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Overview of Floating Offshore Wind

Walt Musial | Offshore Wind Lead | National Renewable Energy Laboratory

Foundations for Ireland-UK Floating Wind | March 12, 2021

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 32 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 ACPA 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’s Covered?

- Wind Basics
- Offshore Wind Status
- Floating Offshore Wind Technology and Status
- Floating Offshore Wind – Where and Why
- Floating Offshore Wind Economics

Why Pursue Offshore Wind Energy?

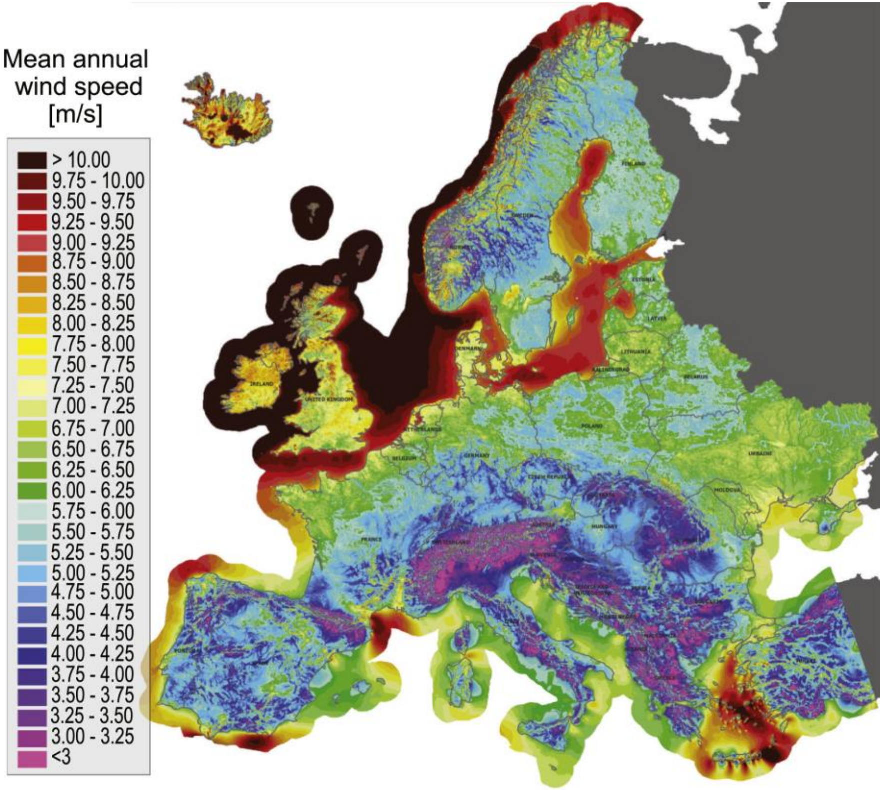


Figure Source: Rodrigues, et al. Trends of Offshore Wind Projects.
https://doi.org/10.1016/j.rser.2015.04.092

- ✓Generation close to load (most 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

How does a wind turbine work?

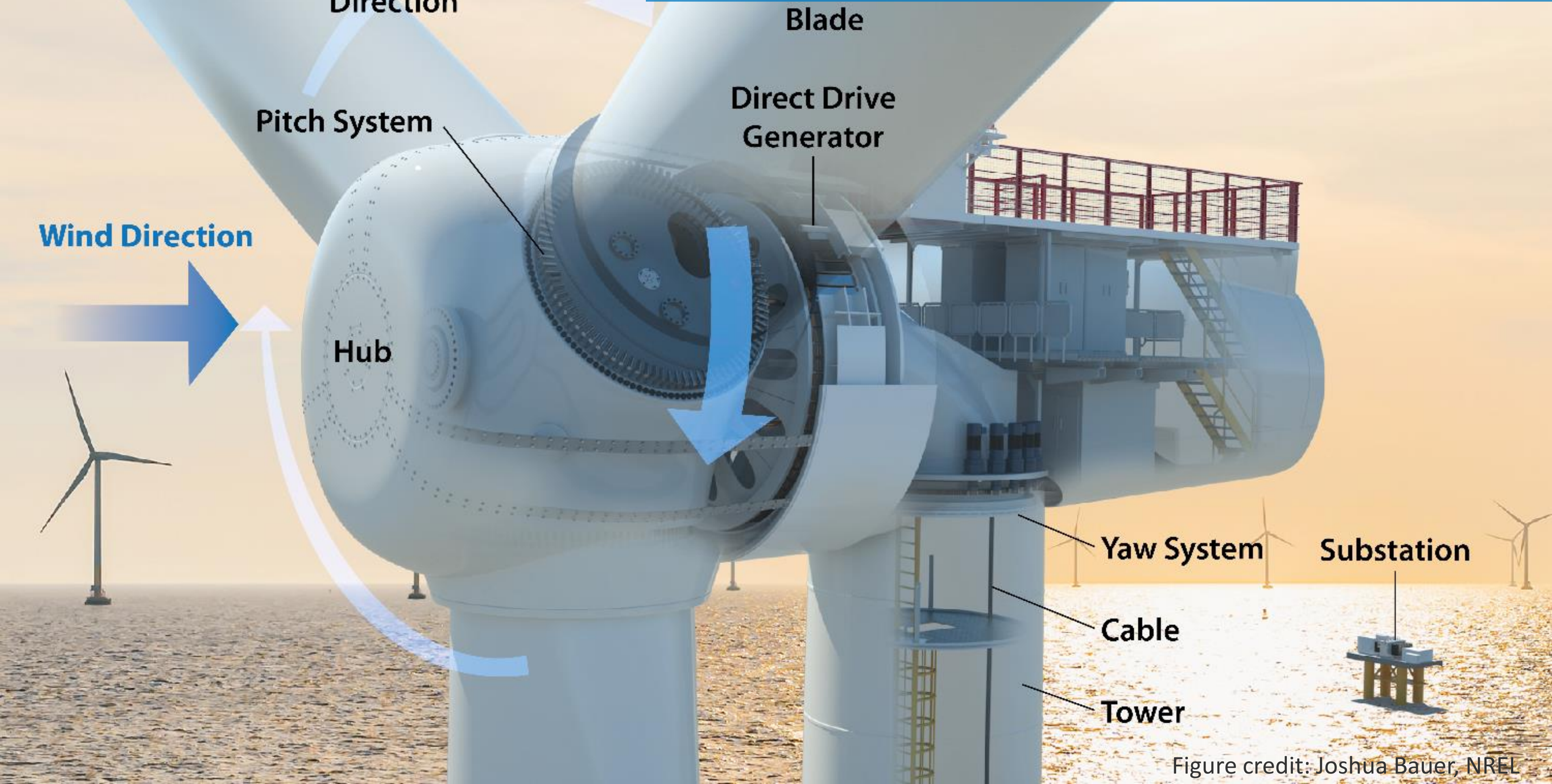


Figure credit: Joshua Bauer, NREL

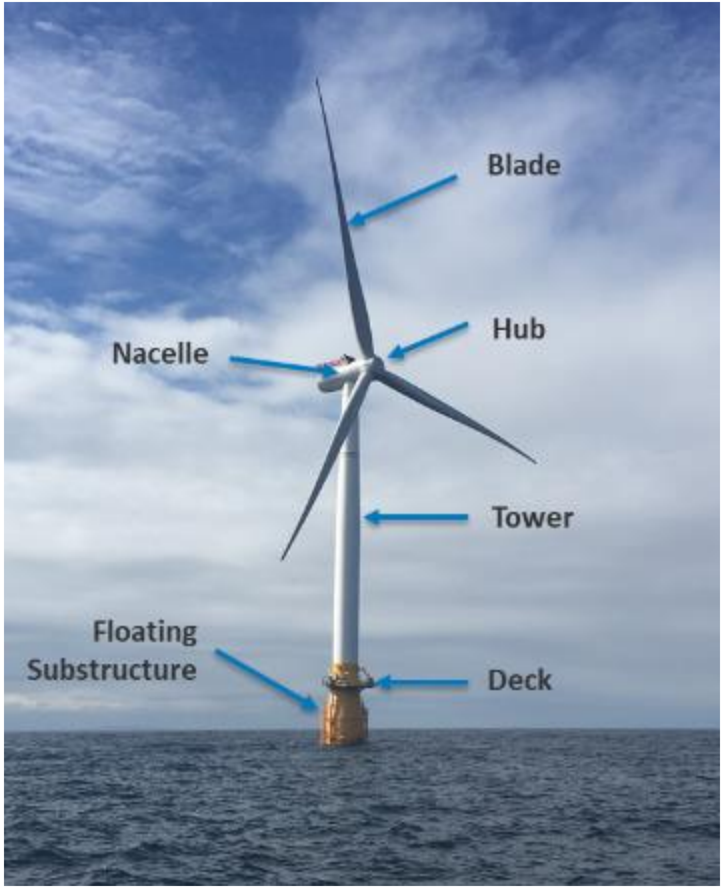
Above-the-water Parts of a Floating Offshore Wind Turbine

Fixed-bottom Offshore wind turbines are the same as *land-based wind turbines* except offshore wind turbines:

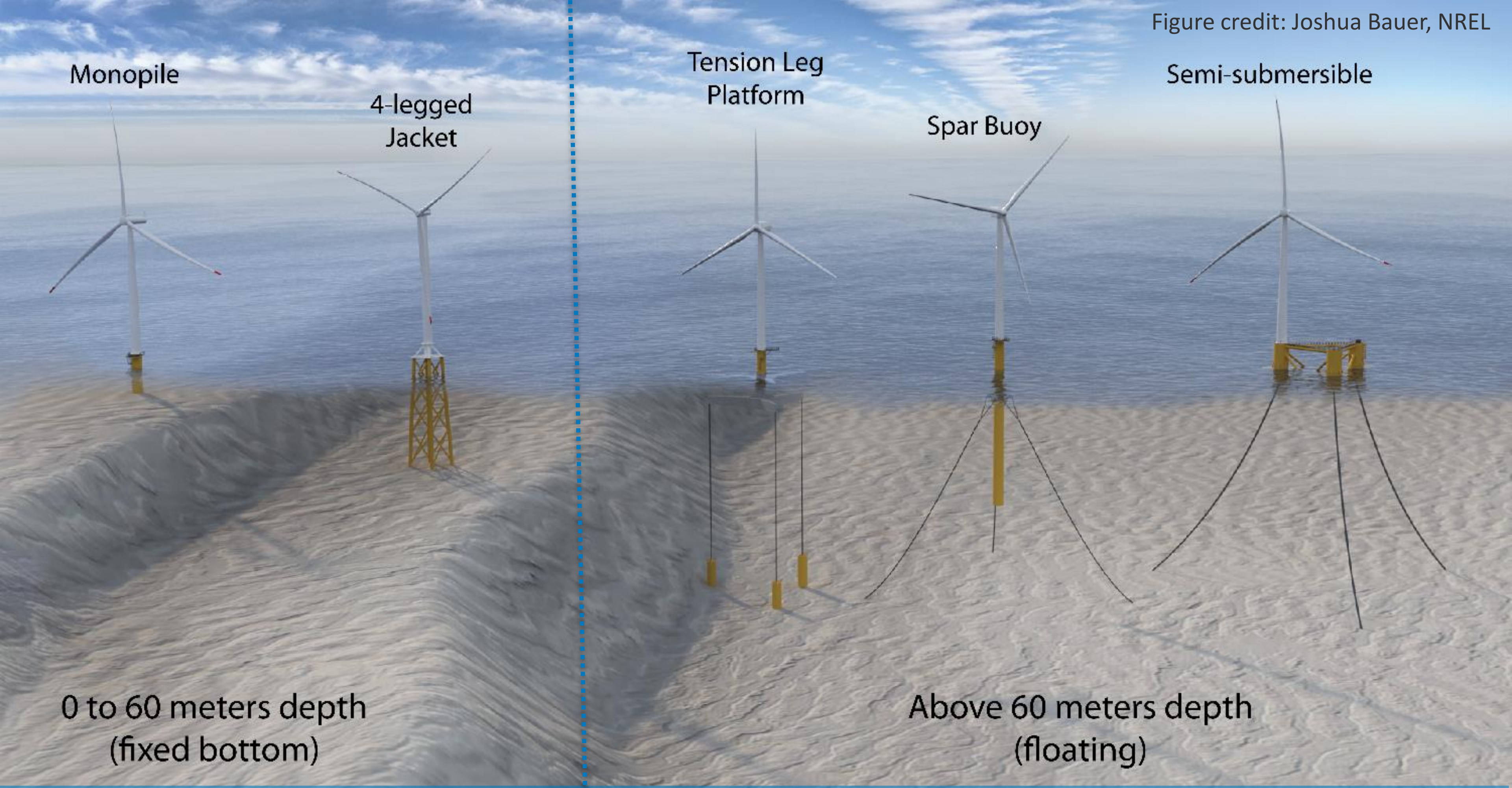
- Are bigger
- Have more complex support structures
- Are designed to withstand the marine environment

Floating wind turbines look very similar to *fixed-bottom offshore wind turbines* from the surface but are supported by buoyant substructures* moored to the seabed.

*The floating wind turbine *support structure* is comprised of the tower, substructure, mooring lines, and anchors



Siemens 6.0 MW Floating Offshore Wind Turbine on a Spar Buoy substructure
Photo credit: Walt Musial (NREL)



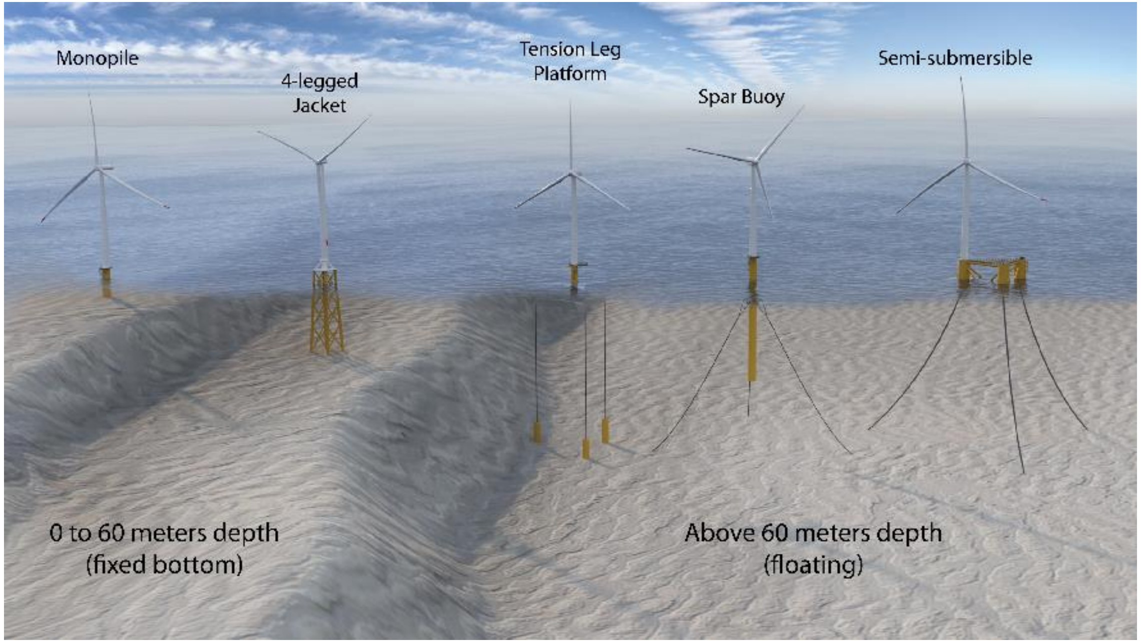
Offshore Turbine Substructure Type Depends on Water Depth

Most Offshore Wind Deployment Has Been on Fixed-bottom Support Structures

Leading Offshore Wind Countries
(Installed Capacity)

United Kingdom	8508 MW
Germany	7441 MW
China	6007 MW
Denmark	1925 MW
Belgium	1556 MW
Netherlands	1136 MW
Sweden	196 MW

Current as of Dec 31, 2019



Fixed Bottom

27,208 MW Installed

Floating

82 MW Installed

However, the future Floating Wind Energy market may be bigger than the fixed-bottom market

Floating Offshore Wind is Being Considered Where Waters Are Too Deep for Current Fixed-Bottom Technology

- 80% of offshore wind resources are in waters greater than 60 meters
- Floating wind enables sites farther from shore, out of sight, with better winds!
- Floating wind technology is expected to be at deployed at utility scale by 2024.

Some Areas of the World Being Considered for Floating Wind

Portions of this slide were adapted courtesy of Aker Solutions

Sources: EIC Global Offshore Wind report 2019; Norwep, Equinor, internal analysis

Where in the U.S. is Floating Offshore Wind Being Considered?

58% of the U.S. offshore wind resource is in water depths > 60m - floating foundations

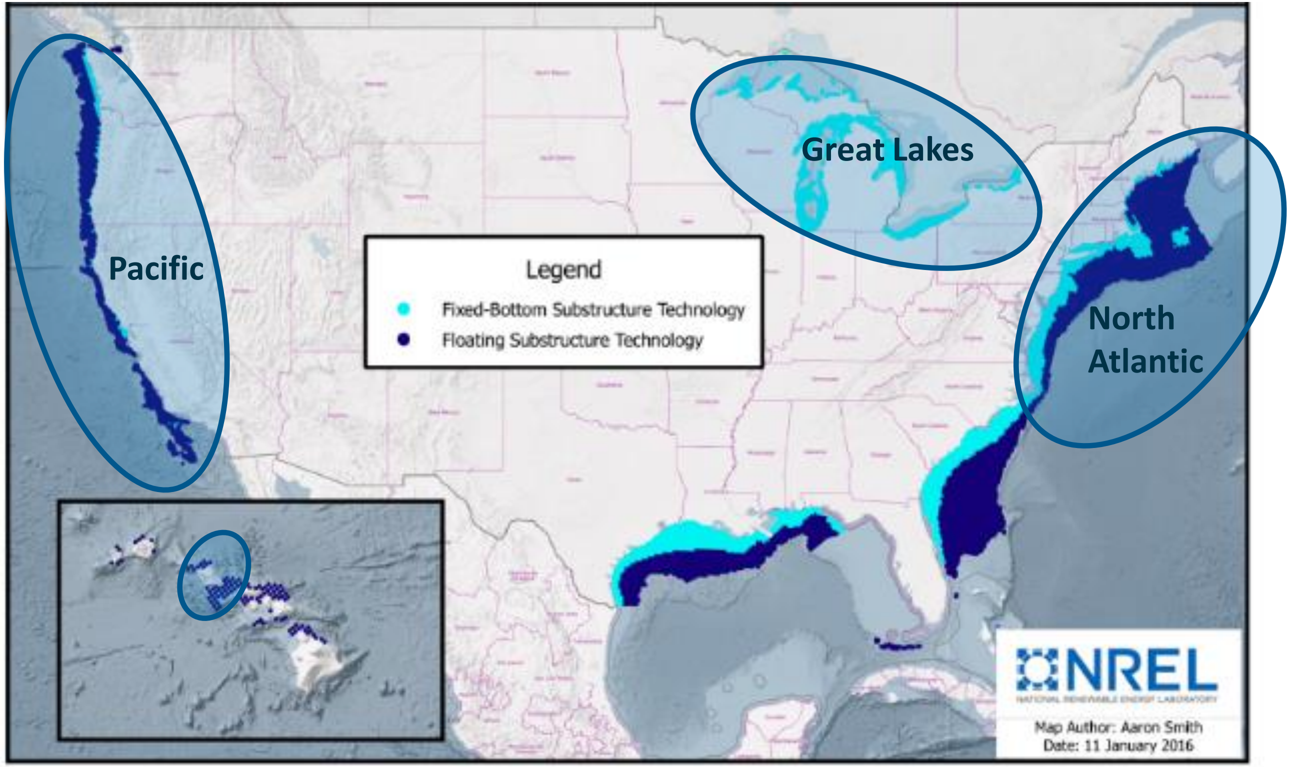


Figure credit: NREL

- **Pacific Region** – High water depths require floating technology
- **North Atlantic** – high demand, scarcity of shallow sites
- **Great Lakes** – visual impacts may require farther distances

Oil and Gas Experience Helped Accelerate First Generation of Floating Wind Turbine Prototypes

- Basic types of floating wind substructures were derived from oil and gas
- Oil and gas criteria alone can result in safe, but bulky and expensive designs
- **Next phase:** Optimized engineering approach will yield commercial mass-produced utility-scale floating wind systems

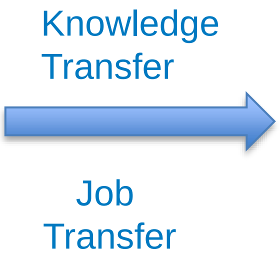


Photo credit: https://www.telegraph.co.uk/finance/newsbysector/energy/oilandgas/10978898/Life-on-an-oil-rig-in-pictures.html?frame=2980750

Photo credit: PPI

All Floating Wind Substructures Rely on These Basic Archetypes

Spar: Achieves stability through ballast (weight) installed below its main buoyancy tank

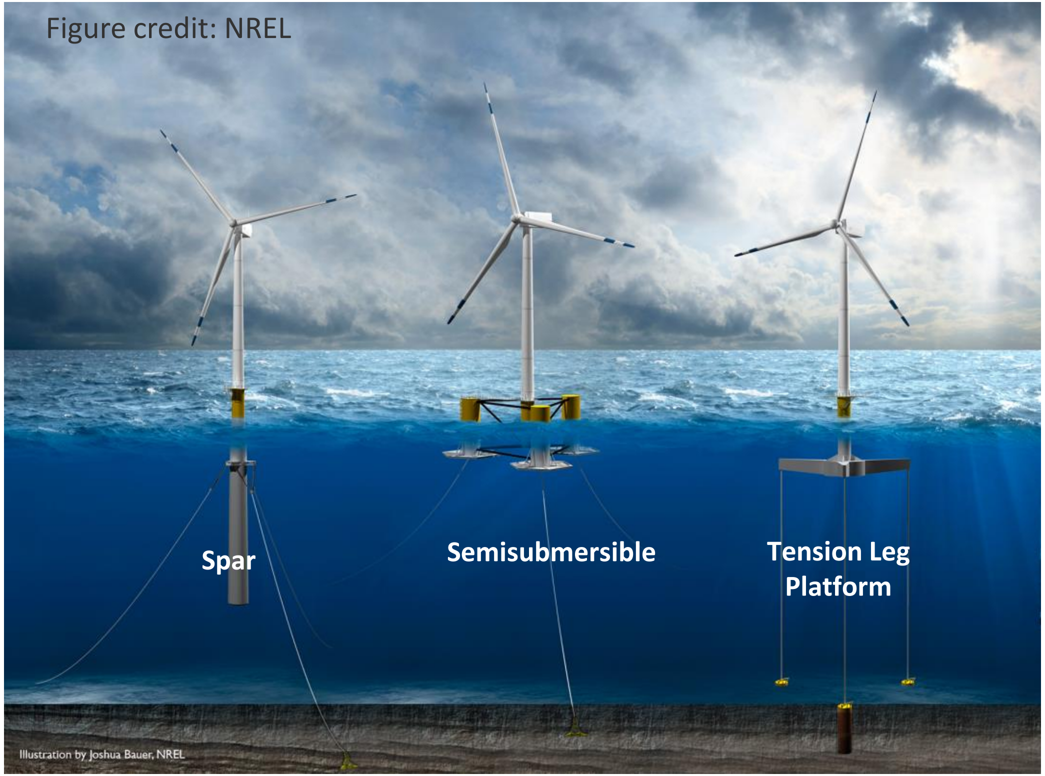
Challenges: Deep drafts limit port access

Semisubmersible: Achieves static stability by distributing buoyancy widely at the water plane

Challenges:
- Higher exposure to waves
- More structure above the waterline

Tension-leg platform (TLP): Achieves static stability through mooring line tension with a submerged buoyancy tank

Challenges:
- Unstable during assembly
- High vertical load moorings/anchors



Three floating offshore wind energy platform archetypes derived from oil and gas experience (spar, semisubmersible, tension leg platform) guide the development of the next generation of optimized floating wind energy systems.

Surface View of Two Types of Floating Wind Substructures

Principle Power – 2.0 MW Turbine in Portugal - 2011
WindFloat Semisubmersible Substructure (photo credit: PPI)

Equinor – 6.0 MW Turbines in Peterhead Scotland
Hywind-2 Spar Substructures (photo credit: Walt Musial)

Floating Wind's Next Generation Platforms

- Lighter and more stable platforms
- Full-system designs that facilitate port assembly, commissioning, and stable tow-out
- 14 Pilot-scale projects are being built to demonstrate next generation technology

TetraSpar

SBM Tension Leg Platform

Examples of Hybrid Systems

Figure credits: Stiesdal Offshore Wind and SBM

Balance of Station – Non-Turbine Equipment

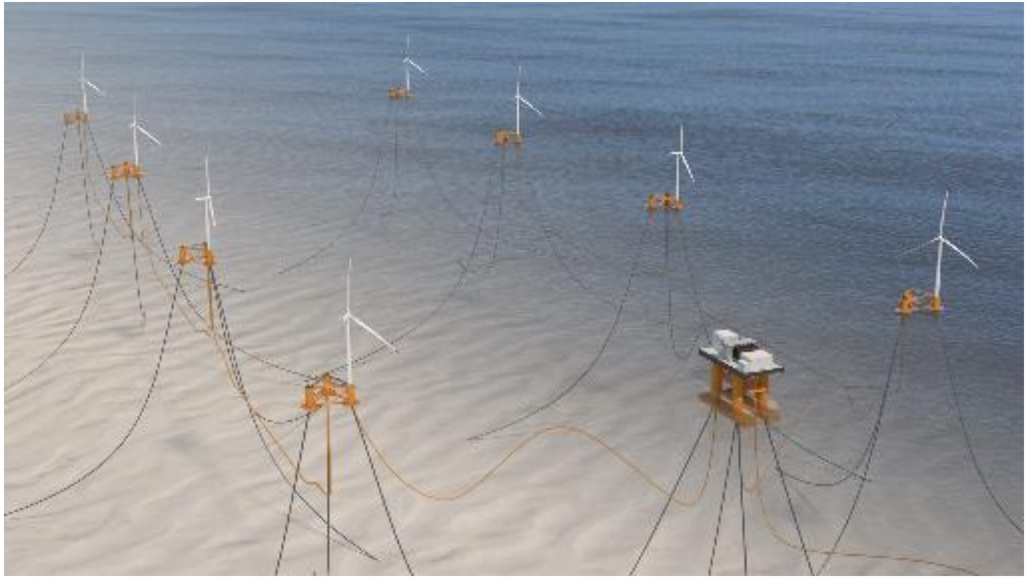
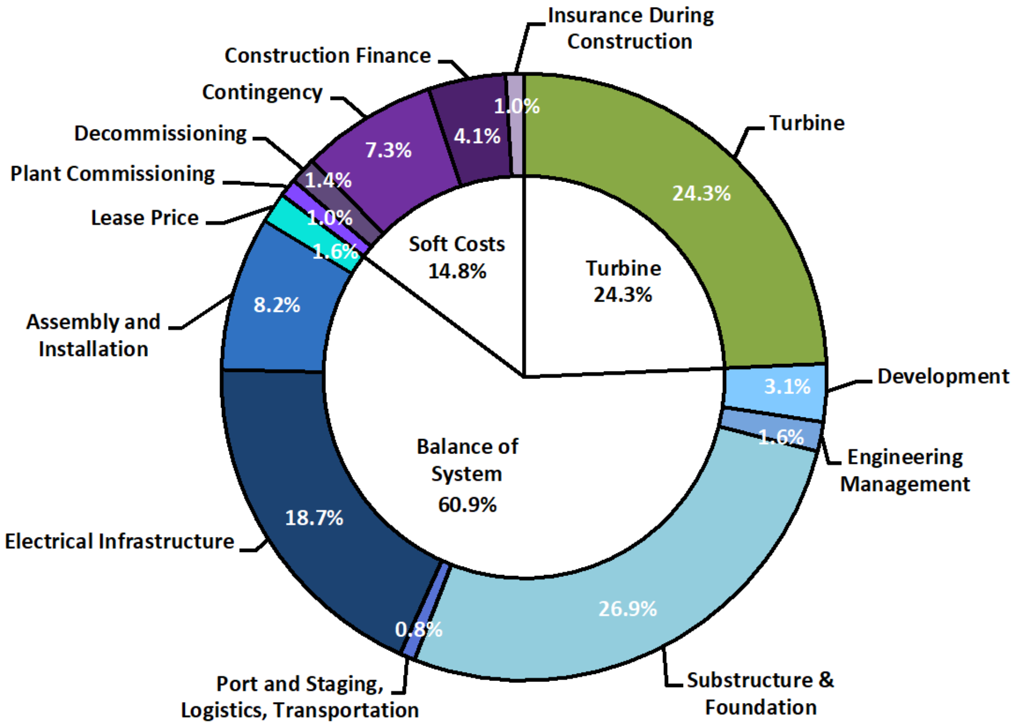


Figure credit: NREL

- Floating substructures
- Dynamic array cables connecting turbines
- Mooring and anchor system
- Installation and assembly
- Offshore and onshore substations
- Export cable (main electric cable to shore)
- Decommissioning after 25-30 years

Non-turbine Costs Account for 75% of the Total Capital Cost for a Floating Wind Farm

What's the Cost Breakdown of a Floating Offshore Wind System?



Floating Offshore Wind Capital Cost Breakdown

- The turbine makes up only 24.3% of the total cost for a floating wind project
- Project cost can be lowered best by reducing balance of system costs

Stehly, Tyler, and Philipp Beiter. 2020. *2018 Cost of Wind Energy Review*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-74598. https://www.nrel.gov/docs/fy20osti/74598.pdf.

Typical Catenary Mooring Line/Anchor Configurations

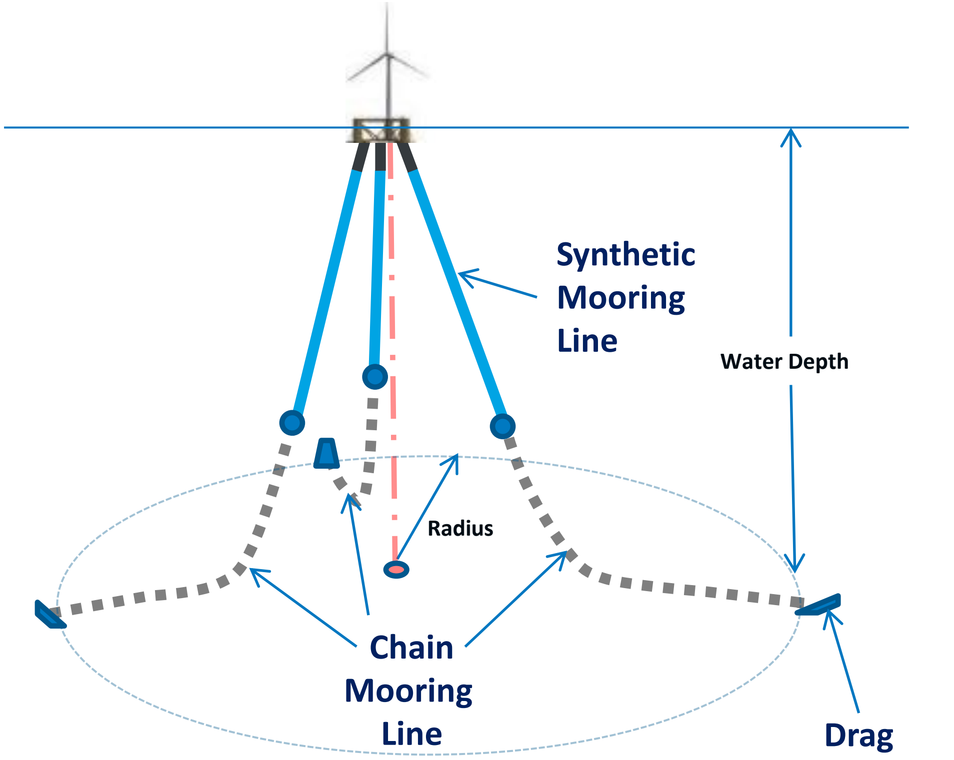
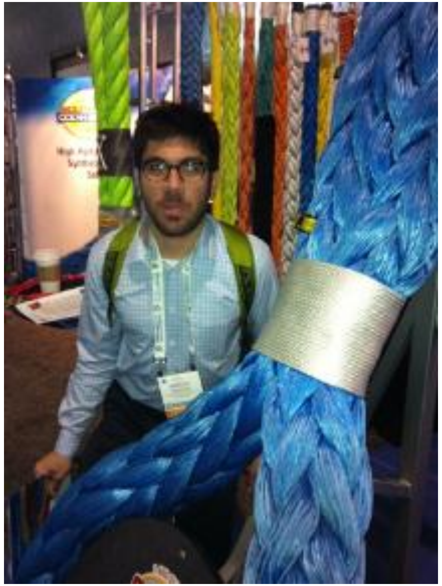
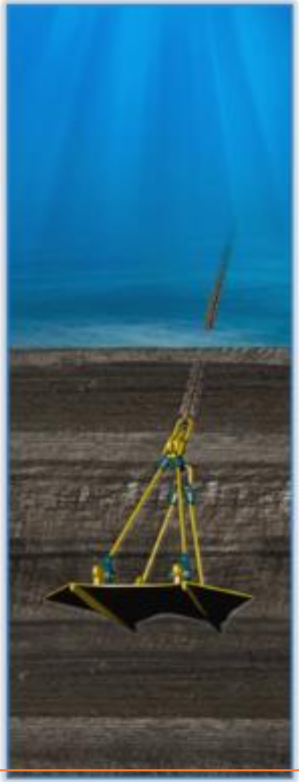


Figure credit: NREL



Synthetic Mooring Line

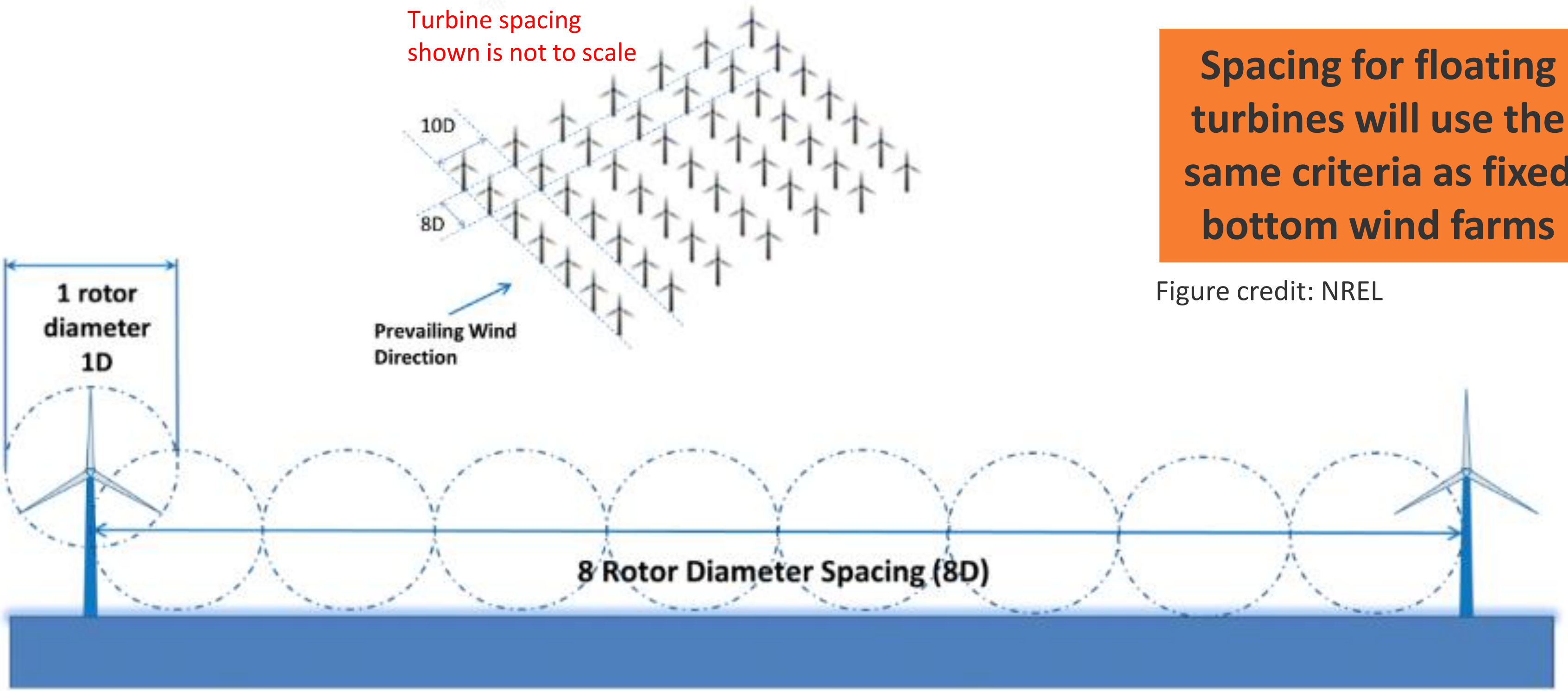
Photo credit: Walt Musial



Drag Embedment Anchor Penetration 10m (33 ft)

Mooring lines are at least 4 times longer than the water depth

Turbine Spacing Increases With the Rotor Diameter



Spacing for floating turbines will use the same criteria as fixed bottom wind farms

Figure credit: NREL

Bigger spacing = higher capital cost due to longer array cables, larger array footprint, but lower wake losses – typical spacing varies between 6D and 8D

Example: A GE 12-MW Haliade-X with 8D spacing, the turbines would be over 1 mile apart

Floating Wind Turbines have Dynamic Array Collection Cable

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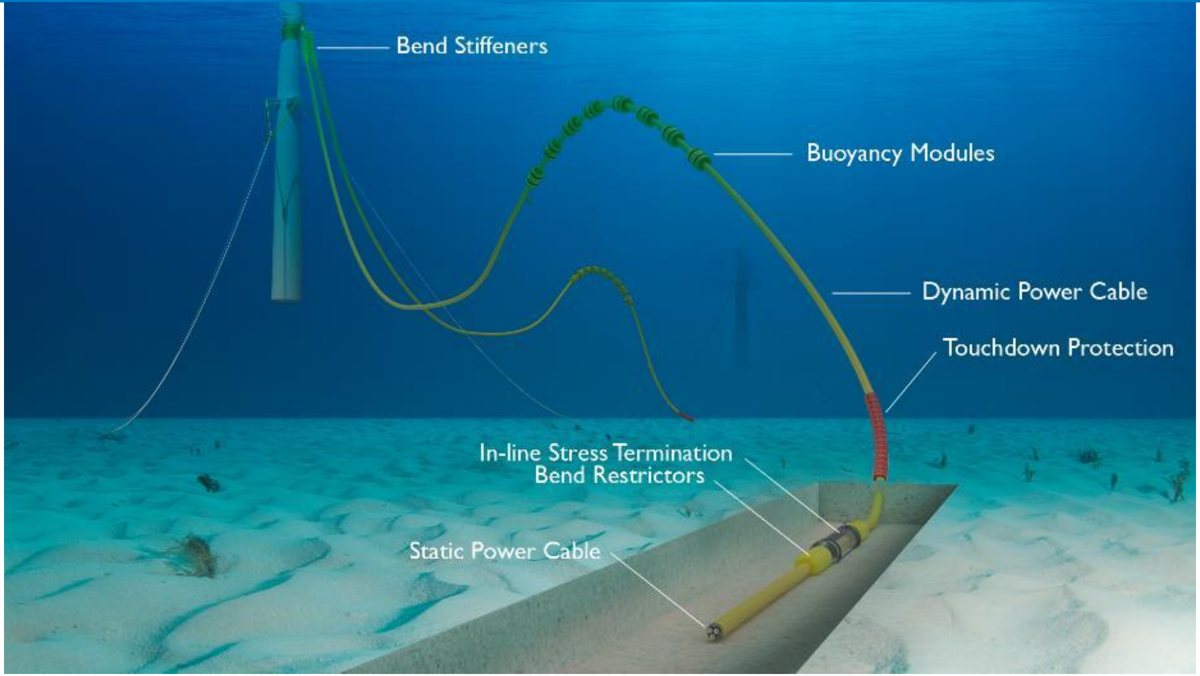


Figure credit: NREL

- Dynamic array cables compensate for movement of floating platform
- Numerous design features help isolate the static cable from platform movements
- Subsea cables may be buried or secured along ocean floor

Offshore Substation

- Utility-scale offshore wind farms collect the power from each turbine at a high voltage substation for transmission to shore

- Floating substations are being developed with high voltage dynamic cables that allow the substations to move with the waves.

London Array Substation on monopile
Photo Credit: Siemens Press

Floating Operations and Maintenance

Turbine Service Vessel Baltic 1

Photo: Walt Musial

Turbine System Tow-out

Photo: Principle Power

Small Repairs: Done in the field using service vessels - Sensors/computers, lubrication, electrical, preventative maintenance

Major Repairs – Blades, Generators, Gearboxes – For floating systems this can be done by disconnecting mooring lines and towing system to port

Global Floating Wind Industry's Path to Commercialization

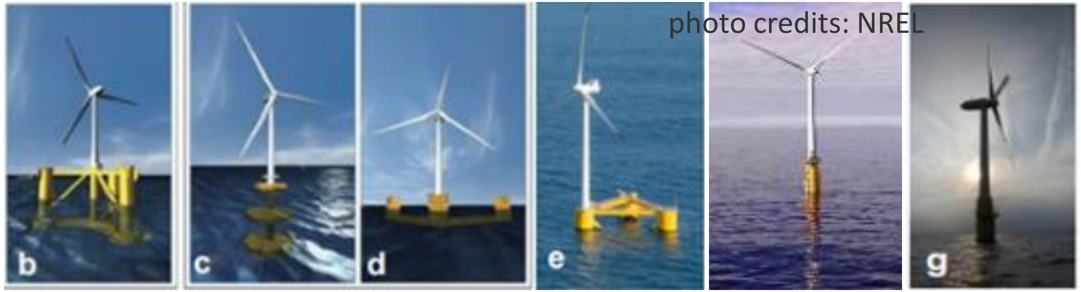


photo credits: NREL

Equinor Peterhead, Scotland 30 MW 5 Turbines Øyvind Gravås / Woldcam - Statoil ASA (right)

PPI 25-MW Windfloat Atlantic (left)

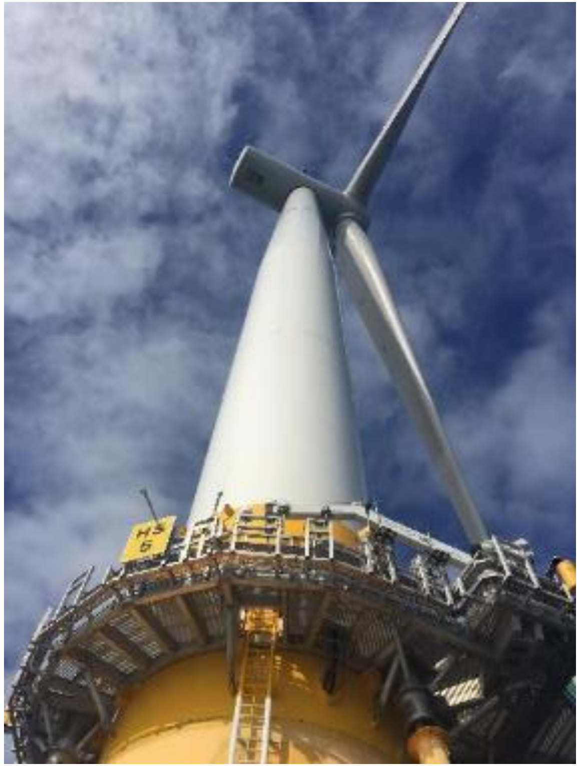
Figure credit: PPI

Proof of Concept Phase
2009 to 2016
Prototypes Ranging from 2 - 7 MW
Research Funded

Pre-commercial Phase
2017 to 2023
Multi-turbine commercial machines
12 – 50 MW – financed with subsidies
14 projects totaling 229-MW

Utility-scale Floating Arrays
2024 and beyond
400-MW+ Capacity
Competitive with Market Conditions

First Pre-commercial Scale Floating Wind Farm



Siemens 6-MW Wind Turbine at Hywind -2

Photo credit: Walt Musial

30-MW Hywind-2 (2017)

- First floating wind farm off Peterhead, Scotland
- Five 6-MW Siemens turbines were installed by Equinor in 2017
- Substructure type: Classic Spar
- Water depth: up to 130 m (427')
- Hub height: 101 m (331')
- Rotor diameter: 154 m (505')

WindFloat Atlantic Floating Wind Farm

Vestas 8-MW Wind Turbine Being Towed to Station at Wind Float Atlantic

Photo Credit: Windplus/Dock90

25-MW WindFloat Atlantic (2019)

- Near Porto, Portugal in 2019
- Windplus consortium includes EDP Renewables, ENGIE, Repsol, and Principle Power.
- Three 8.4-MW Vestas turbines
- Substructure type: Semisubmersible
- First power December 31, 2019
- Water depth: 100 m (328’)
- Hub height: 100 m (328’)
- Max height above water: 190 m (623’)

How Much Does Floating Offshore Wind Energy Cost?

Estimating Floating Wind Cost

- Only 82 MW of floating wind has been installed so far
- No utility-scale projects built yet (pilot scale at least 3x higher cost)
- Cost estimates rely on:
  - Fixed-bottom wind market data validation
  - U.S. power purchase agreement analysis
  - Gap filling from vendor quotes and developers (proprietary)
  - Geo-spatial techno-economic cost models
- Inputs from a wide range of industry literature sources

Recent NREL publications for Cost of Floating Offshore Wind

Musial, W., P. Beiter, J. Nunemaker, D. Heimiller, J. Ahmann, and J. Busch. 2019b. *Oregon Offshore Wind Site Feasibility and Cost Study*. NREL/TP-5000-74597. nrel.gov/docs/fy20osti/74597.pdf.

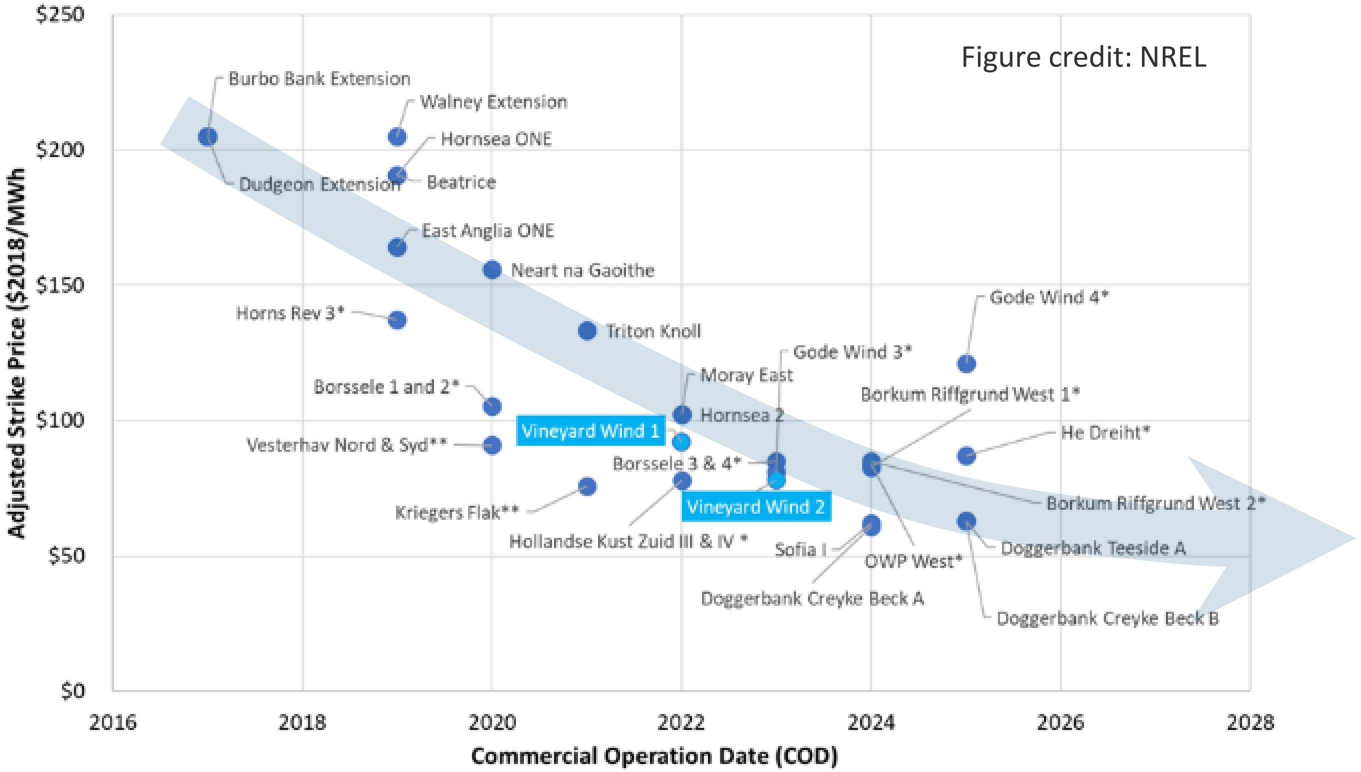
Musial, Walter, Philipp Beiter, and Jake Nunemaker. 2020. *Cost of Floating Offshore Wind Energy using New England Aqua Ventus Concrete Semisubmersible Technology*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-75618. https://www.nrel.gov/docs/fy20osti/75618.pdf.

Beiter, Philipp, Walter Musial, Patrick Duffy, Aubryn Cooperman, Matt Shields, Donna Heimiller, and Mike Optis. 2020. 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.

Prices from Recent European Offshore Wind Auctions Indicate Some Fixed-bottom Projects Can Compete Without Subsidies

Why are offshore wind prices falling?

- Technology improvements (e.g. Larger Turbines)
- Lower risk
- Maturing supply chains
- Increased competition



U.S. power purchase agreement analysis indicates same cost reduction trends

Floating Wind Energy Costs Follow Fixed-bottom Offshore Wind Trends

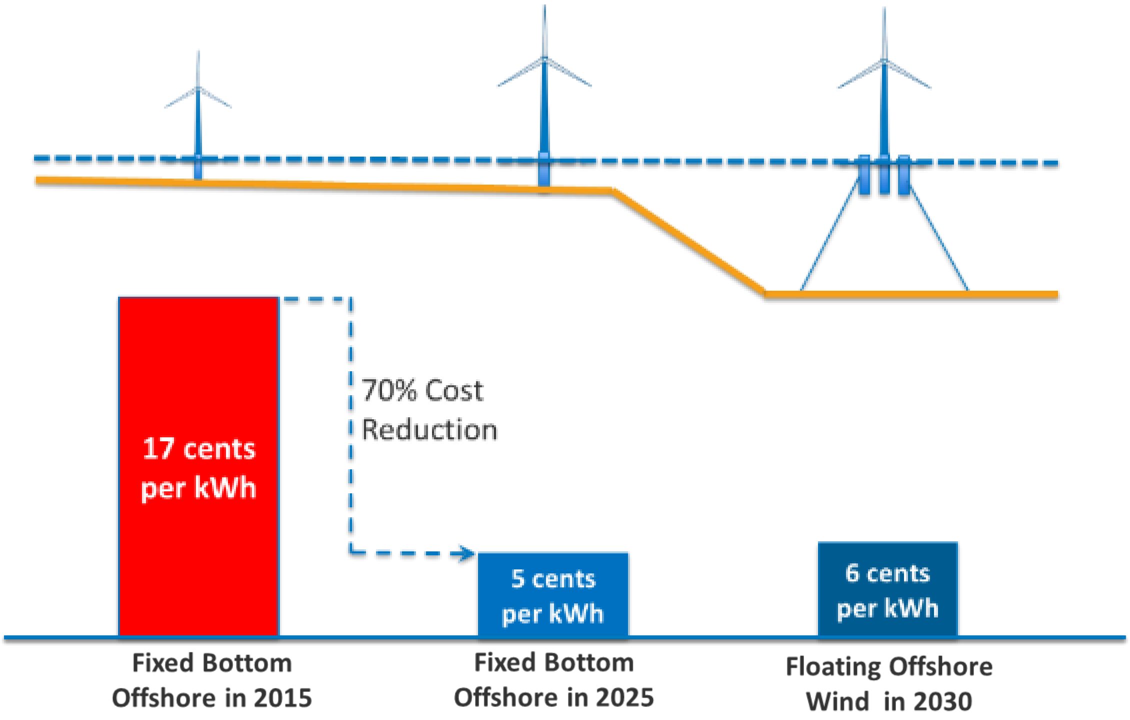
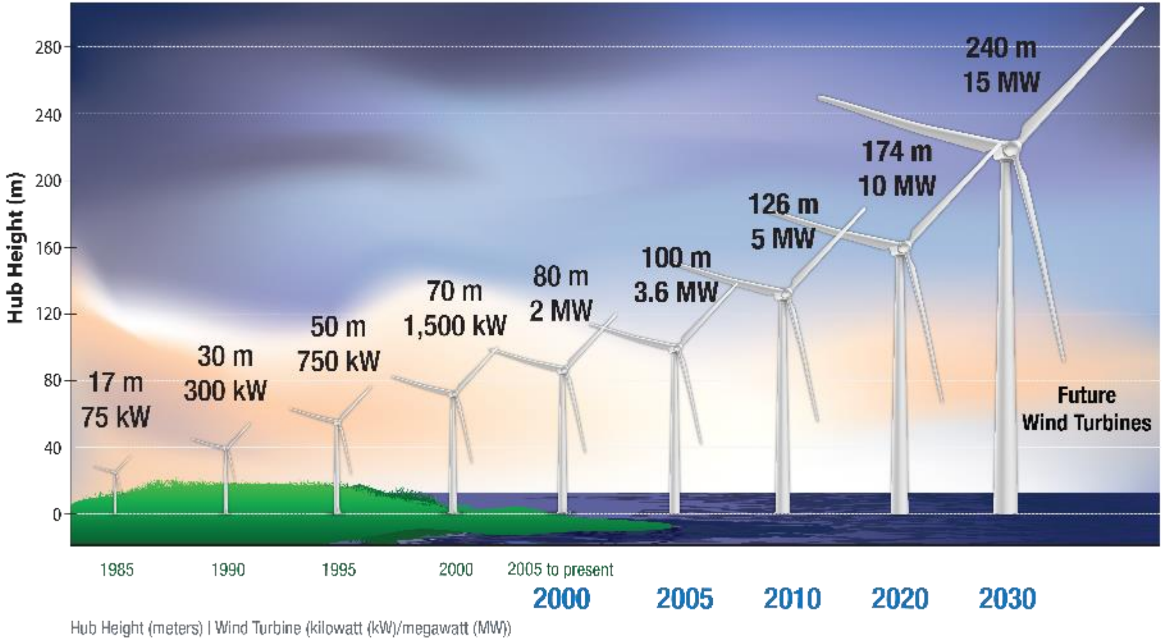


Figure credit: NREL

- Shared supply chains
  - Turbines
  - Array and export cables
  - Regulations
  - Ports and Infrastructure
  - Operations and Maintenance
- Floating cost reductions lag fixed-bottom offshore wind cost by 5 -7 years
- Floating cost are likely to converge with fixed-bottom wind

How Large Will Offshore Turbines Get?



Expected Turbine Growth – 15 MW by 2030

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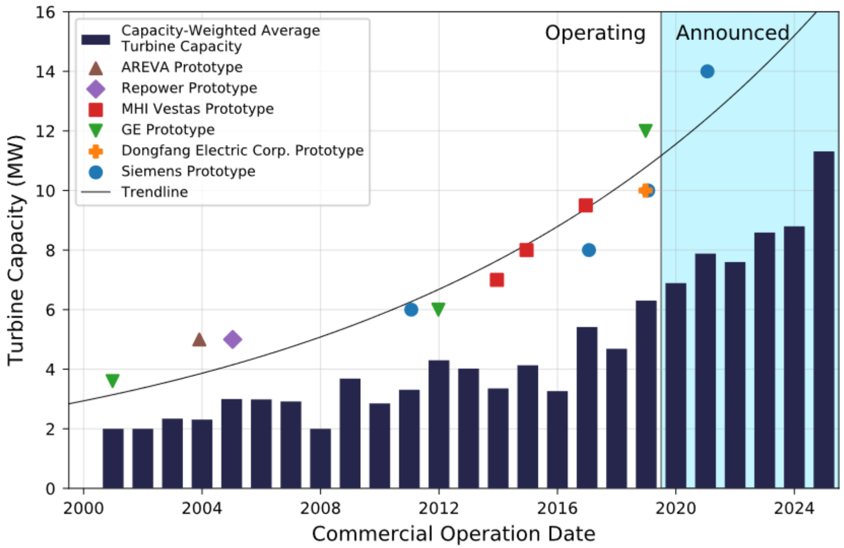
- Offshore turbines are twice as big as land-based
- Fewer installation and transportation constraints offshore
- Larger turbines lower project costs
- Fewer turbines are cheaper to maintain
- No hard limits to further turbine growth
- Floating and fixed-bottom offshore turbines use same turbines....so far.

New Turbine Prototypes Foretell Continued Turbine Growth

- **General Electric announced the 12-MW Haliade-X turbine** prototype now being installed in Rotterdam to be on the market in 2021. The turbine is first in class, with a 12-MW direct-drive generator, 220-m rotor, and 140-m hub height.
- **Siemens Gamesa announced the SG 14-222 DD turbine**—a 14-MW direct-drive turbine with a 222-m rotor planned to be ready for market in 2024.
- **Vestas announced the V236-15.0 MW** – a 15-MW turbine with a 236 m rotor for market in 2024



Average Commercial Offshore Turbine Growth With Prototype Development Leading Further Growth

Source: DOE 2019 Market Report

GE 12-MW Wind Turbine Nacelle – Haliade -X

Photo Source: Greentech Media: https://www.greentechmedia.com/articles/read/ge-finishes-first-nacelle-for-12mw-haliade-x-offshore-wind-turbine#gs.xpxkf6

Key Takeaways

- Offshore wind resources are close to population centers – large scale is possible
- 80% of the global offshore wind resources are suited for floating offshore wind energy.
- Floating wind market could be bigger than fixed bottom markets (eventually).
- Floating offshore wind projects are expected to reach utility-scale by 2024
- Larger offshore wind turbines have led the way for lower cost
- Floating cost reductions lag fixed-bottom wind declines by 5 -7 years, but both floating and fixed bottom offshore wind technologies are expected to reach competitive market costs.

Thank you for your attention!

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Photo Credit : Dennis Schroeder-NREL