Offshore Wind Energy: Technology Above the Water

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Webinar Logistics

- Webinar will be recorded and posted to NREL YouTube channel and WINDExchange.
- Q&A following the presentation.
- Put questions in the Q&A during and at the end of the presentation.

Photo by Gary Norton, DOE 41165

Speaker Bio

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Walt Musial is a Principal Engineer and leads the offshore wind research platform at the National Renewable Energy Laboratory (NREL) where he has worked for 33 years. In 2003 he initiated the offshore wind energy research program at NREL which focuses on a wide range of industry needs and critical technology challenges. He chairs the American Clean Power Association Offshore Wind Standards Subcommittee and is the Senior Technical Advisor to the National Offshore Wind R&D Consortium. Previously, Walt also developed and ran NREL's full scale blade and drivetrain testing facilities for 15 years. Earlier, Walt worked as a test engineer for five years in the commercial wind energy industry in California. He studied Mechanical Engineering at the University of Massachusetts - Amherst, where he earned his bachelor's and master's degrees, specializing in energy conversion with a focus on wind energy engineering.   He has over 120 publications and two patents.

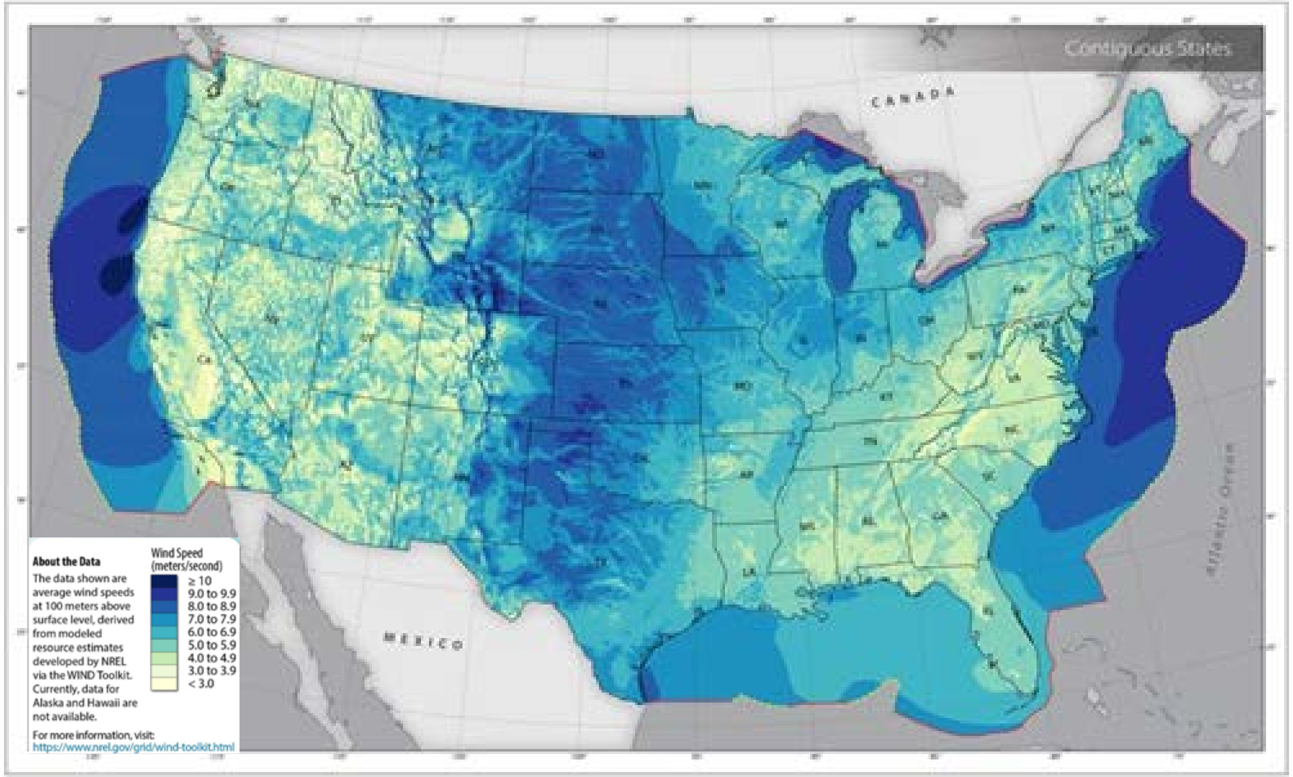
What Will We Cover?

- **Introduction to offshore wind energy**
- **Part 1: understanding the wind resource including:**
  - **Wind resource characteristics**
  - **Technology implications**
- **Part 2: turbine technology**

Photo by Dennis Schroeder, National Renewable Energy Laboratory (NREL) 40463

Introduction to Offshore Wind Energy

Why Pursue Offshore Wind Energy?



Graphic from National Renewable Energy Laboratory (NREL)

- ✔ Generation close to load (80% of the population lives near the coast)
- ✔ Stronger winds
- ✔ Larger-scale projects are possible
- ✔ Unique economic benefits
- ✔ Revitalizes ports and domestic manufacturing
- ✔ Less constrained by transport and construction

Offshore Wind – Global Industry Status

Photo from Siemens, 27892

- At the end of 2020, over 200 projects were installed with a capacity of more than 33,000 megawatts (MW).
- The average project size is getting larger, with some wind power plants exceeding 1,000 MW.
- Over 99% of offshore wind turbines are on fixed-bottom support structures in shallow water (less than 50 meters (m) depth).
- Average turbine rating is currently about 10 MW but will increase to 12 to 15 MW for projects after 2024.
- Rotors are oriented upwind with 170-m diameters, growing to 220 m to 240 m this decade.
- Tower heights increase with blade length (rule of thumb is tower height = blade length plus 30 m).
- Drivetrains are direct drive or geared with medium-speed generators.
- Overall costs are declining but maintenance costs will remain higher than land-based turbines because of difficult access.
- Offshore wind energy leverages existing mature marine industries.

Biden Administration Offshore Wind Goals

In March 2021, the Biden administration announced the following series of coordinated steps to support increased offshore wind energy deployment:

- Set national target to reach 30 gigawatts by 2030
- Advance U.S. wind energy projects to create well-paying, unionized jobs
- Invest in American infrastructure to strengthen the domestic supply chain
- Support critical research and development and data sharing.

Source: The White House Offshore Wind Announcement

Photo from Siemens, 27852

Above the Water: Understanding Wind Resource Characteristics and Technology Implications

Summary: Understanding Wind Characteristics

- Wind Resource Assessment
  - Computer modeling technology
  - Measuring wind using floating lidar or meteorological towers
- Wind Characteristics
  - Annual average wind speed
  - Wind speed probability
  - Wind direction (wind rose)
  - Diurnal (daily) and seasonal variations
  - Wind shear
- Wind Resource Data Access
  - Wind resource mapping
  - How to find and use data

Photo by Gary Norton, DOE 41170

Estimating the Wind Resource Potential

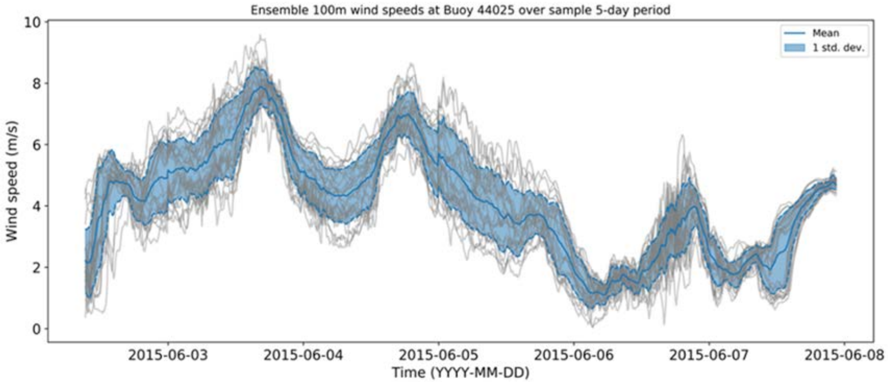
Computer Models

- The mesoscale Weather Research and Forecasting model (WRF) is used to estimate wind speed over various geographic areas and time intervals.
- Models calculate data every 5 minutes and every location on 2-kilometer-by-2-kilometer squares.

NREL is developing The Wind Toolkit Long-term Ensemble Dataset for wind characterization at all time scales.

Measurements

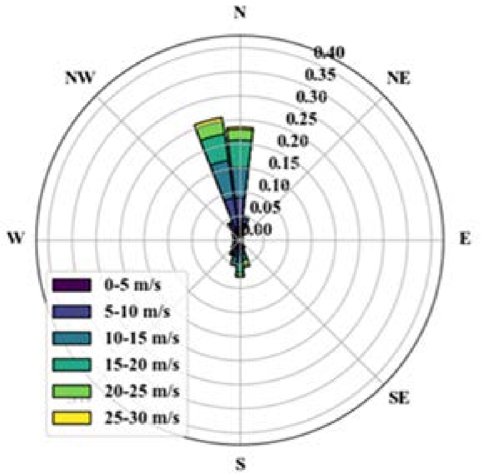
- Measurements are used to validate and improve the accuracy of the models.
- Measurements at sea can be very difficult and expensive.
- Validation is needed to reduce model uncertainty.

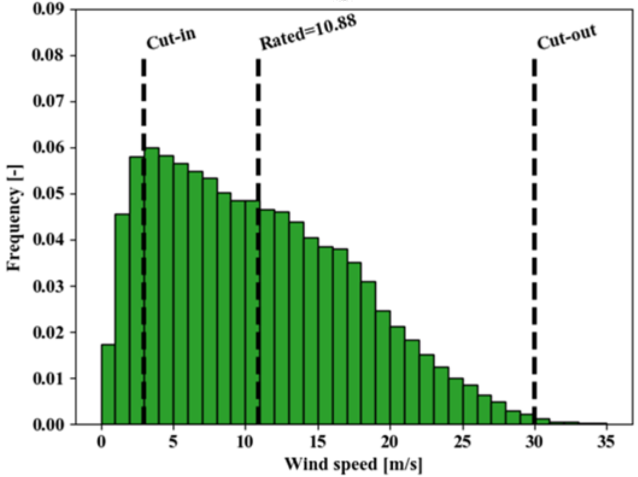


NREL/Rutgers collaboration: multiple ensembles of WRF generated wind speed data at 100 m, plotted over a 6-day period at National Data Buoy Center Buoy 44025 off the coast of New Jersey (m/s = meters per second).

Offshore wind measurements come from ocean buoys, floating lidar* (left) or meteorological towers (right). *Photo courtesy of AXYS Technologies, 35605*

Wind Resource Statistics





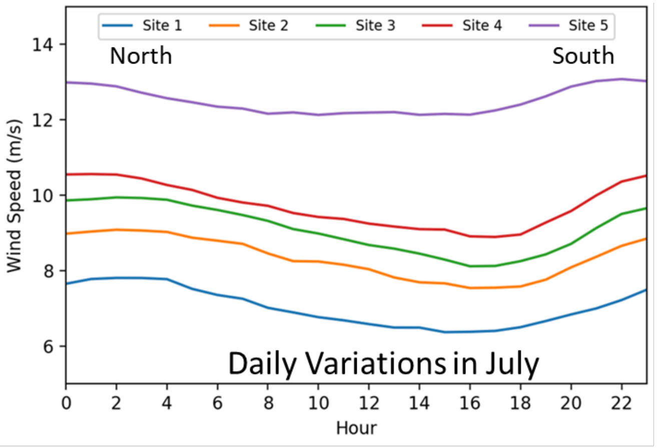
Wind Rose (top) and probability distribution for the Humboldt Call Area in California (bottom)

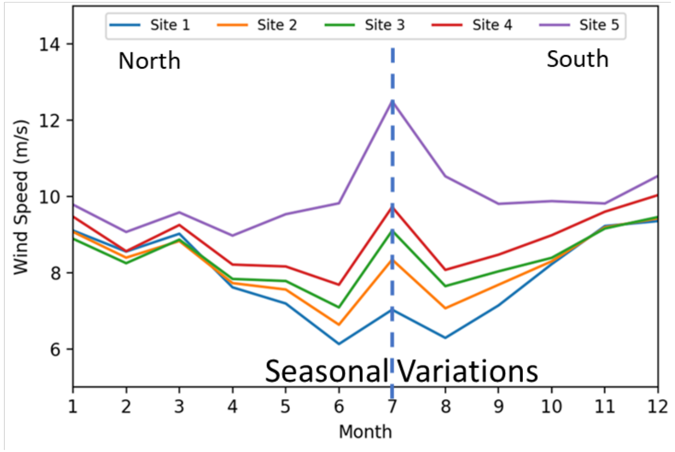
At a given site:

- Wind speed varies by the hour of the day, seasonally, and annually.
- Annual wind speeds are represented by probability distributions (bottom left).
- Wind direction variations are represented by a wind rose (upper left).
- Other important variables include turbulence intensity, atmospheric stability, and wind shear.
- All these characteristics affect energy production—**but wind speed is the most important.**

Beiter, Philipp, Walt Musial, Patrick Duffy, Aubryn Cooperman, Matt Shields, Donna Heimiller, and Mike Optis. 2020b. *The Cost of Floating Offshore Wind Energy in California Between 2019 and 2032*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-77384. https://www.nrel.gov/docs/fy21osti/77384.pdf.

Diurnal and Seasonal Variations



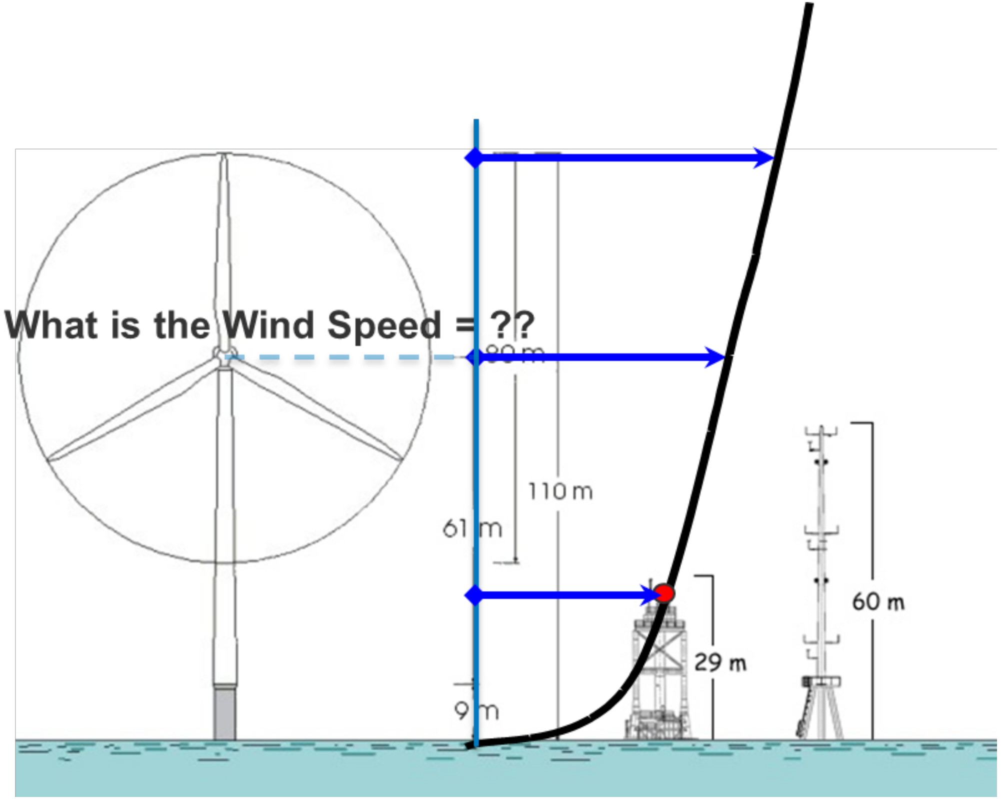


Five sites along the coast of Oregon were analyzed for diurnal and seasonal variations

- Wind speed varies over the course of a day (see average diurnal variations for July in upper left).
- It is important to understand how wind varies during the day so its energy potential can be matched with the electricity use.
- Seasonal variations also needed to be matched with electricity use (e.g., air conditioners, electric heating; see monthly variations in lower left).
- Use patterns will change drastically with grid expansion and electrification (e.g., electric vehicle charging, electrification, energy storage).
- Variations are site-specific.

Musial, Walter D, Beiter, Philipp C, Nunemaker, Jacob, Heimiller, Donna M, Ahmann, Josh, and Busch, Jason. 2019. *Oregon Offshore Wind Site Feasibility and Cost Study*. Golden, CO: National Renewable Energy Laboratory (NREL). NREL/TP-5000-74597. https://www.nrel.gov/docs/fy20osti/74597.pdf.

Wind Speed Increases With Elevation

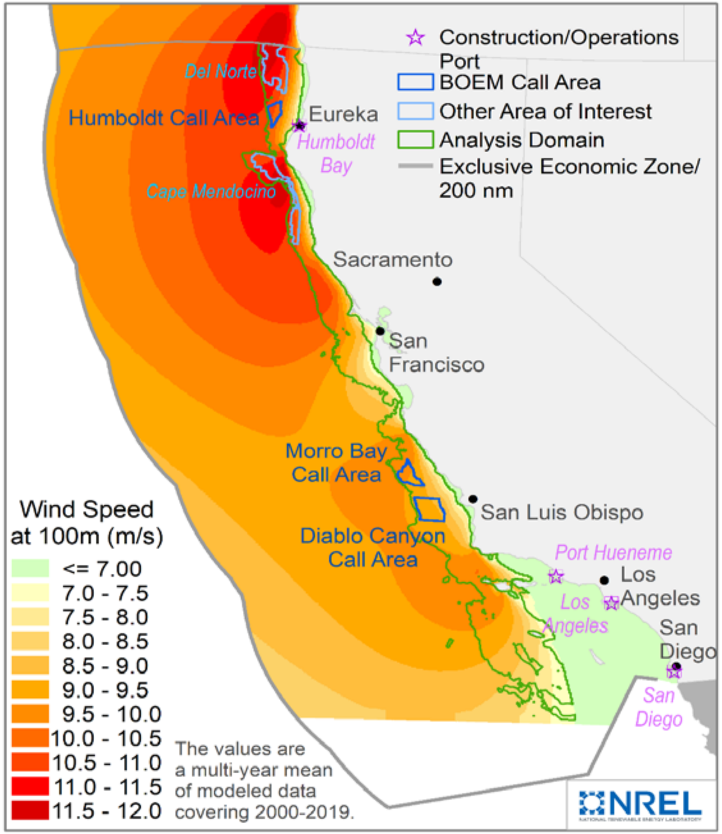


Graphic by Walt Musial, NREL

- Wind speed increases with height (wind shear).
- It is important to know the wind speed at hub height.
- As wind turbines get larger, tower height increases.
- Taller wind turbines generate more electricity.

Wind speed measurements must be made at hub height for accurate energy prediction.

Wind Resource Mapping and Data



Example: 100-m mean wind speed map for California

- Offshore wind speeds for a region are best described by "heat maps" that show the variations in average wind speed geographically.
- The map shown (left) describes the wind resource (CA20) at an elevation of 100 m.
- For offshore wind resource assessments, sites with average wind speeds greater than 7 meters per second (m/s) are considered potentially viable.
- Note the Humboldt Call Area shown earlier is a relatively high-wind site.
- Current wind resource data can be found on Github and Wind Prospector.

Optis, Michael, Rybchuk, Oleksa, Bodini, Nicola, Rossol, Michael, and Musial, Walter. 2020. *2020 Offshore Wind Resource Assessment for the California Pacific Outer Continental Shelf*. Golden, CO: National Renewable Energy Laboratory (NREL), NREL/TP-5000-77642. https://www.nrel.gov/docs/fy21osti/77642.pdf.

Extreme Weather Considerations: Performance and Technology Implications

- Weather extremes can affect both the reliability of wind turbines and their energy production.
- Offshore wind farms must be designed to withstand extreme weather including:
  - Hurricanes
  - Extreme wind/wave events
  - Icy conditions
  - Extra tropical storms
  - Extreme heat or cold
- Climate change may affect the frequency and severity of these weather events and must be accounted for in planning, siting, and operations.

Hurricane Maria Heads for Puerto Rico

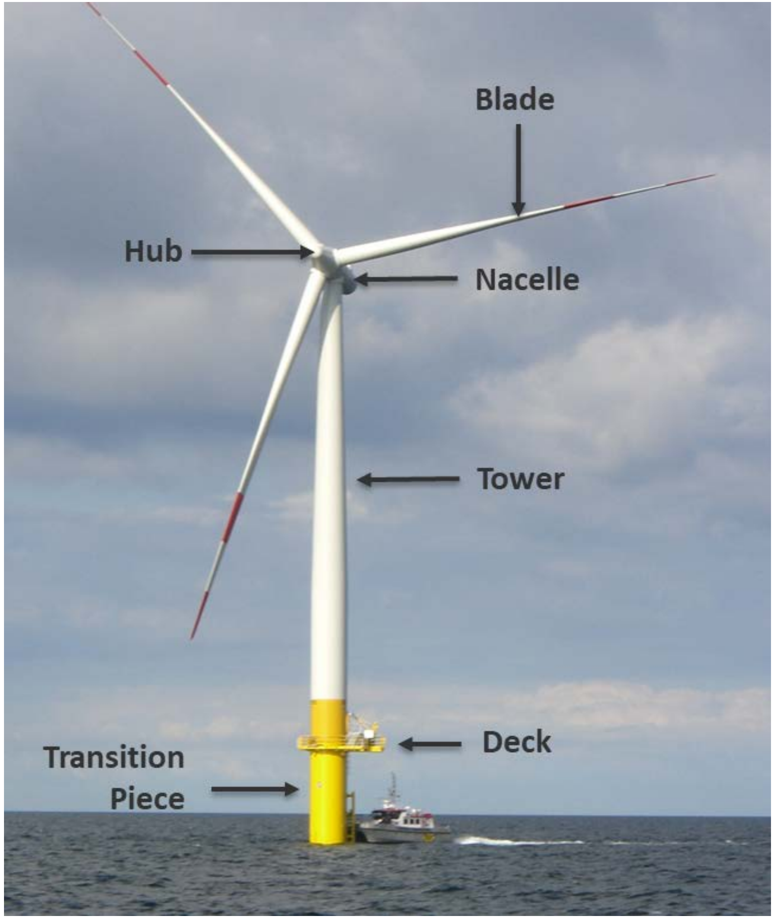
Image courtesy of National Aeronautics and Space Administration/National Oceanic and Atmospheric Administration GOES Project

Above the Water: Wind Turbine Technology

Above-the-Water Parts of an Offshore Wind Turbine

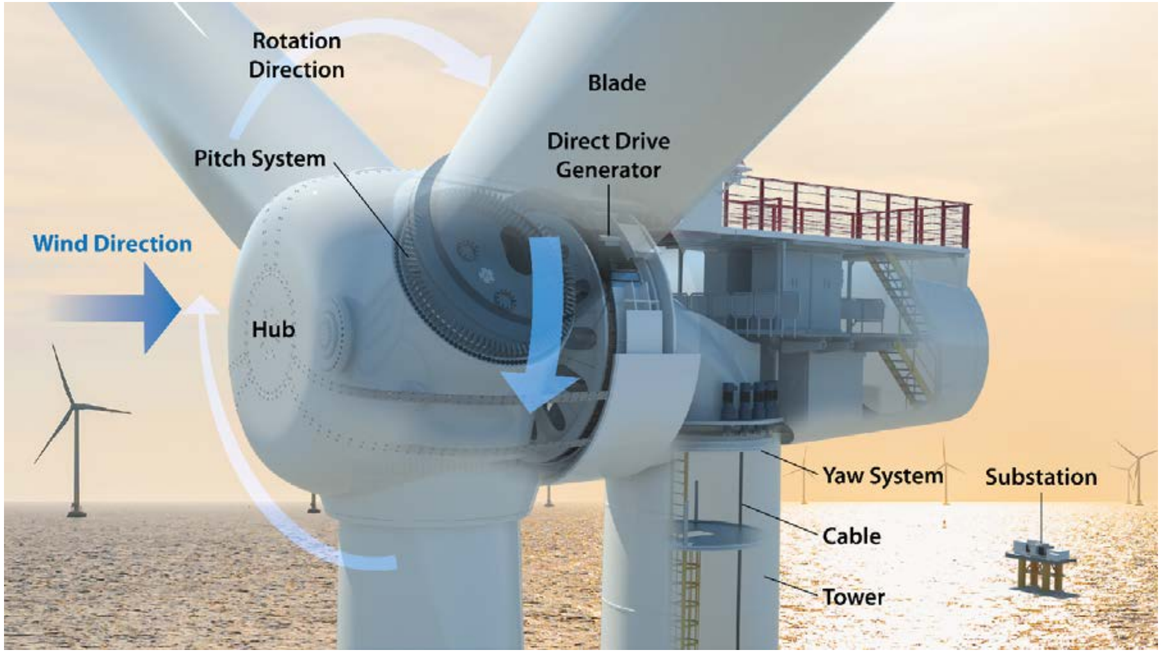
Typically, offshore wind turbines differ from land-based wind turbines in several ways. For example, they:

- Are bigger – In 2020, the average capacity of land-based turbines was 2.75 MW, and the average capacity for offshore turbines was 7.5 MW
- Have more complex support structures
- Are designed to withstand the marine environment



The Siemens 2.3-MW offshore wind turbine in the Baltic Sea, Germany. *Photo by Walt Musial (NREL)*

Offshore Wind Power Plant Basics



Graphic by Joshua Bauer, NREL

- The rotor (hub + blades) converts kinetic energy of the wind to create torque (rotational force) that spins a generator that produces electricity.
- Multiple turbines are connected to a substation that connects a high-voltage cable to the land-based grid.
- Offshore wind plants are growing beyond 1,000 MW in size.
- Peak energy output is comparable to large coal, natural gas, or nuclear power plants.
- One 12-MW offshore wind turbine can power 4,500 U.S. residences.

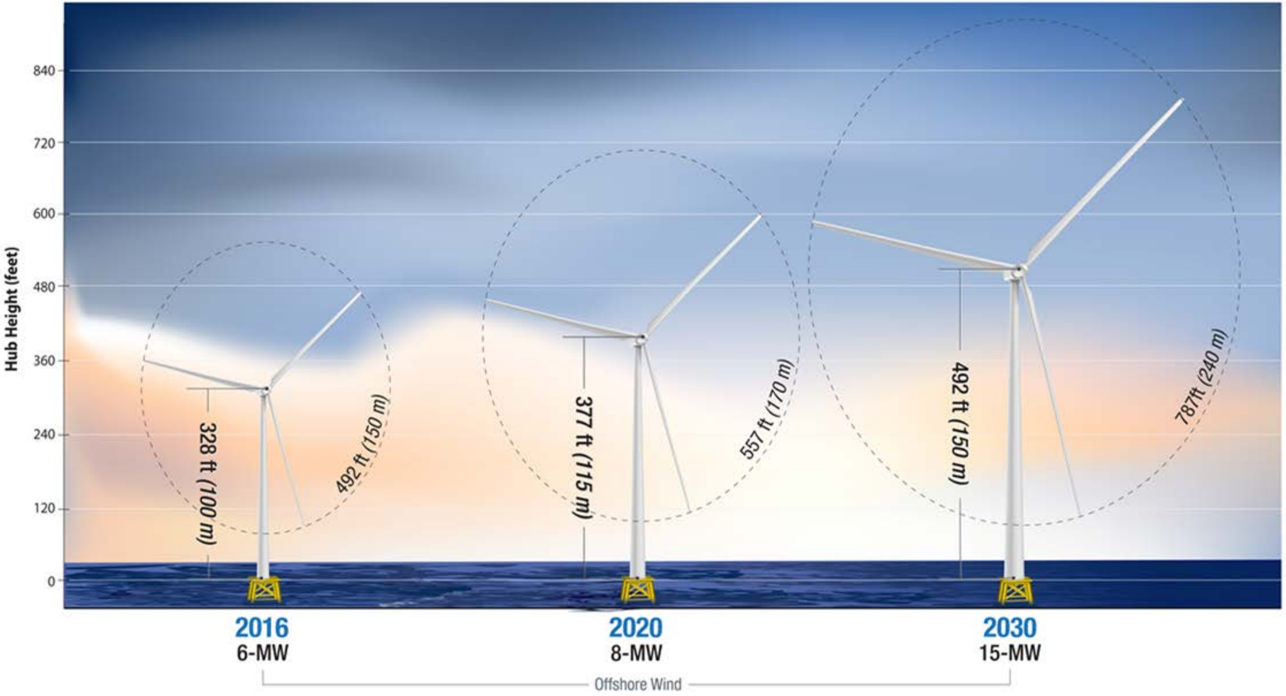
Adapting Offshore Wind Plants for a Marine Environment

Photo by Siemens, NREL 277866

- Corrosion-resistant coatings, developed by offshore oil and gas
- Pressurized nacelles keep the salt air out
- Designed for safety, accessibility, and crew transfer
- Direct-drive and medium-speed generators to lower number of moving parts
- Specialized workforce training to operate and maintain the technology.

Offshore Wind Turbines Are Getting Bigger

- Larger turbines (12 MW to 15 MW) can reduce offshore wind cost by:
  - Requiring fewer installations
  - Reducing the number of turbines to maintain
  - Providing more energy (turbines can access higher winds).
- There are no physical barriers to increasing turbine size.
- Ports and infrastructure must also accommodate new 12- to 15-MW turbines.



Graphic by Joshua Bauer, NREL

By 2024, all major wind turbine manufacturers plan to be producing turbines in the 12-MW to 15-MW range.

The Wind Turbine Tower

- The wind turbine's tower connects the nacelle to the substructure.
- Offshore wind energy uses a "tube tower"; a tapered steel tube that is 100 m or more in length.
- Tube towers are used exclusively because they:
  - —Protect workers and components from the elements
  - —Reduce impact on avian species
  - —Are easy to maintain.
- Tower cross sections have diameters of 5 m or more.
- The inside of a wind turbine tower includes an elevator, ladders, and platforms as well as routing for the power cables.

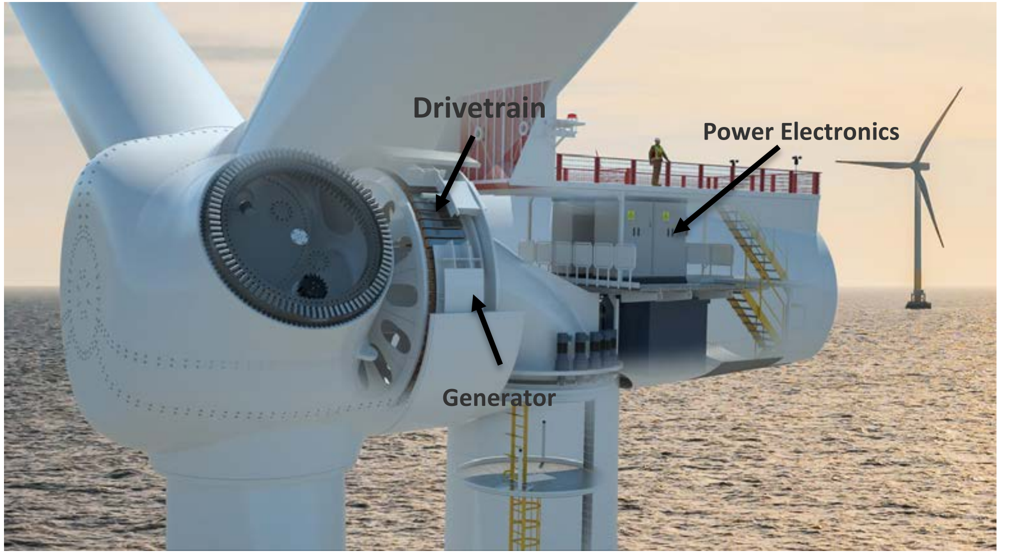
Photo by Walt Musial, NREL 26993

Photos (bottom left and bottom right) by Mary Hallisey, NREL

The Nacelle

The nacelle comprises everything above the yaw bearing except the rotor.

- **Drivetrain.** The drivetrain is the mechanical pathway that converts rotor torque into electricity. It includes the main bearing, main shaft, gearbox (if used), and generator.
- **Gearbox.** The gearbox increases the low-speed shaft rotational speed to spin the generator. Direct-drive offshore wind turbines do not have gearboxes.
- **Generator.** The generator converts mechanical energy into electricity. Some generators are driven by gearboxes and others are attached directly to the generator (direct-drive).
- **Power Electronics.** The power electronics conditioned the power produced by the generator to be sent to the grid.



Graphic by Joshua Bauer, NREL

*Definitions adapted from DOE How a Wind Turbine Works - Text Version

The Yaw Drive System

- **Yaw Drive System.** The yaw drive rotates the nacelle to keep a turbine facing into the wind when the wind direction changes.

- **Yaw Bearing.** The yaw bearing sits on top of the tower to allow for rotation.

Graphic by Joshua Bauer, NREL

Outside the Nacelle

The exterior of the nacelle comprises the following:

- Helideck
  - Service platform for helicopters
- Sensors
  - Anemometers and wind direction control sensors
  - Temperature sensors
  - Accelerometers
  - Displacement sensors
- Aviation warning lights
- Composite nacelle enclosure.

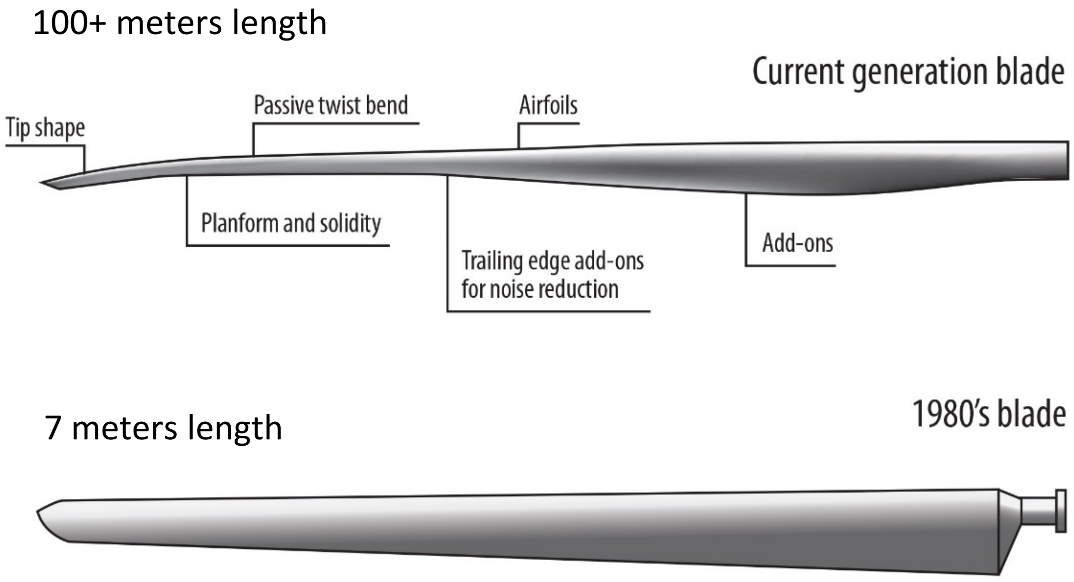
Graphic by Joshua Bauer, NREL

Rotor

Photo by Mary Hallisey, NREL

- The rotor is the assembly comprising three blades and the hub.
- The rotor assembly is attached to the main shaft and drivetrain.
- The blades are mounted to the hub on turntable bearings that allow for 90 degrees of rotation.
- Each blade has an independent pitch control system that pitches the blades to regulate power and to stop the machine.

Wind Turbine Blades



Graphic from NREL; based on a graphic from Kenneth Thomsen, formerly Siemens Gamesa Renewable Energy

Photo from Walt Musial, NREL

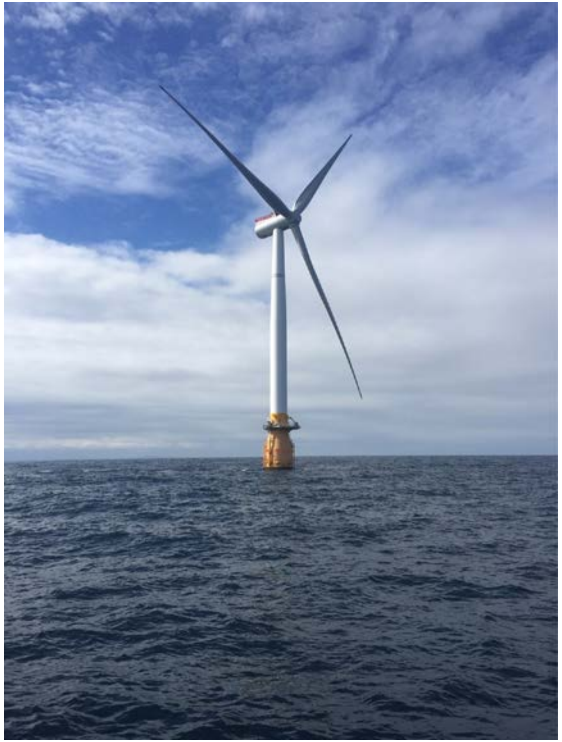
Offshore Wind Substation

- Offshore substations or electric service platforms collect AC power from all turbines across a wind power plant at 66 kilovolts (kV).
- High-voltage transformers step up the voltage to 220 kV and export it to shore through buried subsea cables.
- Substations are attached to the seabed with substructures (e.g., monopiles or multileg jackets similar to oil rigs).
- Some offshore substations may have temporary quarters for on-site personnel.

Photo from Siemens, 27865

Surface View of Floating and Fixed-Bottom Wind Turbines

Principle Power 2.0-MW floating wind turbine in Portugal; 2011
WindFloat semisubmersible substructure.
Photo by Walt Musial, NREL



Equinor 6-MW Siemens floating wind turbine in Scotland; 2017
Hywind-2 spar substructure.
Photo by Walt Musial, NREL

Baltic-1 2.3-MW Siemens fixed-bottom wind turbine in Germany; 2010
monopile substructure.
Photo by Walt Musial

Floating and fixed-bottom offshore wind power plants use the same turbines, and above the water there can be little visual difference

Key Takeaways

- The global offshore wind energy industry is growing rapidly. The United States set a new target for offshore wind to achieve 30 gigawatts by 2030.
- Wind resource is determined by many factors including wind speed, direction, time of day, and season. Wind measurements are key to accurate wind models.
- Offshore wind turbines require adaptation to endure marine environments.
- Offshore wind turbines are getting increasingly larger because bigger turbines are more economical.
- Wind energy technology above the water is similar in both fixed-bottom and floating turbines.

Q&A

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Photo by Dennis Schroeder, NREL 40389

Thank You

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