Scaling the Offshore Wind Industry and Optimizing Turbine Size

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Photo by Dennis Schroeder, NREL

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!

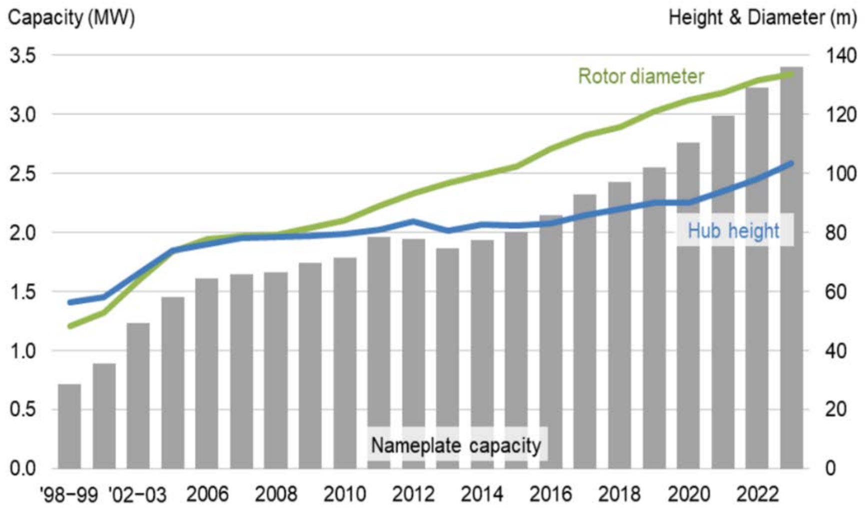
Turbine Upscaling

Offshore Wind Turbine Nameplate Capacity up to 200X Larger!

"Wall of Wind" in Tehachapi, California, circa 1985

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.

Data Source: https://emp.lbl.gov/sites/default/files/2024-08/Land-Based%20Wind%20Market%20Report_2024%20Edition.pdf

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 an envelop of turbine technology and proportionate infrastructure and supply chain scale and capabilities that support the manufacture, installation, and service of a wind industry sector.
  - 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.

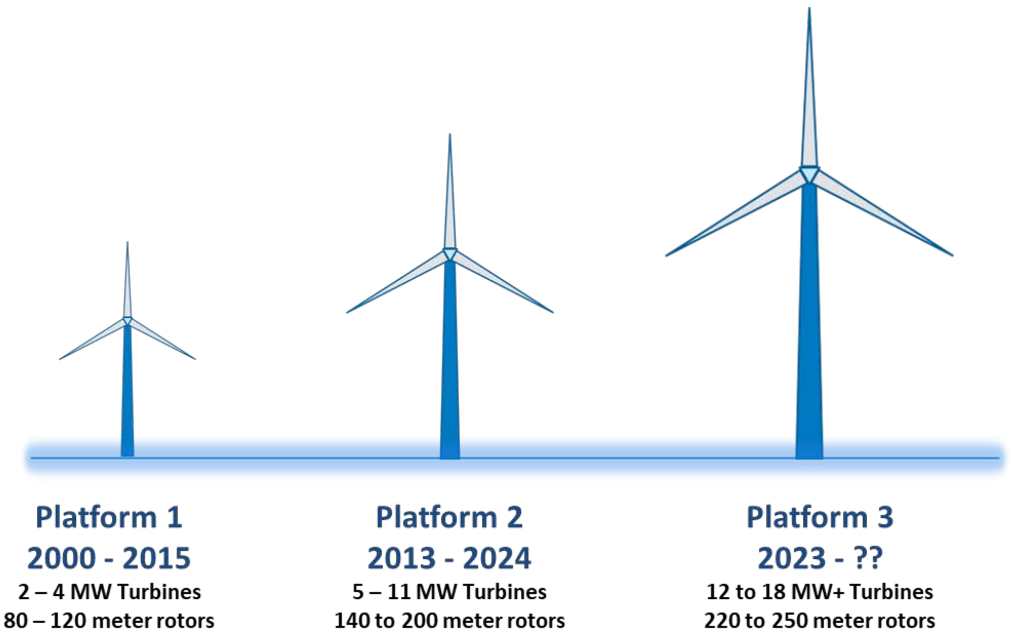
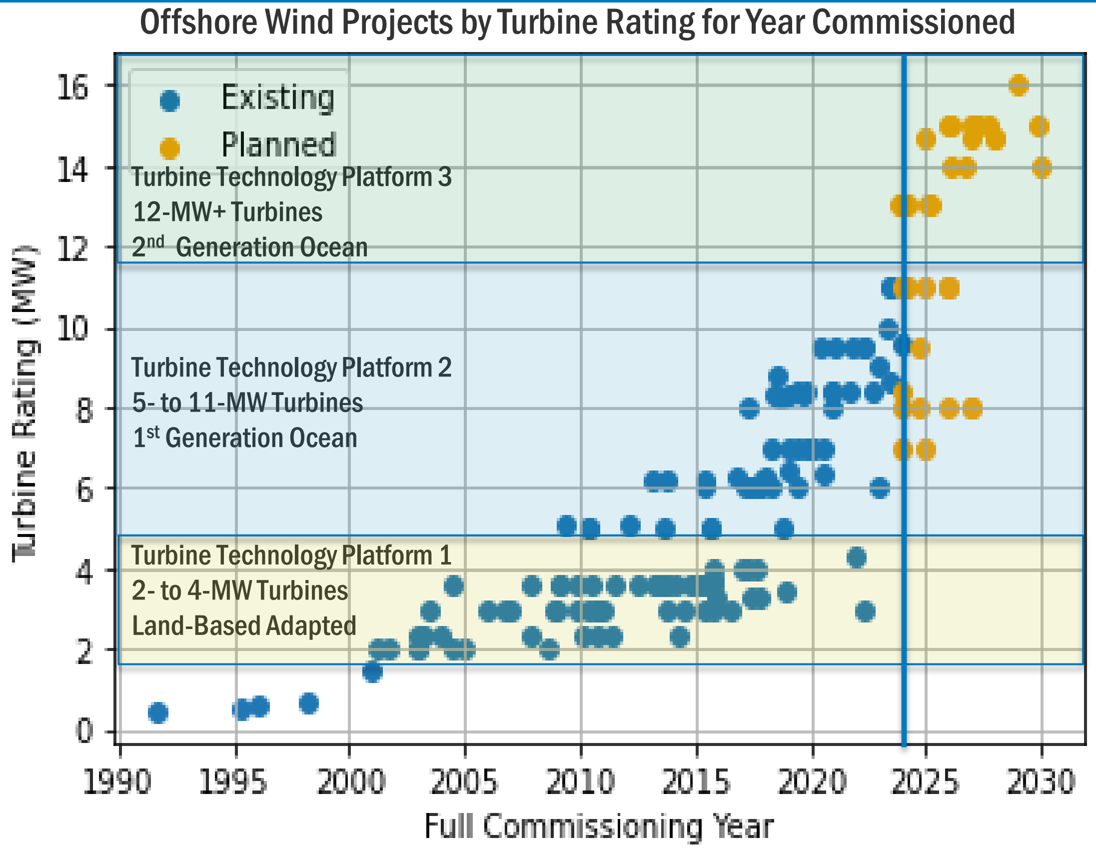


Figure by NREL

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 Turbine Growth by Project



- While land-based upscaling slowed, offshore upscaling has accelerated to a 15-MW scale, 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.

Data from 4C Offshore filtered for projects in Europe and North America with more than 4 turbines
Figure by NREL

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

Siemens-Gamesa 14.7-MW Turbine

Technology Upscaling Enablers:

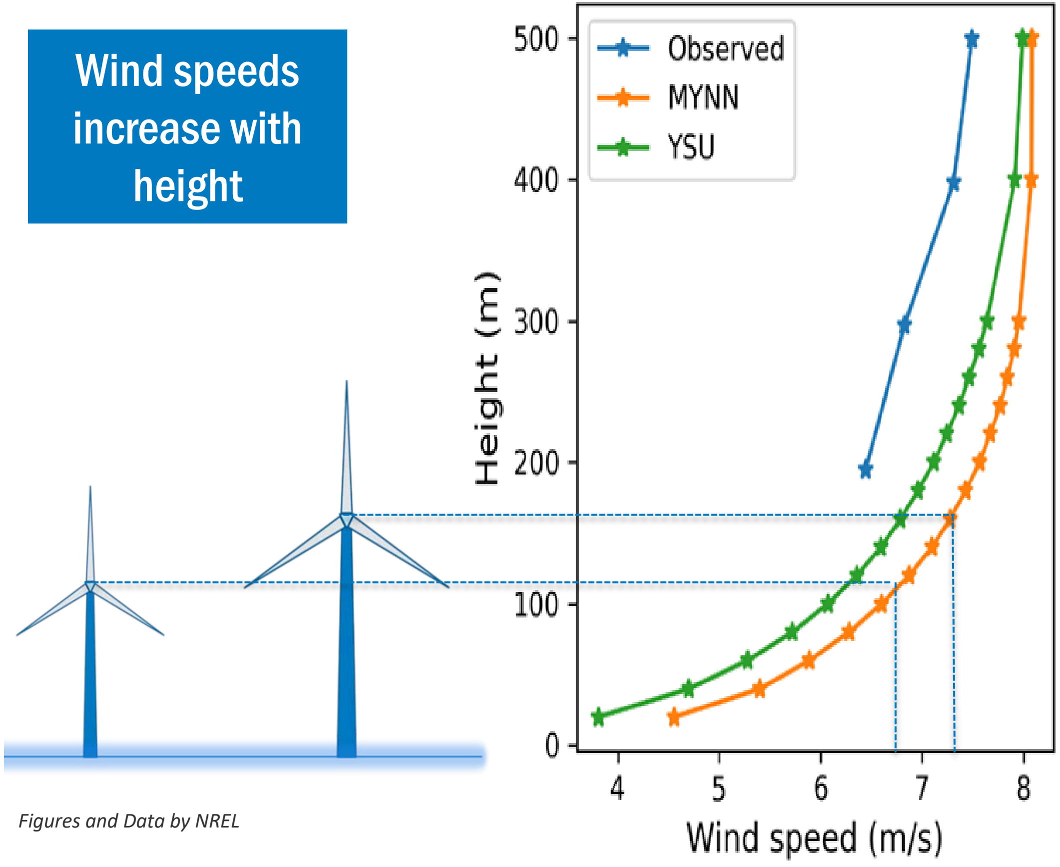
- 6–10-MW technology operating experience
- Advanced lightweight materials
- Innovations in manufacturing and automation
- Advanced load control to protect vital components and reduce weight
- Increased accuracy in high-fidelity design and analysis tools
- Remote diagnostics and repairs.

GE Vernova 13/14-MW Turbine at Vineyard Wind

V236 15.0-MW prototype, Østerild, Denmark

What Are the Benefits of Continued Turbine Upscaling?

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



Figures and Data by NREL

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.

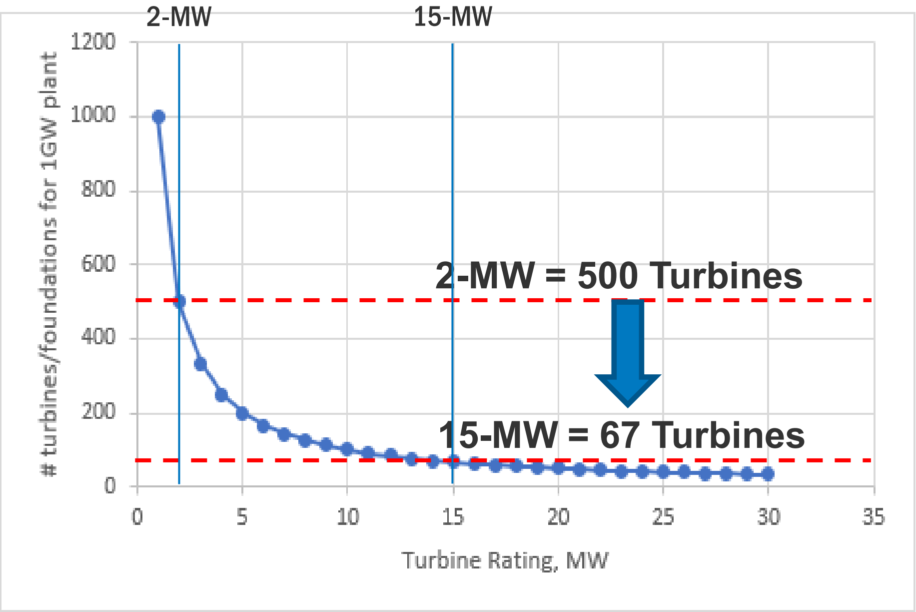
No hard limits to turbine upscaling, but there may be economic and practical limits:

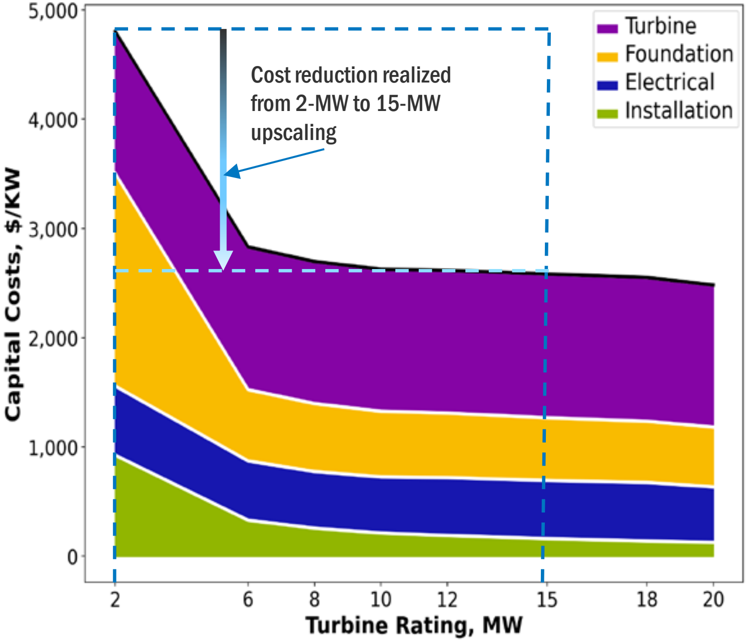
- Diminishing returns on reduced turbine positions
- Turbines may get more expensive per megawatt (square-cube law)*
- Infrastructure investment requirements grow disproportionately
- Immature technology risks
- Lost market opportunities (e.g., repowering, island nations, non-industrialized countries).

** 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

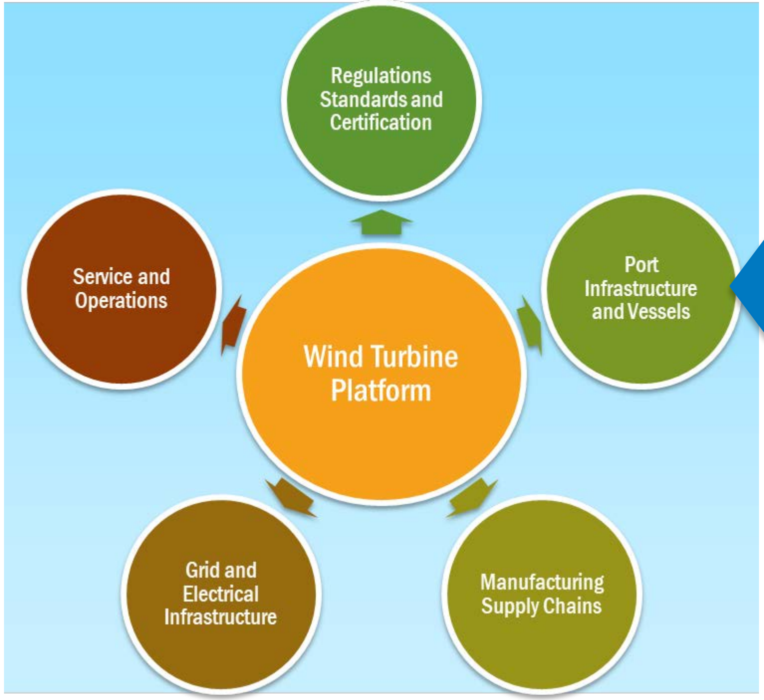


Figure by NREL

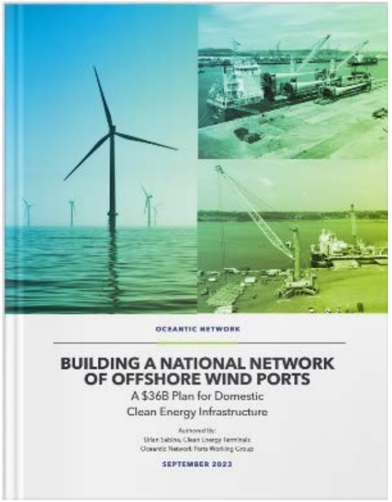


Image from Oceantic Network

- All aspects of the supply chain are dependent on turbine size.
- 15-MW class turbines will require significant port infrastructure investment. Oceantic Network estimates $36B (2023 Oceantic 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

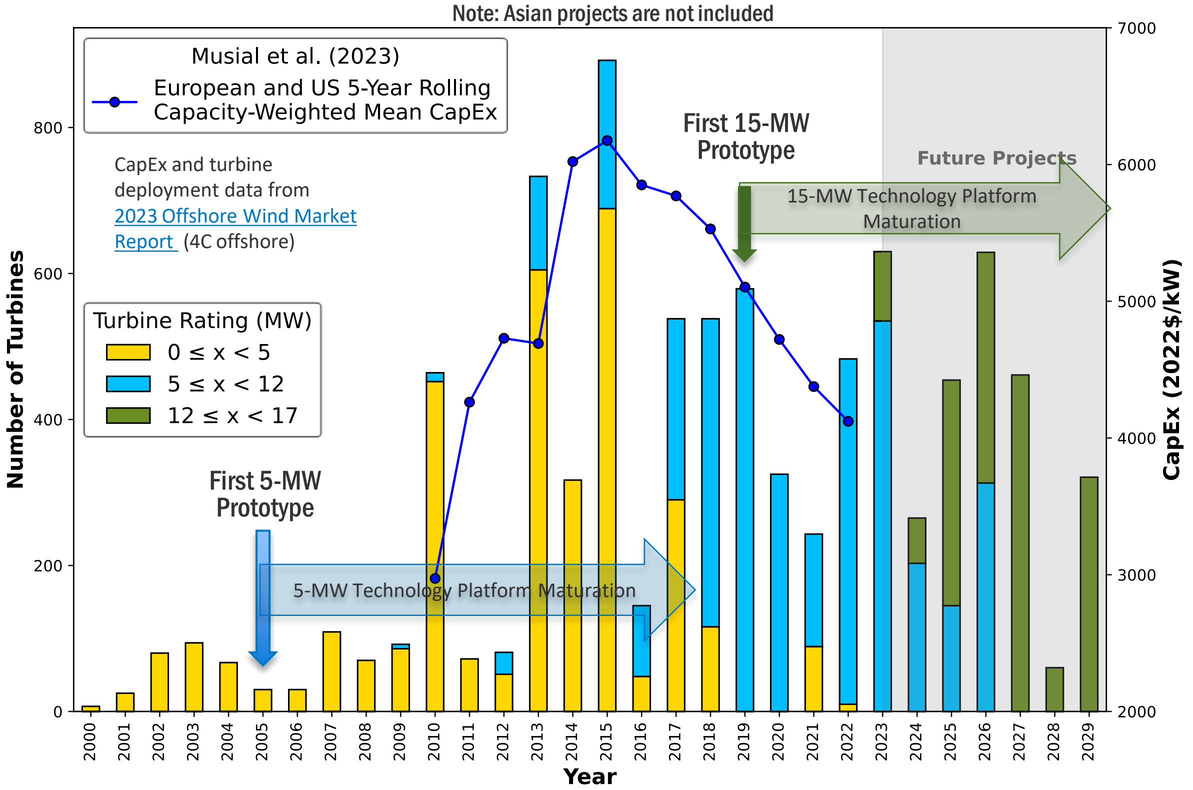
"Jumbo jet era ends as Boeing delivers last 747 plane" January 2023

- 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*.

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

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

Technology risk increases during early stages of new platform development.



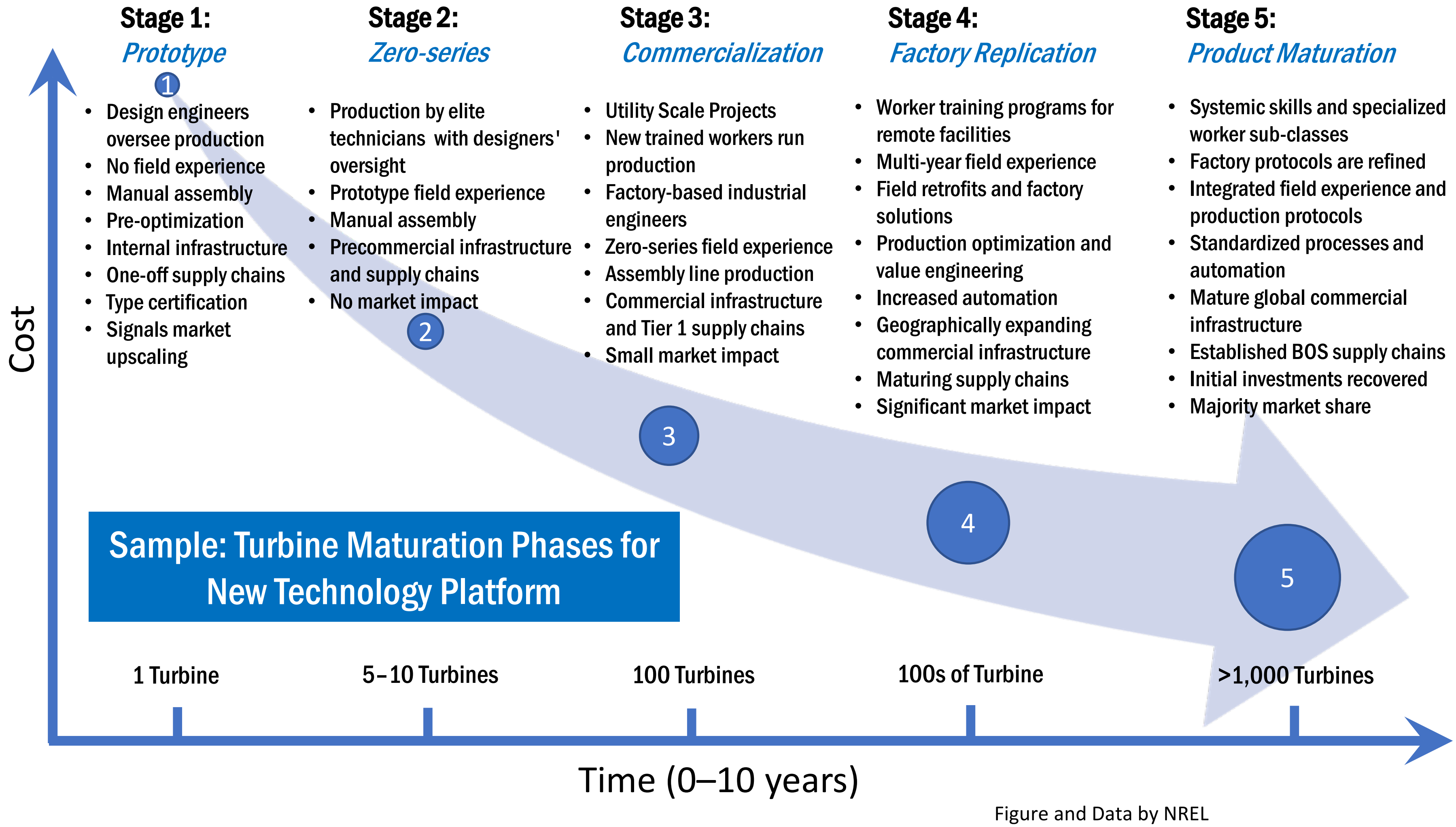
Data from 4C Offshore filtered for projects in Europe and North America with more than 4 turbines; Figure by NREL

Potential Risks Due to New Technology Platform Adoption

- ***Technical risk:*** New turbines are more likely to have design/manufacturing oversights or defects.
- ***Construction risk:*** Logistics depend on the on-time arrival of new infrastructure and vessels.
- ***Supply chain risk:*** New supply chain facilities need to be built. Vulnerabilities increase with larger turbines because investments are greater, and suitable manufacturing locations are scarcer.
- ***Safety risk:*** Greater human safety risks may arise from unforeseen hazards and inexperience.
- ***Operational risk:*** New technology that has not been field verified may have higher failure rates.
- ***Lost market momentum:*** Time to mature technology may delay deployment and increase costs.

Cost Reduction Through Project Scale and Technology Maturation

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


Stage 1:
Prototype
1
Design engineers oversee production
No field experience
Manual assembly
Pre-optimization
Internal infrastructure
One-off supply chains
Type certification
Signals market upscaling
Stage 2:
Zero-series
2
Production by elite technicians with designers' oversight
Prototype field experience
Manual assembly
Precommercial infrastructure and supply chains
No market impact
Stage 3:
Commercialization
3
Utility Scale Projects
New trained workers run production
Factory-based industrial engineers
Zero-series field experience
Assembly line production
Commercial infrastructure and Tier 1 supply chains
Small market impact
Stage 4:
Factory Replication
4
Worker training programs for remote facilities
Multi-year field experience
Field retrofits and factory solutions
Production optimization and value engineering
Increased automation
Geographically expanding commercial infrastructure
Maturing supply chains
Significant market impact
Stage 5:
Product Maturation
5
Systemic skills and specialized worker sub-classes
Factory protocols are refined
Integrated field experience and production protocols
Standardized processes and automation
Mature global commercial infrastructure
Established BOS supply chains
Initial investments recovered
Majority market share
Sample: Turbine Maturation Phases for New Technology Platform
Cost
1 Turbine
5–10 Turbines
100 Turbines
100s of Turbine
>1,000 Turbines
Time (0–10 years)
Figure and Data by NREL

Project Scale: Big Projects Cost Less

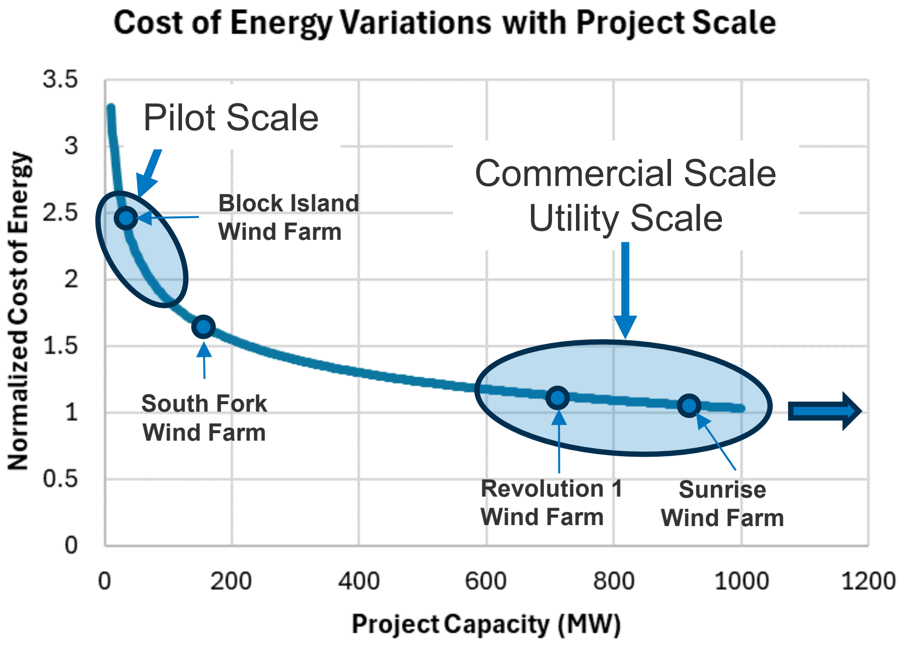


Figure and Data by NREL

- 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 Schroeder

Offshore Wind Market Scale/Market Certainty

- Sufficient market scale is needed to attract infrastructure and supply chain investment and to achieve technology maturity.
- 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.

Photo from Principle Power

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

Offshore Wind Market Scale & Market Certainty

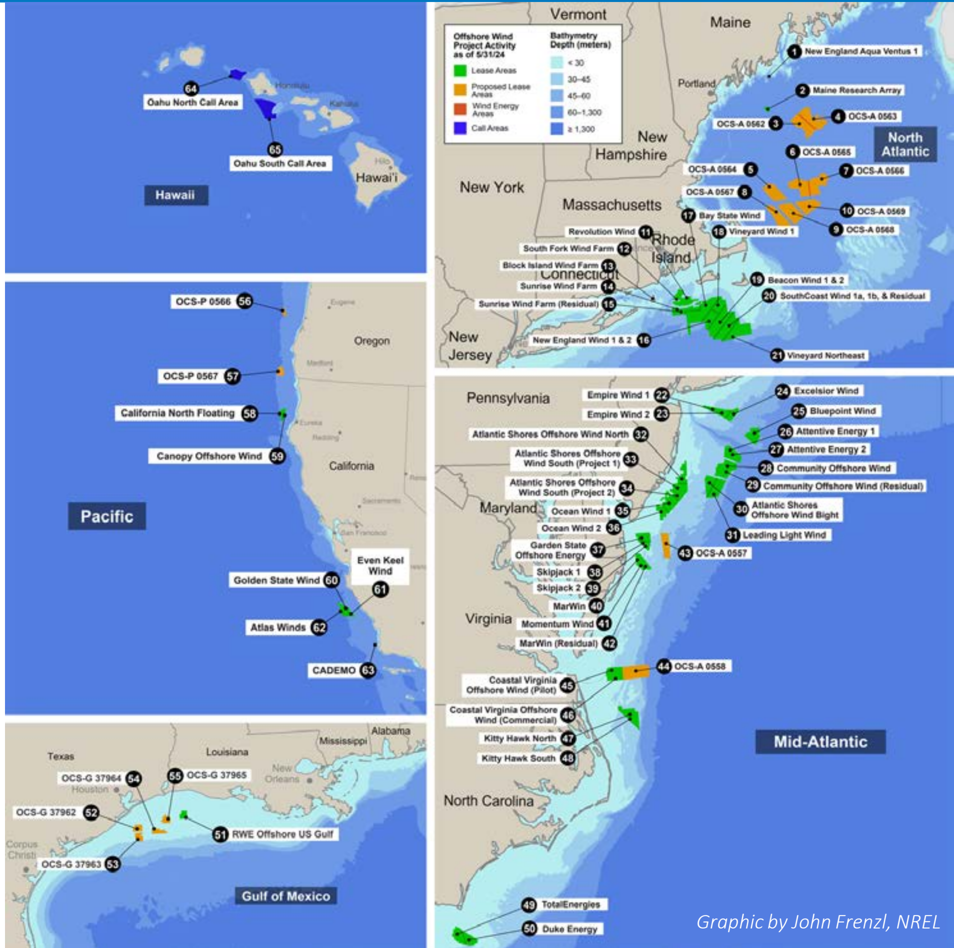
Globally:

- **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):

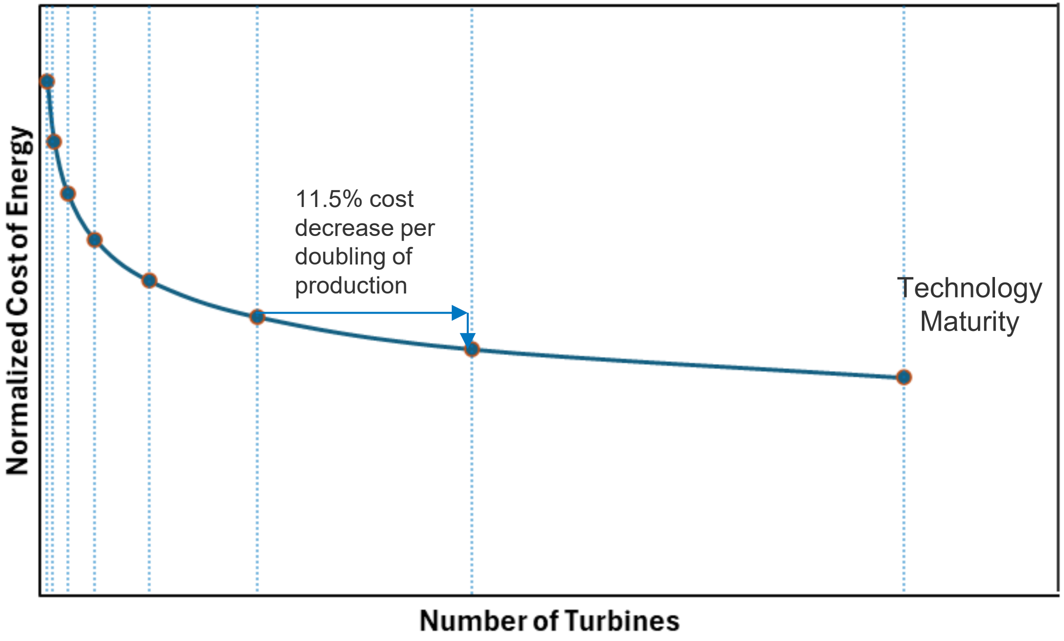
- **80.5 GW** in total U.S. project pipeline – 65 offshore wind “projects” (See Figure)
  - ✓ 25.1 GW of floating wind in the US Pipeline
  - ✓ 55.4 GW of fixed bottom wind in the US pipeline
- **0.174 GW** installed in U.S.
- **7.5 GW** approved and under construction
- **19.8 GW** are in permitting (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

Cost Reduction Through the 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.

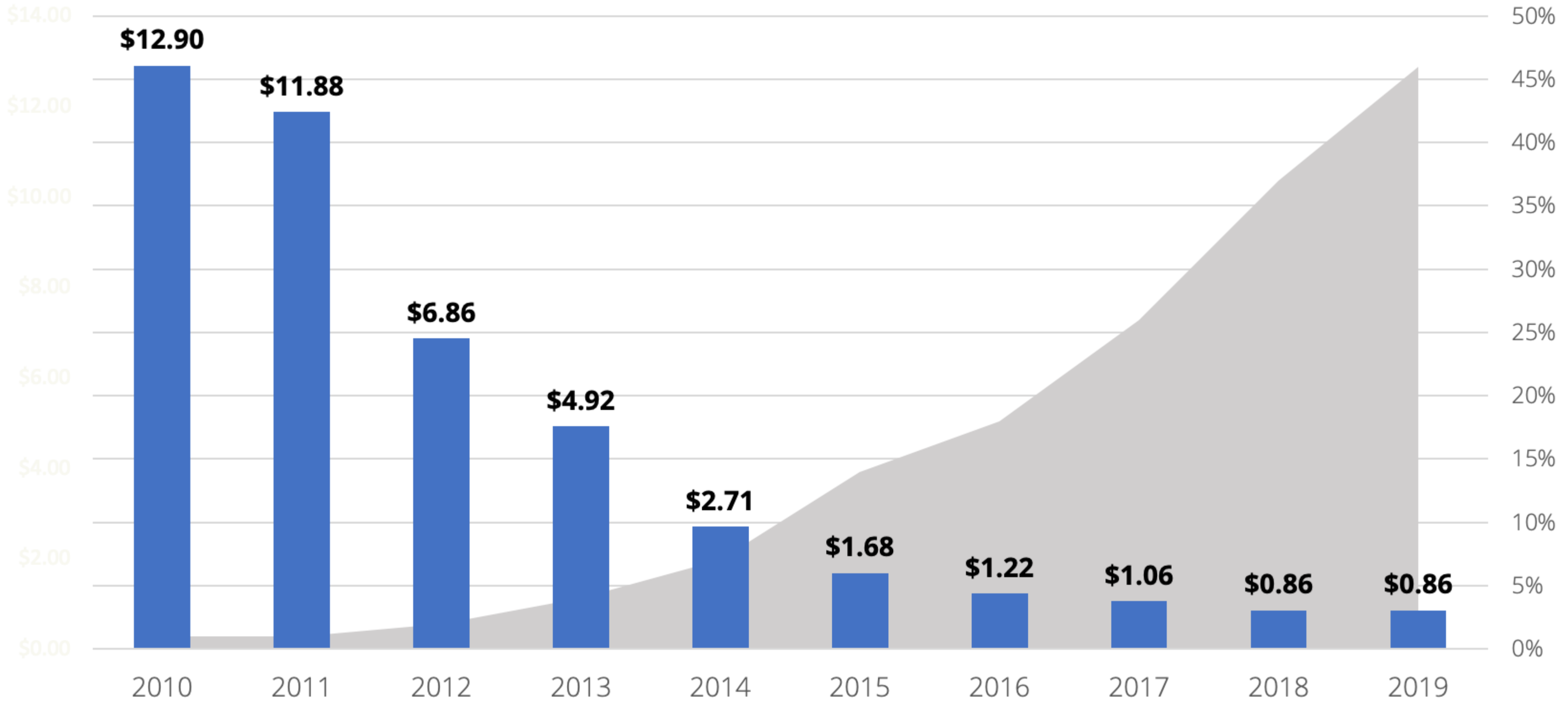
Learning rates vary significantly by industry.

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.

Figure and Data by NREL

LED lighting costs decline as volumes increase

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

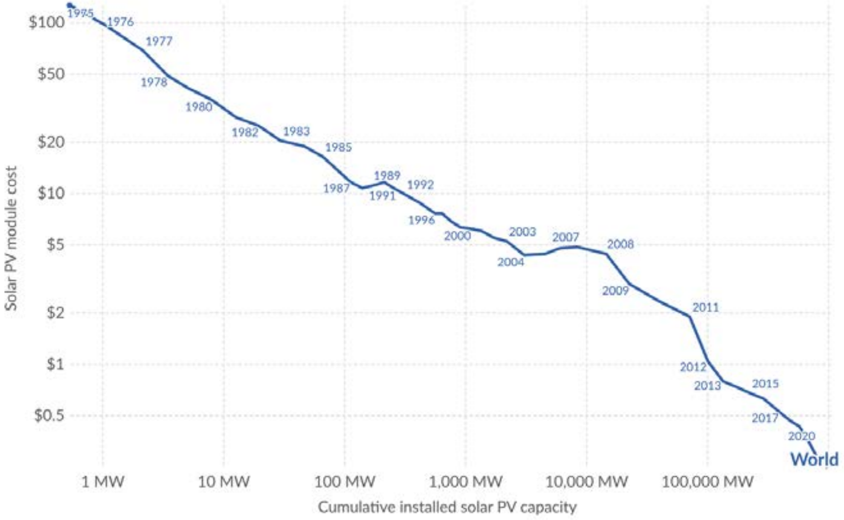


FREEING ENERGY

Sources: U.S. Department of Energy & International Energy Agency | fep.link/g213

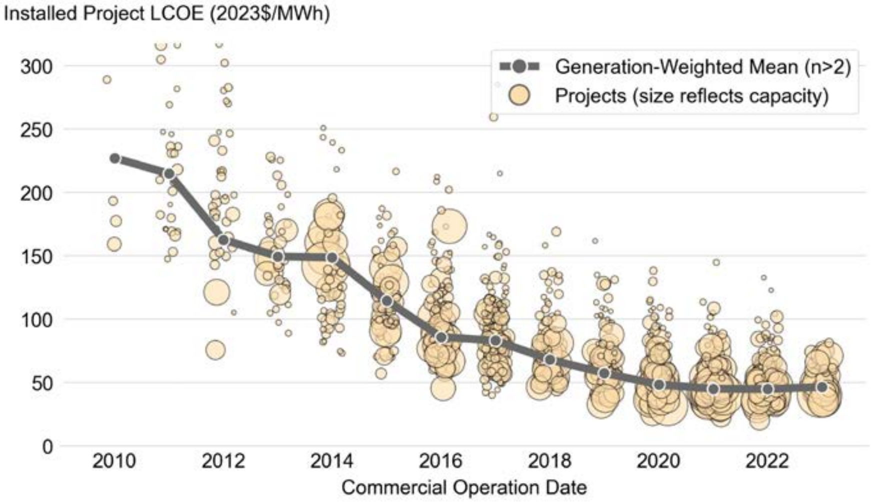
Solar PV Project Costs Have Dropped 80% Since 2010

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.

fsa 8d18718 http://hdl.loc.gov/loc.pnp/fsa.8d18718

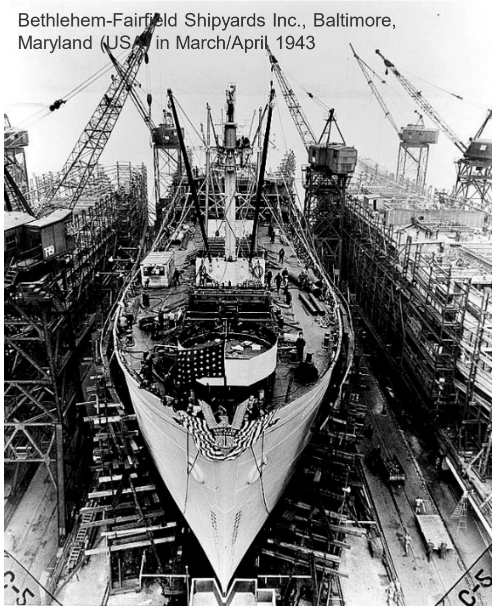
Comparisons with Offshore Wind Semisubmersible Floaters for 15-MW Turbines

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

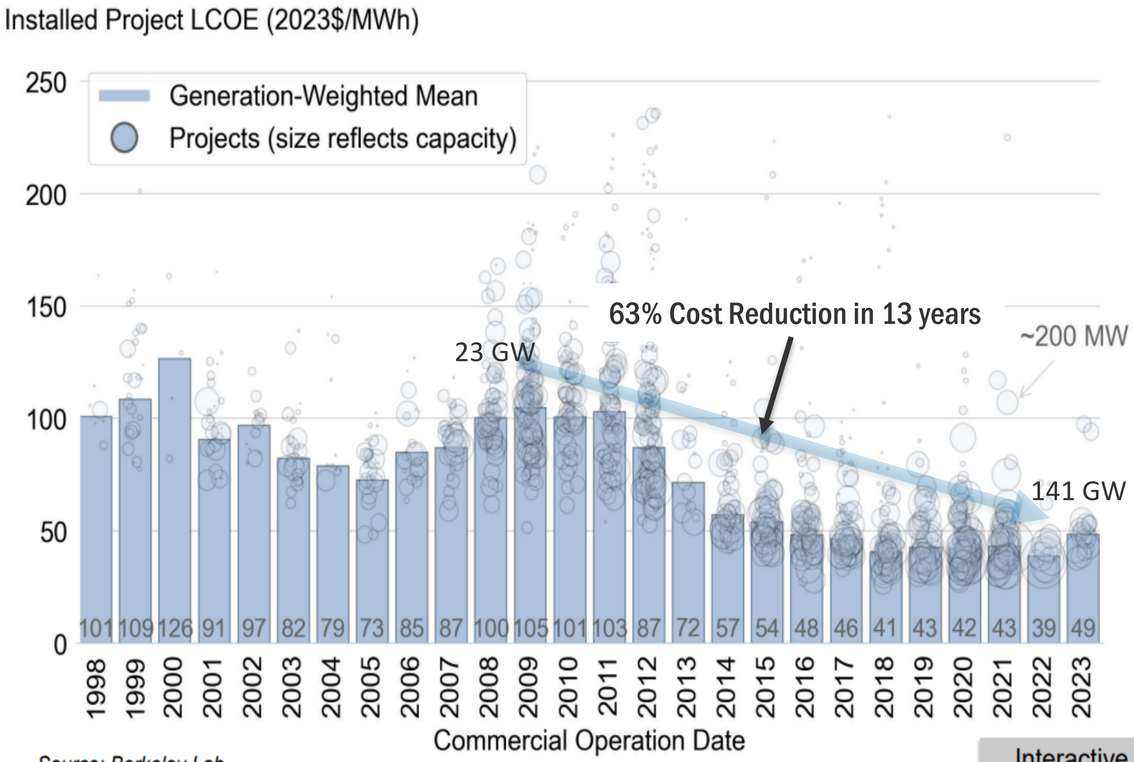
https://en.wikipedia.org/wiki/Liberty_ship#cite_note-FOOTNOTESawyerMitchell198539-2

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



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

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



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.

- 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.
- Total cost reduction was 63% over 13 years.

Interactive data visualization:
https://emp.lbl.gov/levelized-cost-wind-energy

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

- Some learning may be lost due to:
  - 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.

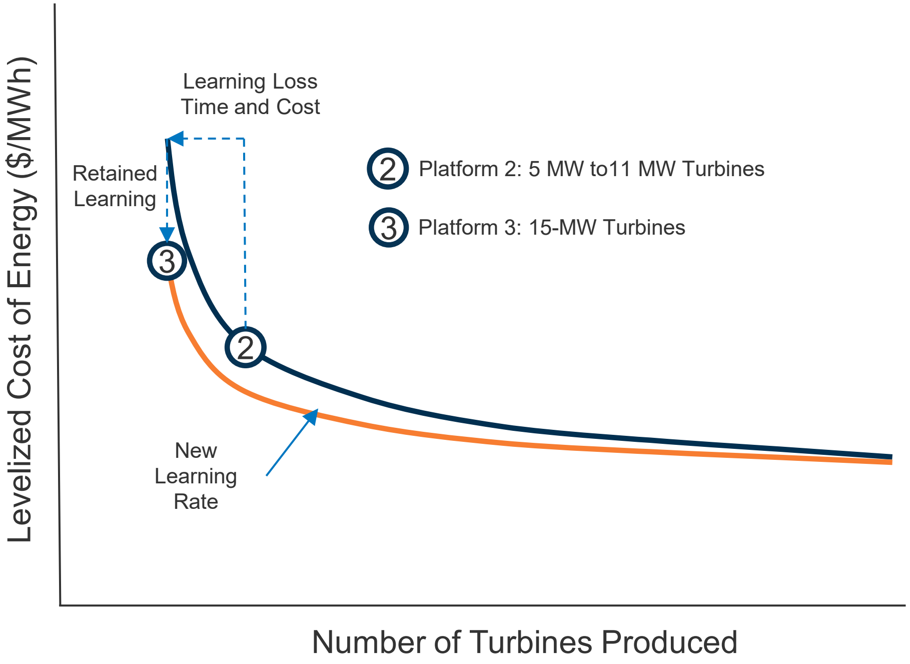

Figure and Data by NREL

China’s Role

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


ENERGY

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

By Abhimanyu 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

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

Photo: Dongfang Electric Corporation


RECHARGE

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

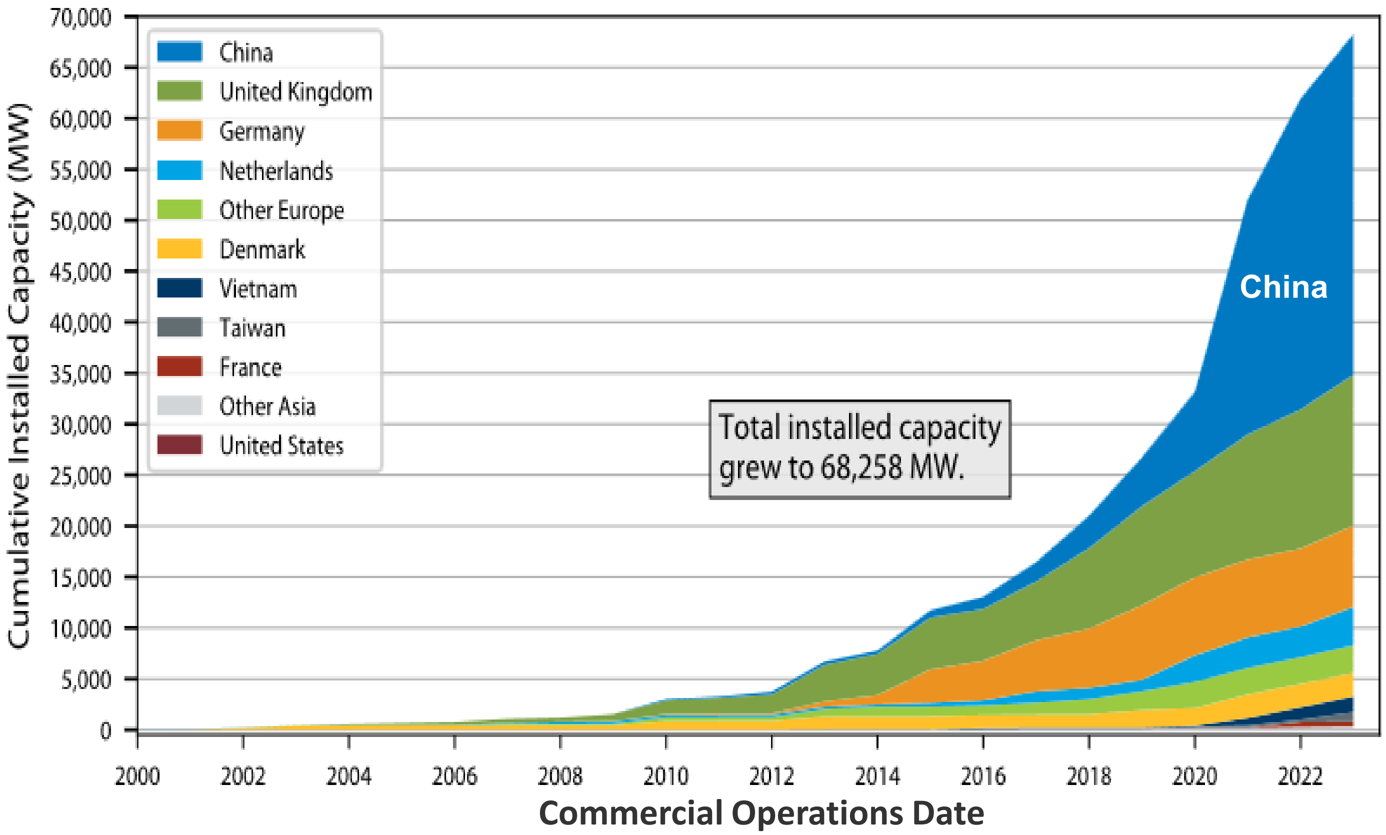
A picture of the new test bench released by Sany. (Photo: Sany)

Cosmo Sanderson

Journalist

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*](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; European markets may be softening.

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.

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/

Upscaling Takeaways

- 15-MW capacity turbines were enabled by technology advancements defying physical upscaling challenges.
- Further turbine upscaling will have dimainishing returns on benefits.
- 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 could 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 address multiple global market types.
- Multiple turbine sizes may be needed to serve diverse global sub-markets.

Thank you for your attention!

Photo by Dennis Schroeder, NREL

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