



Learning from the Experts Webinar Series

Scaling Offshore Wind Turbines



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November 20, 2024

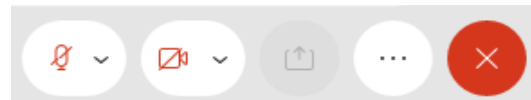
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Learning from the Experts

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Scaling the Offshore Wind Industry and Optimizing Turbine Size

Walt Musial
Chief Engineer – Offshore Wind
National Renewable Energy Laboratory

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Three Ways to Consider Offshore Wind Energy Scale

- **Turbine Scale:** Generally measured by the nameplate generator capacity. Current technology platform is at a ~15 MW turbine scale.
- **Project Scale:** The total nameplate capacity of an entire wind farm comprising multiple turbines. Around 1,000 MW is typically considered “commercial-scale” or “utility-scale.”
- **Market Scale:**
 - The nameplate capacity of the global regulatory project pipeline (~400,000 MW) and/or
 - The cumulative sum of policy commitments and ambitions (~800,000 MW), which may translate to future production volume.

These different types of scaling do not always work together to reduce cost!

Turbine Upscaling

Offshore Wind Turbine Nameplate Capacity up to 200X Larger!



Photo from Getty Images, 1148109714

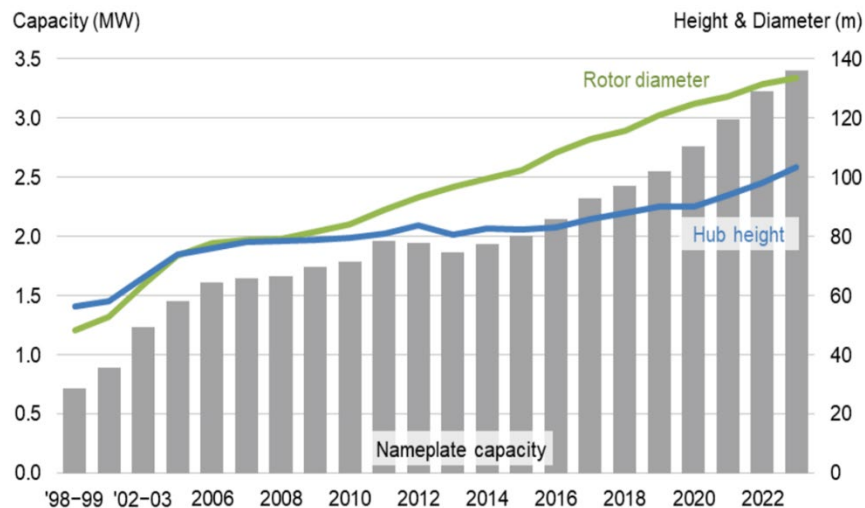
“Wall of Wind” in Tehachapi, California, circa 1985



Photo by Dennis Schroeder, NREL

SGRE 11-MW Turbine: One turbine has approximately the same power output!

Land-Based Wind: Infrastructure Limitations Held Turbine Scale Near 2 MW for a Decade



Average turbine nameplate capacity, hub height, and rotor diameter.



Bridge height (as low as 14 ft [4.3 m]) and limited crane capacity suppressed land-based wind turbine upscaling.

- Stable turbine size enabled industrialization and optimization of the land-based supply chain.
- Mature 2-MW land-based turbines became the first technology platform for offshore wind turbines.

Offshore Wind Turbine Technology Platforms

- For 24 years, the offshore wind energy industry increased turbine size in steps called *turbine technology platforms*.
- NREL's definition: A turbine technology platform is a size envelop of turbine technology and proportionate infrastructure and supply chain capabilities that serve the manufacture, installation, and service of a wind industry sector. It is often shared by multiple parties, lowering risk to individual companies.
 - Platform 1: Turbines adapted from land-based 2-MW machines
 - Platform 2: First generation of offshore-specific turbines (e.g., PMDD generators, medium-speed generators)
 - Platform 3: Second generation of offshore-specific turbines with similar architectures.

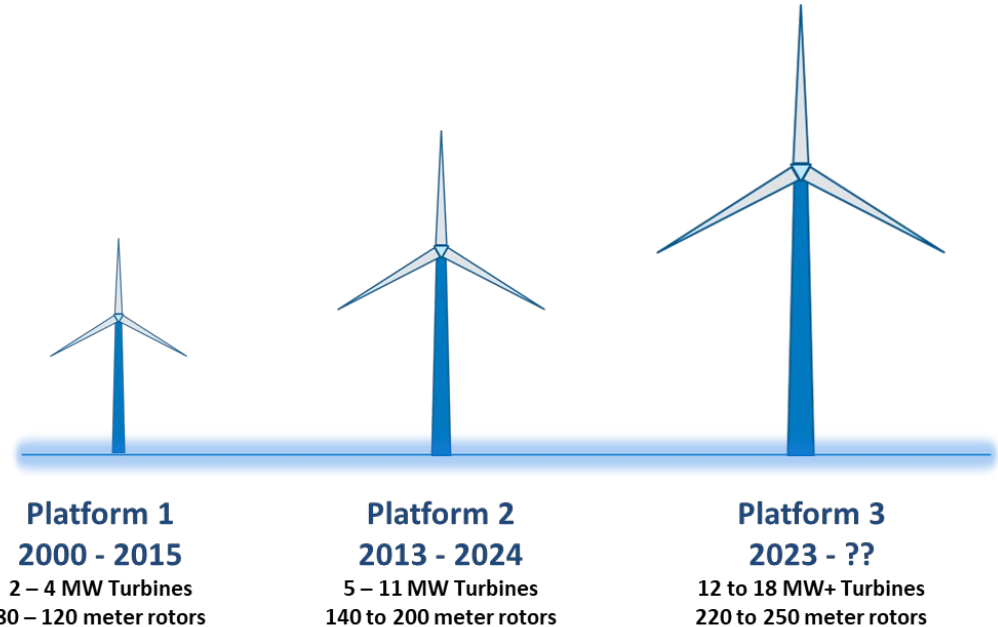
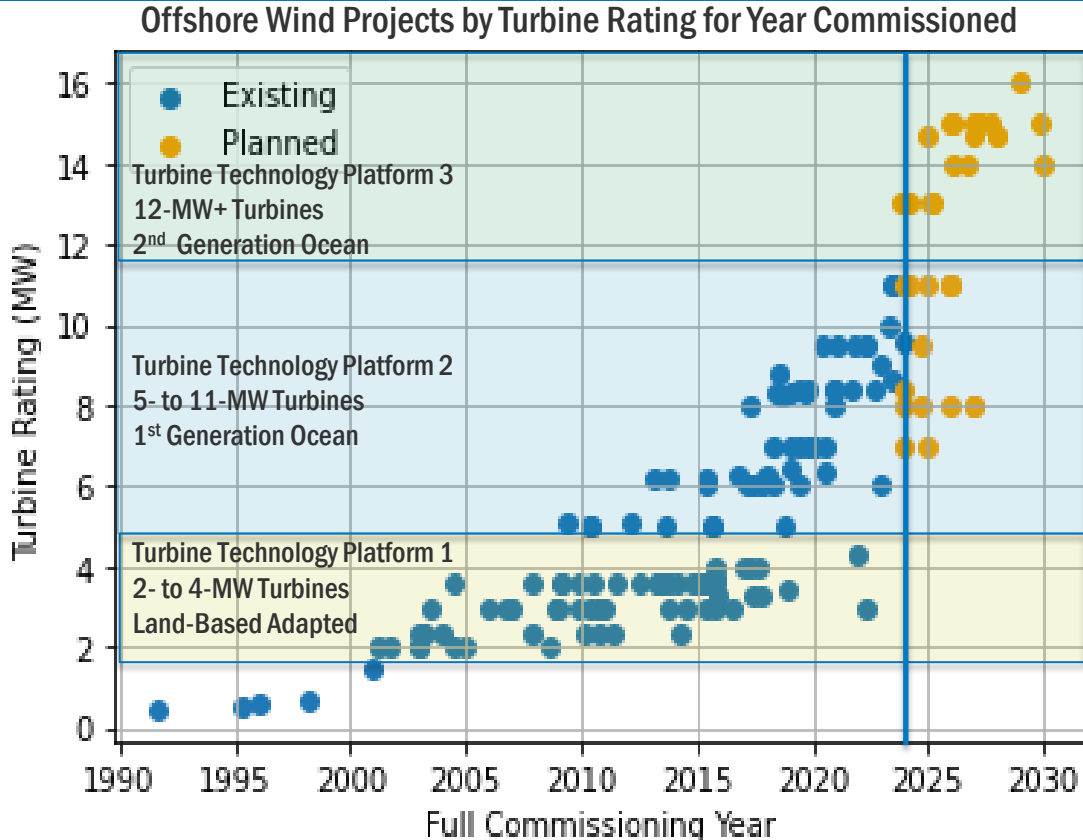


Figure by NREL

Incremental upscaling and design optimization within a turbine technology platform have allowed industrialization and learning bounded by the established infrastructure and supply chain capacity limits.

Historic Offshore Wind Project Growth



- While land-based upscaling slowed, offshore upscaling has accelerated to a 15-MW scale because it was unconstrained by infrastructure ... until now.
- Infrastructure limitations are greater in the United States than in Asia and Europe, and the Jones Act further limits options.
- Platform 3 for 15-MW-scale turbines is still being built, requiring large infrastructure and supply chain investment.

Technical Advancements Have Enabled 15-MW Turbines

Technology advancements over the past two decades have enabled wind turbine manufacturers to build the world's largest rotating machines

Technology Upscaling Enablers:

- 6–10-MW technology operating experience
- Advanced lightweight materials
- Innovations in manufacturing and automation
- Advanced load control to protect vital components and reduce weight
- Increased accuracy in high-fidelity design and analysis tools
- Remote diagnostics and repairs.



Photo from SGRE
**Siemens-
Gamesa
14.7-MW
Turbine**



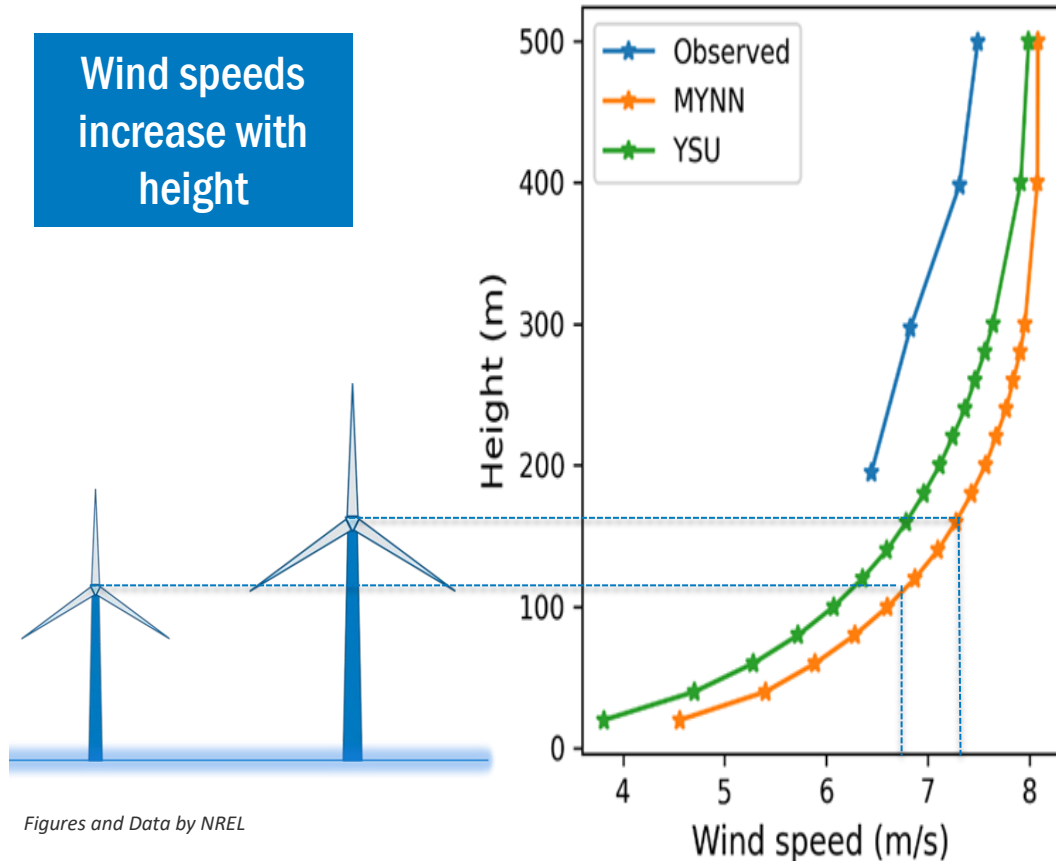
Photo by Dennis Schroeder, NREL
**GE Vernova
13/14-MW
Turbine at
Vineyard Wind**



Photo from Vestas
**V236 15.0-
MW prototype,
Østerild,
Denmark**

What Are the Benefits of Continued Turbine Upscaling?

- ✓ Fewer turbine positions
- ✓ Smaller seabed footprint
- ✓ Wider turbine spacing reduces navigation concerns
- ✓ Reduced costs help win in competitive state procurements
- ✓ Prescribed turbine spacing (like MA/RI spacing of 1×1 nm) incentivizes larger turbines to increase capacity density
- ✓ More energy from taller towers.



What Are the Concerns of Further Upscaling?

The laws of physics are a key consideration:

The “square-cube law” says that a wind turbine’s energy output increases by the square of its rotor diameter, but the turbine’s weight will increase with the cube of the diameter.

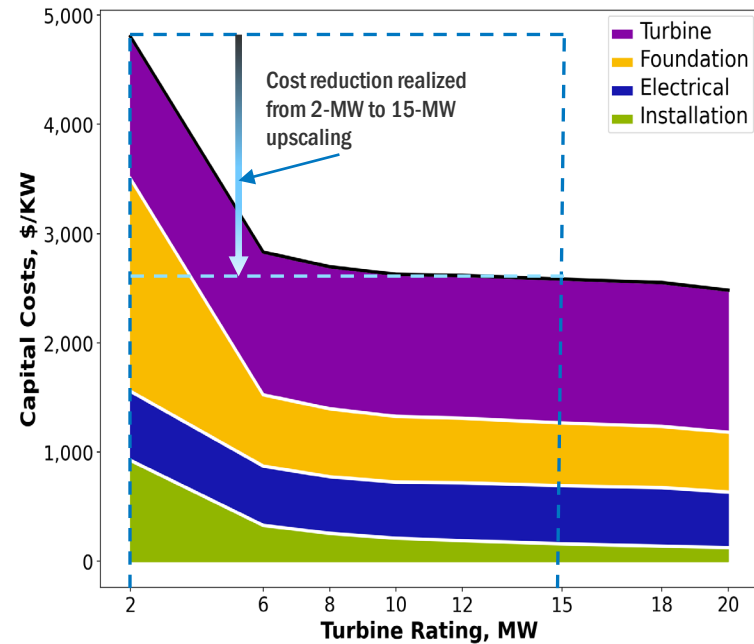
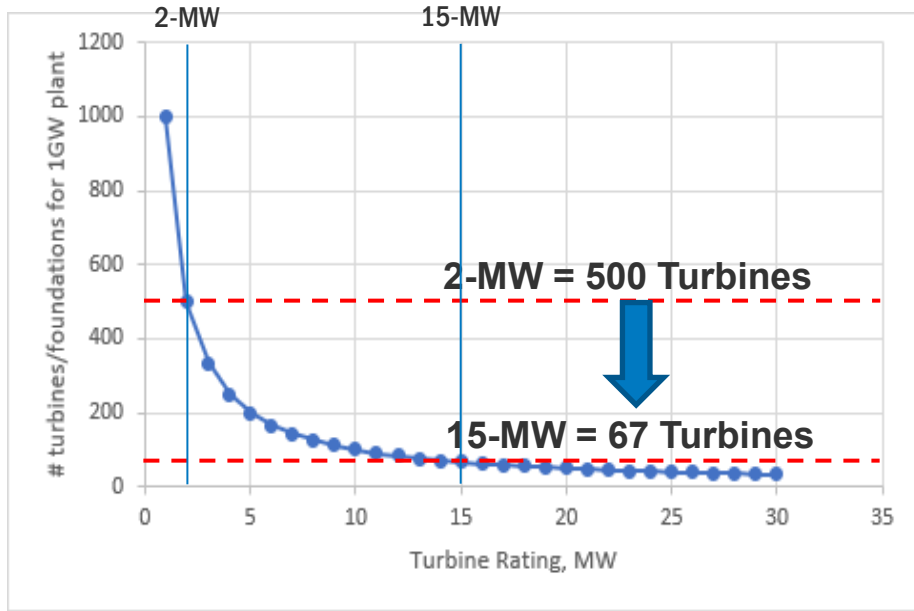
No hard limits to turbine upscaling, but there may be economic and practical limits:

- Diminishing returns on reduced turbine positions
- Turbines may get more expensive per megawatt (square-cube law)*
- Infrastructure investment requirements grow disproportionately
- Unproven technology poses risks and may take years to mature, potentially delaying industry learning, deployment, and cost reduction
- Some future markets may be forsaken (e.g., repowering, island nations, non-industrialized countries).

** Based on testimony from a major turbine manufacturer*

The Primary Business Case for Increasing Turbine Size: Lower Cost by Reducing the Number of Turbine Positions

Based on 1-GW Plant Size



Figures adapted from [Shields et al. 2021. Applied Energy](#)

Most of the low-hanging fruit has been picked.

Offshore Wind Infrastructure Costs Are Rising With Turbine Size

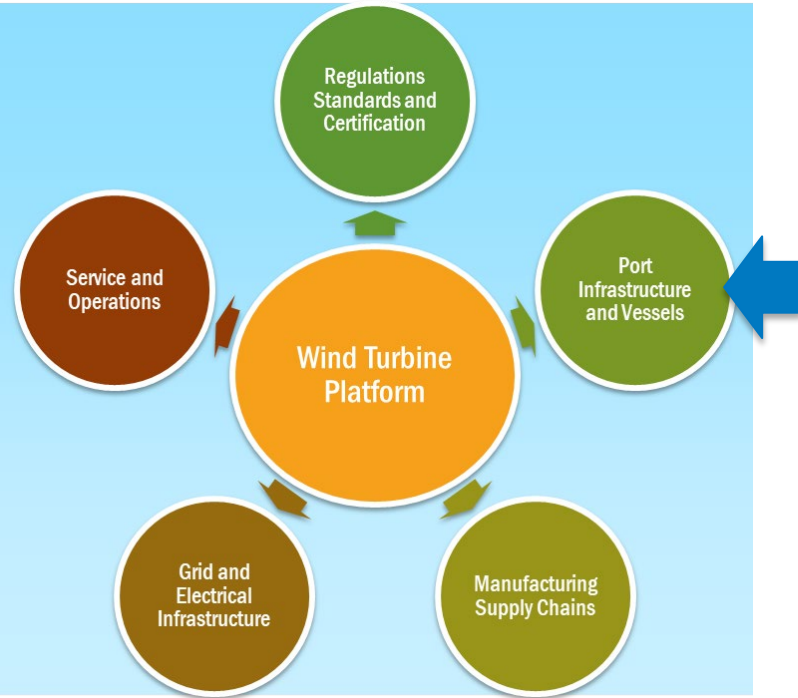


Figure by NREL

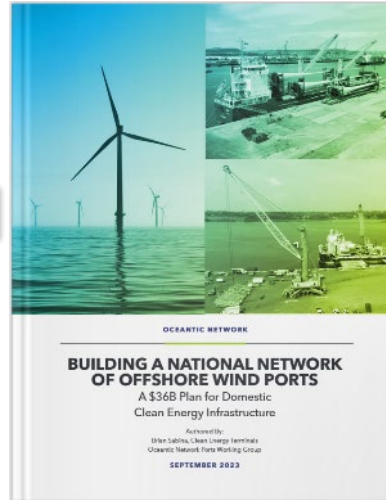


Image from Oceanic Network

- All aspects of the supply chain are dependent on turbine size.
- 15-MW class turbines will require significant port infrastructure investment. Oceanic Network estimates \$36B (2023 Oceanic Network Ports Study).
- These investments are not controlled by developers.
- Uncertainty due to infrastructure and supply chain is a dominant risk factor.
- Stabilizing turbine growth within a particular market may help incentivize infrastructure investments and protect them from premature obsolescence.

What Killed These Jumbo Jets?

“Airbus A380: End of a multibillion-dollar dream” December 2021

“Jumbo jet era ends as Boeing delivers last 747 plane” January 2023

Photo from Boeing



Photo from Getty Images, 157727486s



- Jumbo jets like the Boeing 747 and Airbus A380 require more than 3,000 m of runway while the Boeing 737 can take-off with less than 1,800 m.
- Smaller planes can serve regional airports where many passengers want to go, and airline companies were not able to fill the big planes.
- Airport infrastructure favors smaller aircraft, but larger aircraft are still needed for international flights, cargo, and major hubs.
- Multiple aircraft sizes are needed to serve *diverse global markets*.



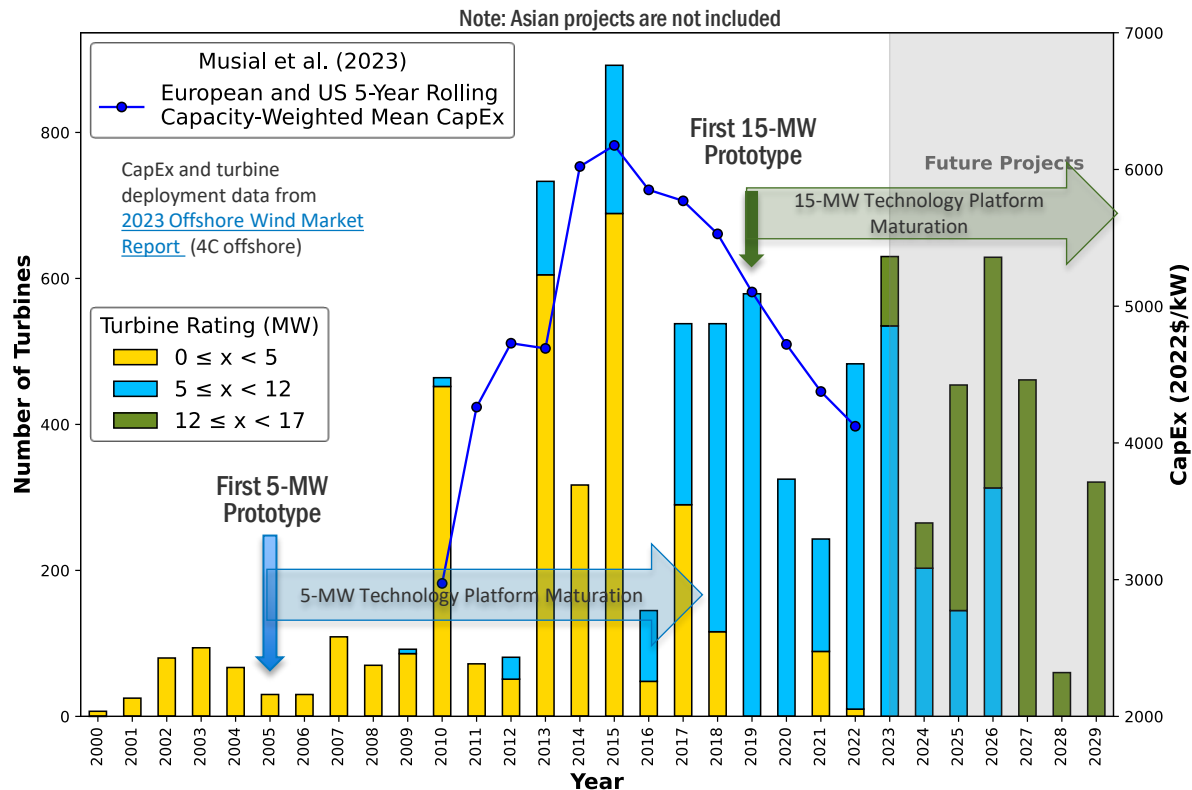
United airlines fleet



Historic Industry Data Show That Commercial Scale Production and Cost Reduction Benefits Can Take 10 Years

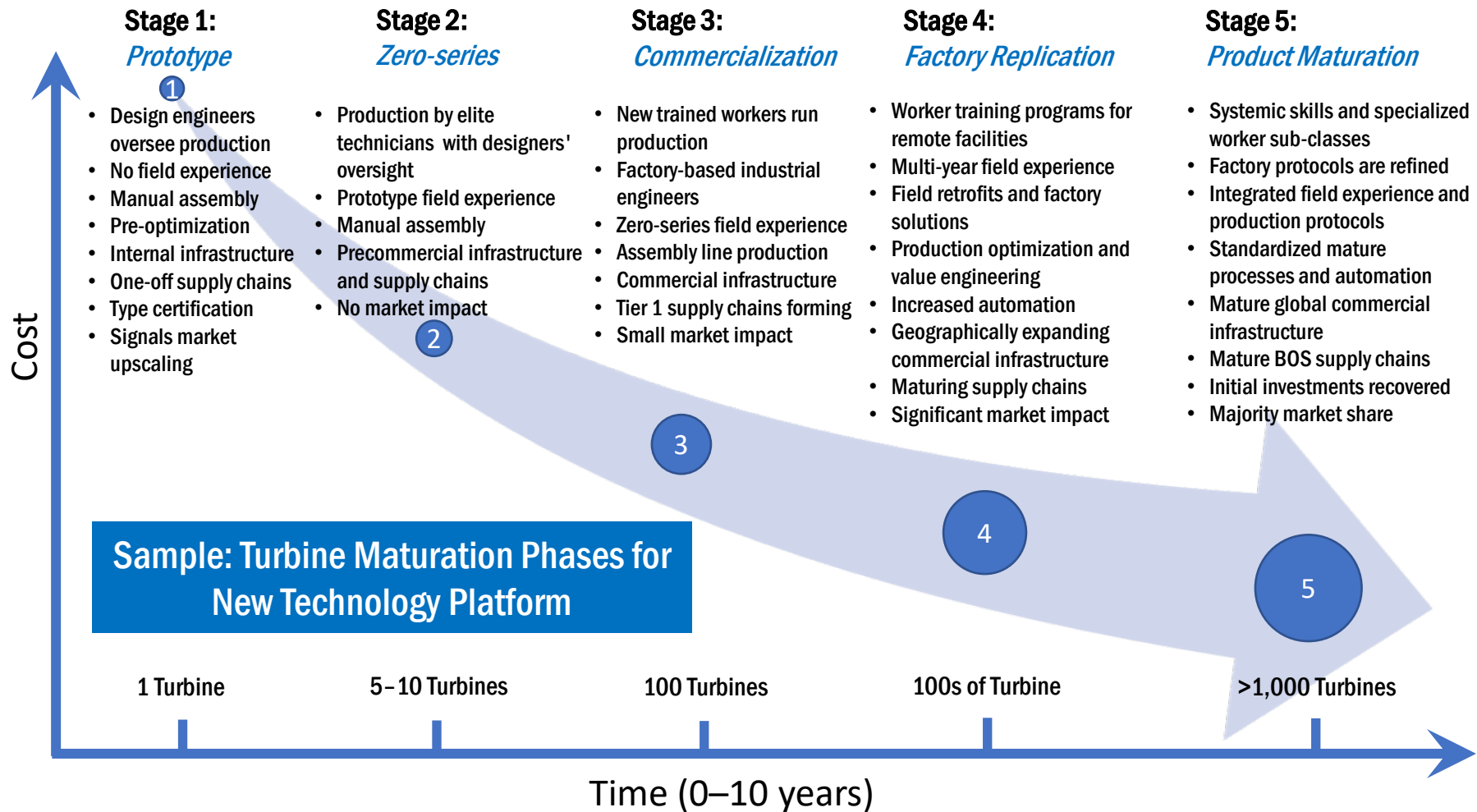
- First prototype 5-MW turbine was deployed around 2005.
- Sustained cost reductions began in 2015 due to:
 - ✓ Maturing supply chains for turbine size of 2–4 MW
 - ✓ Commercialization of 6-MW scale
 - ✓ Competitive auctions
 - ✓ Competition from Asia.

Technology risk increases during early stages of new platform development.



Potential Risks Due to New Technology Adoption

- **Technical risk:** New turbines are more likely to have design oversights or defects.
- **Construction risk:** Logistics depend on new and uncertain infrastructure and vessel development schedules that can delay projects.
- **Supply chain risk:** Critical supply chain facilities need to be built. Vulnerabilities increase with larger turbines because investments requirements increase, and manufacturing locations are scarcer.
- **Safety risk:** Greater human safety risks may arise from new hazards and inexperience.
- **Operational risk:** New turbine technology that has not been field verified may have higher failure rates.
- **Lost market momentum risk:** A new turbine prototype can take many years to mature before cost reductions are realized.



Cost Reduction Through Project Scale



Vineyard Wind 1 – Sept. 10, 2024
Photo by Dennis Schröder

Project Scale: Big Projects Cost Less

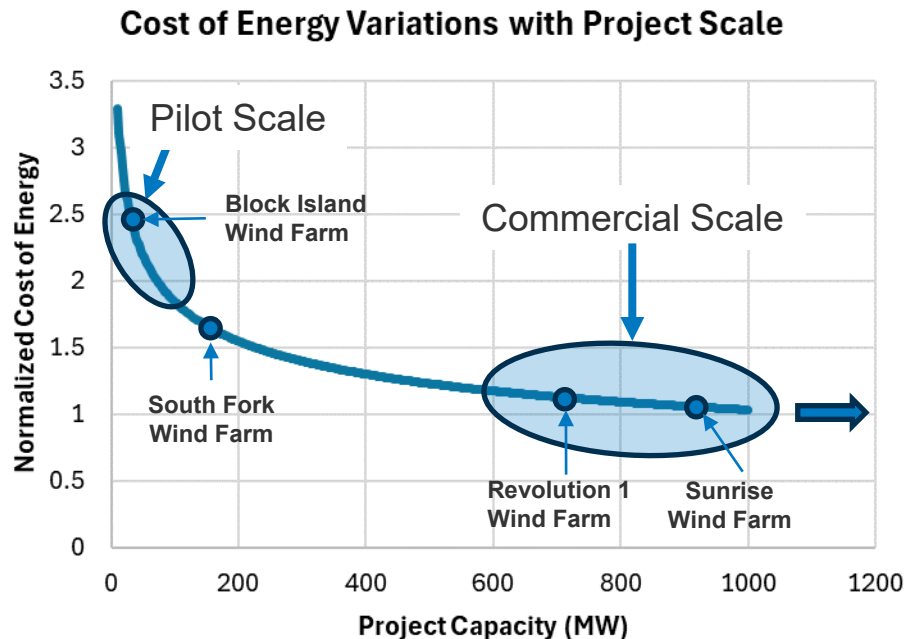


Figure and Data by NREL

- One of the most impactful cost of energy variables.
- Pilot projects (<100 MW) are needed to demonstrate new technology but are 2.5X more expensive than commercial projects.
- Smaller projects have cost inefficiencies due to reduced economies of scale, poor amortization of key components, and poorer procurement leverage.
- Commercial scale is necessary to achieve cost targets and technology maturity—but not sufficient.

Cost reduction benefits from project scaling can be realized immediately and do not depend on turbine size.

Market-Scale Cost Reduction Through Learning



New Bedford Marine Commerce Terminal, Sept. 9, 2024

Photo by Dennis Schröder

Offshore Wind Market Scale/Market Certainty

- Sufficient market scale is needed to achieve technology maturity and to attract infrastructure and supply chain investment.
- Technology maturation comes from industrialization of the supply chains, field experience, sustained innovation, and learning by repetition (mass production).
- Market scale needs to be large enough for investors to recover investment costs.



Demonstrating sufficient market scale AND market certainty are essential to attract domestic supply chain investment and lower costs.

Offshore Wind Market Scale & Market Certainty

(by the numbers)

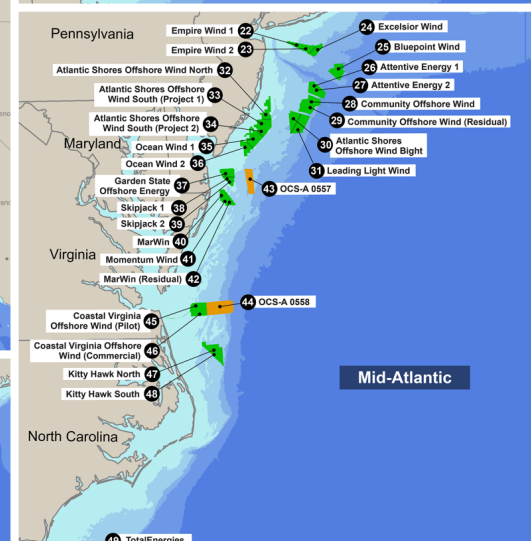
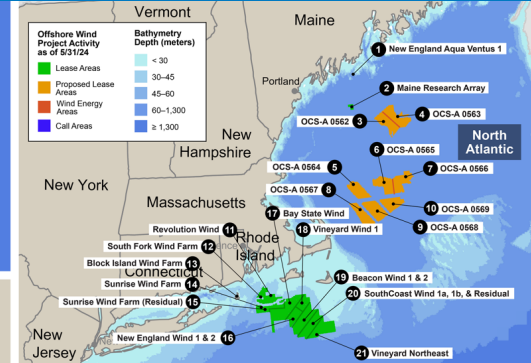
Globally:

- **807 GW** of total offshore wind “ambitions” estimated (TGS market intelligence - 4C Offshore) aggregate of multiple sub-markets.
- **454 GW** in offshore regulatory pipeline

United States (as of May 31, 2024):

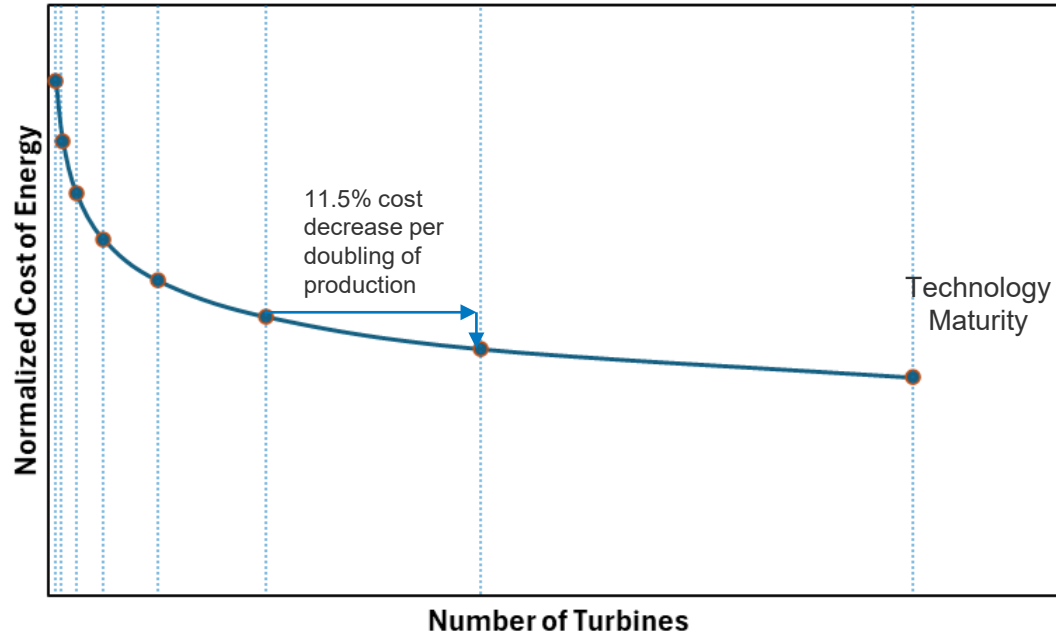
- **80.5 GW** in total U.S. project pipeline – 65 offshore wind “projects” (See Figure)
- 25.1 GW of floating wind in the US Pipeline
- 55.4 GW of fixed bottom wind in the US pipeline
- **0.174 GW** installed in U.S.
- **7.5 GW** approved and under construction
- **19.8 GW** are in permitting (developer has filed a COP or has an offtake)
- **45.7 GW** of procurement mandates in eight eastern states
- **115.1 GW** of mandates & soft targets combined (U.S ambitions)

Source: NREL: [Offshore Wind Market Report: 2024 Edition](#)



Graphic by John Frenzl, NREL

Offshore Wind Learning Curve

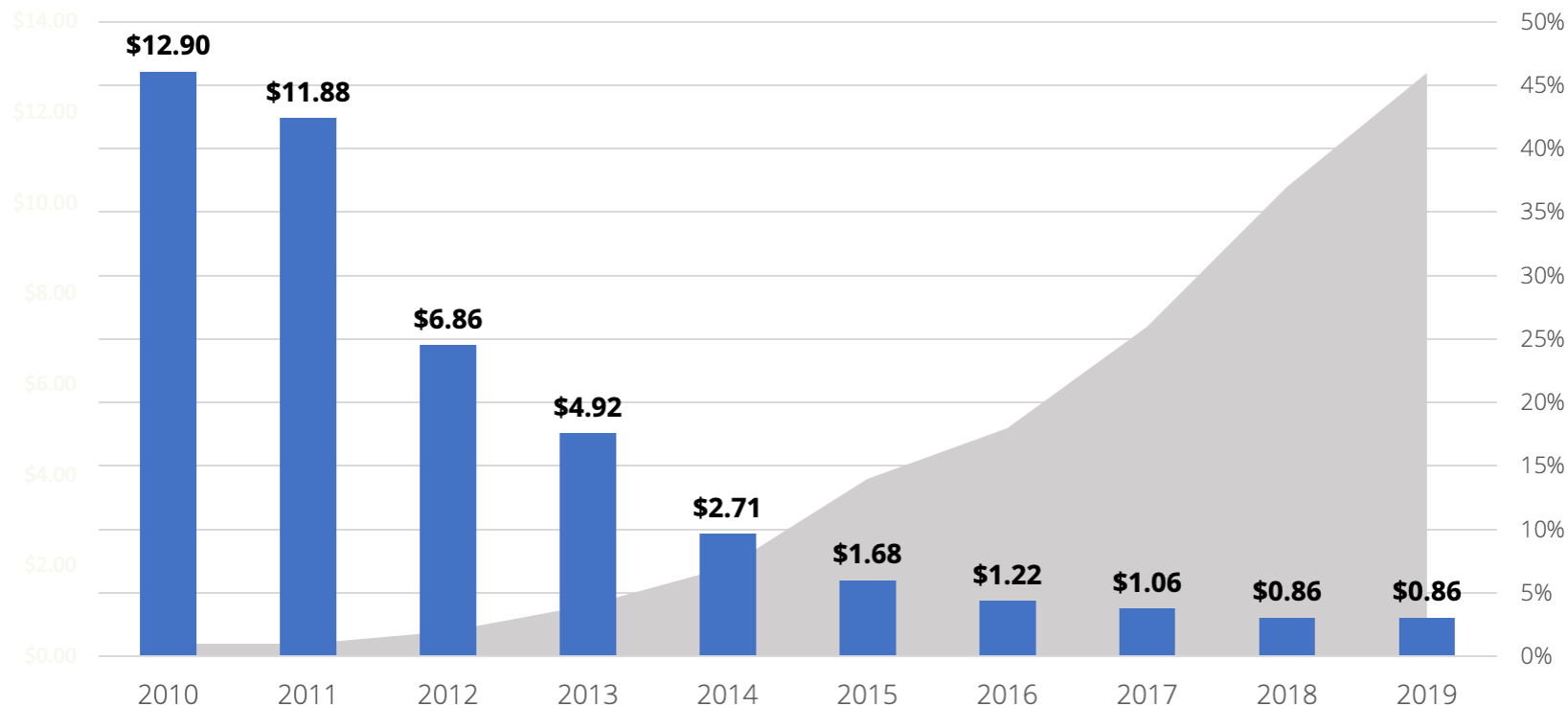


The learning curve is a well-known mathematical concept that says that the average cost of a unit decreases by a fixed percentage each time the production volume doubles.

Example learning curve for offshore wind based on historic industry growth and cost declines. Each vertical line represents a doubling of production volume. NREL's assumed learning rate for floating offshore wind is 11.5% per doubling.

LED lighting costs decline as volumes increase

(US\$ cost per kilolumen / LEDs as a percent of global lights sold)

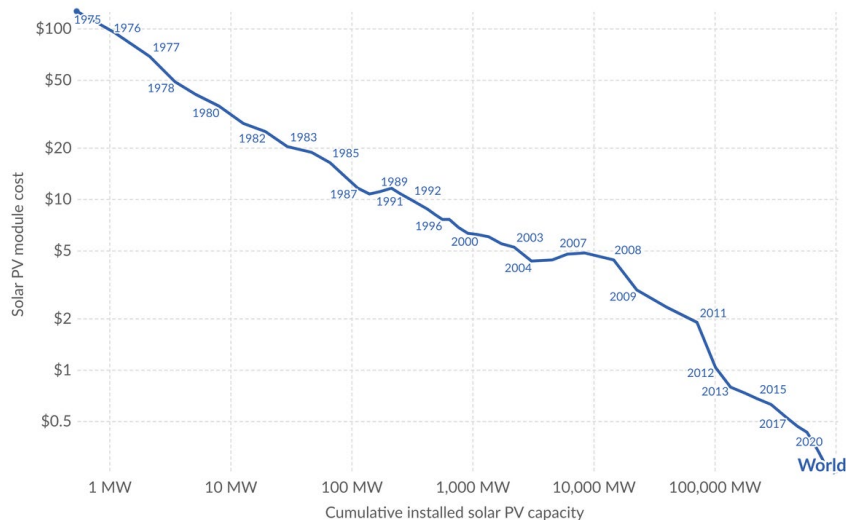


FREEING
ENERGY

Solar PV Project Costs Have Dropped 80% Since 2010

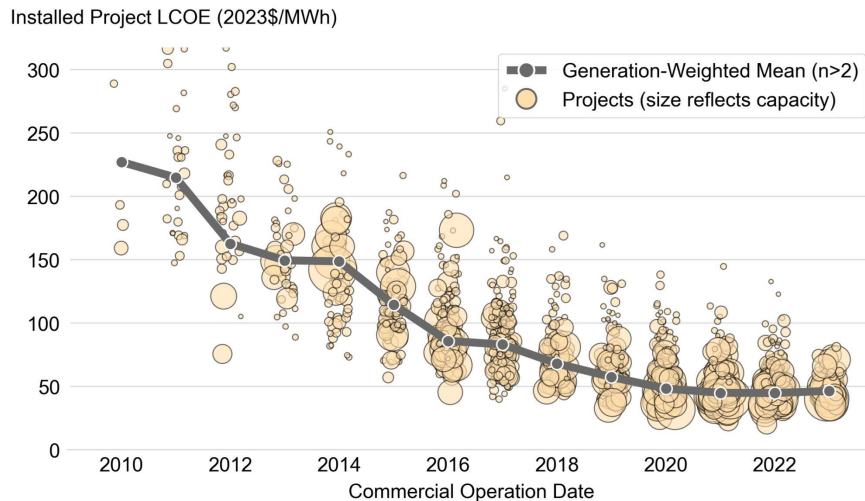
Solar panel costs have fallen by around 20% for every doubling of global cumulative capacity.

(Costs are measured in U.S. dollars per Watt, adjusted for inflation)



Data source: IRENA (2023); Nemet (2009); Farmer and Lafond (2016)

Utility-scale PV average LCOE has fallen by 80% since 2010, driven by lower capital costs and operating expenses, as well as increased project design life.



Source: Lawrence Berkeley National Laboratory: <https://emp.lbl.gov/sites/default/files/2024-10/Utility%20Scale%20Solar%202024%20Edition%20Slides.pdf>

The learning curve has a big impact when production volume is large.

Learning to Build World War II Liberty Ships

- Eighteen U.S. shipyards built 2,710 Liberty Ships between 1941 and 1945, average of three ships every two days.
- Production rate increased by 10X in two years; First ship took 244 days in 1941, while the average was 39 days per ship by 1943.

Comparisons with Offshore Wind Semisubmersible Floaters for 15-MW Turbines

Characteristics	Liberty Ship	15-MW Floating Wind Turbine Hull
Displacement (tons)	14,245	10,000–20,000
Draft (meters)	8.5	~8–10
Length/column spacing (meters)	135	~100
Cost (2024 dollars)	\$43 M	\$30–\$50M
Demand (units)	2,710	2,710 = 40 GW

Top right photo: Kaiser shipyards, Richmond, California. Miss Eastine Cowner, a former waitress, is helping in her job as a scaler to construct the Liberty ship SS George Washington Carver

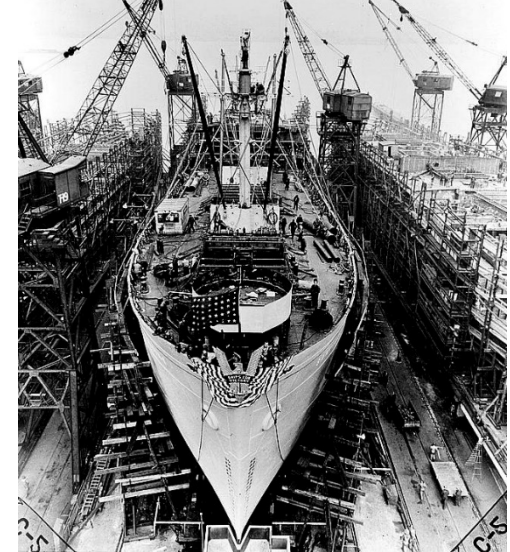
https://en.wikipedia.org/wiki/Liberty_ship#cite_note-FOOTNOTESawyerMitchell198539-2

Sawyer, L. A.; Mitchell, W. H. (1985). *The Liberty Ships: The history of the "emergency" type cargo ships constructed in the United States during the Second World War*. London: Lloyd's of London Press. ISBN 978-1850440499



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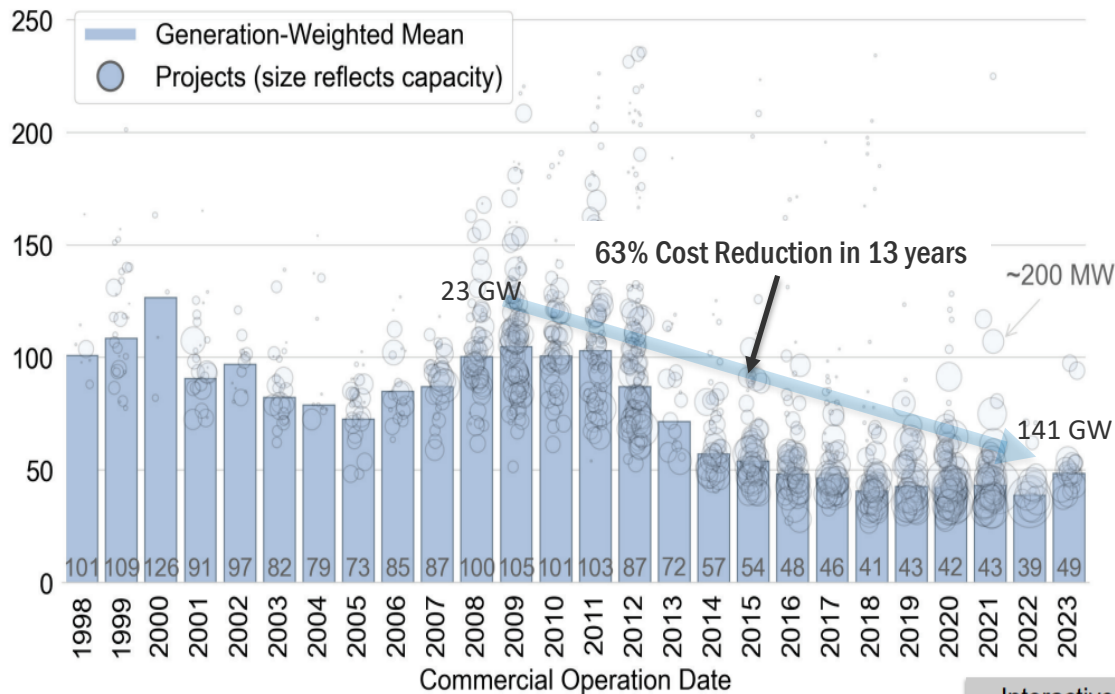
Bethlehem-Fairfield Shipyards Inc., Baltimore, Maryland (US) in March/April 1943



fsa 8e01456 <http://hdl.loc.gov/loc.pnp/fsa.8e01456>

Land-Based Wind Experienced 63% Cost Reductions From 2009 to 2022

Installed Project LCOE (2023\$/MWh)



Source: Berkeley Lab

Note: Yearly estimates reflect variations in installed cost, capacity factors, operational costs, cost of financing, and project life; includes accelerated depreciation but excludes PTC. See full report for details.

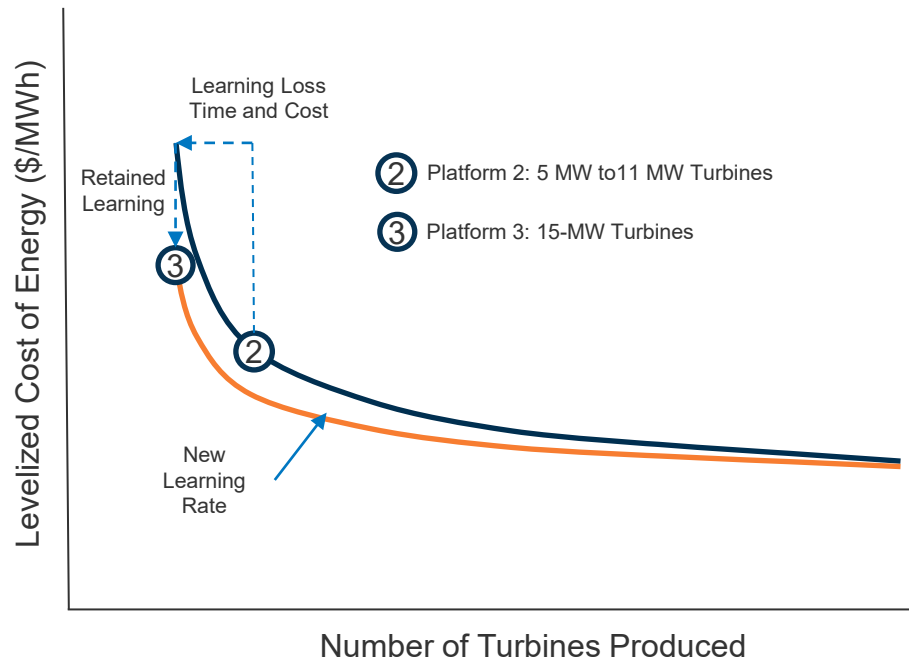
Interactive data visualization:

<https://emp.lbl.gov/levelized-cost-wind-energy>

- U.S. wind deployment at the beginning of 2009 was about 23 GW.
- U.S. wind deployment at the end of 2022 was about 141 GW, 6X growth.
- Cost rise in 2023 due to lower capacity factors and inflation.

Theory of Learning Loss: New Unproven Technology Resets Part of the Learning Curve

- New turbine platforms:
 - New supply chain and infrastructure development
 - Increased technology risk
 - Retraining and workforce development.
- Some learning is retained.
- Total market size may decrease with turbine size because fewer total turbines are needed.
- Some sub-markets may be lost.



China's Role

China Is Going Big on Turbine Size – How Should the West Respond?

Colossal 20-MW wind turbine is the largest on the planet (for now)

By Abhinav Ghoshal
September 04, 2024



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Shanghai Electric unveils 25MW offshore wind turbine

a 25MW offshore wind turbine, which would be one of the most powerful turbines in the world.



electrek

China debuts a record-smashing 26 MW offshore wind turbine

Oct 14 2024 - 1:22 pm PT | 19 Comments



Photo: Dongfang Electric Corporation

China unveils kit to test 35MW wind turbines

News comes just days after 26MW machine was rolled out by another Chinese OEM as supersizing of wind turbines shows no sign of abating



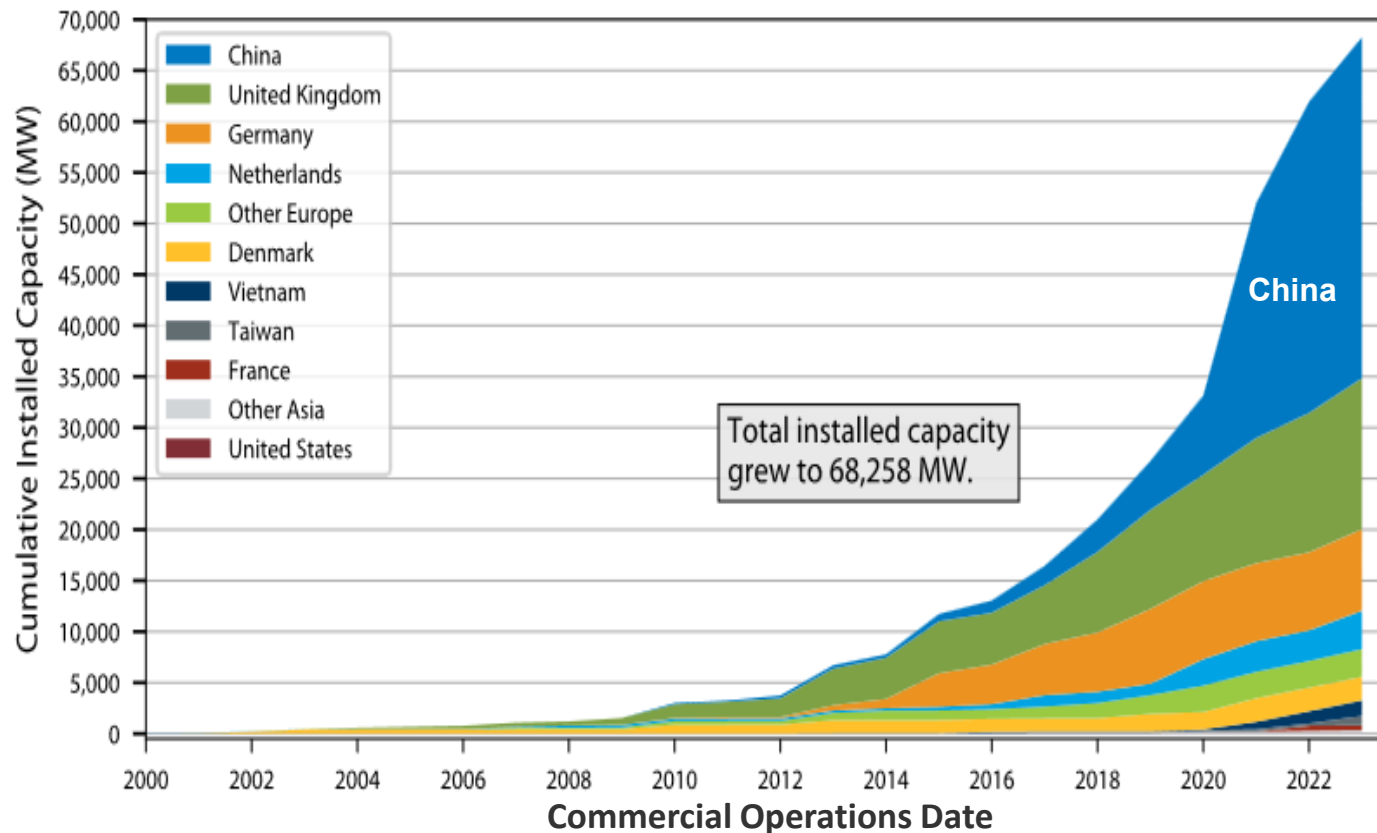
A picture of the new test bench released by Sany. (Photo: Sany)

Casimiro Sanderson
Journalist

Published on 10/14/2024, 10:28 AM

Headlines from the last few months

Chinese Offshore Wind Represents Almost Half of All Deployments



Source: NREL: Offshore Wind Market Report: 2024 Edition
<https://www.nrel.gov/docs/fy24osti/90897.pdf>

Chinese and Asian Offshore Wind Infrastructure Capacity May Be 20X Greater Than U.S. Capacity

- China's market is different; China's massive ports manufacturing and supply chain capacity can accommodate greater upsizing.
 - China has 20 wind turbine installation vessels (WTIV) under construction now. The U.S. has 1 (Wood Mackenzie).
 - China's top-down approach (state-owned companies) has integrated military and civilian shipbuilding. In 2022, 92% of global shipbuilding came from China, South Korea, and Japan.
 - China makes 60% of all offshore turbines, 99% are deployed in Asia but European markets may be softening.



Photo from Cadeler

Cosco Shipyard in China launching Cadeler's newbuild vessel Wind Peak

<https://hbs.unctad.org/merchant-fleet/>

<https://www.oedigital.com/news/510532-chinese-shipyard-launches-cadeler-s-newbuild-offshore-wind-vessel>

<https://asiatimes.com/2023/02/us-navy-laments-chinas-shipbuilding-supremacy/>

<https://green-giraffe.com/publication/blog-post/chinese-turbines-cannot-succeed-in-the-european-offshore-wind-market-because-they-are-not-bankable-myth-or-reality/>

20-MW+ turbine logistics will be difficult outside of Asia; the U.S. does not have the capability to install these machines. A multiscale/multi-market approach may be needed.

Upscaling Takeaways

- 15-MW capacity turbines were enabled by technology advancements despite “square-cubed” physical limits.
- Diminishing returns on benefits of further turbine upscaling.
- Failure to account for risks due to technology immaturity, large infrastructure investments, and increased time-to-market may bias expectations for cost reductions from upscaling.
- Cost reduction potential from industry learning at 15-MW scale may be larger than the benefits of further upscaling.
- Ultra-large 20-MW+ Chinese turbines may be suited for Chinese markets but are not practical for U.S. markets.
- Collective industrywide intelligence is needed to manage upscaling, avoid U.S. supply chain obsolescence and to address multiple global market types.
- Multiple turbine sizes are needed to serve diverse global sub-markets.

Thank you for your attention!

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Photo by Dennis Schroeder, NREL

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