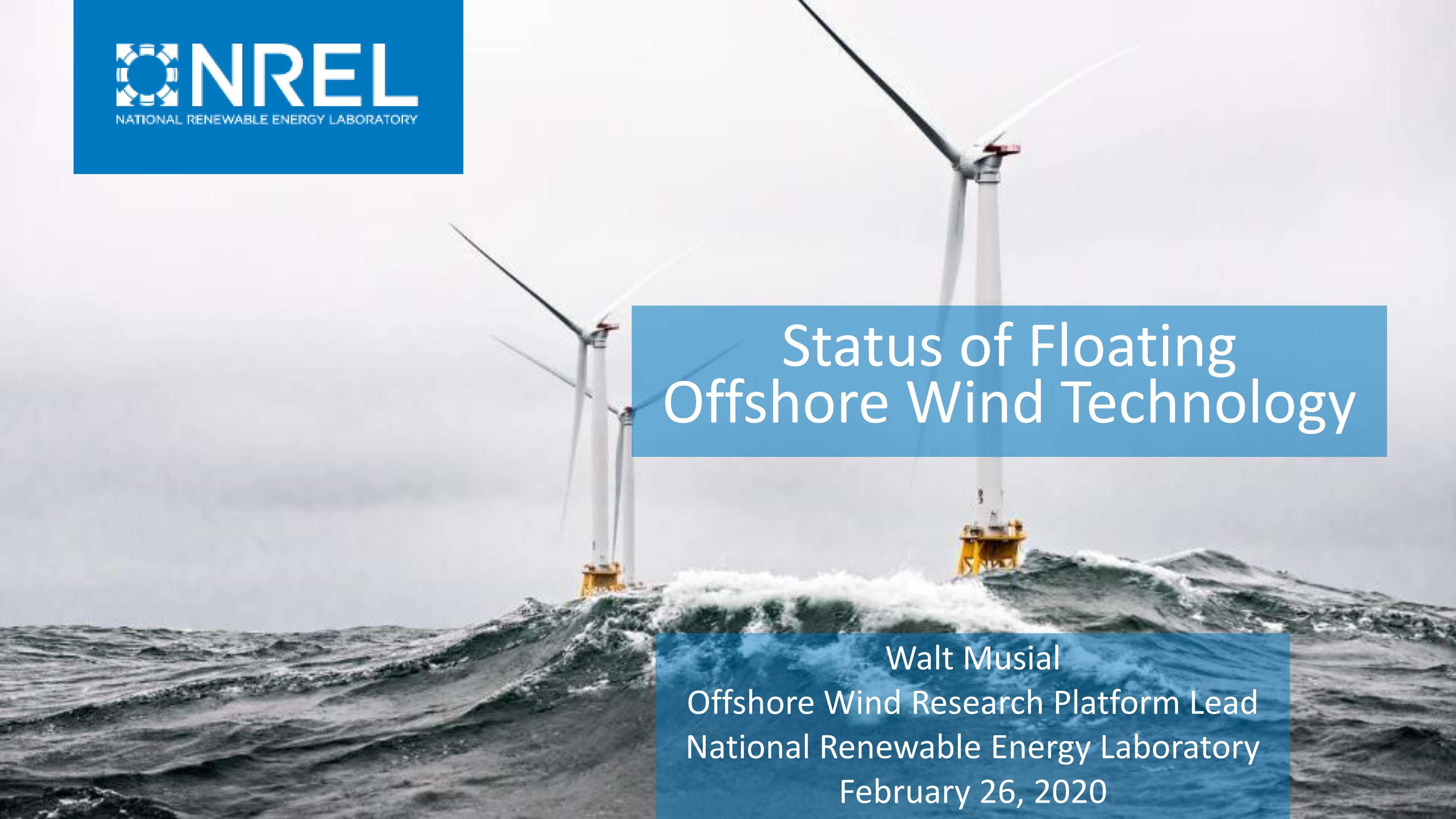

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Status of Floating Offshore Wind Technology

Walt Musial
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National Renewable Energy Laboratory
February 26, 2020

Speaker Bio

Mr. Walt Musial
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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 31 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. 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 100 publications and two patents.

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

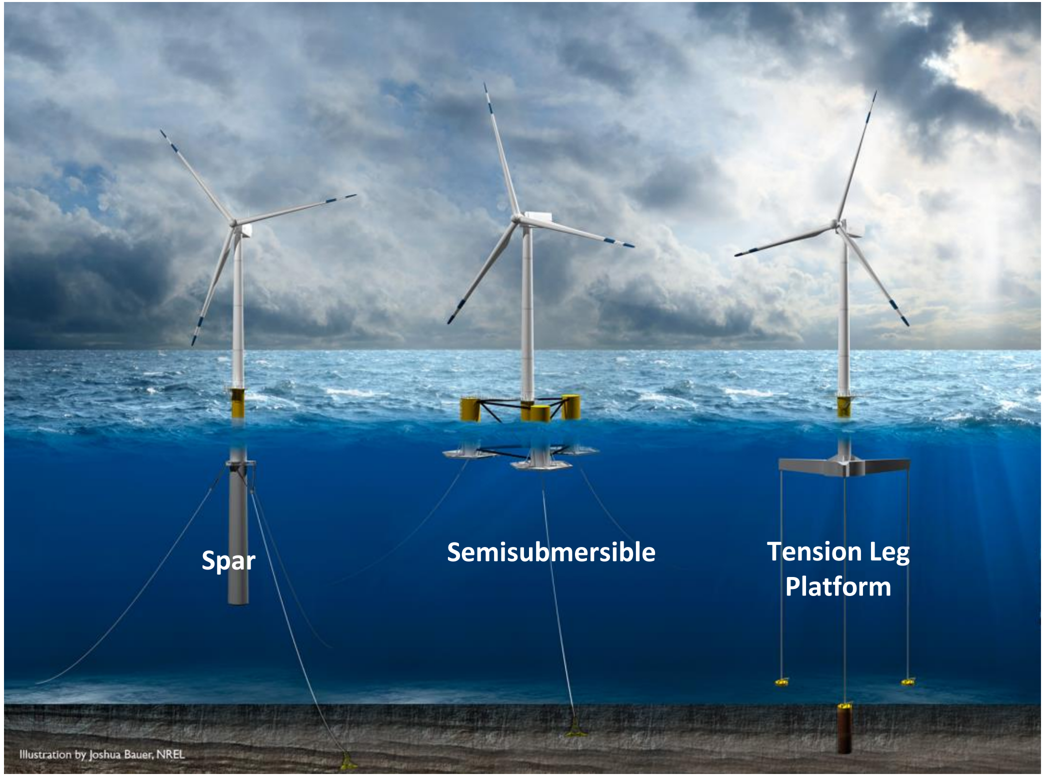
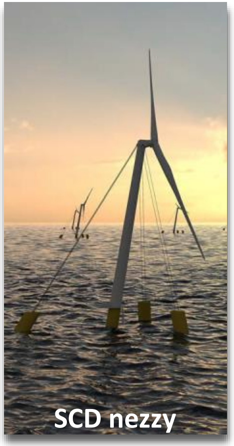
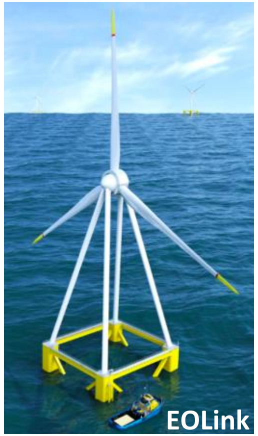


Figure credit: NREL

First Phase of Floating Wind Industry has Spawned Novel Substructure Concepts

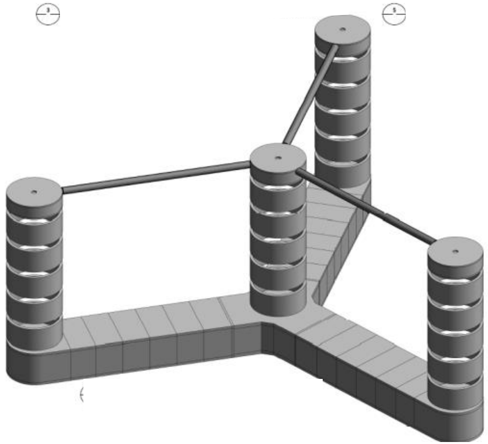




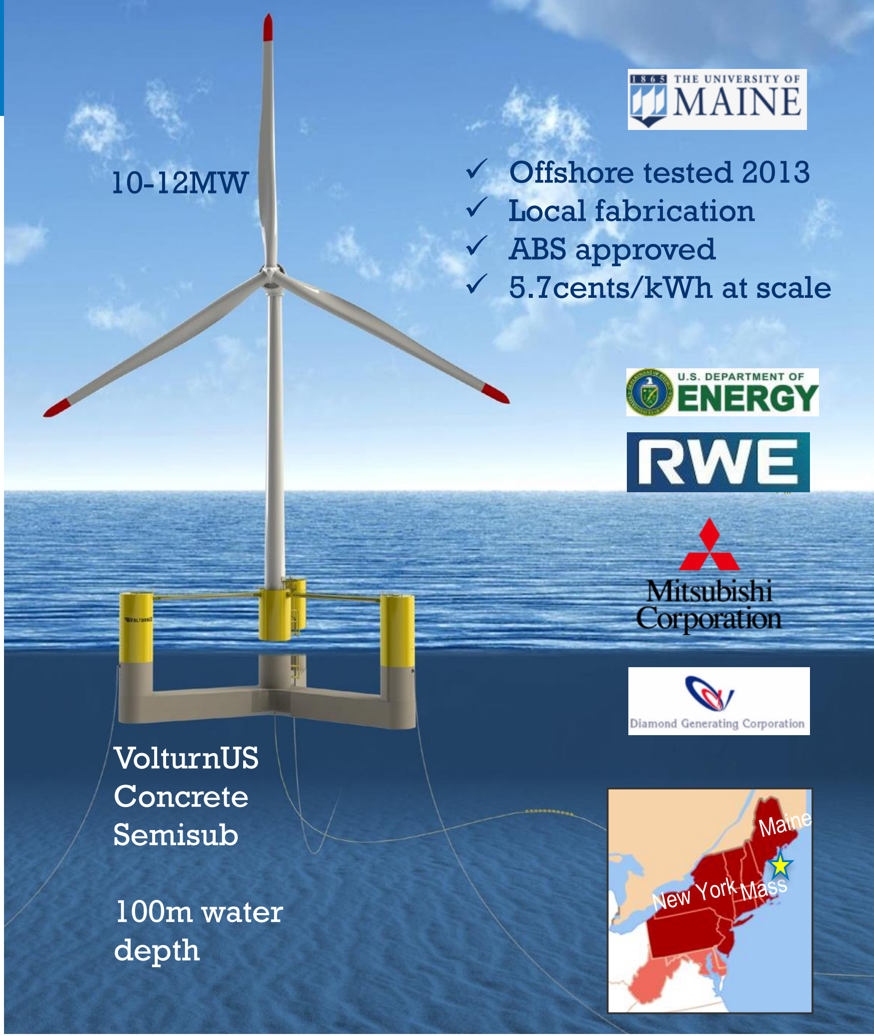
- Designs combine elements from the three archetypes
- Addressing the primary challenges with the archetypes is key to lowering cost
- The objective is to achieve floating system lifecycle costs competitive in U.S. electricity markets
- **Next phase:** Optimized engineering approach will yield commercial mass-produced utility-scale floating wind systems

New England Aqua Ventus I

1. University of Maine VolturnUS Concrete semisubmersible design, has 55 patents
2. US DOE Advanced Technology Demonstration Program for Offshore Wind
3. RWE & Mitsubishi-Diamond Generating Corporation to invest $100 m
4. Site: Monhegan Island, Maine
5. Power Purchase Agreement contract signed 2020
6. Start construction 2022, COD 2023



Locally produced VolturnUS segmental concrete hull



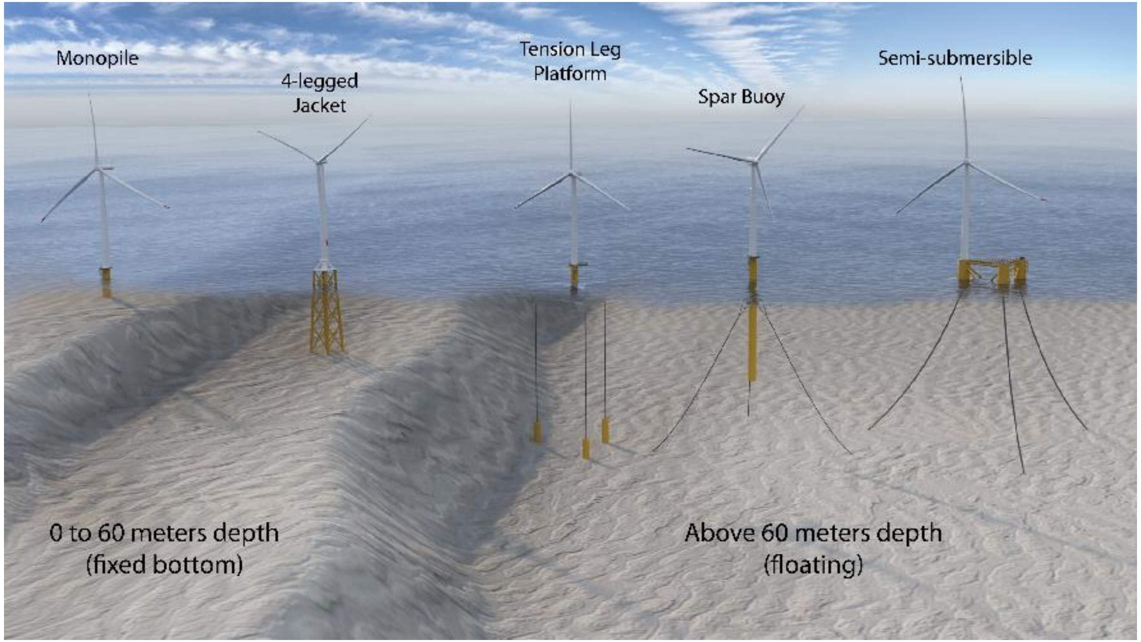
Most Offshore Wind Deployment Has Been on Fixed-bottom Support Structures

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

Figures current as of 31Dec 2019



Fixed Bottom	Floating
27,208 MW Installed	84 MW Installed

The future floating wind energy market may be bigger than the fixed-bottom market

Floating Offshore Wind Will be Developed Where Waters Are Too Deep for Current Fixed-Bottom Technology

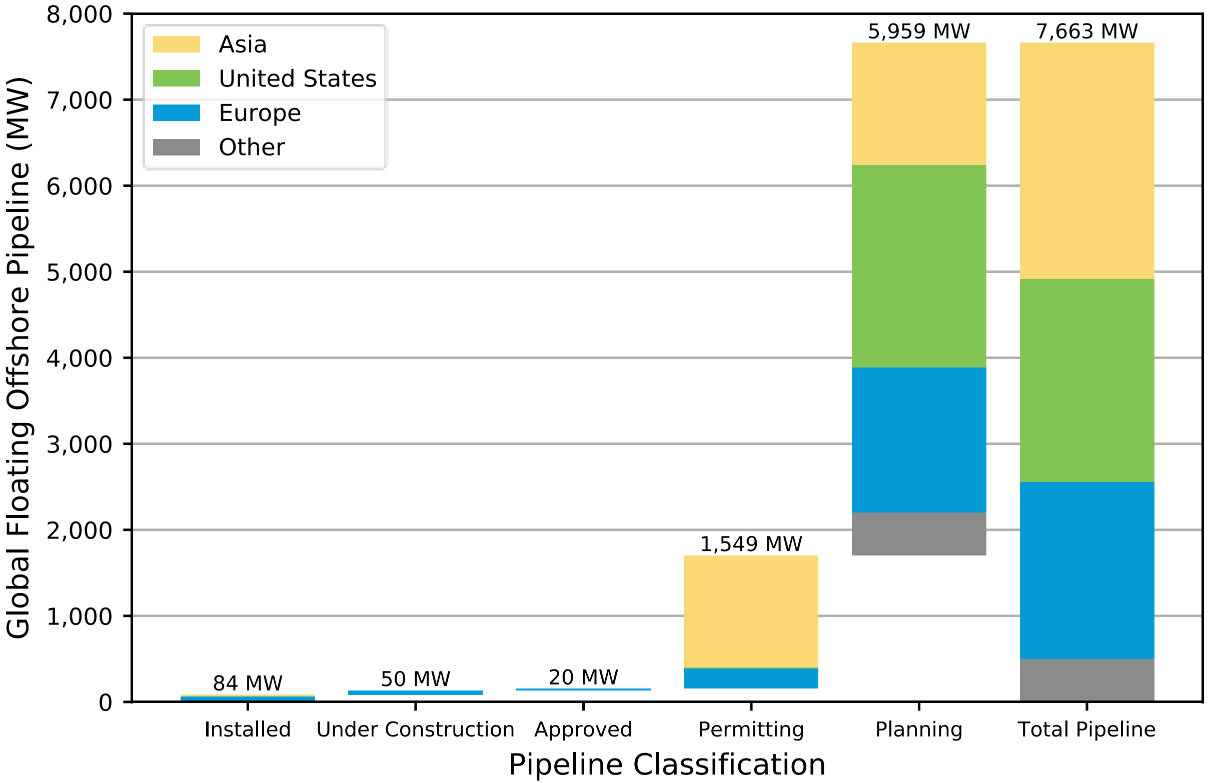
- 80% of offshore wind resources are in waters greater than 60 meters
- Floating wind enables sites farther from shore, out of sight, with better winds!
- Floating wind technology is expected to be at deployed at utility scale by 2024.

Some Areas of the World Being Considered for Floating Wind

Portions of this slide were adapted courtesy of Aker Solutions

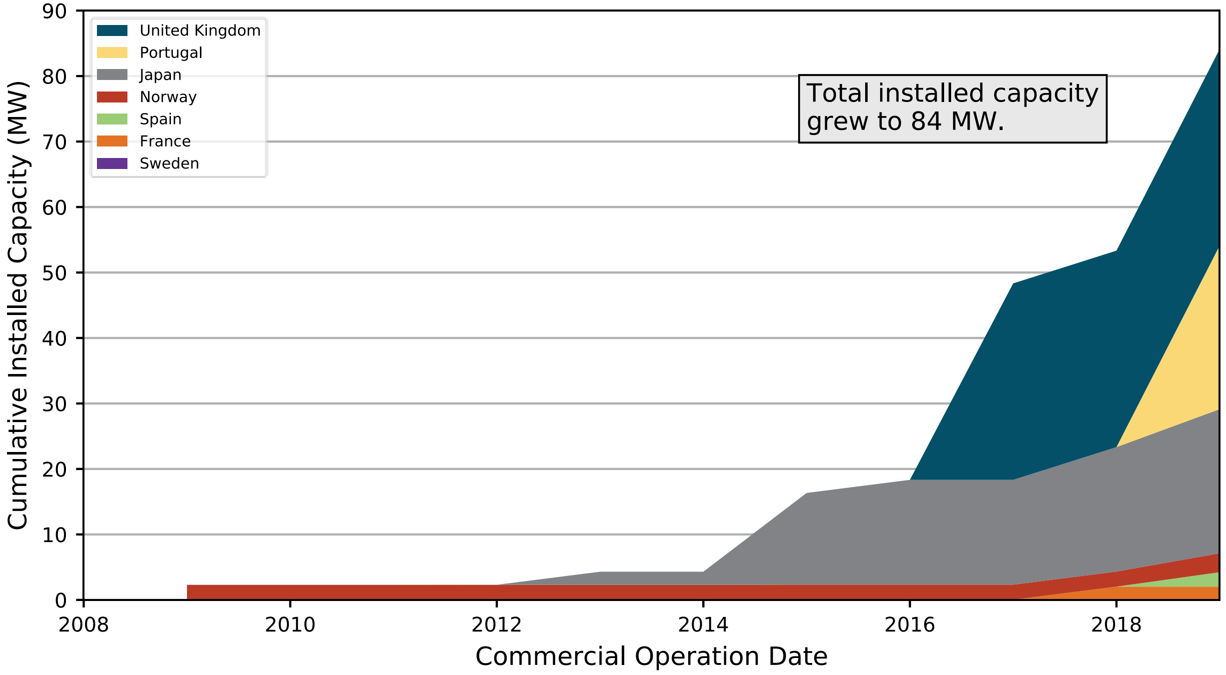
Sources: EIC Global Offshore Wind report 2019; Norwep, Equinor, internal analysis

2019 Global Floating Offshore Wind Pipeline



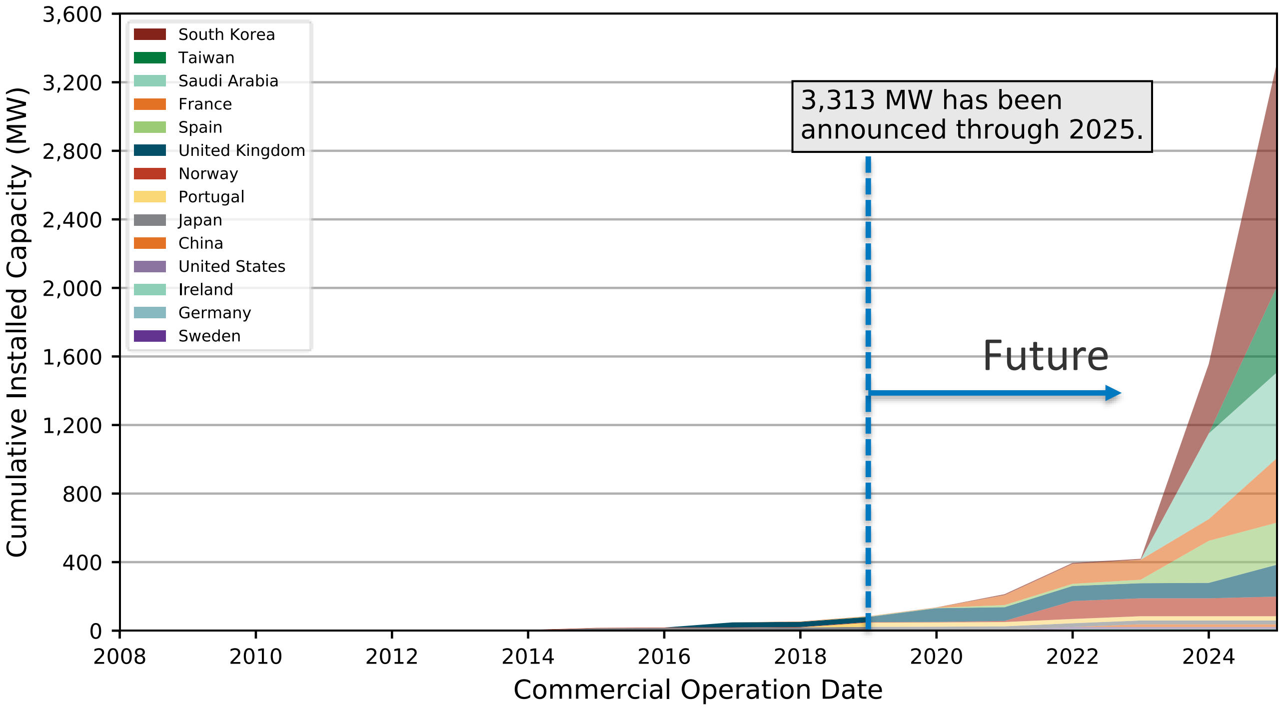
- The total global floating offshore wind pipeline was 7,663 MW at the end of 2019, based on projects that have announced their planned capacity.
- 1,549 MW of floating offshore wind has reached the permitting stage
- The primary driver for pipeline expansion is the movement toward commercial-scale projects developing in Asia.

Cumulative Installed Offshore Floating Wind Capacity by Country to Date



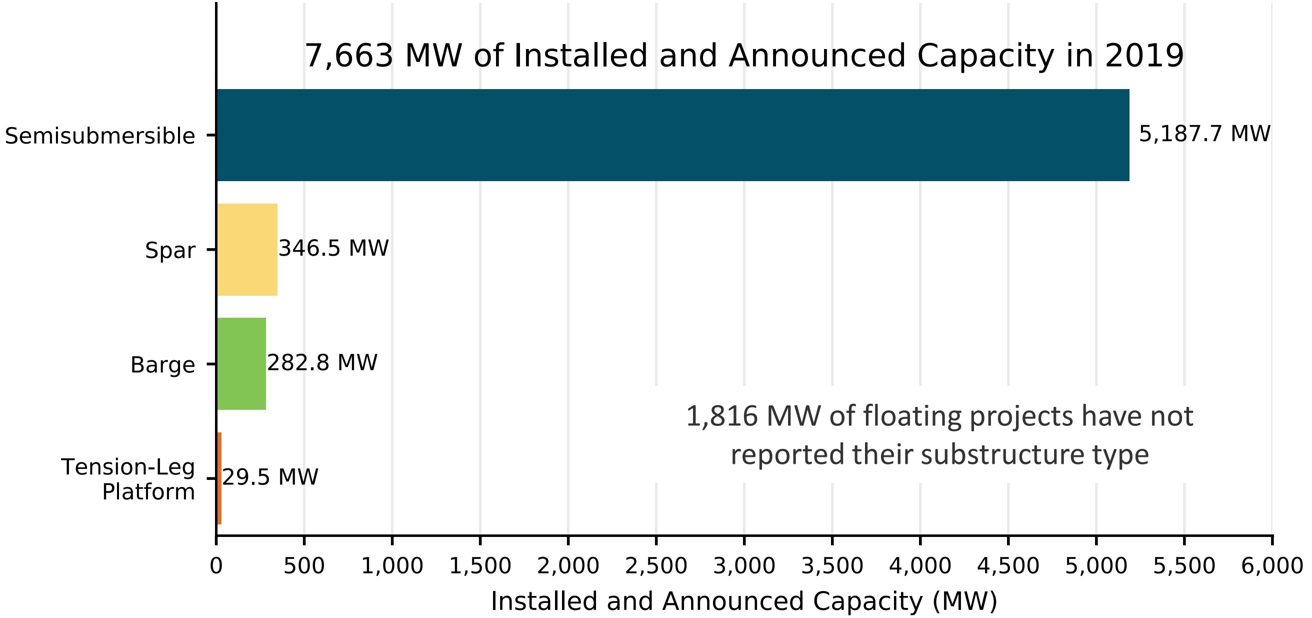
- At the end of 2019, there was 84 MW of installed floating wind capacity globally, growing by 36 MW from 2018.
- Of this installed capacity, there are 16 projects, with 9 projects (62.13 MW) in Europe and 7 (22.06 MW) in Asia.
- Two pilot-scale projects comprising 3 and 5 turbines have been installed in Portugal (2020—labeled as 2019) and Scotland (2017), respectively.

Cumulative Offshore Floating Wind Capacity by Country Based on Announced COD Through 2025



- Projects with announced CODs in 2025 or before total 3,313 MW.
- A small number of commercial projects have announced a COD after 2025.
- Aqua Ventus I is the only U.S. project in the permitting stage and is now expected to reach commercial operations in 2023.

Global Floating Substructure Market Share

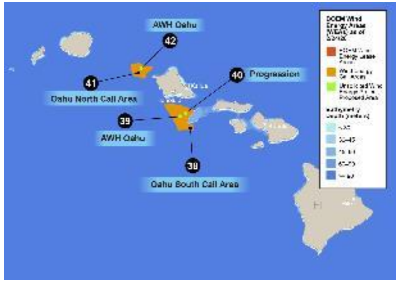


- 5,847 MW of projects in the pipeline have announced their substructure type (76%)
- Semisubmersibles account for about 89% of installed and announced capacity
- Approximately 5% use or plan to use spars (e.g., Equinor’s 30-MW floating wind power plant).
- The remaining substructures are tension-leg platforms and barges.

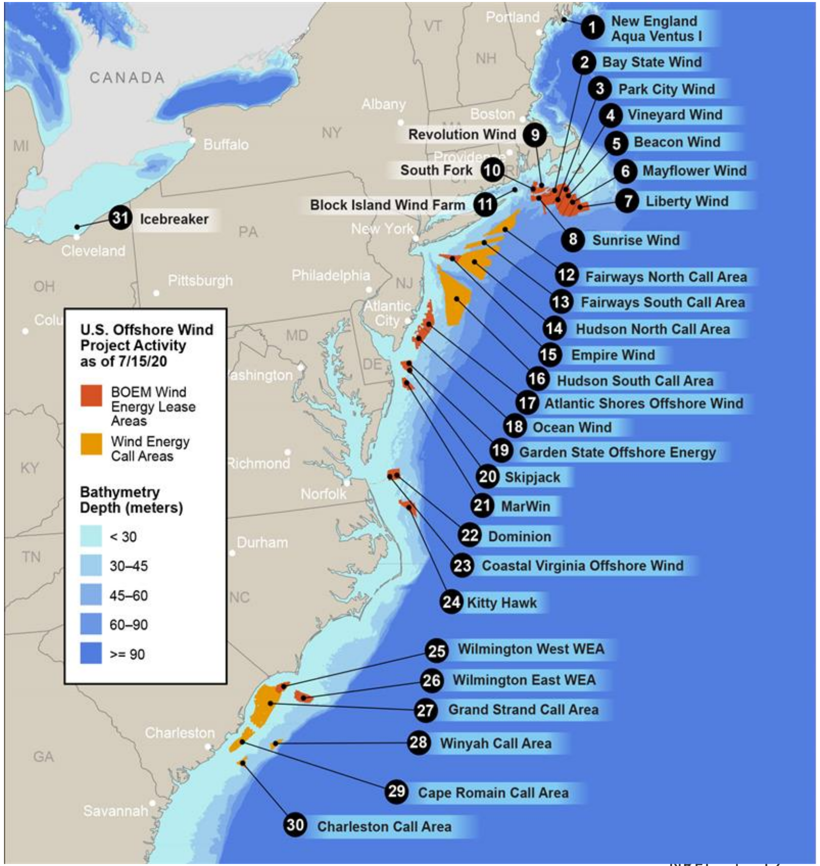
U.S. Regulatory Activity

- There are 15 ***Lease Areas*** in the United States giving developers exclusive site control of about 21-GW of capacity
- BOEM has also identified 13 Call Areas
- ***Call areas*** are potential future wind energy areas that are under public review

Pacific Region (Floating)



Atlantic Region



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

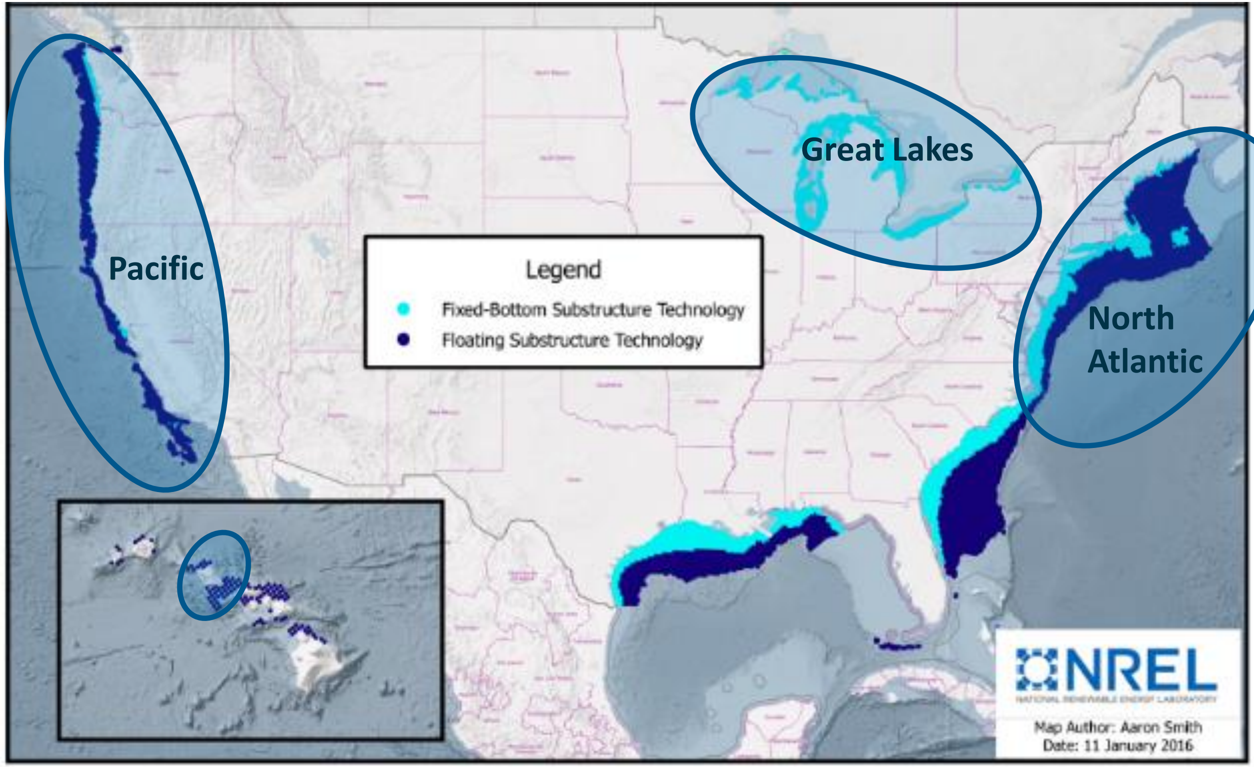
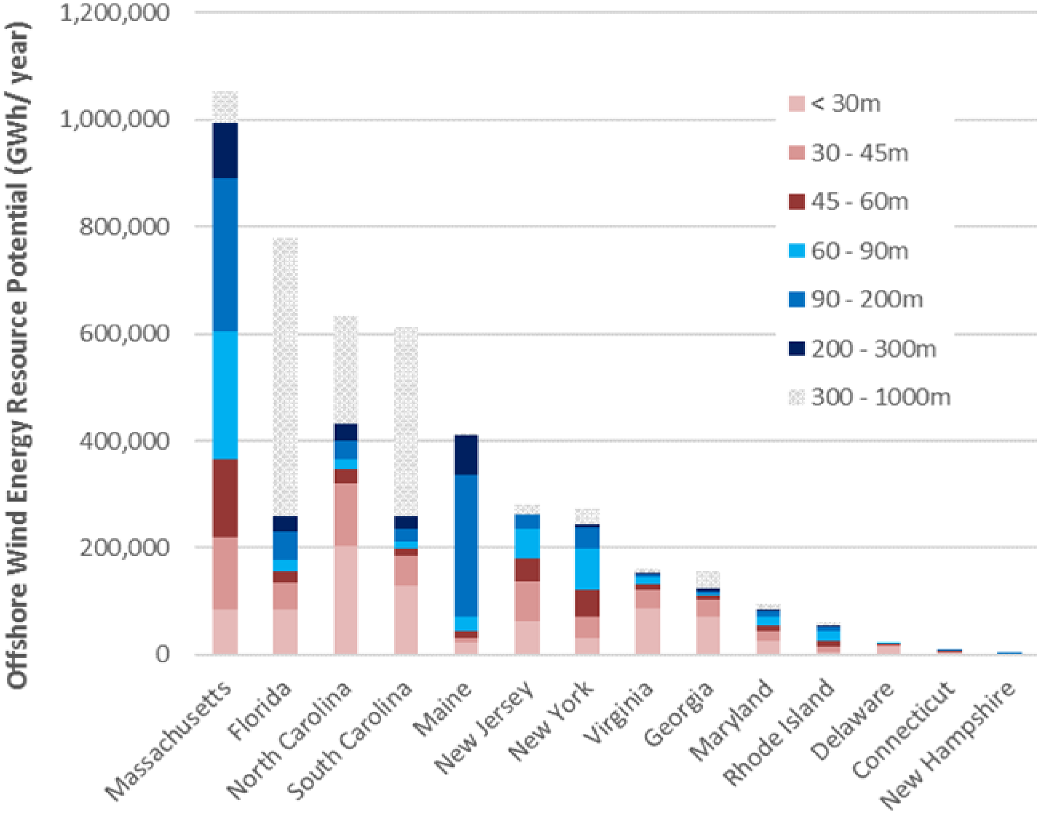


Figure credit: NREL

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

Floating Wind may be Necessary to Meet the Renewable Energy Goals for the U.S. Atlantic Region



- Atlantic offshore wind resource is 55% of total the total U.S. resource
- Approximately 28-GW are in the project pipeline Nationwide
- State commitments continue to grow in the Atlantic
- Shallow sites are becoming scarcer
- 68% of Atlantic resource is greater than 60 m depth.

Balance of Station – Non-Turbine Equipment

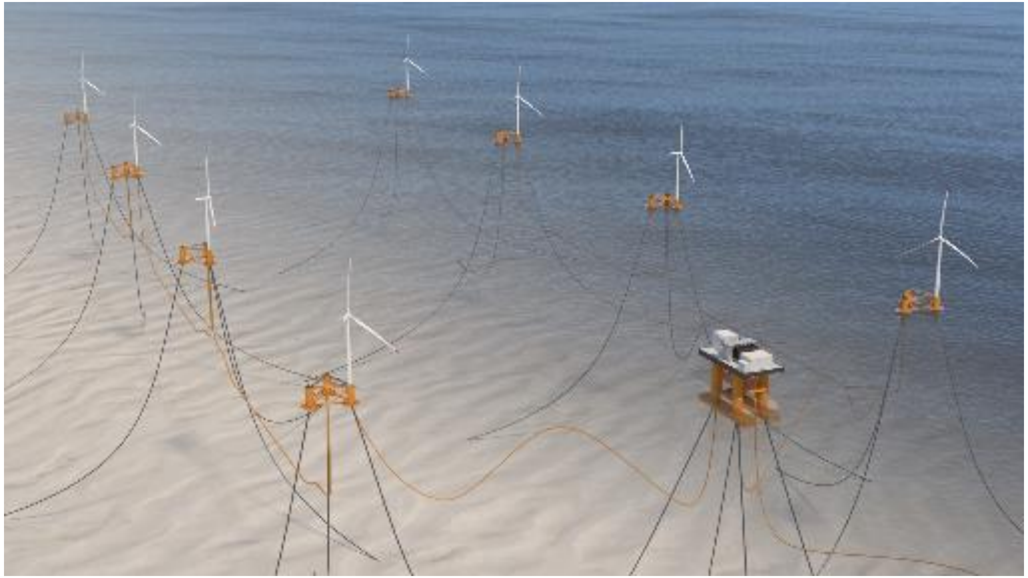


Figure credit: NREL

- 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

Floating Wind Turbines have Dynamic Array Collection Cable

1

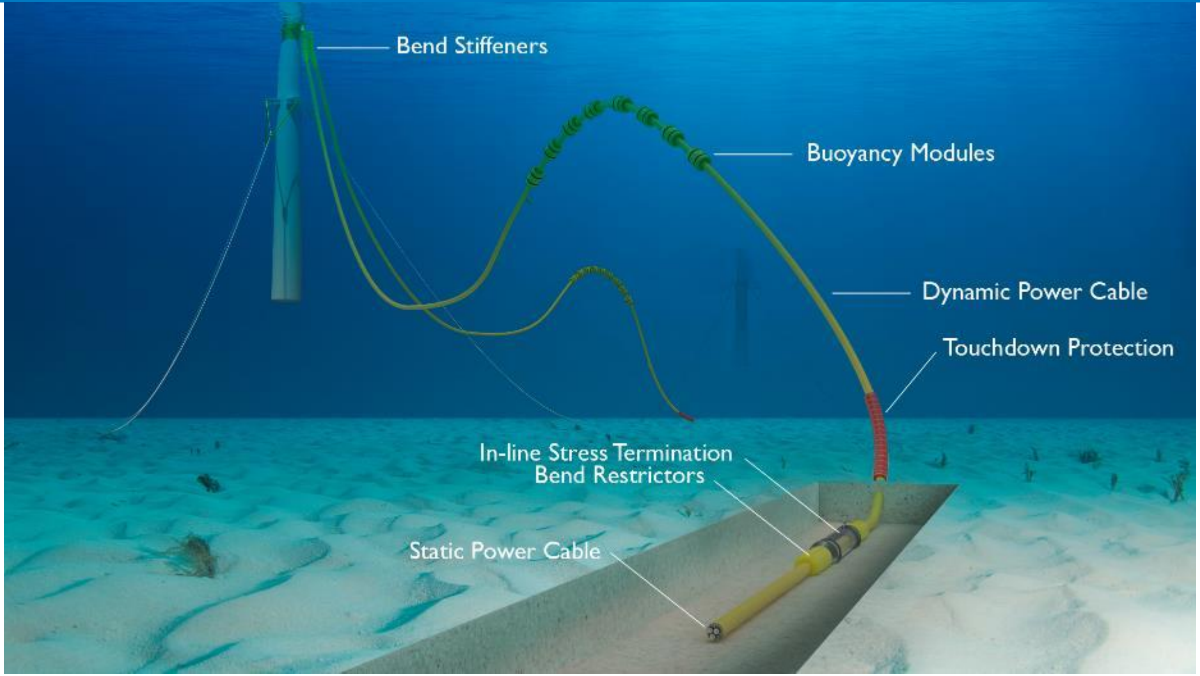


Figure credit: NREL

- 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

Typical Catenary Mooring Line/Anchor Configurations

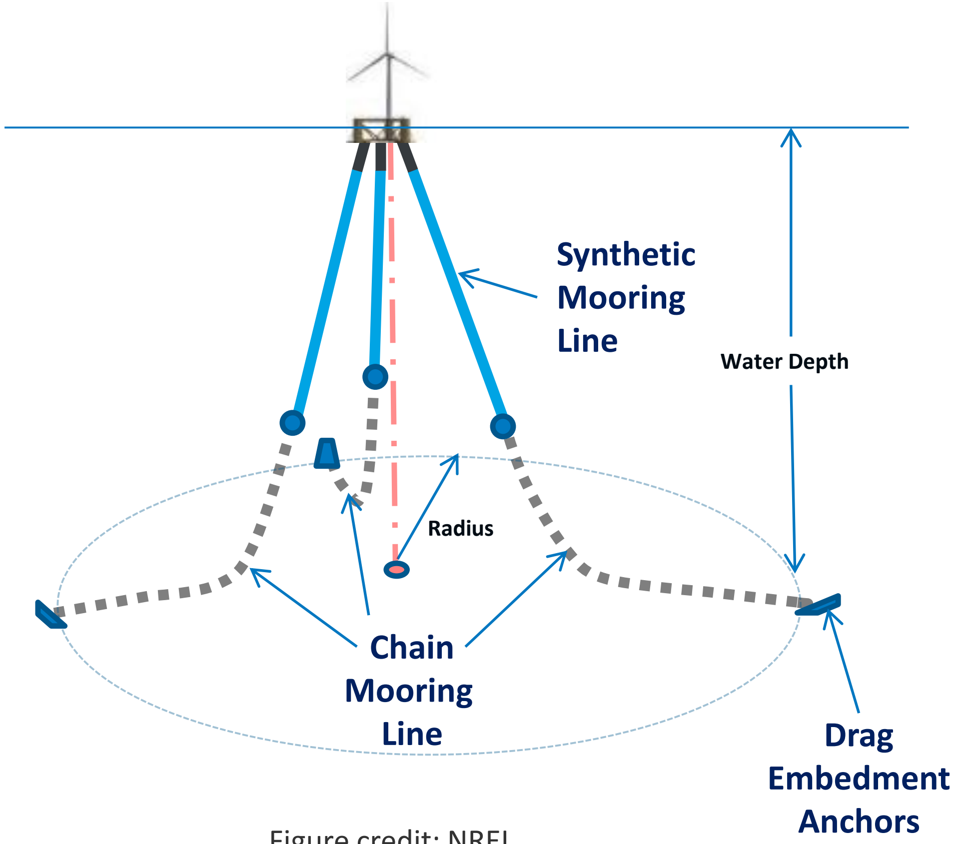
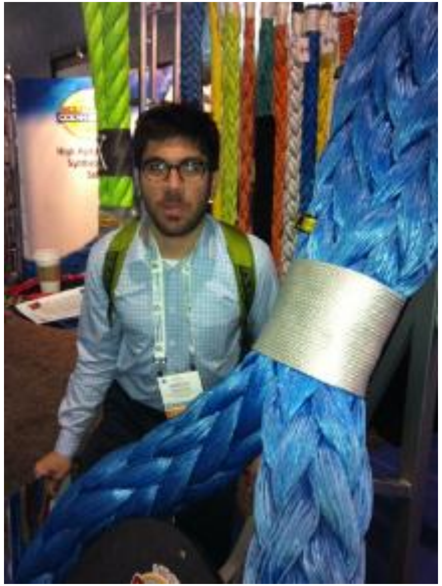
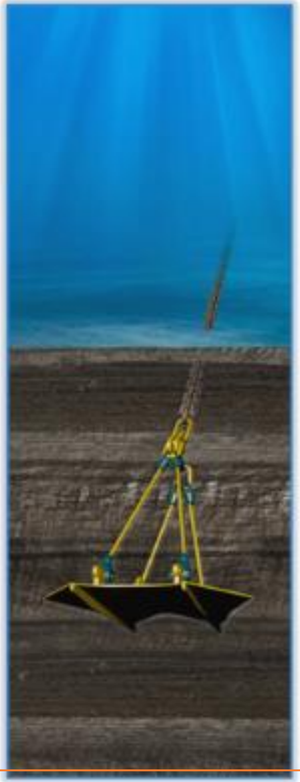


Figure credit: NREL



Synthetic Mooring Line

Photo credit: Walt Musial

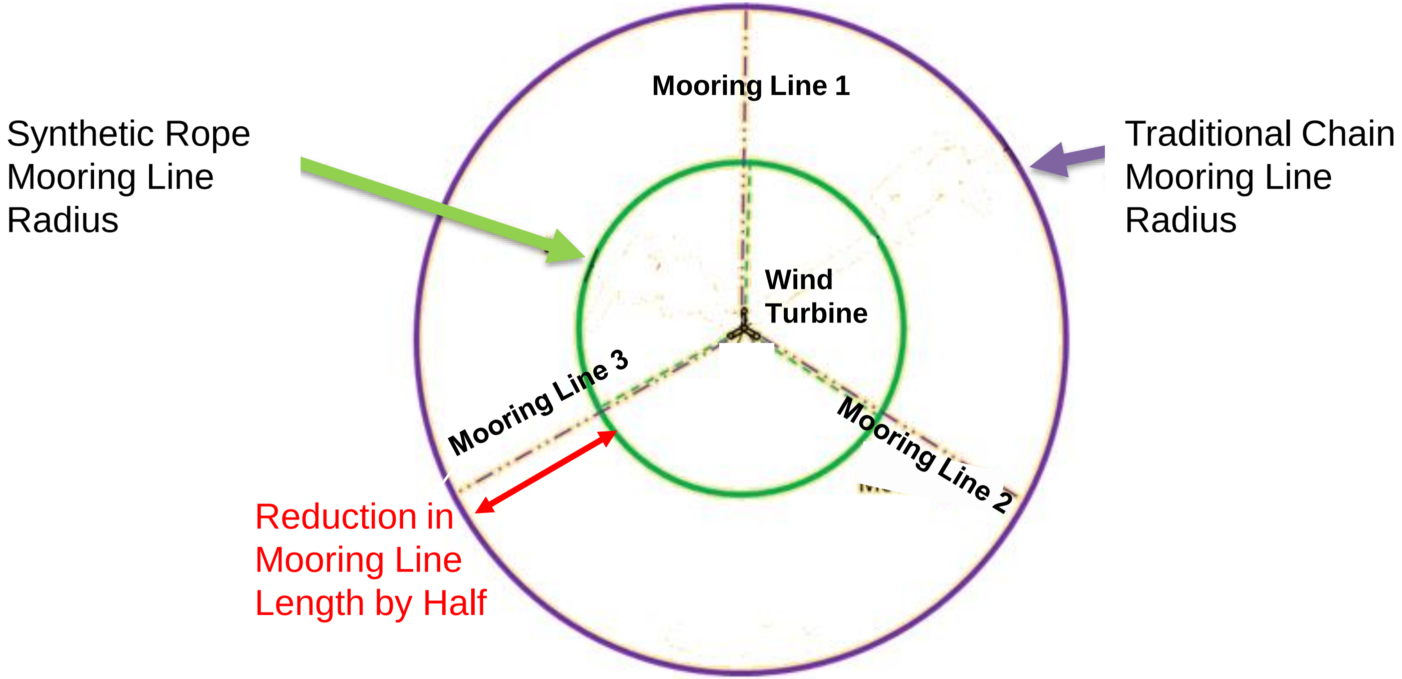


Drag Embedment Anchor Penetration 10m (33 ft)

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

Top-View Comparison of Floating Wind Turbines Moorings

Reduced Foot-print Synthetic Rope Moorings Are Half the Size of Traditional Chain Moorings to Reduce Impact on Fishing



Floating Offshore Wind Port and Infrastructure Requirements

Image by Harland and Wolff Heavy Industries

Wharf

Serial turbine, substructure assembly and component port delivery due to depth, waves off coast

Navigation Channel and Wet Storage

Storage and wet-tow out of assembled turbines with year-round access. Width/depth varies by substructure design

Upland Yard

20 – 100 acre storage and staging of blades, nacelles, towers, possible fabrication of floating substructures

Crane

Minimum 40 – 600 ton lift capacity at 500 feet height to attach components

Crew Access & Maintenance

Moorage for crew access vessels. O&M berth for major repairs of full system

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

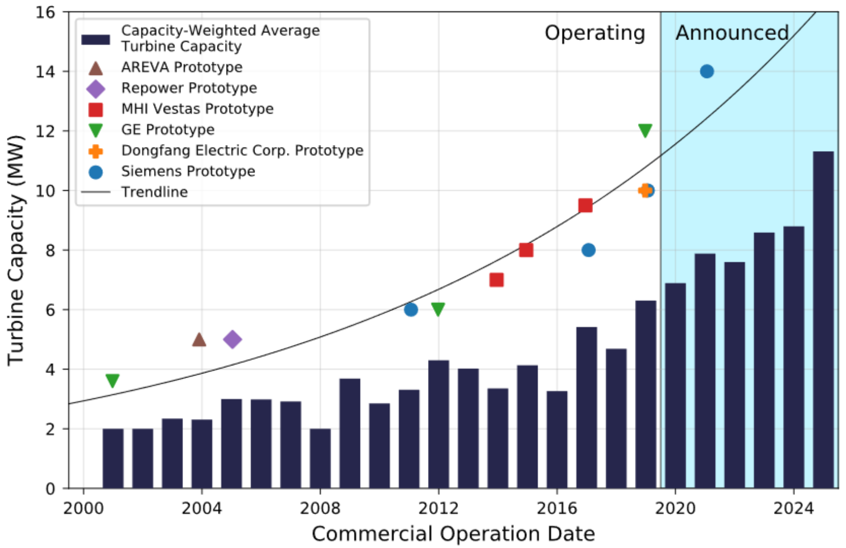
Photo: Principle Power

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

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

- 80% of the global offshore wind resources are suited for floating offshore wind energy
- Floating offshore wind is expected to be deployed at utility-scale by 2024
- Floating wind costs more today due to the immature state of the industry; there are no inherent cost drivers that would make floating more expensive
- Turbine size is approaching 15-MW and spacing is likely to be near 1 nautical mile between turbines.
- Designers are looking at mooring systems to minimize anchor and mooring footprints on seabed and eliminate entanglement hazards.

Thank you for your attention!

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Photo Credit : Dennis Schroeder-NREL