GE 12-MW Turbine Nacelle – 2019

Turbines for Offshore Wind Projects

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Offshore Wind – Global Industry Current Status

GE-Haliade 6 MW Turbines
30 MW Block Island Wind Farm
Rhode Island

- 176 projects, over 22,592 MW installed (end of 2018)
- Typically fixed bottom support structures in shallow water (<50 m)
- Current Installed Turbine capacity 6.0 - 9.5 MW
- Upwind rotors – 150 m -170 m diameter
- Tower height - 25-m plus rotor radius (min)
- Drivetrain - Direct drive or geared with medium speed generators
- Capacity factors up to 55 percent
- Average capital cost $4,350/kW in 2018, declining to below $3,000/kW by 2030
- O&M cost higher than land-based
- Leverages and expands opportunities for existing mature marine industries:
  - Offshore oil and gas
  - Submarine cable
  - Marine operations

U.S. State Offshore Wind Policy Commitments

- 22,480 MW* committed from 8 states by 2035 (and growing)
- 13,956 MW* committed by 2030
- $80 Billion in gross revenue possible
- Regulatory project pipeline for U.S. is calculated at 25,824 MW
- No studies to determine the grid's capacity to inject this amount of power

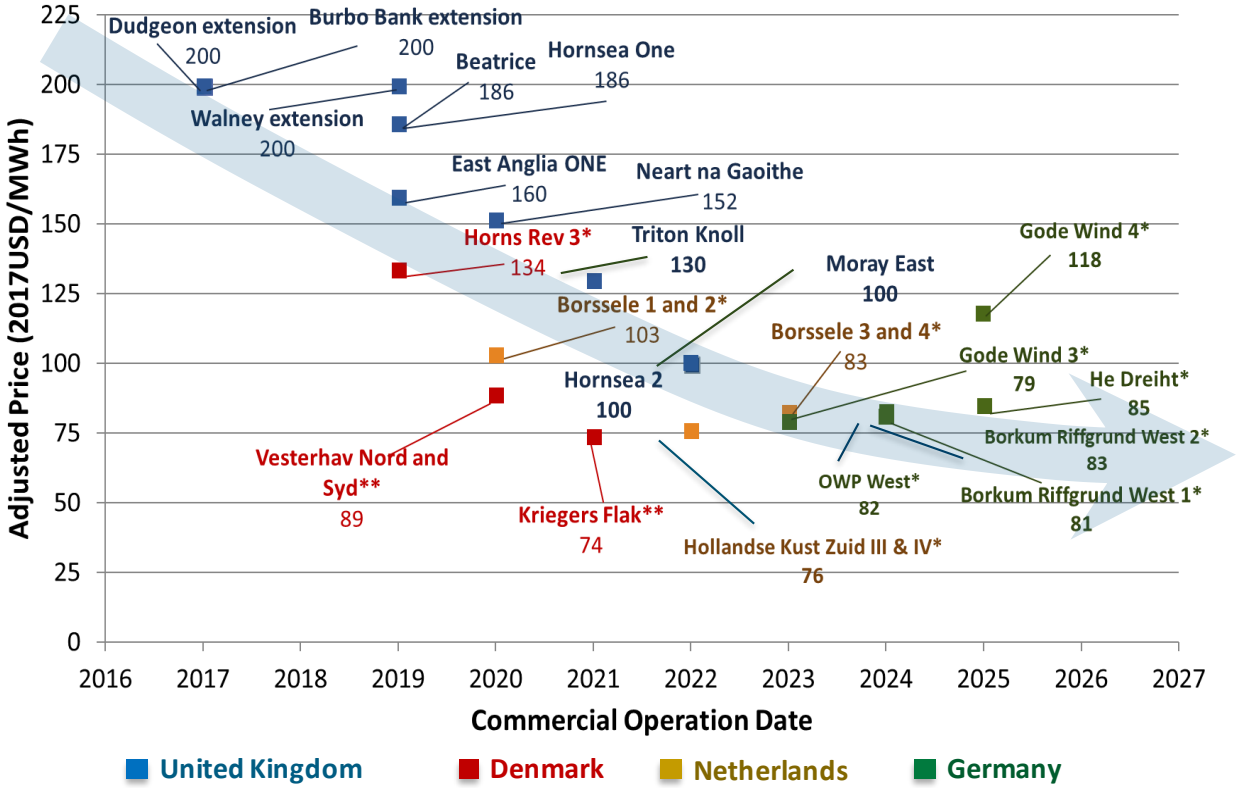
* increased by 2,500 MW from August market report after VA Gov. Northham's Executive Order in Sept 2019

Adjusted Strike Prices from European Offshore Wind Auctions

Data reflect estimated levelized revenue based on winning bids and expected wholesale power market revenues

Why are prices coming down?

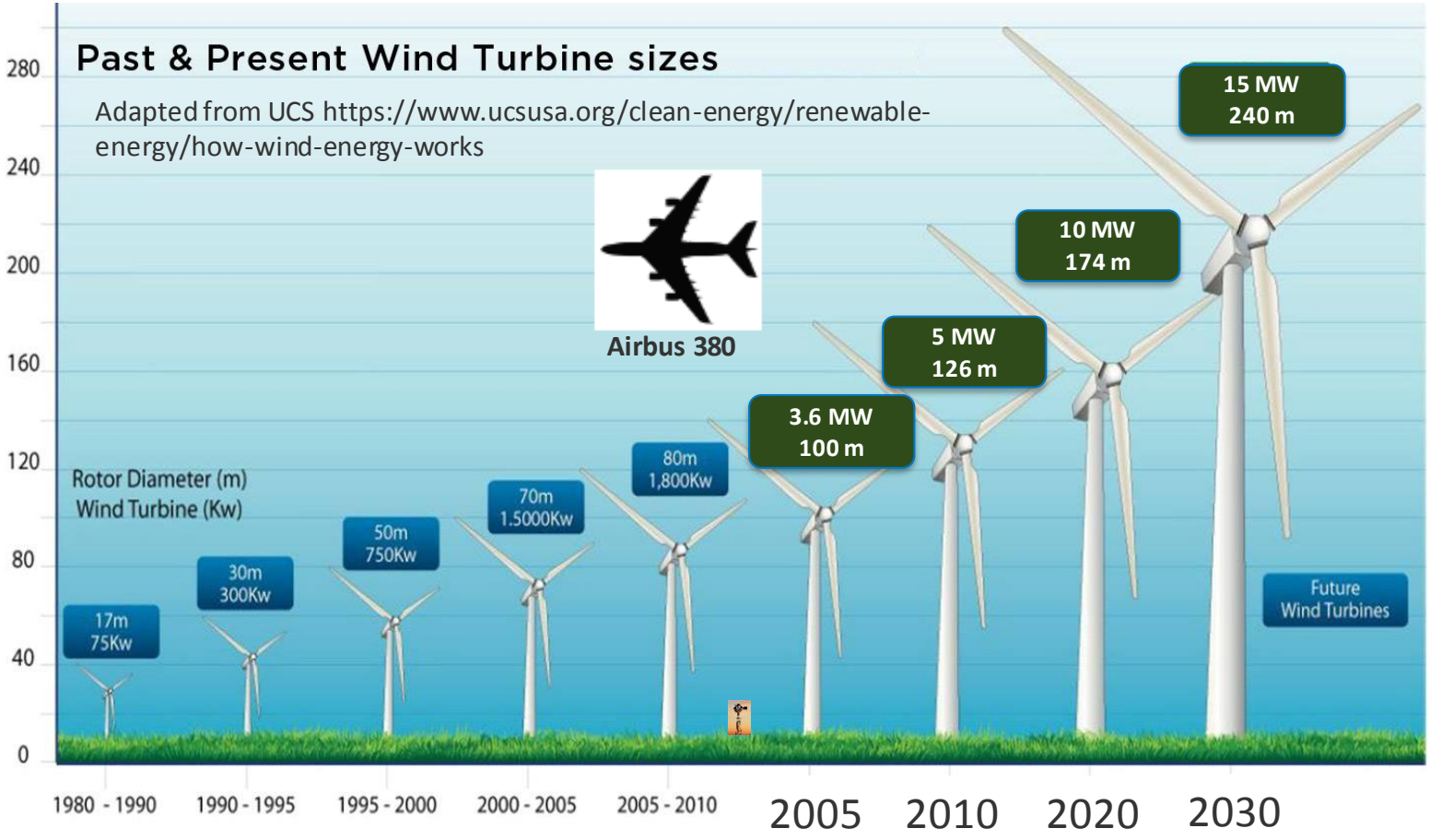
- Technology improvements - larger turbines bring lower project costs
  - Shorter array cables
  - Fewer foundations
  - Lower maintenance
- Larger project sizes (1000-MW)
- Lower risk – lower cost financing
- Maturing supply chains in Europe
- Increased competition

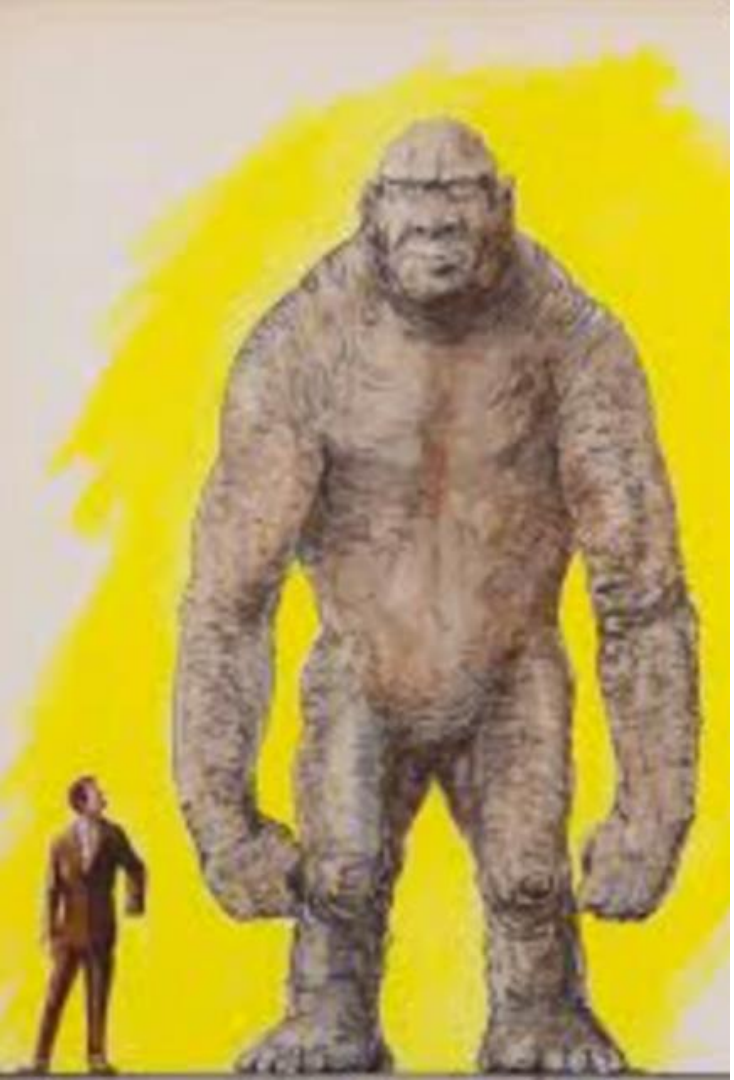


Notes: *Grid and development costs added; **Grid costs added and contract length adjusted

Sources: NREL Spatial Cost Model; BNEF 2017 (German price projections); PBL Netherlands Environmental Assessment Agency (2018) (Dutch price projections)

Offshore Turbine Growth – What are the limits?





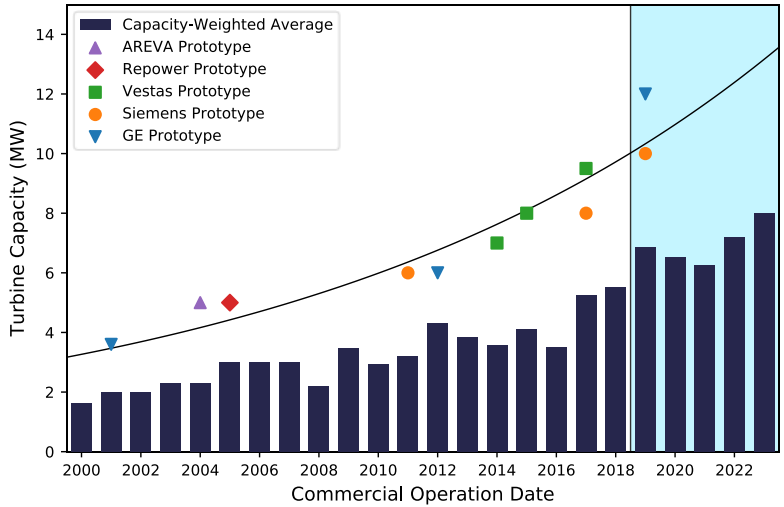
Upscaling Requires Continued Technical Innovation

- Advanced light-weight materials
- Advanced controls to limit loads and protect vital systems
- High-fidelity design and analysis tools
- Material and manufacturing innovations
- Automated service and logistics
- Remote diagnostics and robotic repairs
- Industrialization of the supply chain

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 SG10.0-193 DD turbine**—a 10-MW direct-drive turbine with a 193-m rotor—which is planned to be ready for market in 2022.



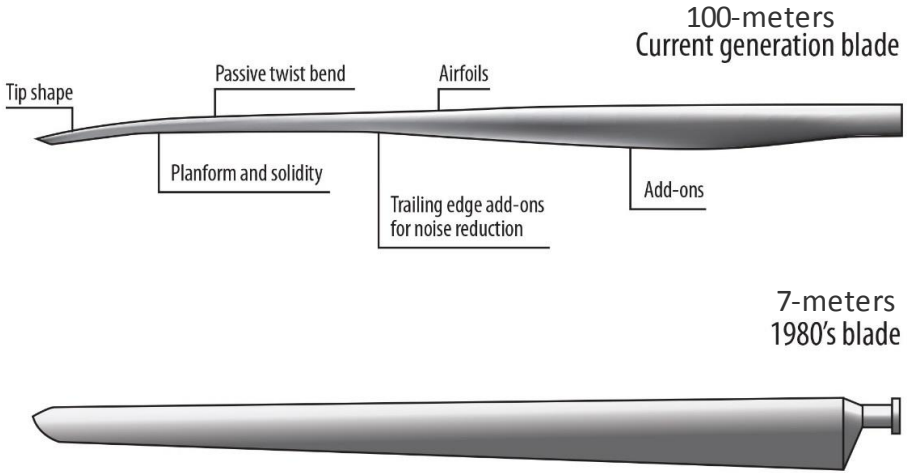
Average Commercial Offshore Turbine Growth With Prototype Development Leading Further Growth

Source: DOE 2018 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

Characterizing the structural, aerodynamic, and hydrodynamics of offshore systems with advanced materials at commodity prices



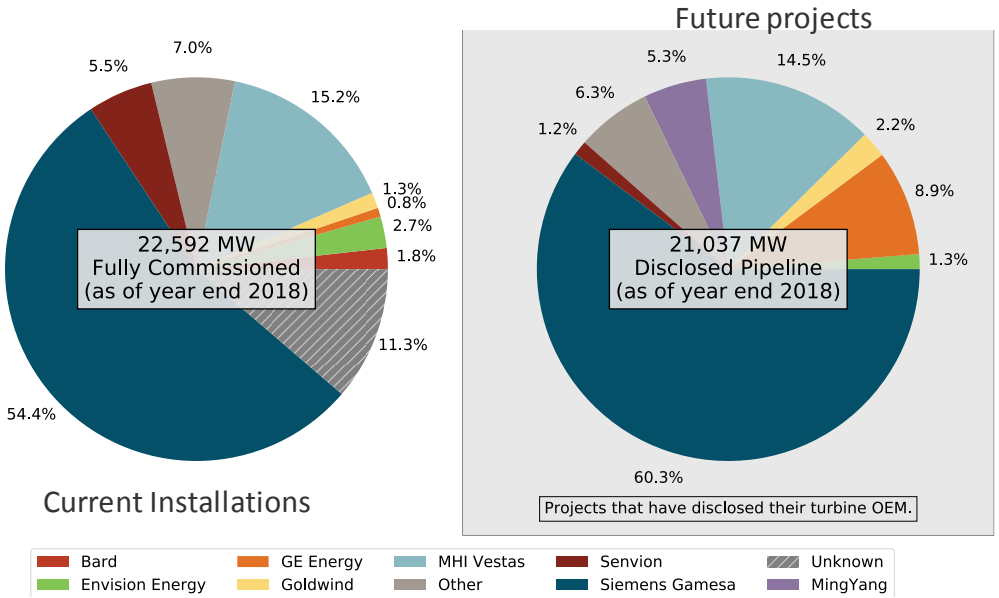
Source: NREL; based on a graphic from Kenneth Thomsen, formerly Siemens Gamesa Renewable Energy.

GE Haliade 12-MW 107-meter Blade Prototype – Longest Blade Ever Built

https://www.ge.com/reports/extreme-measures-107-meters-worlds-largest-wind-turbine-blade-longer-football-field-heres-looks-like/

Siemens Gamesa and MHI Vestas Dominate Offshore Turbine Market

- Siemens Gamesa is largest supplier of offshore wind turbines, with 55% of operating capacity (12.3 GW)
- MHI Vestas has over a 15% share of installed offshore wind capacity
- Siemens Gamesa's global share is projected to grow to 60.3%
- MHI Vestas is expected to hold about a 14.5% share.
- GE's share is projected to grow to 8.9%.
- Goldwind and Ming Yang are building strength in the emerging Chinese market.



OEM: original equipment manufacturer

Chinese Turbine Sizes Also Increasing

Announcement September 25, 2019

RECHARGEWIND

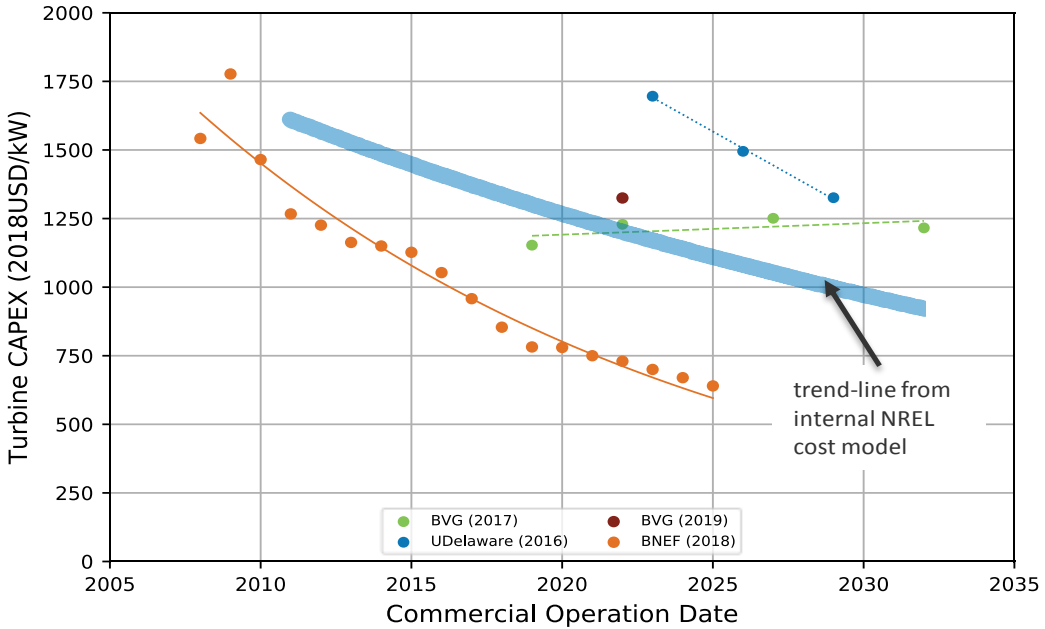
The Dongfang 10MW turbine. Photo: DEC-Zhang

China unwraps first 10MW wind turbine on landmark day

Dongfang unveils nation's first double-digit model and Goldwind reveals 8MW machine as Chinese OEMs ramp-up offshore

Turbine Costs May Decrease Despite Upscaling

- 2018–2019 cost studies indicate turbine CapEx between $800/kW and $1,200/kW
- Innovations may offset cost increases from upscaling.



Source: DOE 2018 Market Report: https://www.energy.gov/eere/wind/downloads/2018-offshore-wind-market-report

Sources: Valpy et al. (2017), Kempton et al. (2016), BVG Associates (2019), and BNEF (2018e)

Commercialization Path for Floating Wind Energy

Photo: Equinor Scotland
30 MW 5 Turbines – Credit: Walt Musial

Proof of Concept Phase
2009 to 2016
6 full-scale prototypes totaling about 20-MW
2 - 7 MW turbines

Pre-commercial Phase
2017 to 2023
Multi-turbine commercial arrays
14 projects
totaling over 200-MW

Commercial Floating Arrays
2024 and beyond
400 MW+ arrays proposed
Principle Power – Hawaii/California
Progression - Hawaii
Equinor - TBD
Trident Wind - California
Dyfed/Kantanes – United Kingdom

Turbines

Adapted land-based turbines

Custom fixed-bottom offshore turbines

Eventual floating-specific turbines

Possible Characteristics of Floating-specific Wind Turbines

- Downwind rotors
  - 30% rotor mass reduction
  - Bigger rotor diameters
  - Rotor tilt (27 degrees) +7% AEP on vertical wake control
  - Yaw stability, yaw system simplification
  - Enabling larger turbines
- Two blades: system weight reduction/simplified installation and maintenance
- High speed/low solidity rotors
- Composite nacelle components /composite towers
- Tilting designs to enable spars at shallow staging sites

Offshore Wind Grid Technology Opportunities

- Large-scale **storage** options
- Multi-wind plant transmission **aggregation**
- Utility-controlled and self-directed **services**
- Offshore **grids**
- **High voltage** array distribution systems
- Wind plant **substation** innovations
- **HVDC** export systems
- Offshore wind value enhancers (2020 BPA study)
- Dry-land burial options

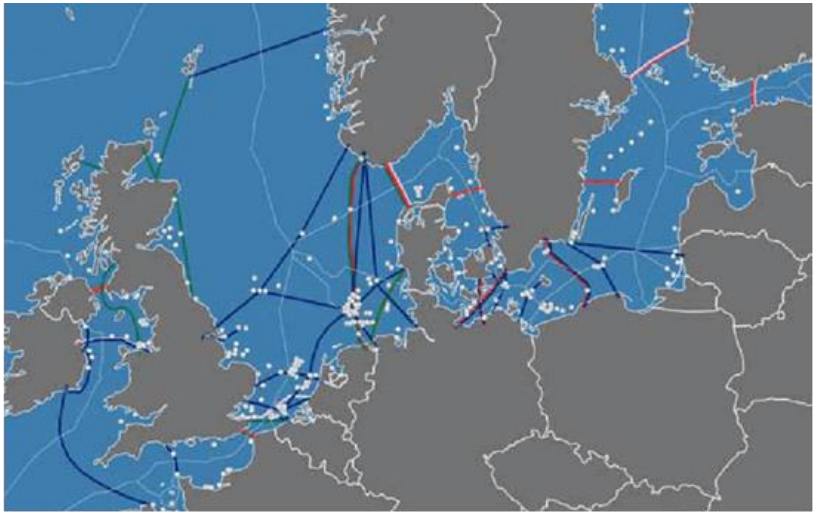


Illustration of possible offshore grid in the North Sea and Baltic Sea
https://www.researchgate.net/figure/Illustration-of-a-possible-offshore-grid-in-the-North-Seas-and-the-Baltic-Sea-source_fig3_318226041

Key Offshore Wind Turbine Challenges

- **Turbine System Upscaling:** Understanding and developing turbine systems and associated infrastructure to scale components, logistics, and operations to 15-MW and beyond while supporting high penetration renewables
- **Providing Grid Services for Integrating 22-GW+:** Strategies to enable more efficient land-based grid connections and offshore transmission expansion to maximize the value of offshore wind while supporting and integrating other renewables
- **Reducing Metocean Uncertainty:** Quantify and validate the offshore wind and wave conditions to raise confidence in power production estimates, resource adequacy, design load calculations, and grid operational strategies at all time scales
- **Hurricane and Low Wind Optimized Turbines:** Hurricane designs optimized to survive in regions where major hurricanes (CAT 3-5) are likely while maximizing energy production in low wind regimes (estimated 1000-GW)
- **Floating Specific Turbines:** Designs, methods, tools and strategies to mature floating wind systems, enabling cost effective offshore wind in deep water regions
- **Reliability Improvements:** Address major industry O&M issues through laboratory testing and validation, improved O&M strategies, remote sensing, high fidelity data analysis, and automation.

Thank you for your attention!

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Photo Credit : Dennis Schroeder-NREL