Offshore Wind Energy: Technology Below the Water

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National Renewable Energy Laboratory

Photo by Dennis Schroeder, NREL 40481

Webinar Logistics

- The webinar will be recorded and posted to NREL's YouTube channel and WINDExchange (https://windexchange.energy.gov).
- There will be a Q&A following the presentation.
- Put questions in the Q&A during and at the end of the presentation.

Photo by Gary Norton, DOE 41187

Speaker Bios

Dr. Sanjay R. Arwade is a Professor of Civil Engineering at the University of Massachusetts, Amherst and is Associate Director of the Wind Energy Center. He studied structural engineering and mechanics at Princeton and Cornell and works primarily in areas of probabilistic mechanics, offshore wind energy engineering, and reliability. His work has been funded by the US National Science Foundation, BOEM, the Massachusetts Clean Energy Center, and industry.

Dr. Amy Robertson is the Offshore Wind Group manager at the National Renewable Energy Laboratory, where she has worked since 2010. She leads activities focused on advancing offshore wind design capabilities and practices. She is the project leader for IEA Wind Task 30, an international research project called OC6 focused on the verification/validation of offshore wind modeling tools; and the ATLANTIS FOCAL project, which is focused on advancing floating wind scaled-model testing to enable the validation of control co-design methods and technologies.

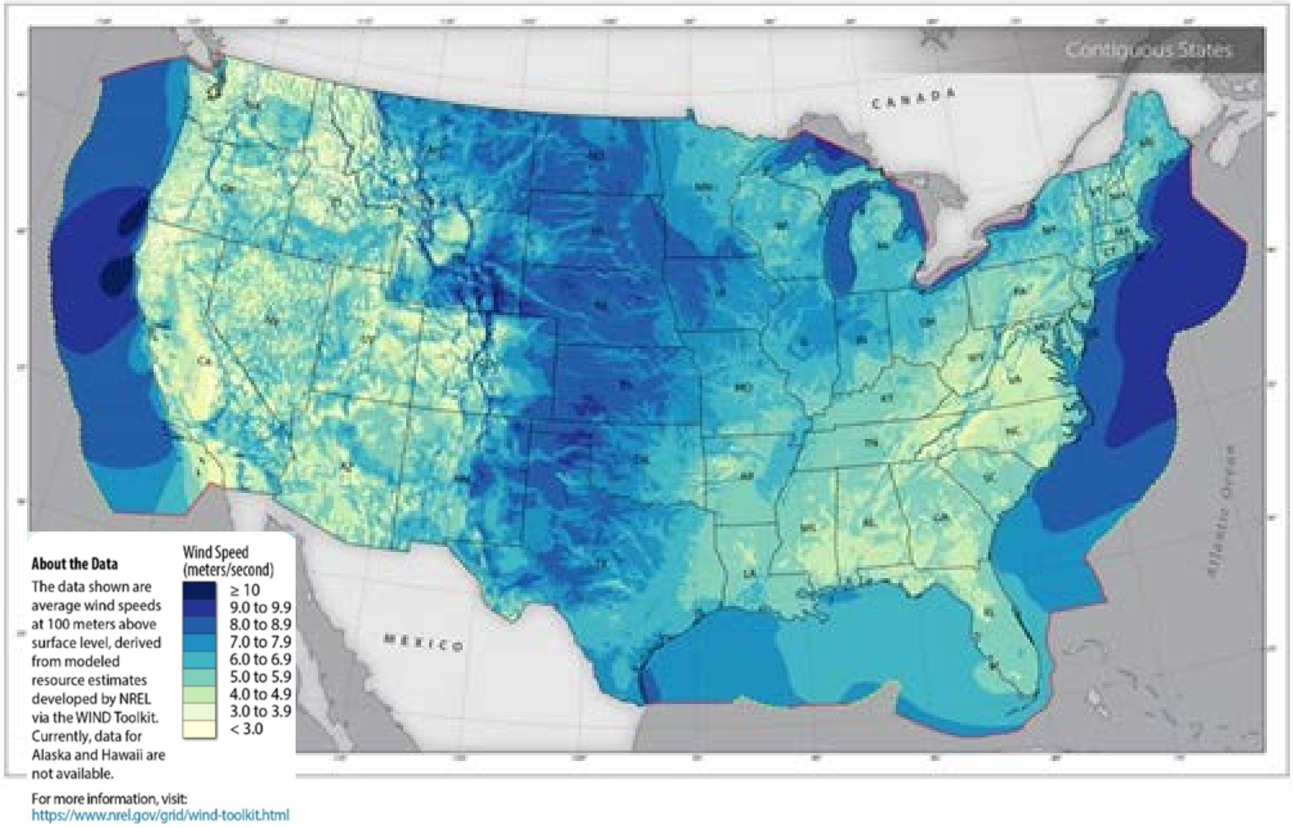
What Will We Cover?

- **Part 1: Introduction to offshore wind energy**
- **Part 2: Technology options**

Photo from Siemens AG, 27872

Introduction to Offshore Wind Energy

Why Pursue Offshore Wind Energy?



Graphic by NREL

Offshore means:

✓ Generation close to the load (80% of the U.S. population lives in coastal states)

✓ Stronger, more consistent wind resources

✓ Larger-scale projects are possible

✓ Economic benefits and workforce development

✓ Revitalization of ports and domestic manufacturing

Offshore Wind – Global Industry Status

Photo from Siemens AG, 27892

- As of 2021, the offshore wind projects installed globally amount to a capacity of more than 50,623 megawatts (MW).
- The average project size is getting larger, with some exceeding 1,000 MW (which can power up to 1 million homes).
- Over 99% of offshore wind turbines are on fixed-bottom support structures in shallow water (less than 50 meters deep).
- Average turbine rating is currently about 10 MW but will increase to 12–15 MW for projects after 2024.
- Overall costs are declining, but maintenance costs will remain higher for offshore turbines than land-based turbines because of difficult access.
- Offshore wind leverages existing mature marine industries.

U.S. Planned Projects

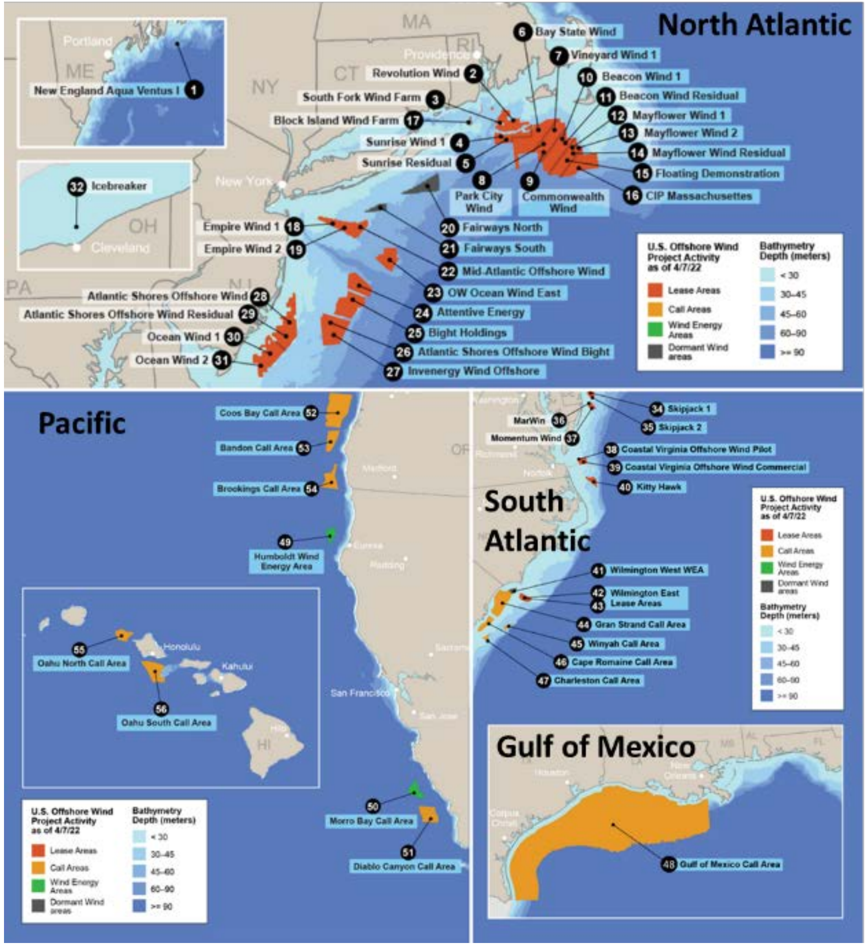
- Offshore wind call areas are being defined in all four major bodies of water: the Atlantic, the Pacific, the Gulf of Mexico, and the Great Lakes.
- There are 42 MW of operational offshore wind energy in the United States.

Block Island Wind Farm

- Operating since 2016
- Capacity = 30 MW
- 5 6-MW Haliade 150 turbines
- Jacket substructures

Coastal Virginia Offshore Wind

- Operating since 2020
- Capacity = 12 MW
- 2 6-MW SWT-6.0-154 turbines
- Monopile substructures



Graphic by NREL

Biden Administration Offshore Wind Goals

- In March 2021, the Biden administration set a national target of installing **30 gigawatts of offshore wind energy by 2030.**[1]
- The steps identified to support this target include:
  - Advancing U.S. wind energy projects to create well-paying, unionized jobs
  - Investing in American infrastructure to strengthen the domestic supply chain
  - Supporting critical research and development and data sharing.[1]

Photo from Siemens AG, 27821

[1] The White House. 2021. FACT SHEET: Biden Administration Jumpstarts Offshore Wind Energy Projects to Create Jobs. March 29, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/29/fact-sheet-biden-administration-jumpstarts-offshore-wind-energy-projects-to-create-jobs/.

Below the Water: Technology Options

Summary: Technology Options

- Overview of substructure types
  - Fixed-bottom substructure overview and options
  - Floating substructure overview and options
  - Foundation installation
- Mooring systems
  - What is a mooring system?
  - Overview of mooring line types and considerations
  - Overview of anchor types
- Cabling technologies
  - Cabling characteristics and array layout
  - Protecting cables and the environment
  - Cabling installation and monitoring logistics
- Decommissioning

Illustration by Joshua Bauer, NREL 49055

Fixed-Bottom vs Floating Components

Fixed-Bottom

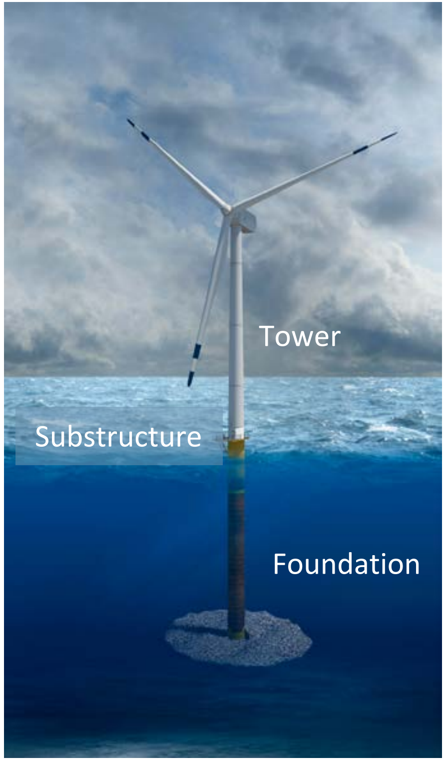


Illustration by Joshua Bauer, NREL 50049

Support Structure
=
Tower
+
Substructure
+
Foundation

Floating

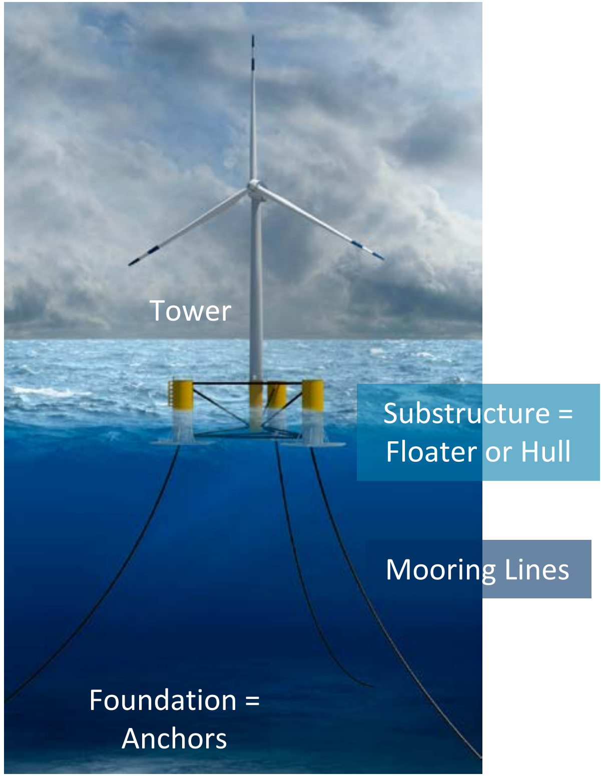


Illustration by Joshua Bauer, NREL 50048

Overview of Support Structure Types

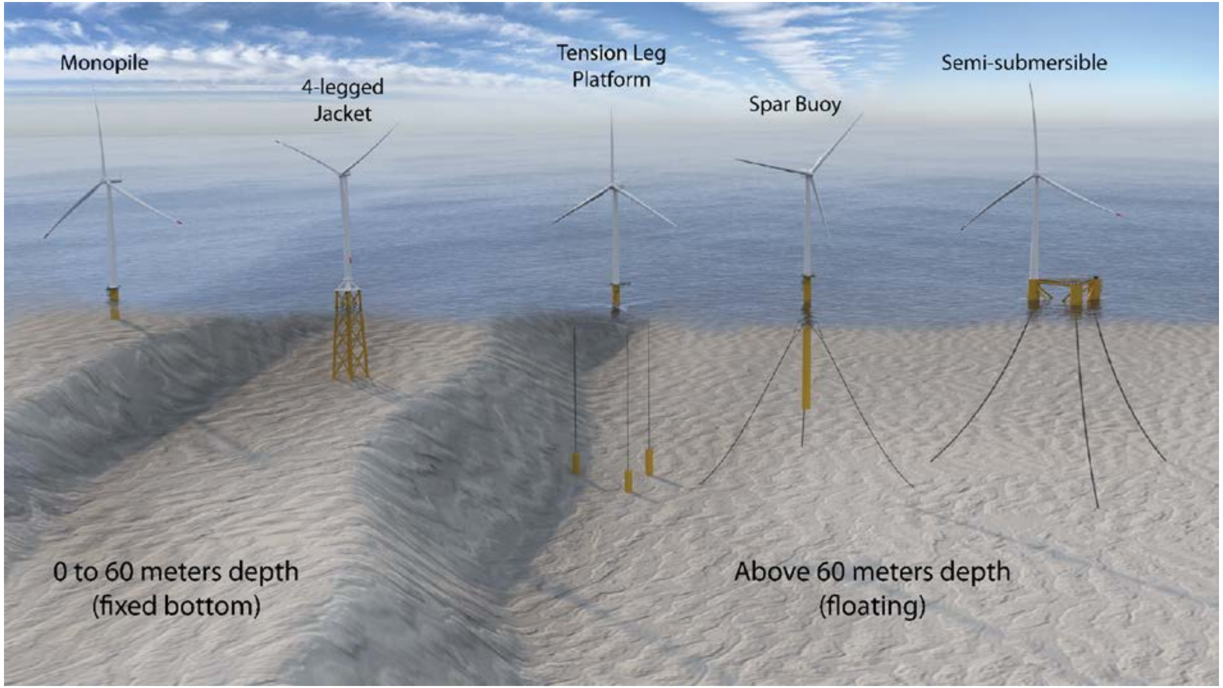


Illustration by Joshua Bauer, NREL

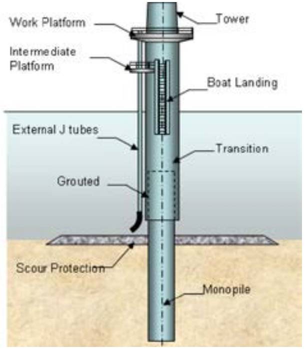
- In water depths 0–60 meters, fixed-bottom support structures are used.
- In water depths >60 meters, floating support structures are used.

Fixed-Bottom Overview

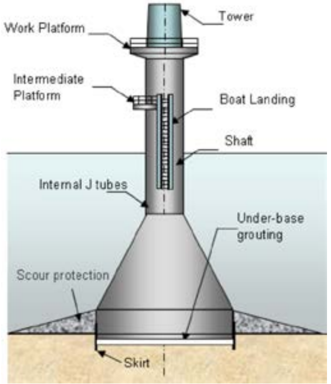
- **Wind turbines placed offshore** are similar to *land-based wind turbines,* except they:
  - Are marinized to withstand the ocean environment
  - Are fixed to the ocean floor via a support structure
  - Are larger and have power capacity that is typically 2 times that of land-based turbines
  - Have more complex support structures
  - Are designed to withstand higher wind speeds and waves associated with storms
  - May feature different drivetrain technology (direct drive instead of gearbox).

Photo by Gary Norton, DOE 41193

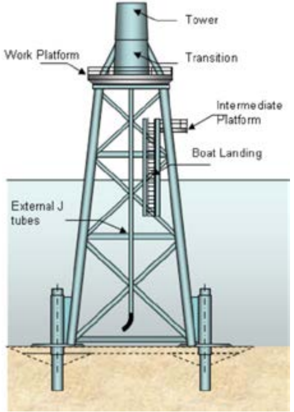
Fixed-Bottom Options



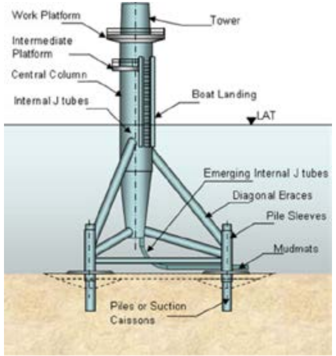
Monopile



Gravity Base



Jacket



Tripod

Illustrations from DNV

- Considerations include cost, seabed characteristics (such as type of soil), and manufacturing.
- **Monopiles** represent over 70% of installed offshore turbines globally.
- **Gravity bases** are extremely durable in harsh marine environments and have lower operation and maintenance costs.
- **Jackets** come in a variety of forms (e.g., 4-legged jacket) and can be fabricated in existing U.S. ship and steel yards currently used for the oil and gas industry.
- **Tripods** are more expensive and less commonly used but may be a better option for low profiles at the water line and visual impacts.

Floating Wind Overview

- Floating wind turbines look similar to fixed-bottom turbines from the surface but are supported by buoyant substructures moored to the seabed.
- Floating wind turbines are less constrained by water depth and show promise as an alternative to fixed bottom structures.
- **58% of the U.S. technical offshore wind resource is too deep for conventional fixed-bottom offshore wind turbines** (both from cost and technical perspectives).
- 17,931 MW of floating wind energy have been either announced or installed globally, as of 2021.
- Smaller installation numbers show the immaturity of technology; as costs come down, many more floating wind turbines will be built.

Photo by Senu Sirnivas, NREL 27602

Regions Being Considered for Floating Wind

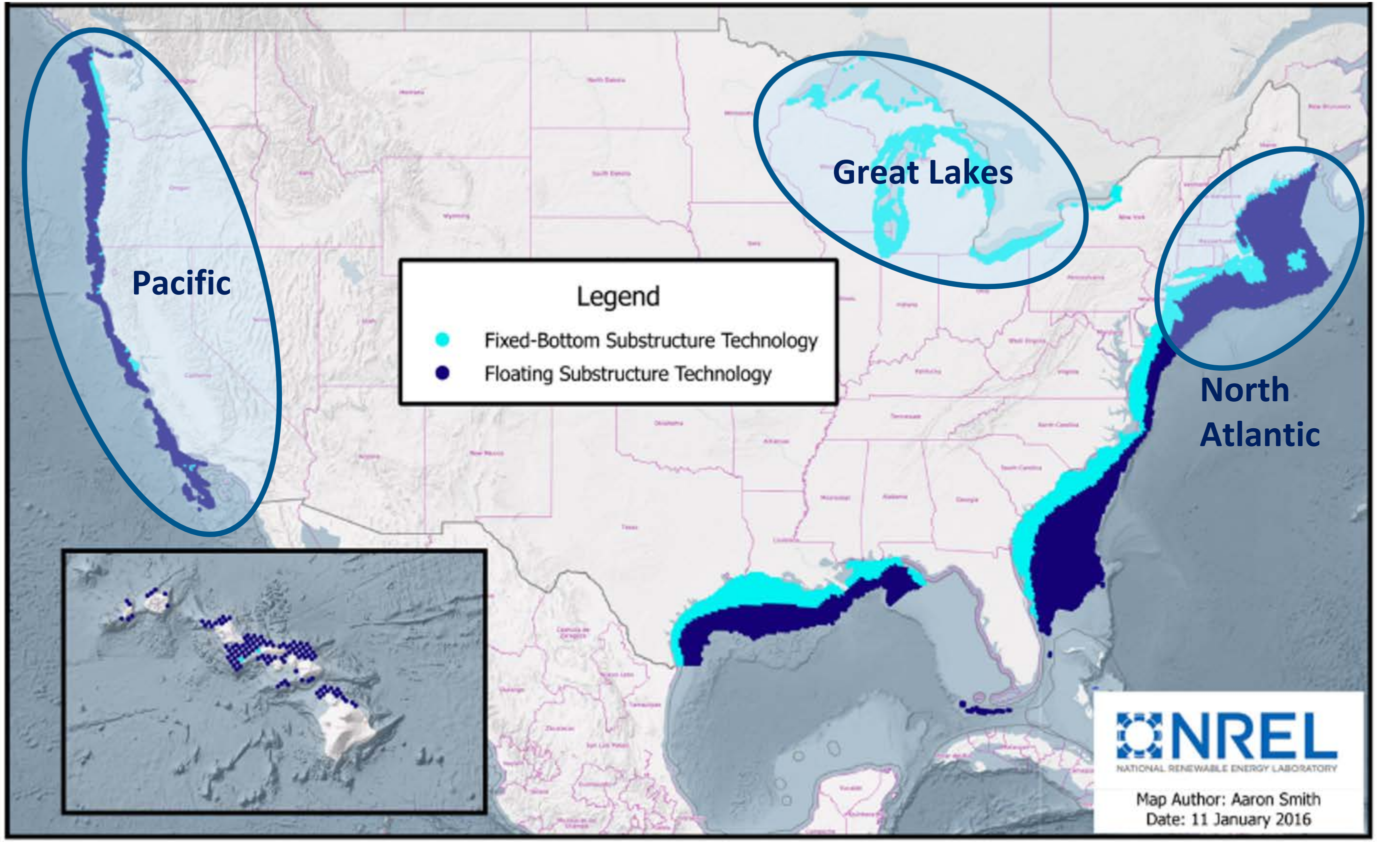


Figure by Aaron Smith, NREL

Pacific: Greater water depth requires floating technology.

North Atlantic: High demand may mean a scarcity of shallow sites.

Great Lakes: Visual impacts may require farther distances from shore.

Floating Wind Options

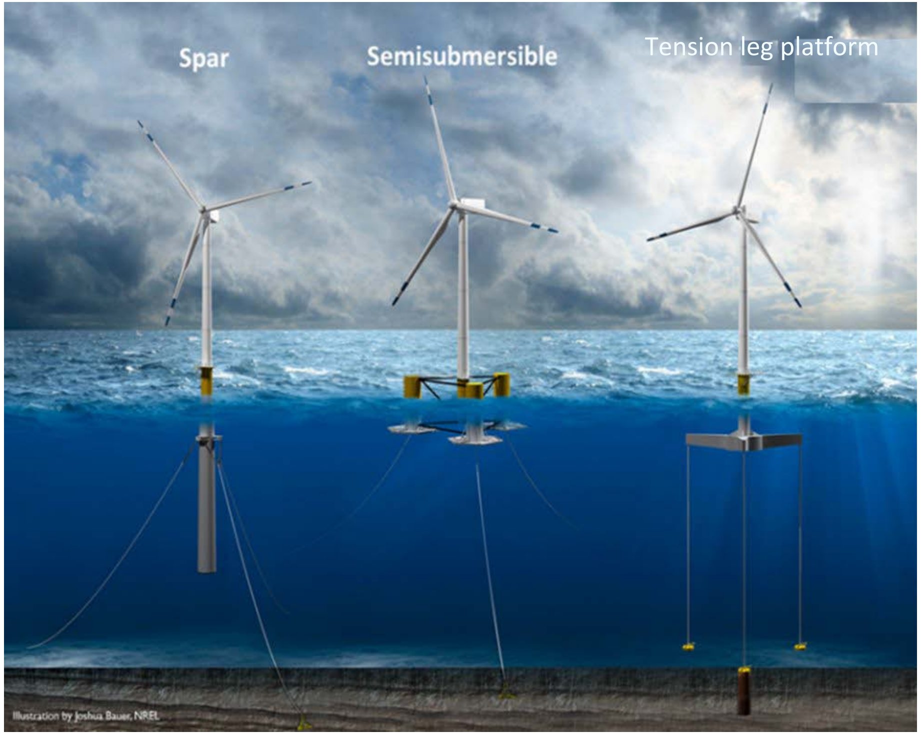


Illustration by Joshua Bauer, NREL

Floating offshore wind energy substructure archetypes are derived from the oil and gas industry.

Substructure	Advantages	Disadvantages
Spar	• Low cost • Low platform motion • Low wave profile	• Wide anchor footprint • Difficult assembly • Deep draft required
Semi-submersible	• Potentially low platform motion • Static stability for assembly and towing	• Wide anchor footprint • Corrosion potential • Wave exposure at waterline
Tension Leg Platform	• Small anchor footprint • Low cost • Low platform motion • Low wave profile	• Unstable without mooring system • High vertical load moorings

Foundation Installation

- Installation processes and considerations are different for each type of foundation.[3]
- Fixed-bottom turbines:
  - **Monopiles** are typically prefabricated, lowered to the seabed in a single piece by a large crane, and then installed with a pile-driven hammer or vibratory method.[3]
  - **Jackets** and **tripods** have a similar installation process to monopiles, but they can be towed to the site and can also be anchored to the seabed using suction caissons in suitable seabed soils.[3]
    - **Jackets** can have multiple pins that need to be driven into seabed; the number of pins depends on jacket design.[3]
  - **Gravity bases** are prefabricated, towed to the site, and ballasted with sand, stones, concrete, or iron ore.[3]
    - **Gravity bases** require more seabed preparation, such as dredging, to make the seafloor flat and level.[3]
  - Scour protection, such as a rock blanket, may be installed around foundations to resist soil erosion.[3]
- Floating turbines:
  - **Floating wind turbines** have a different installation process with no need for specialty installation vessels.[3]
  - Turbine platforms are constructed in their entirety at the port, towed to the site, sunk to the appropriate flotation level, and connected to mooring lines.[3]

[3]Horwath, S., Hassrick, J., Grismala, R., and Diller, E. *Comparison of Environmental Effects from Different Offshore Wind Turbine Foundations*. Sterling, Virginia: U.S. Department of Interior Bureau of Ocean Energy Management. OCS Study BOEM 2020-041. https://www.boem.gov/sites/default/files/documents/environment/Wind-Turbine-Foundations-White%20Paper-Final-White-Paper.pdf.

What Is a Mooring System?

- Mooring lines tether a floating platform to anchors in the seabed.
- This mooring system keeps the floating wind turbine in position, resisting wind and current forces.
- If the floating turbine moved too far, the power cables could be damaged.
- Mooring design determines how deep of a water depth floating wind turbines can be installed in.

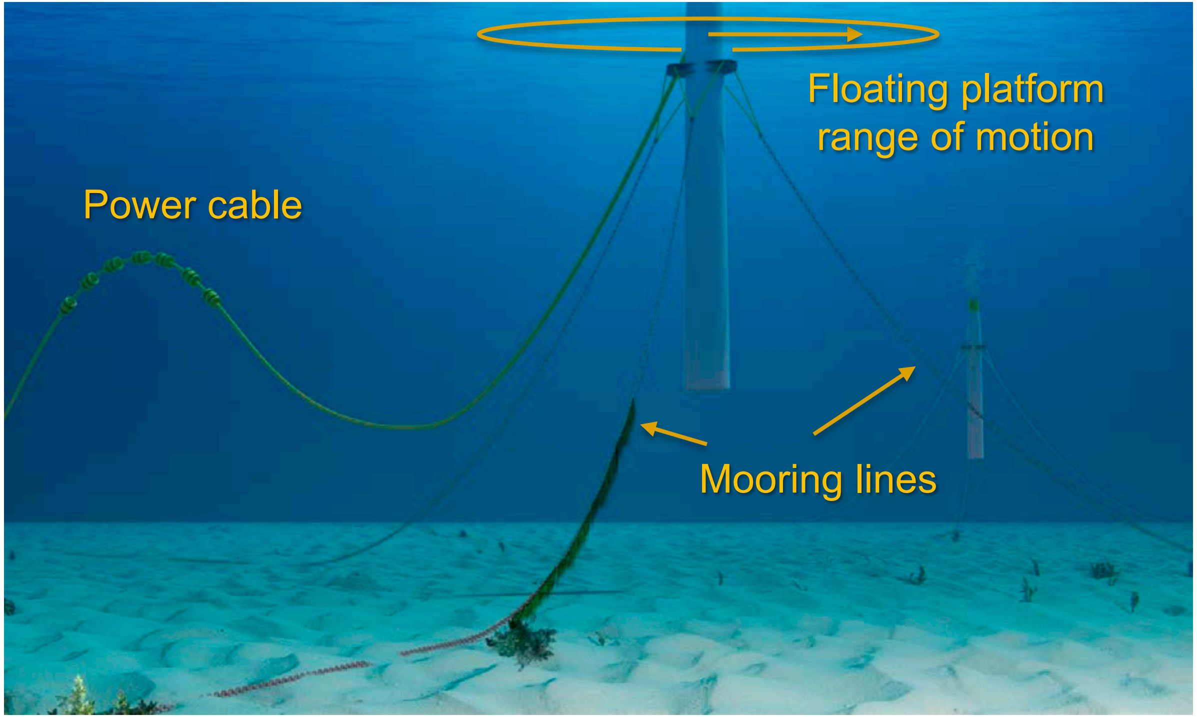


Illustration by Joshua Bauer, NREL

Mooring Line Types and Considerations

- Mooring lines come in a variety of configurations, with different material types, footprint sizes, and anchoring needs.
  - Catenary and semi-taut mooring systems are larger and have heavy chain along the seabed.
  - Taut mooring systems use synthetic ropes and are more compact.
  - Mooring systems for tension leg platforms can use synthetic rope, wire rope, or steel pipe.
- Catenary and semi-taut mooring systems are simplest but face challenges in deep water from weight, cost, and overlapping lines.

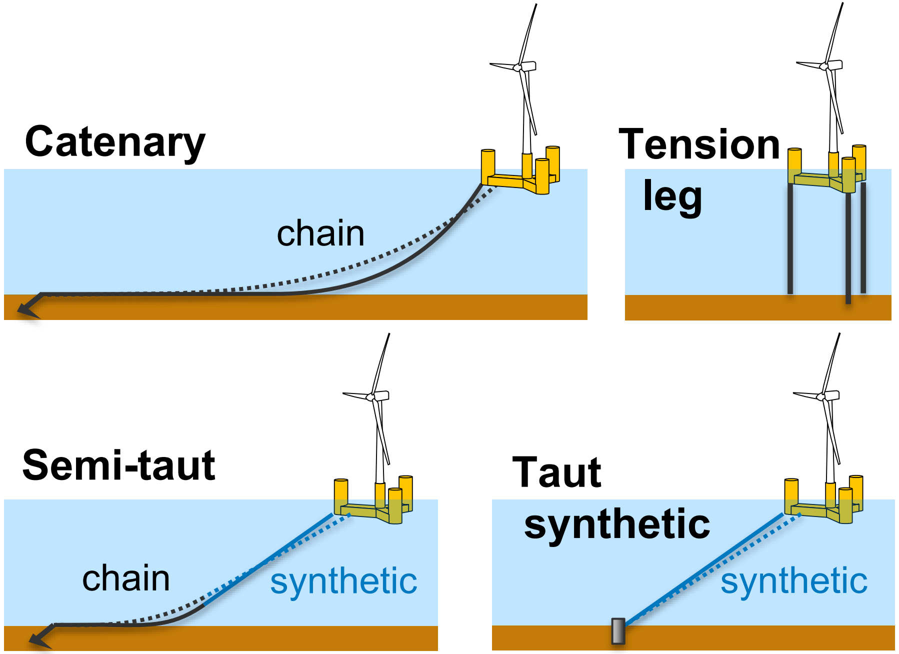


Illustration by Matthew Hall, NREL

Anchor Types

- The appropriate anchor type depends on the mooring configuration and the seabed soil type.

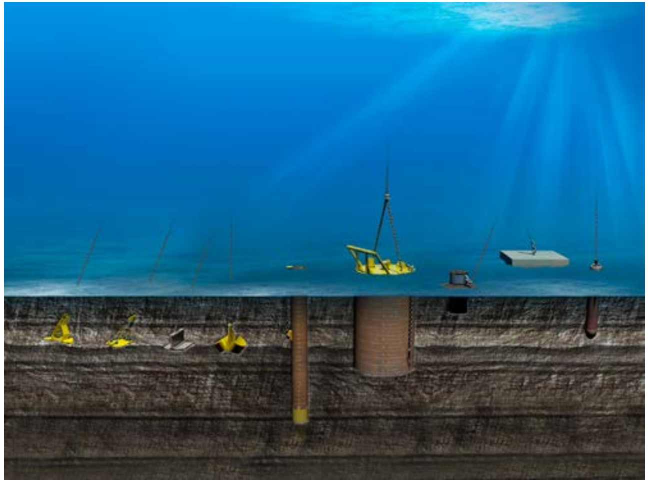


Illustration by Joshua Bauer, NREL

Illustration by Joshua Bauer, NREL

Cabling Technologies

- Electricity produced by offshore wind turbines is delivered to land-based grids through a series of cables which are typically buried in the seafloor.
- **Array cables** link turbines together and deliver electricity to offshore substations.
- **Export cables** transmit electricity from offshore substations to land-based substations.

Photo from Siemens AG, 27869

Cabling Characteristics

- HVAC array cables[4]
  - Outer diameter range: 4.25–6.3 inches
  - Voltage rating: <66 kilovolts (kV)
- HVAC export cables[4]
  - Outer diameter range: 10–13 inches
  - Voltage rating: 132–345 kV
  - Practical maximum length: ~60–70 miles
  - Max power per cable: ~400 MW
- HVDC export cables[4]
  - Outer diameter range: 6 inches
  - Voltage rating: <600 kV
  - Practical maximum length: theoretically unlimited
  - Max power per cable: currently 2200 MW
- Existing offshore wind farms have tended to use AC power for export cables, but DC export cables may become more economical as projects move farther from shore due to their lower cable cost and lower power losses.[5]

Photo from Siemens AG, 27852

[4]Dresser, B. *Offshore Wind Submarine Cabling Overview*. Albany, New York: New York State Energy Research and Development Authority. NYSERDA Report 21-14. https://www.nyserda.ny.gov/-/media/Files/Programs/offshore-wind/21-14-Offshore-Wind-Submarine-Cable-Report.pdf.

[5]Van Eeckhout, B., Van Hertem, D., Reza, M., Srivastava, K. and Belmans, R., 2010. Economic Comparison of VSC HVDC and HVAC as Transmission System for a 300 MW Offshore Wind Farm. *European Transactions on Electrical Power* 20(5), pp.661-671. https://doi.org/10.1002/etep.359.

Typical Array Cable Layout

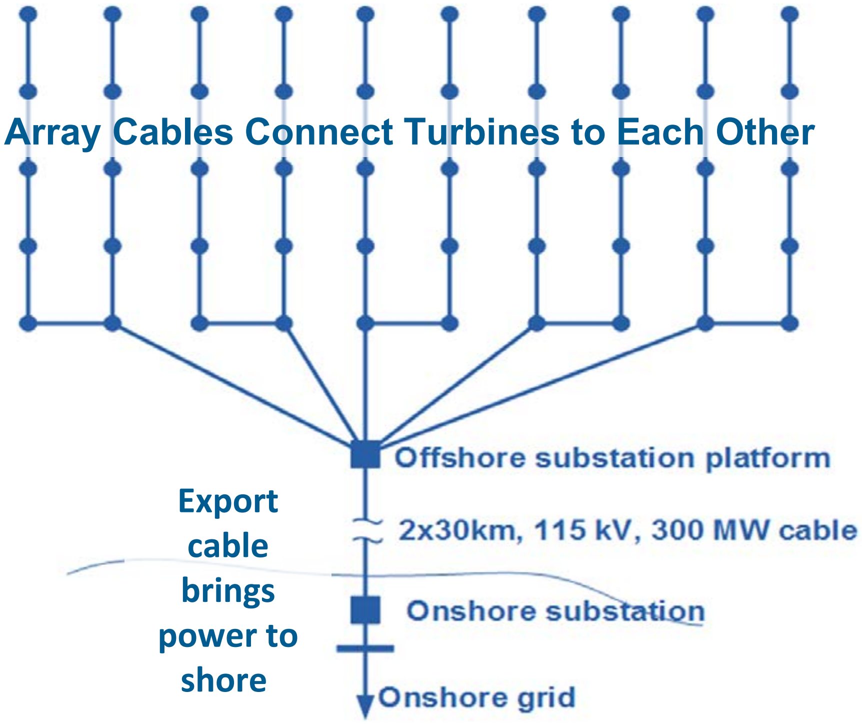


Figure by NREL

- The electrical array cable cost increases with turbine spacing but decreases with wind turbine size.
- The exact turbine spacing is a trade-off between wake losses and array cable costs.
- Other factors, such as navigational safety, array cable voltage (33–66 kV) may play a role in spacing.

Protecting Cables and the Surrounding Environment

- Careful route planning occurs early on in offshore wind energy development processes, with a priority of avoiding areas that are high risk and/or have high environmental sensitivity, such as:
    - Shipping lanes
    - Anchorages
    - Fishing grounds
    - Seabed assets (such as pipelines or other cables)
    - Fish-spawning areas.[4]
- Cable burial is the primary method of cable protection, and the recommended cable burial depth is driven by federal and state agencies and industry guidance:
    - Too shallow = at risk of damage
    - Too deep = expensive, environmental impact, ampacity issues.[4]
- Cable Burial Risk Assessment is used to reduce risk “As Low As is Reasonably Practical"[4]
- Externally applied protection is used where cable burial is not practical or possible, such as points where cables must cross other seabed assets.[4]

[4]Dresser, B. *Offshore Wind Submarine Cabling Overview*. Albany, New York: New York State Energy Research and Development Authority. NYSERDA Report 21-14. https://www.nyserda.ny.gov/-/media/Files/Programs/offshore-wind/21-14-Offshore-Wind-Submarine-Cable-Report.pdf.

Cabling Installation and Monitoring Logistics

- Cable installation options:
  - **Simultaneous Lay & Burial**: A cable lay vessel lays and buries the cable in a single operation; only one vessel is required, but operations are slower.[4]
  - **Post Lay Burial**: A cable lay vessel lays the cable on the seabed, and it is later buried; this requires two vessels but offers more timing flexibility.[4]
- Weather windows matter for operations.
- Cable monitoring occurs throughout the life of a wind farm.
  - Cable surveys are conducted periodically to ensure the cable isn't shifting too far up or down from its burial position.[4]
  - Cable sensing can be done with methods like distributed temperature sensing or distributed vibration sensing.[4]

Photo from Siemens AG, 27865

[4]Dresser, B. *Offshore Wind Submarine Cabling Overview*. Albany, New York: New York State Energy Research and Development Authority. NYSERDA Report 21-14. https://www.nyserda.ny.gov/-/media/Files/Programs/offshore-wind/21-14-Offshore-Wind-Submarine-Cable-Report.pdf.

Dynamic Array Collection Cables

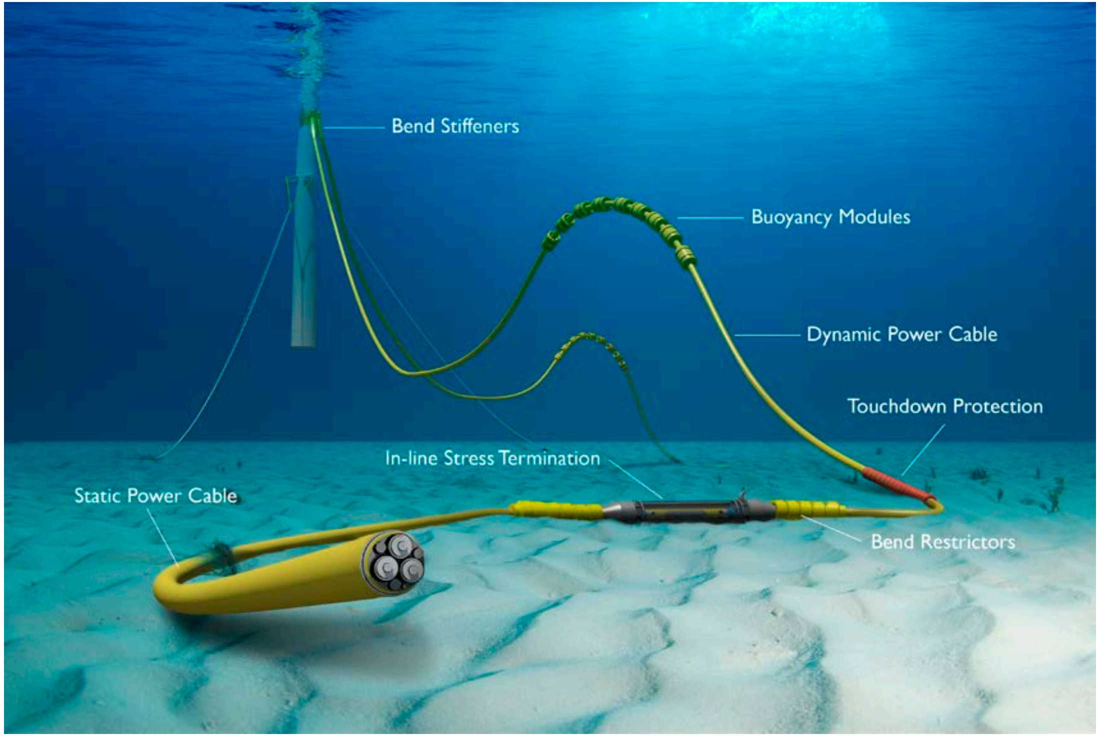


Illustration by Joshua Bauer, NREL 66313

- For floating wind turbines, dynamic array cables may be used because they allow for surge, sway, and heave displacements.
- Buoyancy modules can suspend cables in the water column for very deep sites.

Possible Mooring Lines and Cables Configuration

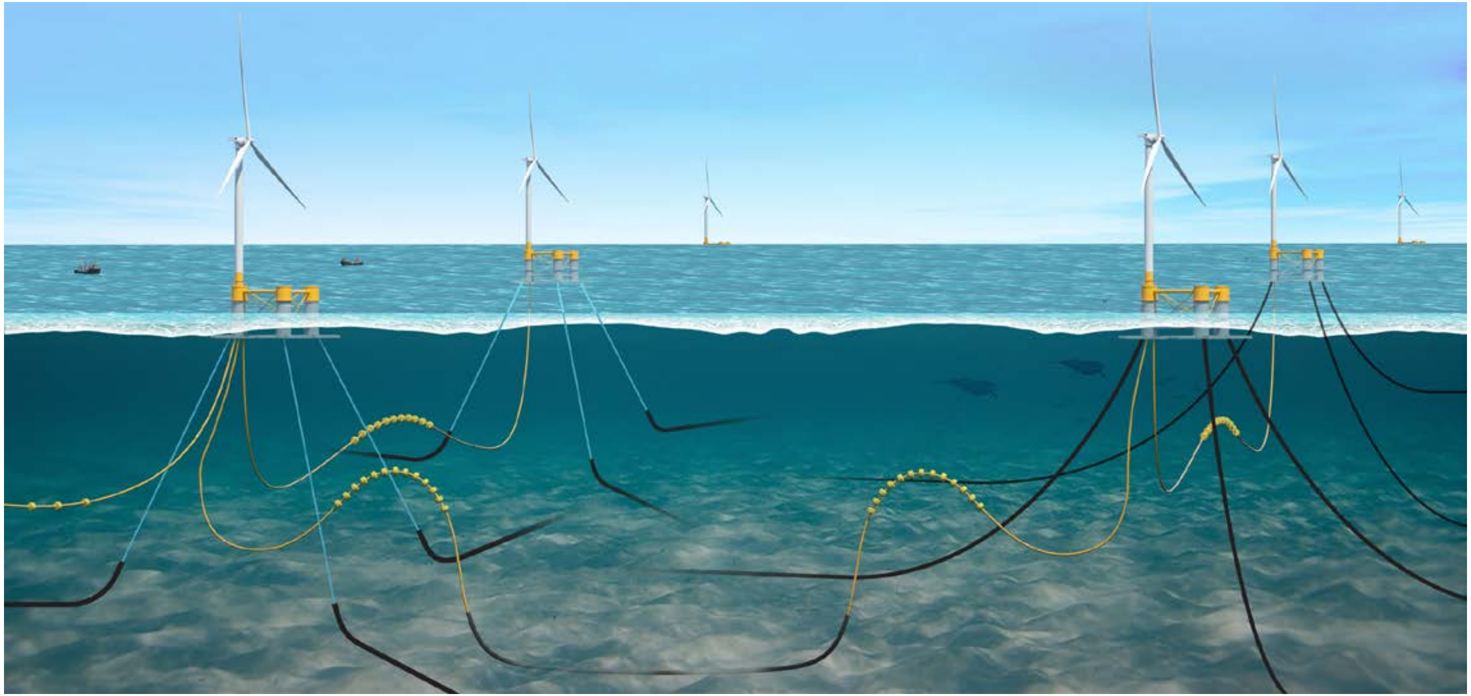


Illustration by Besiki Kazaishvili, NREL

This image depicts a possible configuration of mooring lines and dynamic array collection cables within an array of floating wind turbines, not to scale.

Decommissioning

- Very few offshore wind energy projects have been decommissioned to date, so impacts and considerations are still not fully understood.
- It can be **full decommissioning** (removing all project components) or **partial decommissioning** (leaving some components in place).
- The U.S. government requires all offshore wind energy components be removed down to 15 feet below the seabed unless authorization for partial decommissioning is acquired.[6]
- Removal of components can cause similar effects to those incurred during the construction phase, such as sediment disturbance.[6]
- The benthic community may establish a new steady state while the wind energy project is in operation, which decommissioning may disrupt.[6]
- The "rigs-to-reefs" approach keeps deeper parts of the structure as artificial reefs.[6]

Photo from Siemens AG, 27823

[6]Various authors. 2021. *Benthic Disturbance from Offshore Wind Foundations, Anchors, and Cables.* U.S. Offshore Wind Synthesis of Environmental Effects Research. https://tethys.pnnl.gov/sites/default/files/summaries/SEER-Educational-Research-Brief-Benthic-Disturbance.pdf

Key Takeaways

Photo from Siemens AG, 27824

- Offshore wind energy technology choices depend in part on seabed and oceanographic conditions in the chosen location, such as water depth and the qualities of the seafloor.
- Offshore wind turbines can be fixed bottom or floating, with many technology options within these broad categories.
- Mooring lines attach floating turbines to the seabed.
- Cables, which are typically buried in the seabed, transmit electricity within the array of turbines and to the grid on land.
- Both installation and decommissioning of offshore wind energy projects require consideration of the technical requirements and impacts occurring below the water.

Introducing New Webinar Series

Photo by Gary Norton, DOE, 41175

- An upcoming webinar series will focus on the community impacts, development processes, and economics of offshore wind energy.
- The three webinars will be:
  - Offshore Wind Development Process
  - Economics and Workforce
  - Community Engagement.

Q&A

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