine Offshore Wind Farm Phase 1	2	62 m (203 ft)	Semi-submersible	--
WindFloat Atlantic	8	50 m (164 ft)	Semi-submersible	--
Aqua Ventus I (planned 2022)	6	100 m (330 ft)	Semi-submersible	Suction Caissons
Blue-H (75% scale prototype)	0.08	113 m (371 ft)	TLP	--
Provence Grand Large (planned 2021)	8	30 m (100 ft)	TLP	--
X1 Wind prototype PLOCAN (planned 2021)	TBD	62 m (203 ft)	TLP	--

Source: DOE 2019; Statoil 2015

3 Environmental Effects from Foundations

3.1 Introduction to Environmental Effects Evaluation and Approach

Offshore wind foundations can affect ecological communities when they are introduced into the marine environment. As illustrated in Figure 10, this white paper discusses several ecological communities:

- **Benthic Communities**: Composed of species living on or in the seabed (or *substrate*), benthic communities are divided into two groups:
    - ***"Soft-bottom" benthic communities*** occur where the seabed consists of fine-grained sand, sediments, and mud. Inhabitants of soft-bottom sediments include marine plants and algae, burrowing species (worms, clams), mobile species (sea snails, sea cucumbers), and immobile species (sea pens, sponges). Groundfish (flounder, haddock) that spend most of their time near the sea floor are categorized as *demersal fish*.
    - ***"Hard-bottom" benthic communities*** occur where rock or other hard substrates exist. Species living in hard-bottom benthic communities consist of algae, rock-burrowing worms, crabs, mussels, and structure-oriented fishes, like gobies and black seabass.
- **Pelagic Communities**: Pelagic communities consist of small, drifting phytoplankton, zooplankton, open-water fishes, and invertebrates, as well as large predators, fishes, marine mammals, and sea turtles.
- **Avian Community**: The avian community includes diving seabirds, surface-feeding seabirds, and sea ducks that forage for fish or invertebrate prey in offshore waters.

Offshore wind foundations can affect these communities in several different ways, and effects vary among the foundation types, including:

- Changes in benthic habitat substrate (i.e., the seabed)
- Artificial reef effects
- Invasive species spread
- Wake effects and scour
- Suspended sediment and sediment deposition
- Release of sediment contaminants
- Attraction effects
- Avoidance effects
- Acoustic effects during installation

The following sections describe these effects and discuss how interactions with the physical and biological environment may vary across foundation types. Most changes to physical processes that can affect species and habitats, including hydrodynamic processes (i.e., movement patterns of water) and sedimentary processes (i.e., alterations to the seabed by natural forces), are localized and spatially limited, which means they either occur in the vicinity of the foundation, within boundaries of the offshore wind project, or within the down-current extent of wakes generated by obstruction to prevailing currents. Most changes to physical processes and resulting ecological effects are likely to occur for the duration that the offshore wind foundations are in place. Structures are removed after operations cease, although a scour pad around the footprint may remain if it is determined to be beneficial. Some changes to physical process and resulting ecological effects are more temporary in nature and only occur during installation activities. The discussions below note the spatial and temporal nature of effects when known or estimated.

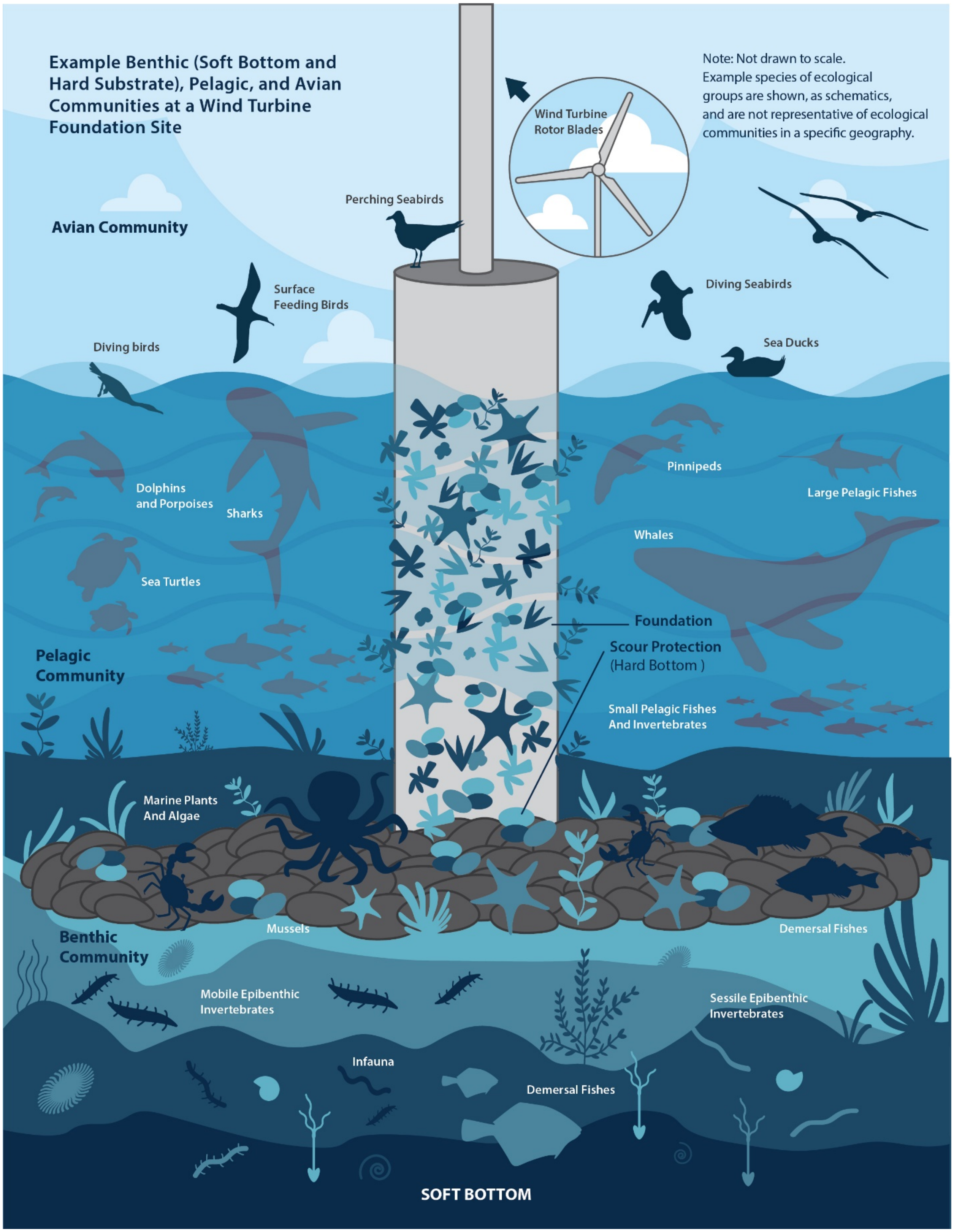

Figure 10: Example ecological communities at a wind turbine foundation site

3.2 Changes in Benthic Habitats

Introducing an offshore wind foundation into the marine environment creates new hard-bottom habitat at the foundation site, which may be composed of soft-bottom substrates. When this new hard-bottom habitat is created, it can cause the loss of soft-bottom habitat, which can affect species that are not mobile; organisms could be crushed when the structure is built or could be smothered when the installation of the foundation displaces sediment. Soft-bottom habitat loss typically occurs on less than 1 percent of a windfarm site's total area (English et al. 2017; Glarou et al. 2020) but can be several times greater with some gravity foundation designs. Because this habitat is widely available in most soft-bottom benthic marine environments, the effect of a small amount of soft-bottom habitat removal within a windfarm site is relatively minor, and the addition of new hard substrate may be beneficial:

- The Block Island Wind Farm (offshore Rhode Island) observed an increased abundance in the existing soft-bottom community near some turbines, rather than a change in the composition of the species (HDR 2018).
- The Horns Rev windfarm site in Danish waters found no indication that construction or operation of the windfarm had a negative long-term effect on the population of soft-bottom invertebrates or fishes at the site. The variation in species abundance and distribution patterns did not differ significantly from similar environments without windfarms (Leonard and Pederson 2006, as cited in English et al. 2017; Stenberg et al. 2011).

Soft-bottom habitat loss could affect marine mammals that use soft-bottom habitats for feeding areas, such as grey whales that feed on infauna and epifauna. Soft-bottom habitat loss might affect some diving seabirds that feed in these habitats, like scoters, which feed on benthic invertebrates, particularly when windfarms are sited in relatively shallow water. However, due to the relatively small amount of habitat loss compared to soft-bottom habitat still existing within a windfarm site and in the areas surrounding it, such effects on marine mammals and seabirds would be minimal. Additionally, if windfarms enhance the abundance of prey within their feeding areas, as discussed in Section 3.3 below, such changes could have a beneficial effect for some species.

Benthic habitat loss is restricted to the foundation footprint and immediate adjacent areas, where scour-protection pads are installed. Effects of habitat loss due to foundation installation and operation is expected to be greatest for foundations with the largest footprint, like gravity, monopile, and suction bucket foundations, relatively smaller for tri-pile, tripod, and jack-up foundations, and smallest for jacket and floating foundations. For floating foundations, the extent to which heavy anchor chains designed to absorb wave action drag along the sea floor is unknown and could disturb a wide area of benthic habitat surrounding the anchors. Preconstruction surveys and habitat mapping conducted in advance of windfarm construction could be helpful for siting windfarms in areas that minimize potential harmful effects to sensitive areas, such as known marine mammal feeding areas.

3.3 Artificial Reef Effect

Offshore wind foundations may function like artificial reefs by creating new habitat which attracts marine organisms that colonize the structures, and potentially increasing the biological diversity of the area (Glarou et al. 2020). The presence of colonizing organisms on the foundation attracts additional organisms that feed on the colonizers or shelter in the habitat created by the colonizers. These additional organisms, in turn, attract larger predatory organisms that feed on them. Such larger predatory organisms attracted to offshore wind foundations include large-bodied fish, marine mammals, sea turtles, and sea birds (Degraer et al. 2020). This is usually considered a neutral or positive effect of offshore wind development (English et al. 2017; Lüdeke 2015). Higher growth rates and densities of larger fish have been found around oil rig structures, compared to those in nearby natural habitats (Love et al. 1999, as cited in English et al. 2017), highlighting the intense biological productivity that can be supported by human-made hard surfaces introduced into offshore areas. For example, a 50–150 percent increase in biomass, primarily of benthic animals, has been observed at the Horns Rev and Nysted offshore windfarm sites in Denmark, compared to what existed prior to the development of the windfarm (Dong Energy et al. 2006).

The introduction of offshore wind foundations may also cause a change in the species composition in the ecological communities of an area (Degraer et al. 2019; Schröeder 2006, as cited in HDR 2018; HDR 2019; Lüdeke 2015; Stenberg et al. 2011). *Epifouling organisms* (i.e., organisms that grow on the surfaces of submerged human-made structures) colonize the structures and the community is initially dominated by invertebrates. Overtime, as these communities mature, more complex communities form as demersal and pelagic fishes are attracted to the increased prey available on and near the structures (Marine Management Organization 2014; Dong Energy et al. 2006, Danish Energy Agency et al. 2013).

In contrast to most natural and artificial reef communities that are limited to reef structures on the seabed, wind turbine foundations extend throughout the water column (i.e., a conceptual column of water from the surface of the water to the seabed), which causes an increase in the variety of organisms from the seabed to the surface (English et al. 2017). Different species exist at different depths, forming communities at each level that are known as *depth assemblages*. For example, a shallow-water depth assemblage exists close to the water surface (e.g., mussels, seaweeds, and barnacles), below which is an upper mid-water assemblage (e.g., anemones, soft corals, kelp, and hydroids), and then a lower mid-water assemblage (e.g., anemones, soft corals, hydroids, and hard corals), and, finally, a deep-water assemblage (e.g., tubeworms and deep-water barnacles) (Ferris et al. 2015). As offshore wind projects age and their associated food webs mature, species become more abundant within each depth assemblage, creating a specialized habitat and community for each layer. Growth typically decreases when waters are deep enough that light cannot penetrate to support photosynthesis (about 200 m), so, in very deep waters, only the upper portions of the water column are densely populated.

Relatively higher species densities, and greater biological diversity, and greater biomass have been observed in the soft-bottom communities in the immediate vicinity of turbine foundations (Degraer et al. 2020). Over the years, shedding of invertebrate shells (e.g., from rough weather events or when shell growths get too large) can result in the accumulation of shell mounds or mussel beds near the base of the foundations that provide additional new habitat for reef-like communities (Degraer et al. 2019; Lüdeke 2015). The nutrient supply to the seabed below the windfarm structure is increased by uneaten food particles, dead organisms, and other waste, which falls as “organic rain,” and can actually increase benthic productivity, creating a more robust species assemblage in the soft-bottom community (Kellison and Sedberry 1998). An increase in biomass of up to 4,000-fold has been documented within turbine footprints (Rumes et al. 2013, as cited in Degraer et al. 2020). Alternately, this excessive organic matter may create areas of anoxia under foundations like jacket structures (HDR 2019).

The artificial reef effect is usually considered a neutral or positive effect of offshore wind development (English et al. 2017; Lüdeke 2015). Though the presence of structure provided by offshore wind foundations is beneficial for some species, recent research suggests that the overall effect may be more neutral than beneficial as these artificial reefs are often less diverse than natural reefs, may aggregate biomass rather than increasing production, and may have negative effects for some species. Offshore wind foundations provide hard structure for colonization, and some of that structure resembles natural reef (e.g., scour protection); however, the species assemblages that colonize these foundations sometimes differ from those found on a natural reef (Coolen et al. 2020). The community that colonizes foundations exhibits high species diversity in the short term (approximately the first two years) but after a period of five to six years is characterized by low biodiversity with one or two dominant species (Kerckhof et al. 2019). For some species, the artificial reefs created by offshore wind foundations serve to increase productivity by enhancing larval settlement, survival, or growth or by reducing energy expenditure (Degraer et al. 2020; Schwartzbach et al. 2020, as cited in Degraer et al. 2020). However, for other species, these artificial reefs aggregate individuals at higher densities in a smaller area but do not increase the number of individuals in a species' population (Degraer et al. 2020). Finally, the artificial reef effect may have negative effects that balance the positive effects for some species. As discussed in Section 3.4, the presence of these artificial reefs could potentially enhance the spread of invasive species. Also, the attraction of organisms to the offshore wind foundations could result in negative impacts to themselves or to other organisms due to increased exposure to predation, potential interactions with fishing gear, or increased risk of collision with turbines (see Section 3.8) (BOEM 2021c; Degraer et al. 2020; Adams et al. 2016).

Foundations with a large surface area, like the lattice configuration of jacket foundations, provide the most habitat for species to colonize and become established. The submerged spars of some floating foundation designs can extend to approximately 80 m (262 ft) deep, which could provide greater amounts of habitat opportunities than could monopiles, tripod, tri-pile, jack-up, suction bucket, and gravity foundations, which only span depths up to approximately 50 m (164 ft). The amount of scour protection used would also contribute to the magnitude of an artificial reef effect; the amount of scour protection would be expected to be greatest for gravity, monopile, and suction bucket foundations, relatively smaller for tripod, tri-pile, jack-up foundations, smallest for jacket foundations, and not typically used for floating foundations that are anchored in very deep waters with little scour anticipated.

3.4 Invasive Species Spread

Wind turbine foundations not only serve as hard structure for local communities but can also be rapidly colonized by invasive species (Mineur et al. 2012). *Invasive species* are defined as those that are not native to a specific area and that tend to spread, resulting in damage to the environment, economy, or human health. From a regional perspective, offshore wind foundations in a large expanse of soft-bottom substrate can provide steppingstones for invasive species to expand further. Invasive species can spread between foundations and nearby hard-bottom areas that might otherwise be too far to reach, like groups of islands or previously uncolonized sections of coastline (Degraer et al. 2019; English et al. 2017; Kerckhof et al. 2011; Vattenfall 2006). Many intertidal and sub-tidal species have larvae (i.e., a distinct juvenile form that many animals undergo before maturation or metamorphosis into adults) that spend a period of time drifting as plankton at sea, which allows them to disperse across long distances before they settle to the bottom and adhere to hard substrate, where they grow and mature. Spread of invasive species like barnacles, mussels, and limpets is of particular concern because they have mobile, planktonic larvae and require hard substrate to recruit[7]. Windfarm foundations can introduce new hard substrate into offshore waters that otherwise would have limited or no existing hard substrates, thereby providing new hard-bottom habitat that the mobile larvae of invasive species can populate, to the detriment of native species (Kerckhof et al. 2011; Glarou et al. 2020).

Although limited information about how windfarms could help the spread of invasive species is available in the U.S., in Europe, where windfarms have been operational for much longer, Adams et al. (2014, as cited in English et al. 2017) modeled how offshore wind projects off Scotland and Northern Ireland could act as steppingstones. Based on the modeling, the foundations could create new dispersal pathways for invasive species and facilitate their progression to northern areas, from the Northern Irish coast to the Scottish coastline, that were otherwise impossible or difficult for invasive species to access.

The degree of isolation likely plays a large role in the extent to which invasive species can establish habitat at wind turbine foundations. The risk of invasive species introduction may differ slightly between foundation types, based on whether the foundation is built in a port versus on land and whether it is carried on top of a ship or towed through the water to the installation site. Some semi-submersible floating foundations, gravity foundations, and suction bucket foundations can be built in the water within ports, and then towed to a windfarm site. While being built in water within a port, the structures

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[7] *Recruitment* is the process by which young individuals (e.g., fish and coral larvae, algae propagules) undergo larval settlement and become part of the adult population.

can be colonized by marine organisms, which then can be transported on the structures to the offshore windfarm site. During the operational phase, floating, jack-up, gravity, and suction bucket foundations may also be towed back to port for major maintenance, which could transport organisms that colonized the structures to a port. Additionally, gravity foundations or dead-weight (gravity) anchors for floating foundations that are made of concrete may be more porous and susceptible to being colonized than foundations made of steel.

Vessels used for installation of windfarm foundations may also facilitate invasive species introduction because organisms could be transported on boat hulls or in ballast water. The risk of introduction from vessels would vary between foundation types, depending on where specialized vessels required for construction, operations, and maintenance hail from. There would be a higher potential for invasive species to be transported on or in a vessel originating from a foreign port, or from an area already experiencing an invasion, than compared to a vessel originating from a nearby port or local area without known invasive species occurrences. For example, the use of specialized wind turbine installation vessels from Europe or the mobilization of oil and gas industry vessels from the Gulf of Mexico could theoretically contribute to the introduction of invasive species to the Atlantic OCS.

3.5 Wake Effects and Scour

Offshore wind foundations cause obstruction of water flow from prevailing currents, tides, and wave action. Accelerated water movement around a structure creates turbulence as water passes the structure, which is known as a *wake effect* (Figure 11). Some species may seek refuge from currents in wake areas or benefit from decreased visibility due to increased suspended sediment within wakes, whereas others take advantage of the concentration of prey at turbulent areas (Lieber et al. 2019; English et al. 2017). Due to changes in water movement patterns, wake effects may affect demersal (i.e., bottom-dwelling) fishes and invertebrates by altering recruitment of larval life stages that settle out of the water column to benthic substrates. Alteration of water movement patterns may also change the availability of food sources for demersal fishes and invertebrates. Suspended sediment concentration and sedimentation can affect not only the availability of planktonic food sources, but also the availability of oxygen and waste removal (Zettler et al. 2006, Schröder et al. 2006, Wilding 2006, and Maar et al. 2009, all as cited in Draget 2014). In areas with tidal currents, turbulence from wake effects has been observed to taper off within a few hundred meters downstream from wind turbine foundations (English et al. 2017). At this scale, turbine foundations can be strategically spaced to minimize cumulative effects beyond the site.

The magnitude of wake effects is proportional to the size of the offshore wind foundation. In other words, wake effects vary across foundation types due to differences in diameter of foundation structures and the volume of impervious structure in the water column and at the seafloor. Monopile foundations have been observed to cause wake effects as far as approximately 200 m (600 ft) down-current (English et al. 2017). Suction bucket and gravity foundations have a wider diameter at the sea floor—for example, 25 to 30 m (82 to 98 ft) compared to 10-m (33-ft)-diameter monopiles—and would likely result in a larger wake effect at depth, but they typically taper toward the surface, where currents are often stronger, so the cumulative wake effect may be similar to monopiles. Wake effects of tripod, tri-pile, and jack-up foundations are estimated to be smaller because each individual leg that has a smaller diameter compared to some monopile diameters. However, the structures have multiple legs. Because jacket foundations have a more open structure and may displace a smaller volume of the water column compared to monopiles, overall wake effects of jacket foundation types are expected to be weaker than monopile foundations. They may have more, smaller-scale turbulent wakes that attenuate more quickly due to the lattice structure design.

Floating foundations may have similar wake effects to monopile foundations in surface water layers. Of the floating foundation types, spars have the most monolithic floating structures and would be expected to cause relatively larger wake effects in surface water layers than would semi-submersibles or TLPs with smaller floating structures, but multiple hulls; thus, overall, the wake effect in surface water layers may be similar for the various floating foundation types. In the water column between the platform of a floating foundation and the seabed, the mooring lines or tendons only present a small impediment to flow and would only create minuscule wake effects. At the seabed, large deadweight anchors may have horizontal dimensions approaching those of a large monopile, 10 m (33 ft), but have limited height above the seabed and smaller wake effects than monopiles. Embedded anchors for floating foundations (e.g., piles, drag embedment anchors, suction-embedded plate anchors) have smaller profiles above the seabed, compared to deadweight anchors, and would have even smaller wake effects. Furthermore, floating foundations are used in very deep waters, where currents are typically weak near the seabed; thus, wake effects near the bottom would be expected to be minimal from a floating-foundation anchoring system.

Scour and erosion of seafloor substrate that develops in response to wake effects over the life of the foundation is potentially a concern in areas with shallow water, where the effect of prevailing currents can have a strong influence on the sea floor. Scour has been documented in depths up to at least 18 m (59 ft) (Whitehouse et al. 2011). Scour and erosion can also occur around scour protection pads (Köller et al. 2006 and Whitehouse et al. 2008, as cited in Coates et al. 2011). At structures surrounded by fine to medium-course sediments, scour can be more pronounced because sediments are more easily resuspended in the water column (Black 2008, as cited in AWATEA 2008; Whitehouse et al. 2011). Ecologically, scour can contribute to additional soft-bottom habitat loss, suspension and down-current deposition of fine sediments, and ongoing release of sediment contaminants.

Scour effects may vary as a function of the extent of a foundation’s obstruction to flow near the sea floor, which would be a combination of the lower foundation diameter and the amount of scour protection used. Gravity and suction bucket foundations present the largest obstructions near the sea floor, followed by monopile foundations, and then tri-pile, tripod, and jack-up foundations. Jacket foundations have smaller leg diameters, small amounts of scour protection, and open, lattice-type structures that would create smaller scour effects. Floating foundations could present the least concern because they are installed in deep water, where currents are typically weak, and some floating foundation types have relatively small anchors on the sea floor, where scour would be minimal.

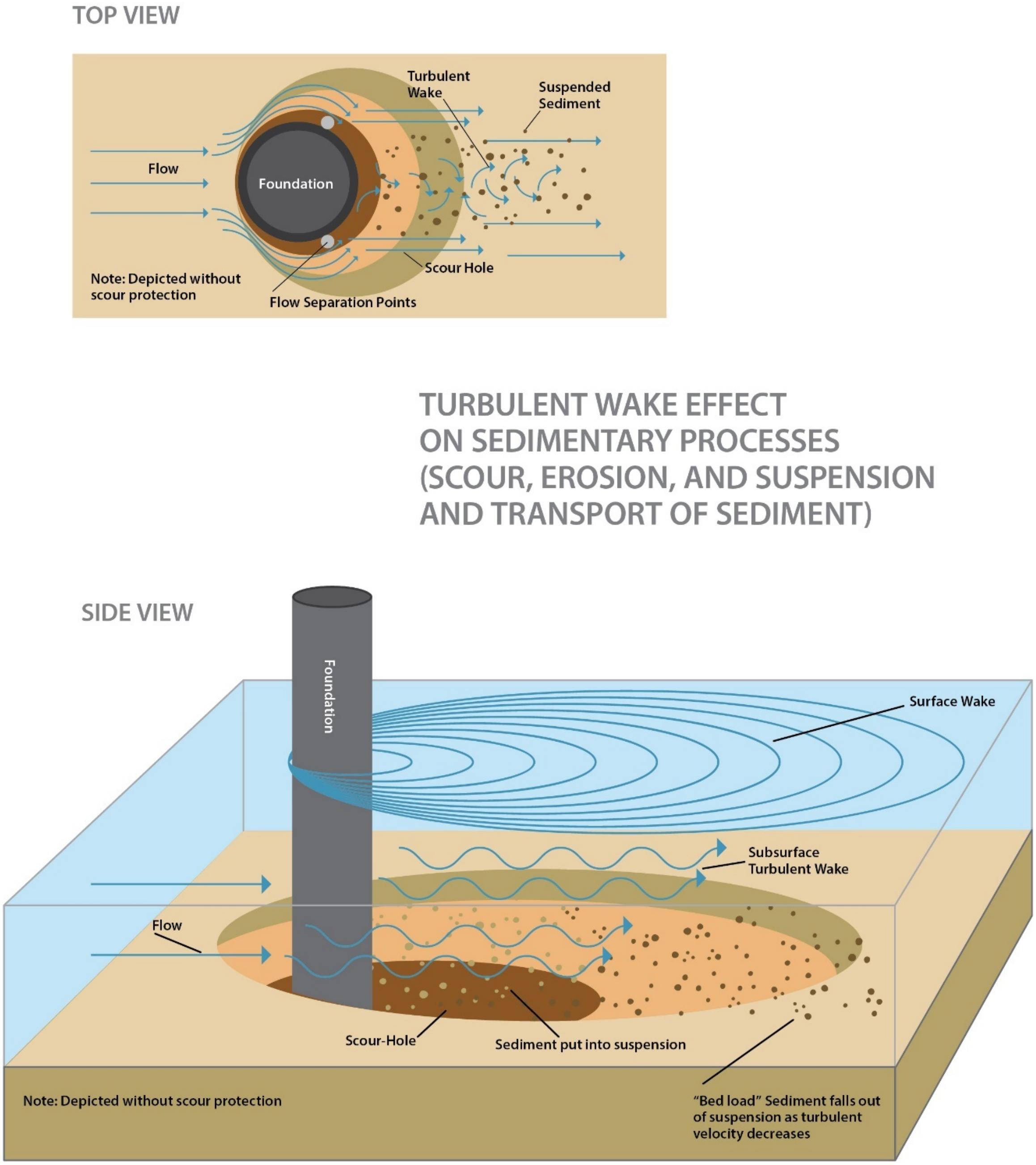

Figure 11: Turbulent wake and scour effects

3.6 Suspended Sediment and Sediment Deposition

During the offshore wind foundation installation process, seabed preparation (e.g., dredging, cutting, excavation, ploughing, jetting), jack-up installation, pile driving, and anchoring support vessels can cause sediments to become suspended in the water column, increasing the suspended sediment concentration. During operations, scour and wake effects can also alter sediment composition in the immediate vicinity of foundations, which may affect organic matter associated with sediment size and benthic productivity. Suspended sediment transported by currents, tidal flow, and wave energy are moved away from the immediate vicinity of the foundation until it falls out of suspension and to the seafloor. While suspended in the water column, there is a small risk for sediment to clog fish gills and compromise organisms' abilities to search for food if they are visual predators or foragers (English et al. 2017). Deposited sediment can threaten immobile benthic species and demersal spawning fish and invertebrates, if eggs or individuals are smothered (Thrush et al. 2004, as cited in AWATEA 2008).

Foundations that require major bottom disturbance, such as by dredging, are expected to have the largest installation-related suspended sediment levels and sedimentation effects on benthic communities. Sediment deposition can also occur during installation if dredged materials from bottom preparation are discharged into the water column or directly onto the seafloor. Such spoil mounds consisting of waste material from installation activities could persist for many years if they are composed of large particles (English et al. 2017). However, discharging dredge material is usually prohibited or controlled to minimize negative effects of direct sediment deposition onto the seafloor.

Monitoring of drilling and pile-driving of monopile foundations at the United Kingdom's Barrow and North Hoyle wind projects in the Irish Sea, which are sited in medium-grained or mixed coarse sand and gravel, found that natural tidal influences and weather conditions had a greater effect on suspended sediment concentration than offshore wind foundation installation activities (National Wind Power Offshore Limited 2003; nPower Renewables 2005; Osiris Projects 2006). At the Ormonde windfarm, also in the Irish Sea, sited in finer substrate, jacket foundation pile driving temporarily produced a sediment plume that did not extend beyond 300 meters from the site (CMACS 2015).

For monopile foundations, as the area of bottom disturbance increases with pile diameter, the potential to elevate suspended sediment concentrations and deposition rates may also increase. Additionally, if a monopile is installed with drilling by reverse circulation methods, it can produce relatively larger releases of fine sediments. Gravity foundation installation may require more extensive seafloor preparation than other foundation types if dredging is needed to level the seafloor before building up the area with gravel or stone for foundation support. Jacket and tripod foundations may use piles that are driven through sleeves or legs that would minimize sediment release. Suction bucket foundations require relatively few bottom-disturbing activities because the caissons penetrate the surficial marine sediments under their own weight, and then negative pressure is applied within them, which causes the caisson to bury into the seafloor. Jack-up foundations also would have relatively little bottom disturbance during installation because the footings are simply placed on the bottom then the structure is jacked-up. Floating foundations that use deadweight anchors or suction caissons also have relatively few bottom-disturbing activities and are not expected to increase suspended sediment concentration and down-current deposition. Floating foundations that use embedded anchors may have similar or more bottom-disturbing activities during installation when compared to monopiles, depending on the size of the anchors and method of installation. As noted above, the extent that anchor rodes drag along the seabed due to the forces on floating foundations is unknown but is likely to produce additional suspended sediment.

During the operational phase of an offshore windfarm, in areas with naturally high suspended sediment concentrations, wake effects can create sheltered areas with finer particles depositing behind turbines (Leonard & Pedersen 2005, as cited in Degraer et al. 2019). Alternatively, scour adjacent to foundations and/or scour pads can alter sediment particle sizes in the vicinity of foundations (Köller et al., 2006 and

Whitehouse et al., 2008, as cited in Coates et al. 2011). It is possible that biodiversity could change in response to changes in organic matter associated with sediment particulate sizes, with an overall shift from areas with coarser sediments and low organic matter to lower-energy areas with accumulation of fine sediment and higher organic content (Vaselli et al. 2008, as cited in Draget 2014; Leonard and Pedersen 2005; and Byers et al. 2004, as cited in Degraer et al. 2019).

The benthic community structure was observed to change in response to shifting coarser and finer sediments around gravity foundations at the Thornton Bank windfarm off the Belgian coast. Dominant species shifts and higher macrobenthic densities were observed closer to the foundations (Coates et al. 2011). However, no substantial change in sediment particle size was observed in proximity to jacket foundations at the at the Horns Rev windfarm in Danish waters (Stenberg et al. 2011). At the Block Island Wind Farm, no substantial change in sediment particle size was observed within the first year of operations (HDR 2018); however, after the second year of monitoring, fine sediment accumulation was observed within the footprint of one jacket foundation but not under the other two foundations included in the study (HDR 2019). These observations highlight the influence of hyper-localized water movements and bottom conditions on sediment responses to the addition of foundations on the seabed. Higher organic content in the sediment (i.e., *organic enrichment*) may be trapped by finer sediments in sheltered areas behind foundations (Leonard and Pedersen 2005 and Byers et al. 2004 as cited in Degraer et al. 2019). Organic enrichment has been observed in proximity to monopiles at Thornton Bank windfarm in the Belgian part of the North Sea, but effects appear to be site-specific and might be more dependent on local factors, like current velocities and size of particles able to remain suspended, than on foundation type (Lefaible et al. 2018, as cited in Degraer et al. 2019). Because these effects are localized, no changes at the windfarm scale were observed in native benthic communities or epifouling communities as result of hydrodynamic changes and scour at Danish wind projects (Dong Energy et al. 2006).

In summary, case studies indicate that, during the operational phase of offshore wind-energy installations, the effects of increased suspended sediment concentration and down-current deposition are restricted to the vicinity of the foundation only as far as the wake effects extend, which is up to a few hundred meters. They do not regionally affect suspended sediment concentrations if turbine foundations are adequately spaced to reduce cumulative wake effects. Compared to monopiles, tripod, tri-pile, and jack-up foundations are expected to have less suspended sediment and fewer effects from sediment deposition due to their relatively lower scour potential. Jacket foundations are expected to have even fewer sediment effects due to lower scour potential and smaller wake effects. Gravity foundations and suction bucket foundations may have larger sediment effects than monopiles because of their larger scour potential. Floating foundations are used in very deep water, where currents near the seabed are relatively weak; thus, sediment effects from their anchors would be expected to be minimal; however, movement of anchor rodes may cause similar levels of ongoing sediment disturbance effects compared to scour- and wake-associated sediment disturbance effects of monopile foundations.

3.7 Release of Sediment Contaminants

Marine sediments may contain a variety of harmful chemical substances, including arsenic, heavy metals, oil, organotin, PCBs, and pesticides, that were disposed of in the ocean by humans. Activities that disturb the seabed can release and mobilize contaminants into the marine environment. Discharge of large amounts of sediment, such as by dredging or reverse-circulation drilling, have the largest potential for releasing sediment contaminants. Over the life of the windfarm, ongoing scour can facilitate exposure, release, and transport of contaminated sediments, although the amount of sediment affected would likely be much less compared to that affected during installation. Resuspension of contaminants at offshore sites for wind projects are therefore of most concern during the installation period.

Negative physiological effects (e.g., toxicity) and behavioral effects (e.g., avoidance) on marine species can result from sediments that are disturbed during installation (English et al. 2017). Contaminants and pollutants can also bioaccumulate (i.e., become concentrated inside the bodies of living things) and spread from benthic-oriented or planktonic-feeding organisms through the food web. The release and transport of sediment contaminants is of greatest concern in areas with high contaminant loads, like estuaries or nearshore environments that historically received polluted runoff or dumping (e.g., dredge disposal sites).

If installation occurs in an area with high contaminant loads, gravity foundations and monopile foundations using reverse-circulation drilling are likely to cause more contaminants to be released than monopiles or jacket, tripod, tri-pile, jack-up, and floating foundations that are installed by piling. Suction bucket foundations and floating foundations that use embedded anchors, suction caissons, and deadweight anchors are likely to cause even less resuspension. Over the life of the windfarm, release of sediment contaminants is only likely to occur relative to the amount of scour associated with a foundation type.

3.8 Attraction Effects

The presence of human-made structures in the water column can attract fishes by creating artificial reef-like habitats, and predators attracted to these areas may feed on prey residing on both the structures themselves and in adjacent natural habitats (Kellison and Sedberry 1998; Davis et al. 1982). Foundation and scour pad structures can support a complex food web, attracting species that feed on the *epibenthic* (organisms that live on or just above the bottom substrates) communities and their predators, and can become areas of dense aggregations of certain species (Degraer et al. 2019; Wilhelmsson et al. 2010; Reubens et al. 2011; Lüdeke 2015).

Increased predation on small pelagic species that congregate to feed on the epibenthic community could result in an "ecological trap" where predators can hunt more efficiently, with potentially negative effects on prey populations (Wilhelmsson 2013). This could happen when habitat only aggregates individuals and does not contribute to their reproduction, as would occur if juveniles of a species recruit to a structure, but do not have adequate spawning habitat to reproduce.

For migratory species that use the mid-Atlantic coastal shelf as a seasonal "flyway", such as striped bass (*Morone saxatilis*) and Atlantic sturgeon (*Acipenser oxyrhynchus oxyrhynchus*), there is concern that the introduction of wind turbine foundations in the otherwise featureless offshore environment could alter species' migration patterns by attracting them to linger at wind farm areas (Rothermel et al. 2020). Within Maryland wind energy areas, seasonal and migratory habitat uses by Atlantic sturgeon and striped bass have been documented ahead of wind farm development, suggesting future windfarm development should further evaluate potential effects of wind turbine foundations on migratory species' behaviors and consider use of seasonal work windows to minimize adverse effects from installation activities (Secor et al. 2020). Ongoing monitoring surveys of black sea bass (*Centropristis striata*) and adult and larval American lobster (*Homarus americanus*) at the proposed Vineyard Wind I offshore energy project, offshore of Massachusetts and Rhode Island, are collecting baseline population and distribution data to evaluate effects of windfarm construction and operation on these species' movements and spatial and temporal abundances (UMass Dartmouth SMAST 2020).

Marine mammals, such as harbor seals (*Phoca vitulina*) and harbor porpoises (*Phocoena phocoena*), are attracted to foundations to forage, and sea lions may use them as a source of shelter (Russell et al. 2014, as cited in English et al. 2017; Lindeboom et al. 2011). Hawksbill sea turtles (*Eretmochelys imbricata*) are also known to use artificial reef-like structures for foraging (Gorham et al. 2014) and other sea turtles, primarily loggerhead sea turtle (*Caretta caretta*) as well as green sea turtle (*Chelonia mydas*) and Kemp's ridley sea turtle (*Lepidochelys kempii*), have also been found to associate with offshore oil rigs in the Gulf of Mexico (Lohoefener et al. 1990). While the foundations may provide foraging opportunities and shelter, they may also lead to increased interactions with fishing gear if fishermen target these structures (BOEM 2021c).

Sea birds, particularly piscivorous (i.e., fish-eating) divers, like cormorants (taxonomic family *Phalacrocoracidae*), can be attracted to improved feeding opportunities created by artificial reef effects at foundations (English et al. 2017). Wake effects behind foundations can provide enhanced feeding opportunities, when prey seek flow refuge behind the structures and where turbulence allows fish-eating birds better access to prey (Lieber et al. 2019). Diving bird species that eat invertebrates, like scoters (*Melanitta* spp.), eiders (*Somateria* spp.), and razorbills (*Alca torda*), may seek out benthic prey that colonizes the foundations, such as bivalves like mussels (Bouma and Lengkeek 2009, as cited in English et al. 2017), provided other factors like vessel or turbine disturbance do not deter them from entering the windfarm area. Perching birds, such as gulls (taxonomic family *Laridae*), cormorants, and pelicans (*Pelecanus* spp.), are attracted to artificial structures in the open ocean because they provide resting and roosting areas, in addition to increased feeding opportunities (Wiese et al. 2001; Degraer et al. 2019; Lüdeke 2015), although some foundation structures are designed to reduce or eliminate perches to prevent roosting. Though sea birds may benefit from increased foraging and roosting habitat provided by offshore wind foundations, attraction to these structures would also lead to increased risk of collision with the turbines (BOEM 2021c; Degraer et al. 2020).

Attraction effects from foundations are likely beneficial to pelagic fishes, some species of seabirds and marine mammals, and sea turtles, due to the improved feeding opportunities and available roosting and resting areas. However, for some species these beneficial effects will be offset by negative effects associated with increased interactions with fishing gear or increased risk of collision with turbines. Turbine foundations with larger surface areas may offer greater beneficial effects, as well as larger structure volumes creating larger wakes may also offer greater beneficial effects. Thus, overall attraction effects are expected to be similar across monopile, jacket, tripod, tri-pile, jack-up, suction bucket, and gravity foundations types based on a combination of useable surface area, artificial reef effects (food sources), and/or magnitude of wake effects. Floating foundations may have similar beneficial effects at floating components in the surface water layer, but would have less attraction effects at greater depths, where only tether lines and anchor structures are present.

3.9 Avoidance Effects

Visual and spatial disturbance from increased vessel activity, foundation installation, and ongoing maintenance activities also has the potential to cause marine organisms, such as marine mammals and seabirds, to exhibit avoidance behavior at windfarm sites (Dong Energy et al. 2006). Barrier effects can occur if a windfarm is located between feeding grounds and breeding areas or along migration routes, creating obstacles to movement patterns. This is a concern for some seabirds, such as wide-ranging albatross (*Diomedea* spp.), that forage at night across large distances, or sea ducks, like scaup (*Aythya* spp.), that raft at night and may commute to and from foraging sites across windfarm sites. If such avoidance changes species' energy requirements or causes disorientation during migration, there could be negative effects on overall fitness. Additionally, potential increases in time off the nest could result in increased chick predation (English et al. 2017). Some seabirds are relatively more disturbed by vessel traffic and artificial lighting, such as northern gannet (*Morus bassanus*) and common guillemot (*Uria aalge*), and will avoid windfarms during periods of heavy human activity like during foundation installation (Diershke et al. 2016, as cited in English et al. 2017; Degraer et al. 2019). Such species-specific avoidance responses, like increased movement along perimeters, have been observed at Danish windfarms; however, this is unlikely to have biological consequences if foundations are not sited near nesting areas (Dong Energy et al. 2006; Danish Energy et al. Agency 2013).

Displacement from foraging areas within windfarm sites may occur and can result in increased competition for food resources at adjacent foraging areas (English et al. 2017) or long-term reductions in fitness (Robinson Willmot et al. 2013). Bird species that rely on shallow, coastal areas are considered most at risk from displacement, as these locations are currently favored for windfarm siting (English et al. 2017). Some species of diving birds and sea ducks at Danish and German wind project sites were reduced or eliminated within wind project sites, and this may have occurred because loss of open-ocean foraging habitat; such loss is a minimal proportion of available habitat in the greater surrounding areas, but could have cumulative effects if birds are forced to use larger foraging ranges to meet energetic demands (Dong Energy et al. 2006; Danish Energy Agency et al. 2013; Lüdeke 2015). Displacement of migratory species including sea ducks, loons, and some species of auks from foraging areas within wind farms may have long-term implications on the fitness of these species, which would not be as readily apparent as the impacts of mortality caused by collision with turbines (Robinson Willmot et al. 2013). Other species, like guillemots and razorbills, became habituated to foundations and returned to use habitat within windfarms (Danish Energy Agency et al. 2013; English et al. 2017; Lüdeke 2015). Site-specific factors, like food abundance and foundation configuration, may play greater roles in observed avoidance and habituation (Degraer et al. 2019; Lüdeke 2015).

Avoidance effects from visual disturbances are not expected to differ across foundation types except that floating foundations have relatively less infrastructure extending throughout the entire water column. Their cables and anchors do not require as much disturbance of the seabed to deploy.

3.10 Acoustic Effects

The installation and operation of offshore wind farms involve a variety of noise-producing activities. Noise associated with the installation of the various foundation types may result from impact pile driving and vibratory pile driving, as well as installation vessels; sources of installation vessel noise include vessel engines, dynamic positioning thrusters, and auxiliary engines. During operation of the offshore wind farm, turbine foundations transmit noise and vibration from the operating WTGs into the water and seafloor. These noise-producing activities may have acoustic effects on aquatic organisms, including marine mammals, fishes, invertebrates, sea turtles, and sea birds. Such effects vary among species due to differences in hearing abilities and whether the species is migratory or stationary. The magnitude of the effect is influenced by the intensity, acoustic frequency, and duration of the sound produced.

Whales, dolphins, and porpoises have air spaces in the lungs and inner ears that are particularly sensitive to loud noises due to the amplification of sounds by these organs. Seals and sea lions have middle ears, like humans, that are filled with air between tympanic membranes (that is, ear drums) and contain middle ear bones. As a group, marine mammals are capable of hearing a wide range of frequencies. Baleen whales hear best at low frequencies (NMFS 2016), while most of the toothed whales and dolphins hear best in mid-frequencies, and porpoises, along with a few dolphin and toothed whale species, hear best at high frequencies. The hearing ranges of seals and sea lions generally fall between baleen whales and toothed whales. Acoustic effects on marine mammals range from physical injury to behavioral effects. Intense sounds within a marine mammal’s hearing range can cause temporary or permanent hearing damage. Hearing damage can impair an organism’s ability to communicate, which can affect the ability to find a mate. Such an impact could be significant for critically endangered species such as the North Atlantic right whale (*Eubalaena glacialis*). Hearing damage may also impair foraging and predator avoidance (Weilgart 2007). Less intense sounds can result in behavioral effects, including disturbance, changes in diving or calling behavior, and avoidance of the noisy area. These behavioral effects can interrupt critical functions, such as foraging, or cause increased energy expenditure. Less intense sounds can also lead to masking effects where the noisy activity reduces the ability of the animal to detect biologically significant sounds. Masking can reduce species communication distances or impair the ability to detect prey and/or predators (BOEM 2021a). Some species have developed strategies to compensate for masking (see Erbe et al. 2016), but these strategies generally have an energetic cost. Impacts of acoustic effects are expected to be greatest for baleen whales.

Like whales, many fish also have air-filled organs that are sensitive to pressure waves. In fish, these air-filled organs are called swim bladders. Fishes that have swim bladders use these organs for buoyancy control. Some species' swim bladders are connected to their auditory system; those fishes have the most sensitive hearing abilities. Fishes that lack swim bladders have limited ability to detect sound pressure waves but are less at risk of injury from noise because they lack the internal air space of fishes with swim bladders. Fish hearing abilities are generally confined to low frequencies (see Popper and Hawkins 2019). In addition to pressure waves, fish are also able to detect particle motion created by underwater sound. However, particle motion is not well-understood and there is currently no regulatory guidance to evaluate the impacts of particle motion on fish. Intense sounds, such as those generated by impact pile driving, can cause mortality or physiological injury in fishes, including damage to organs and hearing tissue (Mooney et al. 2020). Some fishes, including fish with swim bladders and their larvae, may suffer mortality near intense sound sources (Richardson et al. 1995; Popper et al. 2014; Natural Power Consultants 2013). Further from the sound source, non-lethal internal injuries could occur. Less intense sounds can cause stress, changes in respiration, and behavioral effects, including startle responses, changes in swim speed or direction, disturbance, and avoidance (Mooney et al. 2020). Similar to marine mammals, these behavioral effects can result in interruption of critical functions and increased energy expenditure. Less intense sounds may also result in masking (Mooney et al. 2020). The effects of masking on fish are not well understood. Though fishes may have some capacity to counteract masking effects, potential strategies to cope with masking have rarely been documented (Pine et al. 2020).

Among the marine invertebrates, species including cephalopods, crustaceans, and bivalves can detect particle motion (André et al. 2016; Hawkins and Popper 2014), similar to fishes. Marine invertebrates have been considered less susceptible than mammals and fish to loud noise and vibration because they generally do not possess air-filled spaces like lungs, middle ears, or swim bladders. However, noise at the levels associated with impact pile driving has been reported to cause short-term behavioral responses in marine invertebrates within approximately 10 m of the disturbance (McCauley 1994; Brand and Wilson 1996). Squid are known to exhibit behavioral responses to pile driving noise and have also shown sensitivity to low-frequency non-impulsive sounds (BOEM 2021b). Bivalve mollusks, like clams, mussels, and oysters, may also exhibit behavioral responses to sound exposure (BOEM 2021b). Invertebrate behavioral responses to noise include interruptions to feeding and resource gathering, startle responses, and escape behaviors (Mooney et al. 2020). Bivalves withdraw their siphons, while polychaete worms retract their appendages and may withdraw rapidly to the bottom of their burrows in the seafloor. Physiological damage has been observed to be indirectly caused by underwater noise, such as DNA damage in blue mussels (*Mytilus edulis*) (Wale et al. 2016) and protein damage in Mediterranean common cuttlefish (*Sepia officinalis*) (Solé et al. 2016).

Though sea turtle hearing is not well understood, these species possess auditory organs that are adapted for underwater hearing (Dow Piniak et al. 2012, as cited in BOEM 2021a). The hearing range of sea turtles is limited to low frequencies (BOEM 2021a). Exposure to intense underwater sounds may lead to physiological injury, including potential hearing damage (BOEM 2021c). Similar to other animals, less intense sounds may lead to increased stress or behavioral effects, including startle responses, increased swimming speeds, disturbance, and avoidance (BOEM 2021c). Though such behavioral effects would increase energy expenditure, such an increase would be small relative to the energy required for their long-distance migrations (BOEM 2021c).

Underwater hearing in sea birds has only been studied in a limited number of species. These studies indicate that sea bird hearing abilities at low frequencies may be similar to that observed for toothed whales, seals, and sea lions (Anderson Hansen et al. 2020). Additional sea bird species have exhibited behavioral reactions to underwater sounds, including seismic survey noise, SONAR sounds, broadband bursts, and predator calls. These sounds elicited startle responses or avoidance behavior (Anderson Hansen et al. 2020). Behavioral effects on birds are limited to a small area in the vicinity of the noise source, and impacts associated with offshore wind foundations are expected to be negligible (BOEM 2021c). Potential hearing damage due to underwater noise exposure has not been studied in sea birds.

Impact pile driving during installation is the most intense sound associated with the construction and operation of offshore wind farms. The sound energy generated by impact pile driving is concentrated in the low frequencies (Mooney et al. 2020), overlapping with the frequency range where hearing is most sensitive for baleen whales, fish, invertebrates, and sea turtles. Impact pile driving creates underwater noise at sound levels that may cause hearing damage or behavioral effects, including avoidance behavior, in marine mammals (BOEM 2021c; Nedwell et al. 2003; Richardson et al. 1995). For example, there is evidence for behavioral avoidance in harbor porpoises during pile driving (Carstensen et al. 2006). These effects do not appear to be permanent because porpoises have been observed returning to an area after pile driving ceased (Dähne et al. 2013).

Sound levels associated with impact pile driving may potentially cause mortality, tissue damage, or behavioral effects, including displacement, in fish and invertebrates (BOEM 2021c; Popper and Hastings 2009). Noise produced during impact pile driving could also cause injury or behavioral effects in sea turtles and stress or behavioral effects in sea birds (BOEM 2021a, 2021c). The two components of underwater sound (vibration and pressure) change significantly with distance from the source. The spatial extent of impact pile driving noise will vary among projects based on water depth and temperature, seafloor sediment type, and pile and hammer characteristics, among other factors. Generally, sound levels causing behavioral effects extend significantly further from the pile than those causing injury. However, it is important to note that exposure to sounds above the behavioral threshold does not necessarily mean that an animal will elicit a behavioral response; alternatively, in some cases, animals may be behaviorally affected by sound levels below the behavioral threshold. For projects on the Atlantic OCS, marine mammals and fish and invertebrates could potentially experience behavioral effects of pile driving noise up to several miles from the pile. Sea turtles could experience behavioral effects within approximately one mile from the pile (BOEM 2021a). Effects on diving sea birds would be limited to close proximity to the pile (BOEM 2021c). Impact pile driving is a temporary, intermittent noise source, occurring for only a few hours each day (BOEM 2021c). The duration of the most wide-reaching acoustic effects associated with impact pile driving (i.e., behavioral effects) is generally expected to be limited to the time of active pile driving (BOEM 2021c), though it may take a few hours for displaced organisms to return to the area. The duration of physiological acoustic effects may range from short-term to permanent.

Underwater sound levels generated by the operation of WTGs are significantly lower than those generated by impact pile driving during foundation construction, and the characteristics of operational sound differ from those associated with construction. Though operational sound levels are relatively low, the operational noise from an entire windfarm can increase sound levels in naturally quiet areas (e.g., areas with low ship traffic), potentially having negative effects on aquatic organisms (Tougaard et al. 2020). Because of the relatively low amplitude and steady oscillation of sound produced by WTGs, operational sound levels are not expected to cause physiological injury to any aquatic organisms; however, operational sound levels could cause behavioral effects on marine mammals. These behavioral effects are only expected to occur within a short distance of the foundation (BOEM 2021a). More recently, Stober and Thomsen (2021) used monitoring data and modeling to estimate operational noise from larger (10 MW) current generation direct drive WTGs and concluded that these designs could generate higher operational noise levels than those reported in earlier research. Acoustic effects of operational noise would occur whenever WTGs are operating over the life of the wind farm, generally 25 to 30 years (BOEM 2021c).

Noise impacts can be mitigated by a variety of measures, including noise abatement systems, protected species observers, and timing restrictions. Noise abatement systems that have been utilized for offshore wind foundation installation include bubble curtains, noise mitigation screens, and Hydro Sound Dampeners (Bellmann et al. 2020). Employing protected species observers during pile driving provides a mechanism to call for cessation of pile-driving activities if a marine mammal or sea turtle is spotted in the area, reducing the risk of exposure to injurious sound levels. Timing restrictions avoid or reduce risk by prohibiting noise-producing activities during times when sensitive species are most likely to be present or during seasons when breeding or spawning are occurring.

Impact pile driving during installation of some monopile, jacket, tri-pile, and tripod foundations produces acoustic effects that are anticipated to be relatively similar across foundation types, though the spatial extent of effects would be smaller for jacket, tri-pile, and tripod foundations. Anchors for floating foundation can also be installed by impact pile driving, with a smaller anticipated acoustic impact associated with smaller piles. Other installation methods or activities, such as dredging for site preparation of gravity foundations, vibratory pile driving, and reverse-circulation drilling, also produce noise. However, those activities would create lower noise levels that are not as impactful to organisms because of the nature of the sound wave, which is steady and continuous rather than impulsive like impact pile driving. Relatively quiet construction activities occur during installation of suction bucket foundations and floating foundations that use suction caissons or drag, dead-weight, or embedded anchors. Operational noise produced by wind turbine generators sitting atop the foundations may radiate through the foundation and into the water column and, in the case of fixed-bottom foundations, into the seafloor. This operational noise may result in behavioral effects on marine organisms. Such effects would be similar across fixed foundation types. Unlike fixed foundation noise, operational noise associated with floating foundations would not affect benthic species as the noise would not radiate into the seafloor and would result in a smaller spatial scale of effects for non-benthic species.

4 Summary and Conclusions

4.1 Types of Foundations and Site Suitability

The offshore wind industry has adopted several of the foundation types that have proven successful for the oil and gas industry for many years. Prototypes and early projects used monopiles, small steel-truss jackets, and gravity structures in shallow waters, typically less than 15 m (50 ft) deep. As turbine locations moved into waters up to about 40 m (131 ft) deep, larger steel monopiles dominated. From depths of 40 m to 60 m (131 ft to 197 ft), monopiles face competition from various space-frame configurations (i.e., jackets, tripods, and tri-piles). Beyond about 60 m (197 ft) deep, offshore wind projects are expected to transition from fixed-bottom structures to floating structures. Several floating offshore wind projects for deep water have now been deployed or are in the advanced planning stages.

Monopiles and tri-piles are driven into the seabed and are not well-suited for geological conditions with shallow bedrock, boulders, or coarse gravel layers. Jackets, tripods, and some anchors for floating foundations require soil conditions in which piles or suction caissons can be embedded and tolerate obstructions better than monopiles. Gravity foundations and dead-weight anchors for floating foundations sit directly on the seabed and can therefore be located where it is not practical for the foundation to penetrate the seabed. Table 10 summarizes the water depths and geological conditions suitable for various foundation types.

Table 10: Site conditions and foundation selection

Foundation Type	Maximum [1] Water Depths	Geological Conditions
Monopiles	50 m (160 ft)	- Sands and clays preferred. - Not suitable for shallow bedrock or strata with boulders, cobbles, or coarse gravel.
Jackets	60 m (200 ft)	With piles: - Stiff clays and medium to dense sands preferred. - Possible in softer silts and clay, and in very soft sediments overlying stiffer soils or bedrock. - Less well suited for locations with many boulders. With suction caissons: - Medium stiff clays and fine to medium sand preferred. - Not suitable for strata with cobbles, boulders, or coarse gravel layers or in very soft soils.
Tripods	50 m (160 ft)	- Same as jackets.
Tri-Piles	40 m (130 ft)	- Sands and clays preferred. - Not suitable for shallow bedrock or strata with boulders, cobbles, or coarse gravel.
Jack-Up	100 m (330 ft)	- Hard bottom conditions, stiff clays, and medium-to-dense sands preferred. - Possible in softer silts and clay, and in very soft sediments overlying stiffer soils or bedrock.
Suction Buckets	30 m (100 ft)	- Medium stiff clays and fine to medium sand preferred. - Not suitable for strata with cobbles, boulders, or coarse gravel layers or in very soft soils.
Gravity	40 m (131 ft)	- Sand, medium to stiff clays, bedrock, and strata with cobbles, boulders, or coarse gravel. - Not suitable for very soft soils or weak clays.
Floating	220 m (720 ft)	- Medium stiff clays, fine to medium sands, coarse sands, and gravel. - Less well suited for locations with many boulders.

[1] Maximum refers to the current or typical maximum water depth for currently constructed or planned offshore wind projects, not the technological limit for each foundation type.

Wind turbine spacing is not dependent on the type of foundation selected. Regardless of the type of foundation, the cumulative areas of the wind turbine foundation footprints, including any scour protection, covers less than 1 percent of the area of an offshore wind project (English et al. 2017). However, during installation of foundations requiring more extensive seabed preparation, an area several times larger than the foundation footprint itself may be disturbed.

4.2 Ecological Effects Summary

Table 11 summarizes the ecological effects on communities from the installation and presence of the various foundation types. The most common foundation type used for offshore windfarms to date and the type with which most people are familiar is the monopile foundation. To compare the ecological effects among the foundation types, Table 11 first describes the potential effects from a representative monopile foundation, and then discusses how those effects would differ for representative examples of other foundation types. In practice, the effects would also differ in magnitude due to project-specific structural, seabed, and ecological details.

Table 11: Comparison of effects of foundation type on ecological communities relative to monopile foundations

Effect Type	Relative Level of Effect Compared to Monopile Foundation Type[1]					
	Monopile	**Jacket**	**Tripod/Tri-pile/Jack-up**	**Suction Bucket**	**Gravity**	**Floating**
Habitat Loss: - Species displacement and/or mortality - Soft bottom habitat loss	Approximately 1,960 m^2 of habitat loss. Foundation and scour protection footprints are less than approximately 1% of the overall windfarm area.	Approximately up to 201 m^2 of habitat loss. Disturbance of overall windfarm area percentage similar to monopile.	Approximately 235–530 m^2 of habitat loss. Disturbance of overall windfarm area percentage similar to monopile.	Approximately 1,590 m^2 of habitat loss. Disturbance of overall windfarm area percentage similar to monopile.	Approximately 6,360 m^2 of habitat loss. Some designs may temporarily disturb an area several times larger than the footprint itself, or up to approximately 2.5% of the overall windfarm area.	Approximately up to 113 m^2 of habitat loss per foundation (for suction caisson anchors). Disturbance of overall windfarm area percentage similar to monopile.
Artificial reef effects: - Introduction of organisms that grow on the surfaces of foundations - Increase food source and increased source of prey	Potentially beneficial effects for some species due to the creation of habitat in the water column and introduction of hard surfaces by foundations and scour protection.	Larger potential beneficial effects compared to monopiles due to much greater surface area of lattice structure.	Similar effects to monopile, though less effects if less scour protection is used.	Similar effects to monopile.	Similar effects to monopile.	Similar effects to monopile or potentially larger beneficial effects, depending on depth and diameters of submerged structures (spars, submersibles, TLPs).
Invasive species spread effects: - Introduction of invasive species	Colonization limited to surface area of foundation/ scour pad; regional risk of “stepping stone” spread varies with geographic location.	Similar risk to monopile if shipped to site, larger risk if towed from port to windfarm site.	Similar risk to monopile.	Similar risk to monopile if shipped to site, larger risk if towed from port to windfarm site.	Larger risk than monopile because structure can be towed from port to windfarm site.	Larger risk than monopile because structure can be towed from port to windfarm site, also may be towed back for major maintenance.
Wake and scour effects: - Increased concentration and/or availability of prey in wakes - Altered conditions can affect recruitment of larvae of benthic species, suspended sediment concentration and sedimentation, availability of food, oxygen, and waste removal. - Additional benthic habitat disruption or loss due to scour	Turbulent wake may extend approximately 200 meters down current of foundation, with additional hydrodynamic changes off each side. Scour can occur adjacent to scour pads.	Smaller-scale wake effects due to less volume of structure in water column and lattice design. Smaller scour effects due to smaller wake effect and smaller foundation/scour pad footprint.	Similar overall wake effects due to less individual structure volume, but with 3 wakes and vortex shedding. Smaller scour effects due to smaller foundation/scour pad footprint.	Similar wake effects to monopile. Potentially larger scour effects at base due to wider foundation diameter.	Potentially larger wake effects at base due to wider foundation diameter, but smaller wake effect near surface due to taper of structure. Potentially larger scour effects at base due to wider foundation diameter and larger scour protection.	Similar wake effects to monopile near the surface, but smaller wake effects near the bottom due to weaker currents at greater depths. Smaller scour effects at seabed.

	Relative Level of Effect Compared to Monopile Foundation Type[1]					
Effect Type	**Monopile**	**Jacket**	**Tripod/Tri-pile/Jack-up**	**Suction Bucket**	**Gravity**	**Floating**
Release of suspended sediment and sediment deposition effects: - Decreased water quality due to increased suspended sediment - Smothering of species and habitats by deposited sediment - Avoidance of area by species due to increase sediments - Changes in organic matter content in sediments associated with sediment particle size - Exposure to toxic contaminants within sediment	Effects primarily occur during installation by piling, with relatively larger effects if reverse circulation drilling is utilized. During operations, effects restricted to the vicinity of the foundation as far as wake effects extend.	Smaller effect than monopiles if installed by piling (much smaller piles), and much smaller effect if installed with suction caissons. Fewer effects during operations due to decreased scour potential.	Tri-piles may have similar effect to monopiles. Tripod may have smaller effects if installed by piling (much smaller piles), and even less effect if installed with suction caissons. Jack-up would have less effects than monopiles. Fewer effects during operations due to decreased scour potential.	Fewer effects than monopiles during installation. Greater effects during operations due to increased scour potential.	Greater effects than monopiles because require more seabed preparation (e.g., dredging) for installation. Larger effects during operations due to increased scour potential.	Smaller effects than monopile if installed by piling (much smaller piles) or drag anchors; less effects if installed by deadweight anchors, dynamically embedded anchors, or suction caissons. Potentially similar effects during operations due to ongoing seabed disturbance from anchor rode.
Attraction effects: - Refuge/resting areas for sheltering from currents and/or predation - Increased prey availability due to artificial reef effect and wake effect - Increased predation rates due to higher predator abundance	Large surface area (10 m leg diameter) for marine organism growth. Large volume of structure for wake effects.	Similar overall effect to monopiles due to artificial reef effects. Smaller wake effects, but greater sheltering opportunities.	Similar overall effect to monopiles due to artificial reef effects and similar overall wake effects.	Similar overall effect to monopiles due to artificial reef effects and similar wake effects.	Similar overall effect to monopiles due to artificial reef effects and overall wake effects (larger near bottom but smaller near surface).	Potentially similar attraction effects at surface, but less attraction effects at greater depths where the only structures in the water column are cables and anchors.
Avoidance effects: - Displacement of species from windfarm site (disturbance effects) - Disruption of migration routes (barrier effects)	During installation, temporary displacement of species from vicinity of foundations and/or windfarm site. During operations, effects limited to the vicinity of the windfarm.	Similar effects to monopiles.	Similar effects to monopiles.	Similar effects to monopiles.	Similar effects to monopiles.	Potentially similar avoidance effects at surface, but less avoidance effects at greater depths where the only structures in the water column are cables and anchors.

	Relative Level of Effect Compared to Monopile Foundation Type[1]					
Effect Type	**Monopile**	**Jacket**	**Tripod/Tri-pile/Jack-up**	**Suction Bucket**	**Gravity**	**Floating**
Acoustic effects: - Mortality or physical injury from noise - Behavioral alterations like startling, fleeing, or hiding -Masking of biologically significant sounds	During installation, activities that create noise may harm or displace marine animals. Impact pile driving creates the largest effects and effects from reverse circular drilling or vibratory pile driving would be smaller.	Similar effects to monopile though the spatial scale of effects would be smaller.	Similar effects to monopile though the spatial scale of effects would be smaller.	Less effects than monopiles due to less noise inducing activities during installation.	Less effects than monopiles that are installed with pile driving because less noise is emitted from site preparation compared to pile driving.	Smaller effects than monopile if installed by piling (much smaller piles); less effects if installed by deadweight anchors, drag anchors, dynamically embedded anchors, or suction caissons.

Notes:

[1] Except as noted and for comparative purposes only, the dimensions of the representative foundations are based on typical designs scaled for a 40-m (131-ft) water depth, recognizing that not all designs would be economically competitive at that water depth. The area covered by scour protection at a particular site is dependent on the sediment and current conditions. For illustrative purposes, the size of a scour protection pad is assumed to be about 3 to 5 times the diameter of the structure obstructing the flow.

Representative-monopile foundation:

- 10-m (33-ft)-diameter-monopile.
- 50-m (164-ft)-diameter rock blanket for scour protection or 1,960 m^2 (21,100 ft^2) total footprint.

Representative jacket foundation:

- Tubular steel lattice frame with a square base 20 m (66 ft) on a side, jacket tapers to a 10-m (33-ft) square above the water line.
- Four 1.8-m (6.6-ft)-diameter legs.
- 8-m (26-ft)-diameter rock blanket for scour protection around each leg or 201 m2 (2,120 ft2) total footprint.

Representative tripod foundation:

- Triangular base 25 m (82 ft) on a side connecting to a 6-m (20-ft)-diameter central support column at about 15 m (49 ft) above the seabed.
- 10-m (33-ft)-diameter rock blanket for scour protection around each leg or 235 m^2 (2,500 ft^2) total footprint.

Representative tri-pile foundation:

- Three 3.4-m (11-ft)-diameter legs forming a triangle 20-m (66-ft) on a side.
- 15-m (49-ft)-diameter rock blanket for scour protection around each leg or 530-m^2 (5,700-ft^2) total footprint.

Representative jack-up foundation:

- Three 3.7-m (12-ft) diameter legs spaced 63-m (208-ft) apart.
- 12-m (39-ft)-diameter rock blanket for scour protection around each leg or 340 m^2 (3,650 ft^2) total footprint.

Representative suction bucket foundation:

- Base diameter of 25 m (82 ft) with protrusion of 3 m (10 ft) above the seabed and 10-m (33-ft)-diameter central support column.
- Scour protection blanket around the base an additional10 m (33 ft), bringing the total diameter to 45 m (148 ft) or 1,590 m^2 (17,200 ft^2) total footprint.

Representative gravity foundation:

- Conical base with a-maximum diameter of 30 m (98 ft) tapering to an 8-m (26-ft) central support column 10 m (33 ft) above the seabed.
- Scour protection blanket around the base an additional 30 m (98 ft), bringing the total diameter to 90 m (295 ft) or 6,360 m^2 (68,500 ft^2) total footprint.

Representative floating foundations:

- Floating foundations would typically not be used in waters only 40 m (131 ft) deep, but except for the lengths of the-mooring lines, the typical dimensions would not be particularly sensitive to the water depth.
- Four suction caisson or dynamically embedded anchors.
- Suction caisson anchors 6 m (20 ft) in diameter, or 113 m^2 (371 ft^2) total footprint area for four anchors, protruding 2 m (6 ft) above the seabed.
- 10-m (33-ft) diameter of scour protection around each suction caisson (if used) or 314 m^2 (3,380 ft^2) total footprint.
- Dynamically embedded anchors would be completely below the seabed.
- Spar and semi-submersible floating foundations would have heavy anchor chains (i.e., anchor rode) that could drag on the seabed.
- Tension leg foundations would have vertical tendons that connect the anchors directly to the floating turbine support structure.

4.3 Conclusions

The type of offshore wind foundation utilized is highly dependent on the geological conditions and water depths of the windfarm site. The environmental effects of offshore wind turbine foundations are generally limited to the immediate vicinity of the foundations and the windfarm site area. The magnitude of the effects may vary among foundation types, primarily due to each type's underwater surface areas, volume it occupies in the water column, and its footprint on the seabed. Specific conclusions are as follows:

- Direct effects from the presence of the foundation structure on benthic species and habitats are typically greatest at monopile foundations and least at floating foundations. However, the effect across all foundation types is minimal, considering that typically less than 1 percent of the area of an offshore wind project site over which wind turbines are deployed is covered by structure footprints, including scour protection (English et al. 2017). However, seabed preparation for some gravity foundation designs may temporarily disturb an area several times larger than the foundation footprint itself.

- Foundations can act as artificial reef-like structures, which can have beneficial ecological effects for some species. Compared to monopiles, these beneficial effects could be larger with a jacket foundation, given the much greater surface area associated with its lattice structure, and may be greater with some types of floating foundations depending on depth and surface area of the submerged structures.

- Risk of the spread of invasive species varies primarily with geographic location. For example, ocean current dynamics can influence transportation of invasive species to windfarm sites and presence of invasive species in the vicinity may increase the likelihood of spread to new structures. Risks are largest for gravity and floating foundations, compared to other foundation types, because they are generally towed to the site from ports, which increases the potential for the introduction of invasive species at the windfarm site.

- Wake effects, which include hydrodynamic changes, for example increased concentration of prey in wakes and changes to larval recruitment dynamics, would be similar across most foundation types. Compared to monopiles, smaller wake effects would be expected at jacket foundations, due to relatively less structure volume in the water column, and near the seabed at floating foundations, due to weaker currents at greater depths. Larger scour effects would be expected at gravity and suction bucket foundations compared to monopiles, due to the wider diameter of the base of gravity foundations near the seabed.

- Effects associated with the release of suspended sediment are mostly associated with installation activities. The smallest effects are expected for suction bucket foundations, which involve relatively little sediment disturbance during installation. The largest effects are expected for gravity foundations that require seabed preparation (e.g., dredging) and for monopiles if they use reverse circular drilling, which both cause more extensive sediment disturbance than pile driving does during installation.

- Some species seek out wind turbine foundations for resting areas or enhanced feeding opportunities. However, this attraction could place them at increased risk of predation, collision with turbines, or interactions with fishing gear. For migratory species, there is concern that introduction of foundations in the otherwise featureless offshore environment could alter species' migration patterns by attracting them to linger at wind farm areas. This attraction effect is expected to be similar across foundation types, except for floating foundations, which have relatively less infrastructure extending through the entire water column.

- For species sensitive to visual or spatial disturbances, avoidance effects may result in effective loss of utilized habitat within, or species displacement from, an offshore wind project site, but typically an abundance of available surrounding habitat exists. Like the attraction effect, this avoidance effect is expected to be similar across most foundation types, but likely would be smaller for floating foundations, which are installed in very deep water and have relatively less volume of infrastructure extending through entire the water column.

- Underwater noise, particularly noise caused by foundation installation activities, may cause mortality or injury to marine mammals, fishes, invertebrates, and sea turtles. Behavioral alterations from acoustic affects, such as startling, fleeing or hiding, may occur during foundation installation activities, such as pile driving. Impact pile driving during installation of some monopile, jacket, tri-pile, and tripod foundations produces acoustic effects that are anticipated to be relatively similar across foundation types, though the spatial extent of effects would be smaller for jacket, tri-pile, and tripod foundations. Floating foundation anchors can also be installed by impact pile driving, with a smaller anticipated impact associated with smaller piles. Other installation methods or activities, such as dredging for site preparation of gravity foundations, vibratory pile driving, and reverse-circulation drilling, also produce noise. However, those activities would create lower noise levels that are not as impactful to organisms because of the nature of the sound wave, which is steady and continuous rather than impulsive like impact pile driving. The least noise-emitting activities occur during installation of suction bucket foundations and floating foundations that use suction caissons, drag, dead-weight, or embedded anchors. Operational noise produced by wind turbine generators sitting atop the foundations may radiate through the foundation and into the water column and, in the case of fixed-bottom foundations, into the seafloor. This operational noise may result in behavioral effects on marine organisms. Such effects would be similar across fixed foundation types. Unlike fixed foundation noise, operational noise associated with floating foundations would not affect benthic species as the noise would not radiate into the seafloor and would result in a smaller spatial scale of effects for non-benthic species.

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