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Reconsidering Wind

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Emerging Trends: The Case for Wind

Key messages
The Case for Wind

Wind has the potential to abate 10% to 20% of all CO_2e emissions by 2050 through the clean electrification of power, heat, and road transport.

To get to zero emissions by 2050, wind must grow sixteenfold to 38 TWh annual production**; the more likely Economic Transition Scenario is wind growing sevenfold to 15 TWh.**

Today, wind is the largest renewable electricity source, **making up 8% of global production.**

- **Wind electricity generation** reached **~2,304 TWh in 2023** with 13% CAGR 2018-2023, driven by a 19% CAGR in China.
- **28% of global wind capacity is in China**, 29% in the EU/UK, and 22% in the US.

Onshore wind LCOE has dropped 70% since 2009 to $50/MWh by 2023, significantly lower than fossil fuel costs, which are $75 to $120/MWh. **Offshore wind is on par with fossil fuels, with LCOE decreasing 60% to $75/MWh today.**

- A steeper learning curve for wind will lead to wind becoming the most deployed and cheapest renewable as of 2025.

Wind LCOE has decreased at a stable learning rate of 15% for each doubling of capacity since 1982.

- The learning curve for wind is driven mostly by innovations in turbine technology, which has led to 2-3x higher capacity factors, economies of scale resulting in cheaper CapEx, and a 50% longer project life.

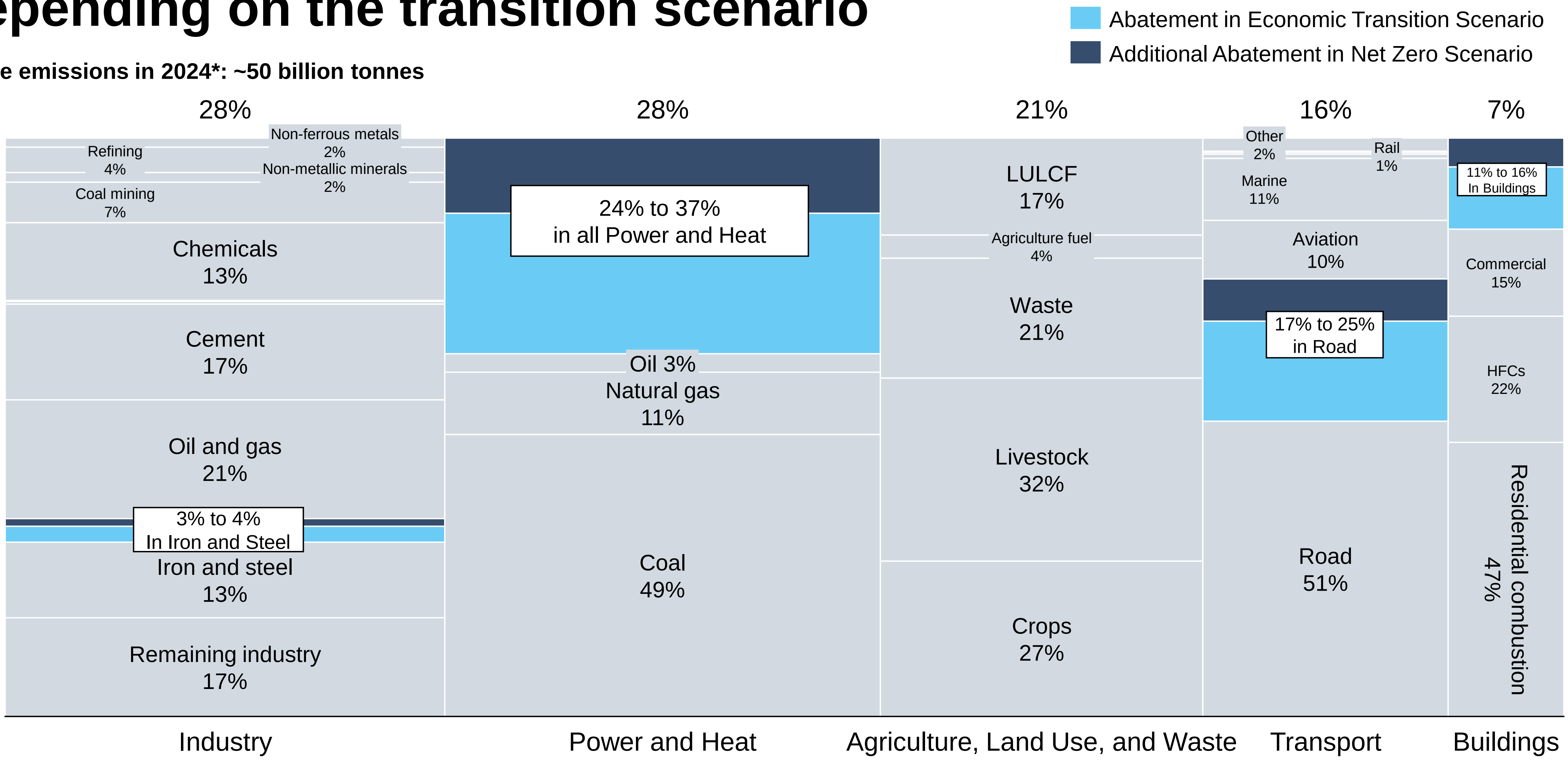
Looking ahead, onshore and offshore LCOE is expected to decrease another 30% to 45% by 2035 and a total of 45% to 55% by 2050. Lower CapEx due to more installed capacity is the main contributor to lower LCOE.

Ørsted moved from 80% coal and gas in 2006 to 70% wind power in 2023, while increasing total heat and power production, the first fossil fuel company demonstrating such a major shift.

Sources: IEA, Net Zero Roadmap (2023); Our World in Data, Electricity generation from wind power (2024).
Credit: Taicheng Jin, Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

Wind can abate 6 to 9 Gt CO_2e by 2050 in select subsectors depending on the transition scenario

CO_2e emissions in 2024*: ~50 billion tonnes



(*) 2024 emissions based on projections.
Sources: Scope 1 emissions from Rhodium Group Climate Deck (September 2024); abatement estimates from BloombergNEF, IRENA, and IEA (2023).
Credit: Hassan Riaz, Theo Moers, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

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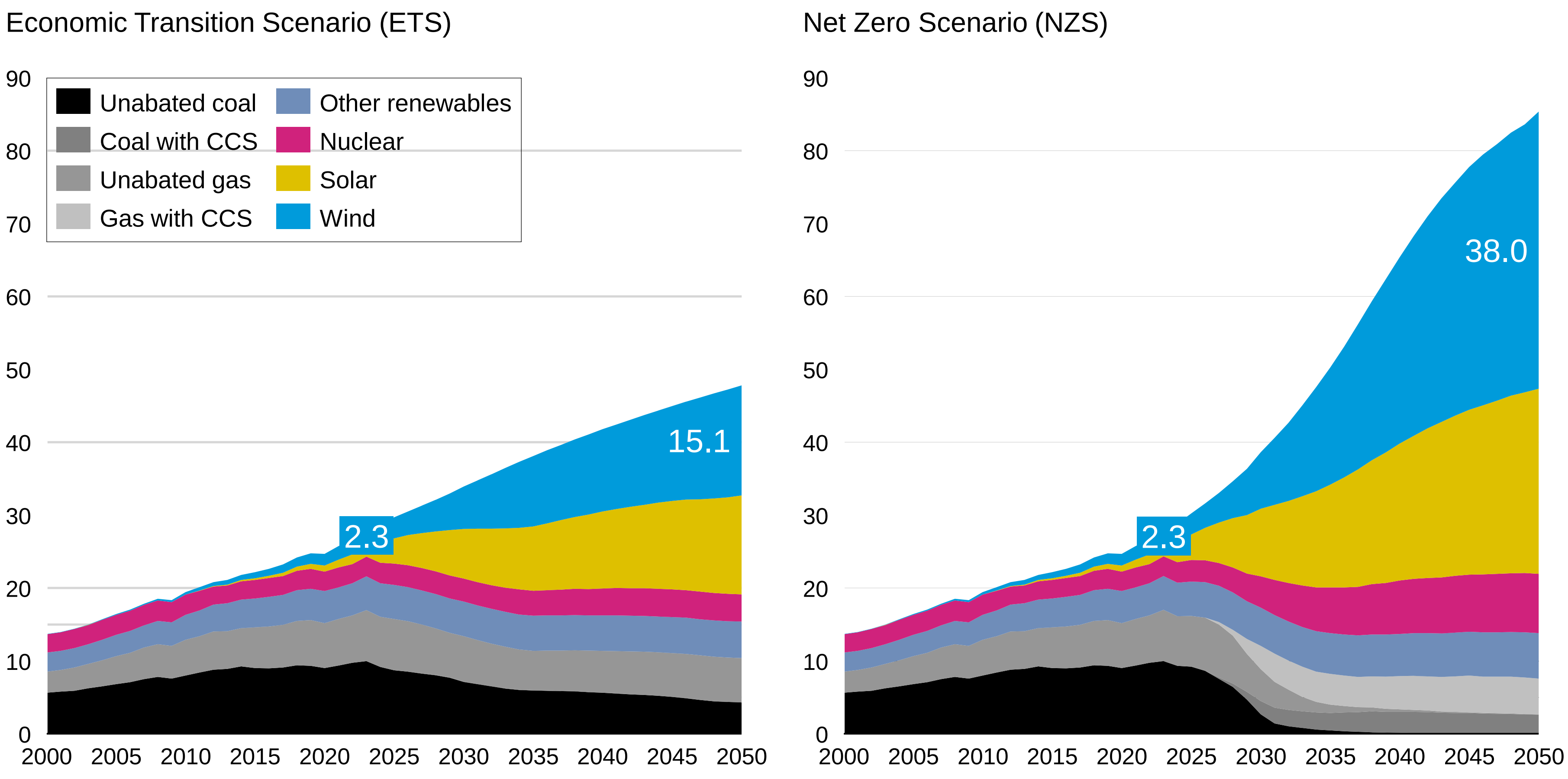
Wind electricity generation to grow 16-fold until 2050 in net zero scenario, compared to only 7-fold in Economic Transition Scenario

Electricity generation by source, *2000-2050, thousands of TWh*



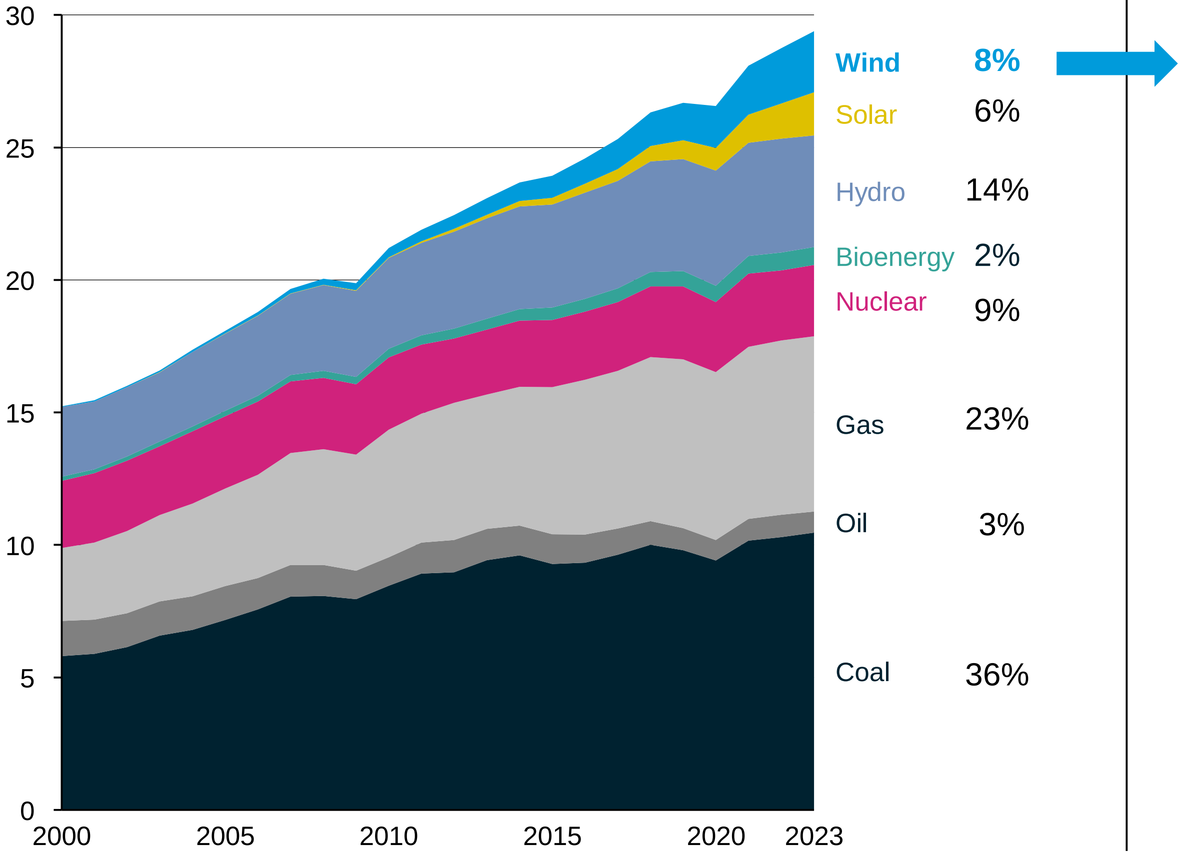
Observations

- Electricity generation is the **largest source (36%) of** energy-related **CO_2 emissions.**
- **Global electricity demand** is expected to increase from ~**25,000 TWh in 2022** to ~**60,000 TWh in 2050.**
- **Projected increase in electricity demand** is driven by:
  - **Increased electrification, expansion of hydrogen electrolysis, population growth,** and an **increase in living standards.**
- To reach NZS by 2050, **which envisions approximately 7,400 TWh of wind electricity generation in 2030, the CAGR needs to increase ~17%.**
  - Achieving this will require increasing annual capacity from about 75 GW in 2022 to 350 GW in 2030.

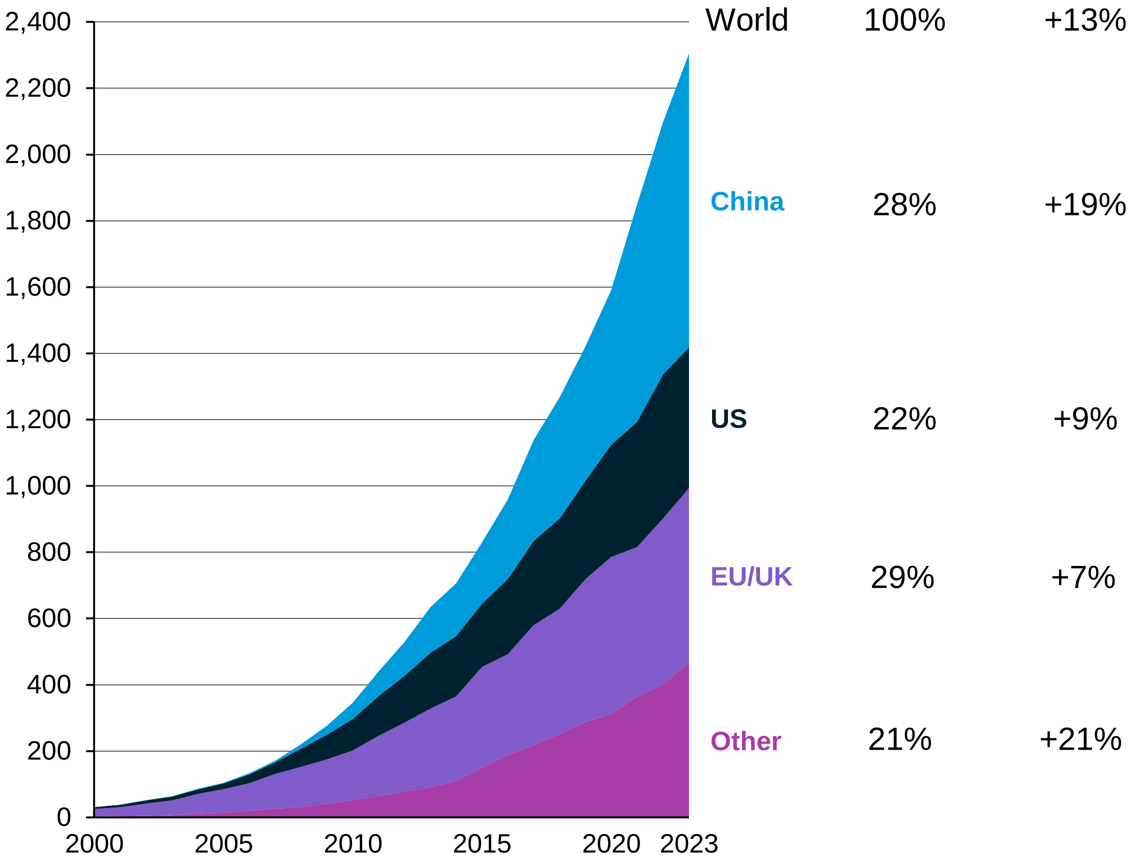
Sources: BloombergNEF, 1Q 2024 Global PV Market Outlook (2024); IEA Electricity (2024).
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Wind now makes up ~8% of global electricity production, driven by China, Europe, and the US, representing ~87% of capacity

Electricity generation by source, *2000-2023, TWh* — **% of 2023 production**



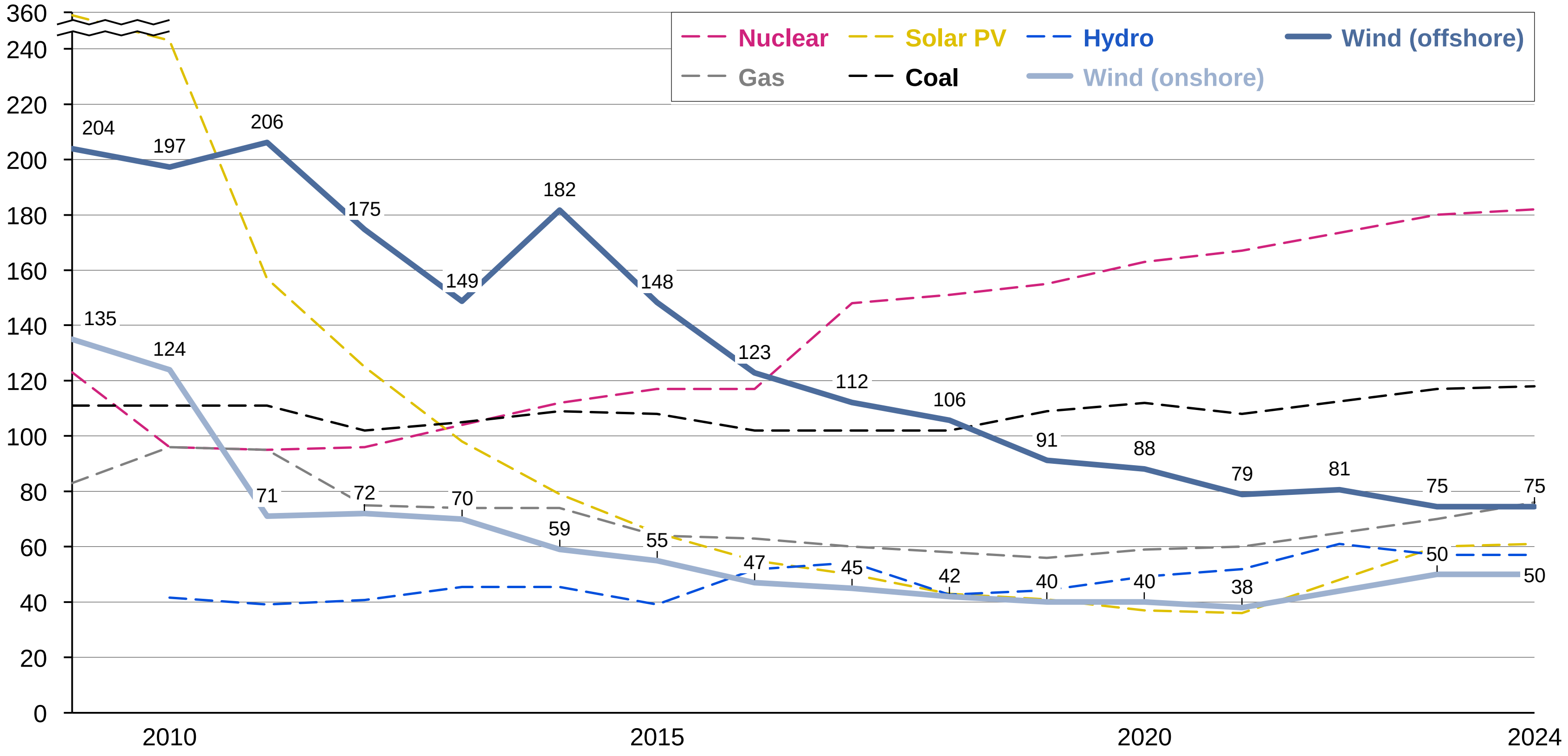
Capacity by country, *2000-2023, MW* — **% of 2023 capacity** — **CAGR 2018-23**



Sources: Our World in Data, using Ember's Yearly Electricity Data; Ember's European Electricity Review; Energy Institute Statistical Review of World Energy.
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Onshore wind LCOE dropped 70% since 2009 and offshore dropped 60%; only solar has seen a steeper decline in costs

LCOE by technology, *$/MWh*



Observations

- Modern wind power adoption was motivated by the **OPEC crisis in the 1970s.**
- Between 2010 and 2023, the **onshore LCOE fell by 70%,** from USD $107/MWh to $33/MWh.
- **Offshore LCOE fell by around 60%,** from $197/MWh to $75/MWh.
- **The learning curve is by far steepest for solar PV,** which saw the LCOE drop from ~$450/MWh in 2010 to $35/MWh in 2023.
- **This is likely to lead to solar PV overtaking wind as the dominant renewable in the years ahead.**

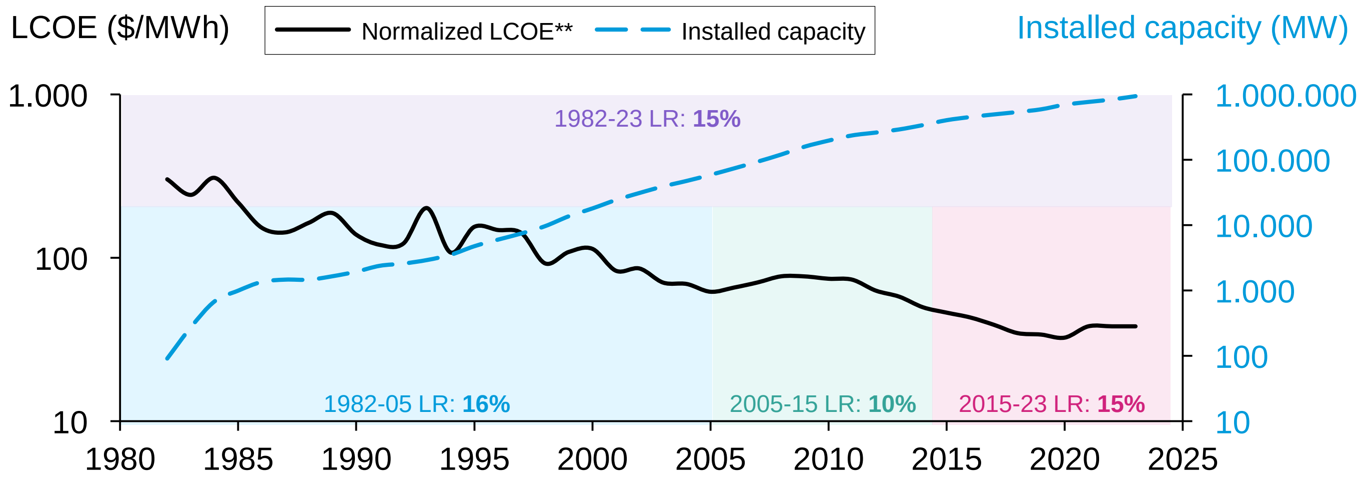
(*) LCOE breakdown for wind in Appendix

Sources: Ibenhalt, Explaining learning curves for wind power (2002); IRENA, Renewable Power Generation Costs (2024); Bolinger et al., Levelized cost-based learning analysis of utility-scale wind and solar in the US (2022); Our World in Data, Levelized cost of energy by technology, World (2023); IEA, Wind Energy Annual Report (2000); DNV, Energy Transition Outlook (2024); Lazard, LCOE (2024).

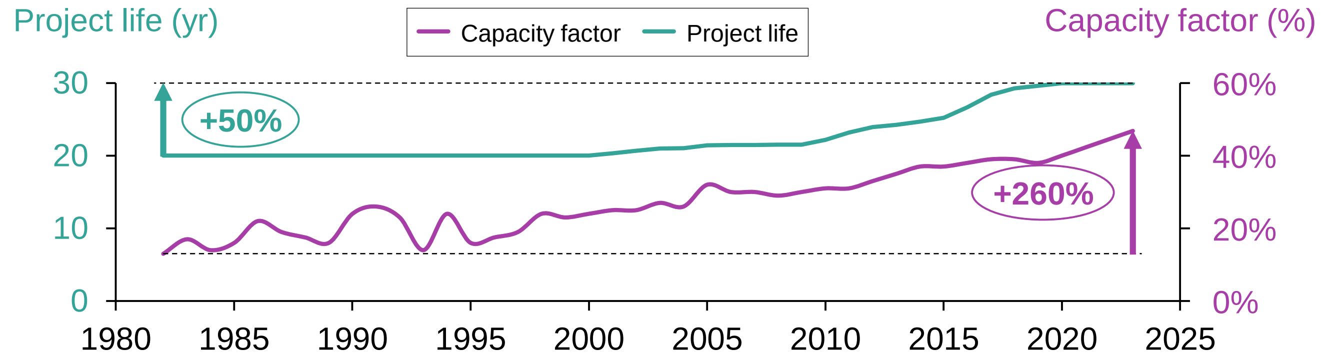
Credit: Taicheng Jin, Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

Wind LCOE with stable learning rate of 15% for over four decades, driven by improving technology and economies of scale

LCOE, installed capacity and learning rate (LR*), *1982-2023*



Project life and capacity factor, 1982-2023



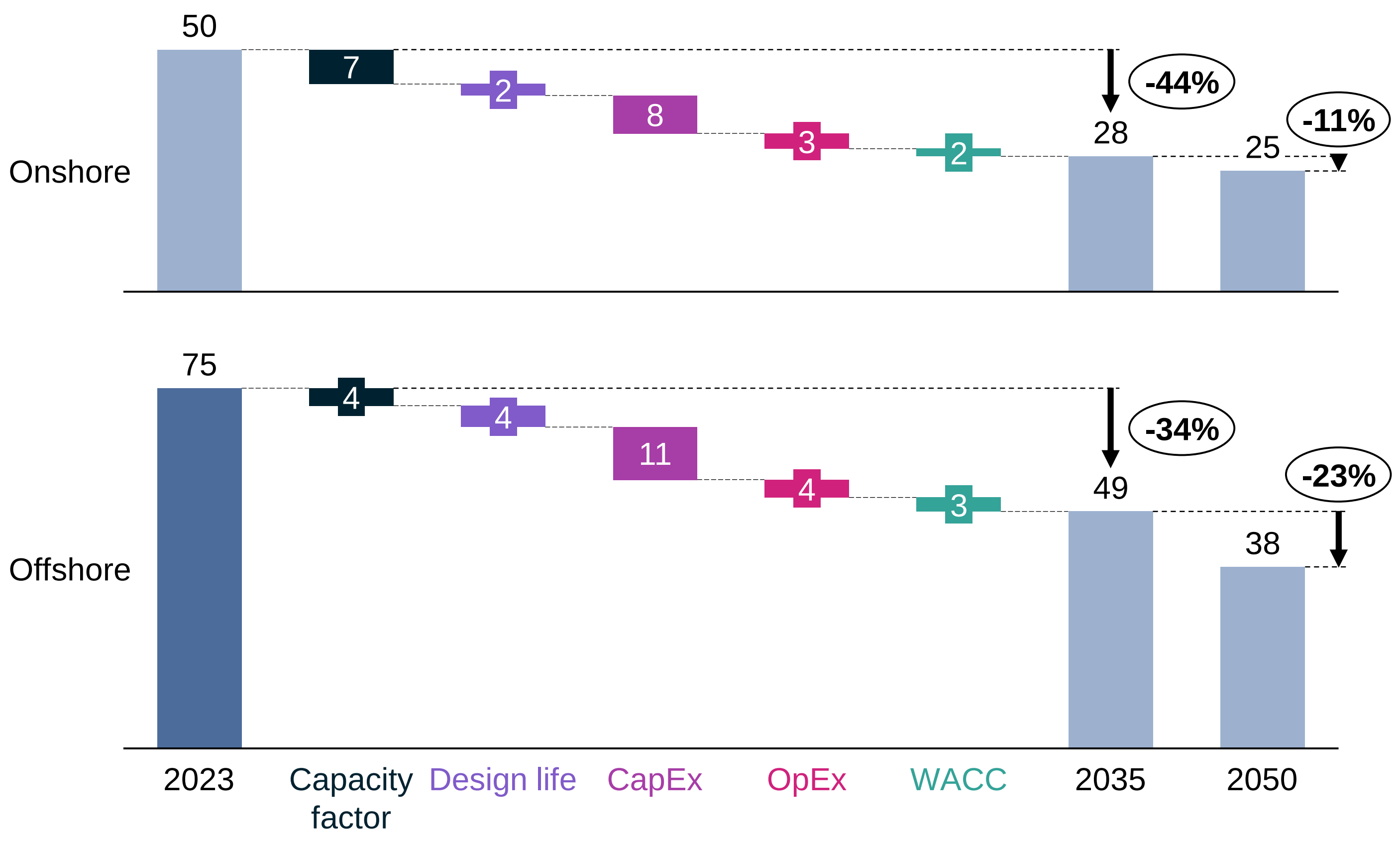
Observations

- **The normalized cost of wind energy has come down 87% since 1982 as the capacity has increased by 10,000x.**
- **The learning rate for wind energy for the same period is 15%,** a constant except for a slight decrease between 2005 and 2015.
- **The overall decrease in wind energy costs is driven by innovation in turbine technologies and economies of scale.** For certain short-term decreases, the cost decline is driven by lower commodity prices or lower cost of capital (e.g., between 2008 and 2022).
- **Improvements in technology are represented by the longer project life of wind projects** (30 years today vs. 20 years in the 1980s) **and increased capacity factors** (~45% today compared to ~15% in the 1980s).

(*) Learning rate defined as the % decrease in normalized LCOE for doubling of capacity. (**) Normalized LCOE controls for exogenous influences by excluding regional, economic, and policy factors.
Sources: Bolinger et al., Levelized cost-based learning analysis utility-scale wind and solar in US (2022); IRENA, Renewable Power Generation Costs (2023); NREL, Cost of Wind Energy Review (2022).
Credit: Taicheng Jin, Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Wind prices projected to decrease 30%-50% by 2035 and another 10%-25% until 2050, with scale and efficiency driving down CapEx

Impact of drivers for median-scenario LCOE reduction in 2035 and 2050*, *$/MWh*



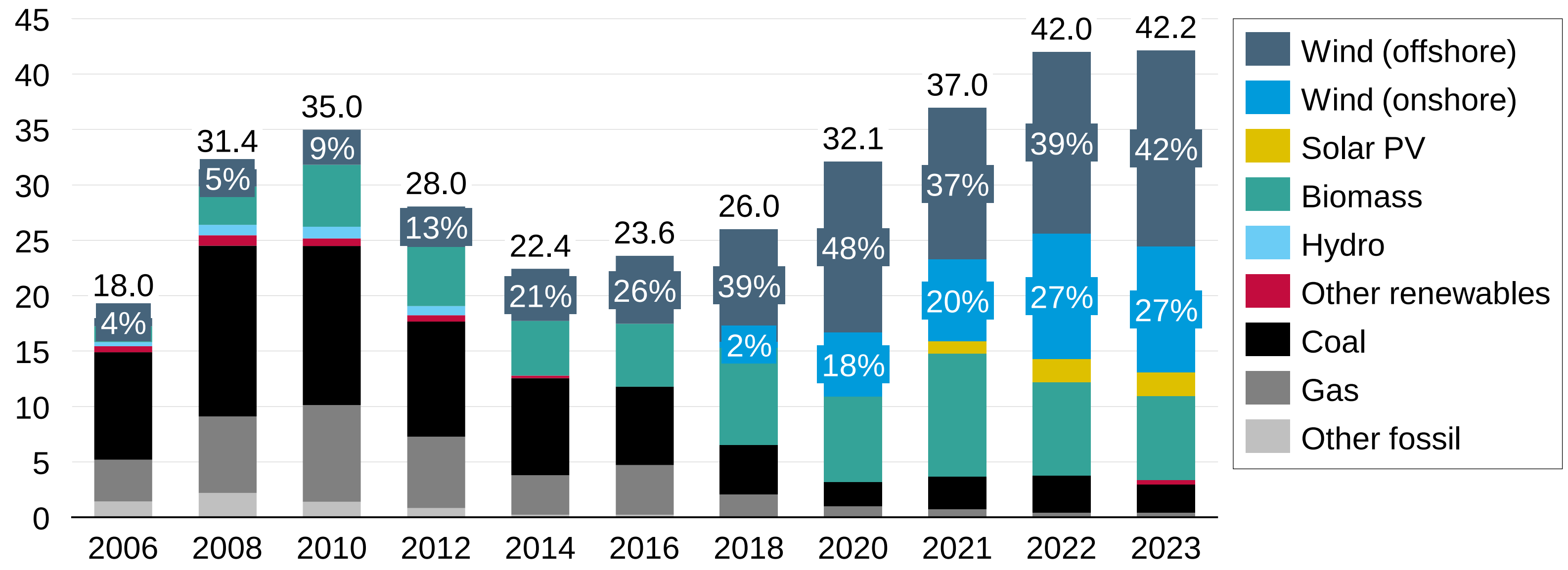
Observations

- **Onshore wind LCOE is expected to drop 44% until 2035.** – Corrected for a bump in prices in 2022-2023, this drop is 26% with respect to 2021. A further drop is expected until 2050, although the pace slows.
- **Offshore wind LCOE is expected to drop 34% by 2035 and another 23% until 2050,** halving the total price per MWh.
- **Capacity factors are unlikely to increase much further due to less attractive positioning of farms.**
- **Most of the LCOE decrease comes from improvements in turbine capacity, hub heights, and rotor diameters.** For example, typical turbine ratings are forecast to increase from 3.25 MW (2030) to 5.5 MW (2035) for onshore and from 11 MW (2030) to 17 MW (2035) for offshore wind.

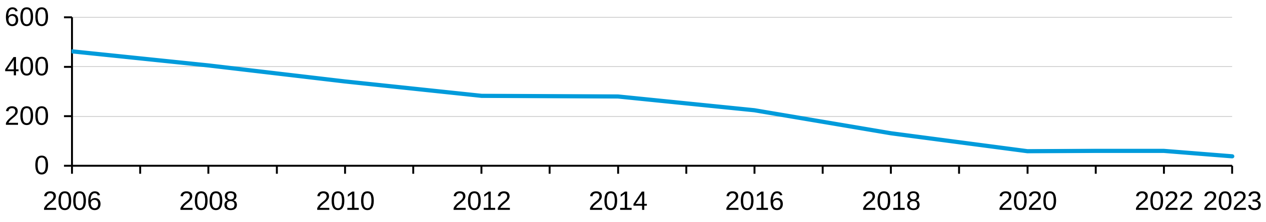
(*) Future outlook numbers based on survey amongst experts, N=140
Source: Wiser et al., Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050 (2021).
Credit: Taicheng Jin, Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Ørsted transitioned from fossil fuel to 69% wind power in a decade, reducing gCO_2e/kWh by 92%

Ørsted heat and power production by source , *2006-23, TWh*



Emissions from electricity production, *2006-23, gCO_2e/kWh*



Observations

- **Ørsted realized in 2008 that it needed to change from fossil fuel to sustainable energy,** after the EU announced in 2007 that 20% of energy should be renewable by 2020.
- **The largest investments Ørsted made were in offshore wind, building 500 MW of offshore wind in 2009.**
- In the following decade, the company expanded its offshore wind capacity, and **in 2018, Ørsted purchased Lincoln Clean Energy, a US onshore wind developer.**
- **Between 2006 and 2023, Ørsted reduced its emissions per kWh by 92%,** from 462 gCO_2e to 38 gCO_2e.

Sources: Ørsted, Powering the world with green energy; Ørsted, Annual Reports (2006-2023); Heal, Usher & Wagner, "Ørsted's Case for Offshore Wind," *Columbia CaseWorks* (2025).
Credit: Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

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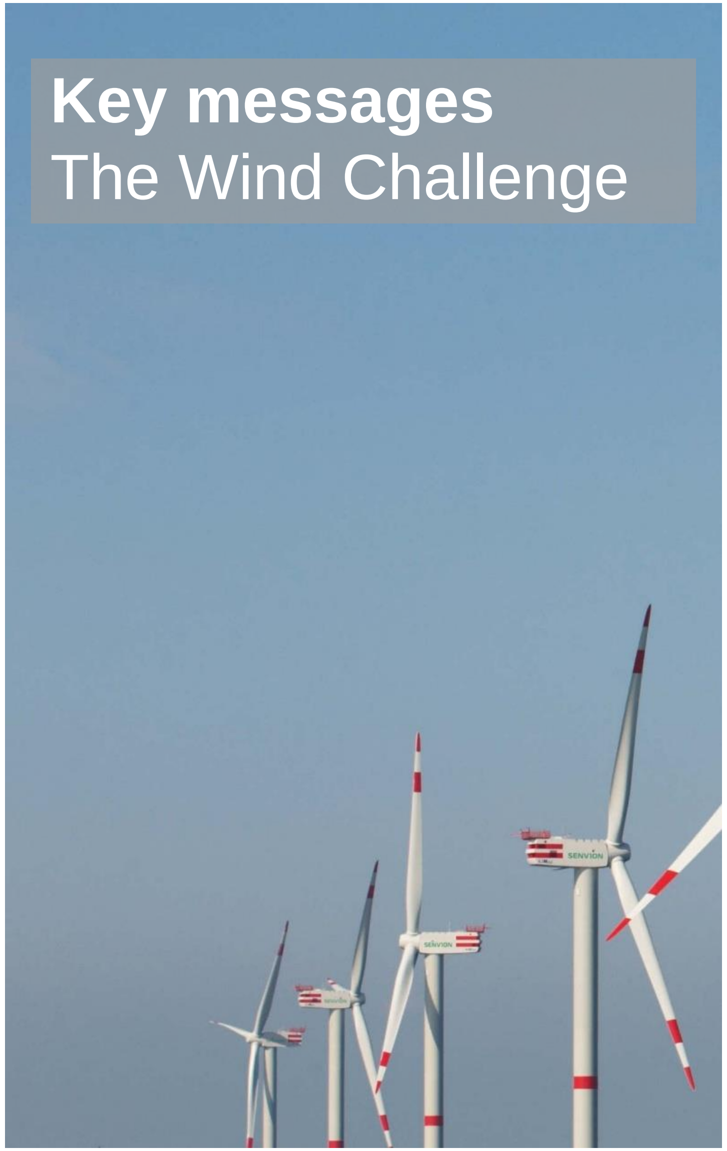
Emerging Trends: The Wind Challenge



Key messages
The Wind Challenge

Growth in investments in new wind energy projects slowed from 12% CAGR between 2013 and 2020 to 4% CAGR in the past three years, most significantly in onshore wind.

– Also reflected in slowing of M&A transactions outside of China, specifically in onshore, where the transactions dropped 10% from 2022 to 2023.

The power and renewables sector has seen the steepest increase in cost of debt, from 1% to 4% WACC.

– Renewables are especially vulnerable to interest rate increases, experiencing a 15% to 20% LCOE increase for a 2 percentage point interest rate increase.

Average power purchase agreement prices have declined from $83/MWh to $26/MWh since 2009, but higher commercial electricity prices since 2022 indicate a PPA increase is to be expected.

– Gas prices have also decreased in recent years, becoming competitive with wind once again.

– PPA prices vary widely among regions – e.g., prices are higher in California and New York.

– Offshore wind projects rely on government support and higher electricity prices in coastal regions for PPA prices above the market average to compensate for higher LCOE.

Permitting delays and interconnection queues are creating practical obstacles for wind. In some states, onshore or offshore wind projects represent 50% to 70% of the interconnection queue.

– 40% of all wind projects in the pipeline are held up in the permitting phase.

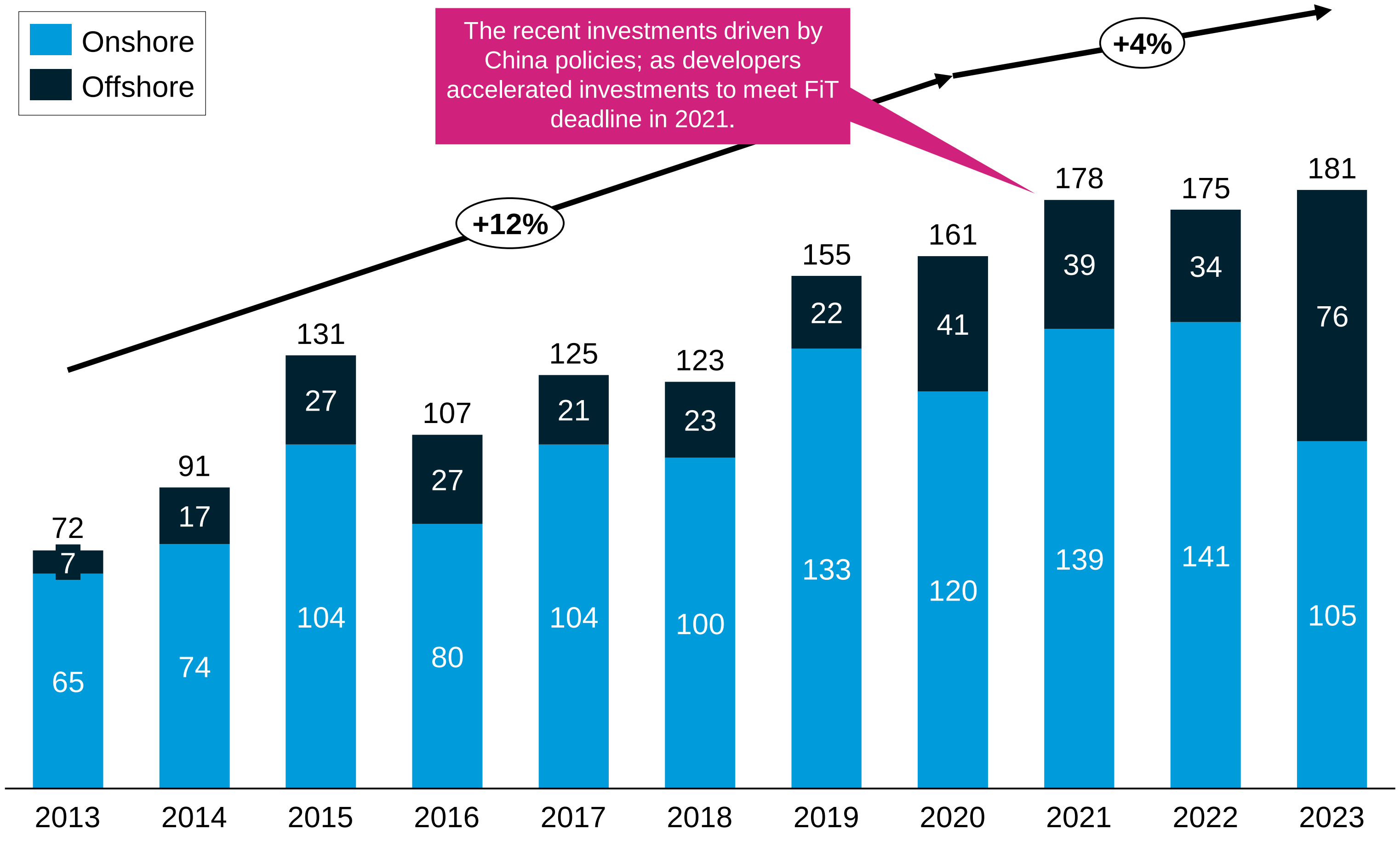
– A total of 246 GW of wind projects is in the queue for transmission connections.

30 GW of planned offshore wind capacity in the US is at risk with the new Trump presidency, which has indicated a halt on new land leases for offshore wind farms.

There is an expected gap of 125,000 workers in wind by 2030, especially wind development.

Investments in wind energy have plateaued since 2020-2023, was historically bad for onshore and good for offshore

Investment trends in wind energy, *$ billions*



Observations

- During 2013-2022, onshore wind accounted for 80% of total investment in wind technologies.
  - In 2019, onshore wind investment witnessed an increase of 32% from 2018 to reach USD $133 billion before declining 9% in 2020.
  - Offshore wind investment reached USD $40 billion in 2020, nearly doubling the 2019 total.
- **The bulk of annual wind power investment goes to the installation of new onshore wind power capacities**, despite disappointing results in recent years.
- **Offshore wind has offset some of the investment decrease in onshore** but was unable to demonstrate significant growth for the sector as a whole.
- **Total CAGR decreased from 12% p.a. between 2013 and 2020 to 4% p.a. from 2020 until 2023.**
- Future investments are projected to expand from $181 billion in 2023 to an impressive $260.8 billion by 2034. The market is anticipated to grow at a CAGR of 10.2% over the next decade.

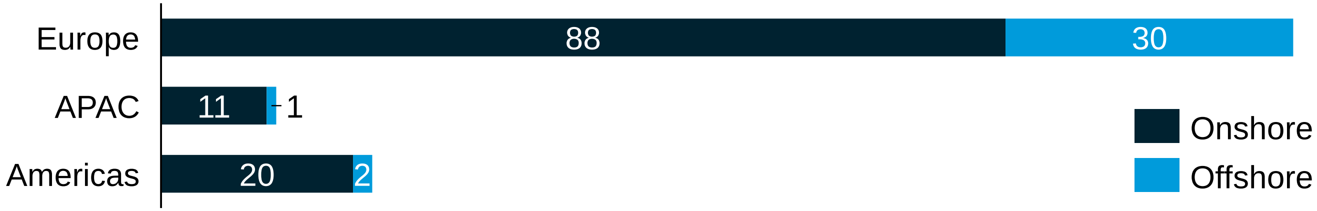
Sources: Peak Wind, Global Renewable Energy M&A Report (2023); IRENA Investment (2023); IEA, World Energy Investment (2024); BNEF, Offshore Wind Investment Hit All-Time High in 2023 (2024); BNEF, Renewable Energy Investment Hits Record-Breaking $358 Billion in 1H 2023 (2023).
Credit: Abha Nirula, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

In 2023, M&A transactions outside China recorded a decline due to economic uncertainty, but offshore and China did see growth

Summary of key findings from asset transactions 2023

	Onshore		Offshore	
	2022	2023	2022	2023
Deal count (excl. China)	134	125	32	33
Transacted capacity (excl. China)	41	27.6	12	24.8
Average deal size (excl. China)	307 GW	221 GW	371	721 GW
Average deal multiple (excl. China)		€1.3M/MW	€3.3M/MW	€2.5M/MW
Deal count (China)	71	113		

Regional deal composition for wind projects, number of deals, 2023



Key deals

Onshore wind

1.04 GW (100%)

Deal value: €1.49B

Deal multiple: €1.44M

Offshore wind

4.2 GW (100%)

Deal value: €1.1B

Deal multiple: € 0.2M

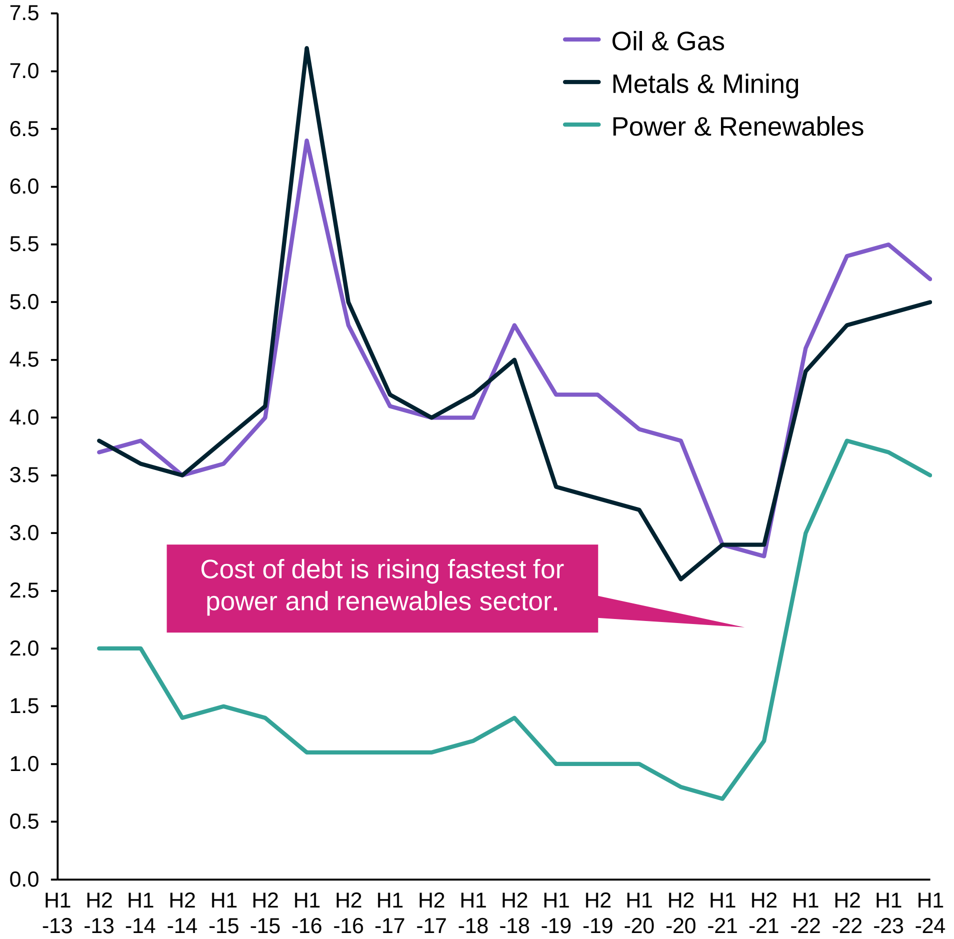
Observations

- While the transactions for offshore wind remained stable, deals for onshore wind declined by 7% from 2022 to 2023.
- However, the acquisition percentage of offshore wind was 41%, which can be due to higher capital expenditure, operational challenges, and lack of maturity for such projects.
- In 2023, nearly 40% of offshore wind deals involved development projects, while for onshore wind, 62% of the deals were for operational projects, as they allow stable long-term returns.
- Developers of off-shore wind are selling part of their stake prior to completion to manage risks and improve their finances.

Sources: Peak Wind, Global Renewable Energy M&A Report (2023); PWC, Retrospective and Outlook of M&A in China's New Energy Industry (2023).
Credit: Abha Nirula, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

High interest rates are driving up the cost of capital for renewables and the power sector, affecting wind in particular

Weighted average cost of debt, *2013-24, %*



Capital intensity of US generation, *2024, %*

Renewable technologies (wind and solar) have higher capital intensity (CapEx %) compared to gas-based technologies, while also showing higher sensitivity to changes in LCOE.

Technology	CapEx %	Change in LCOE (from 2 percentage point rate increase)
Offshore wind (Fixed)	21%	16%
Onshore wind	21%	19%
Utility solar	18%	20%
Gas with carbon capture	9.5%	17%
Gas (OCGT)	9.5%	14%
Gas (CCGT)	6.5%	11%

Assumption: Debt 55%, 15-year term

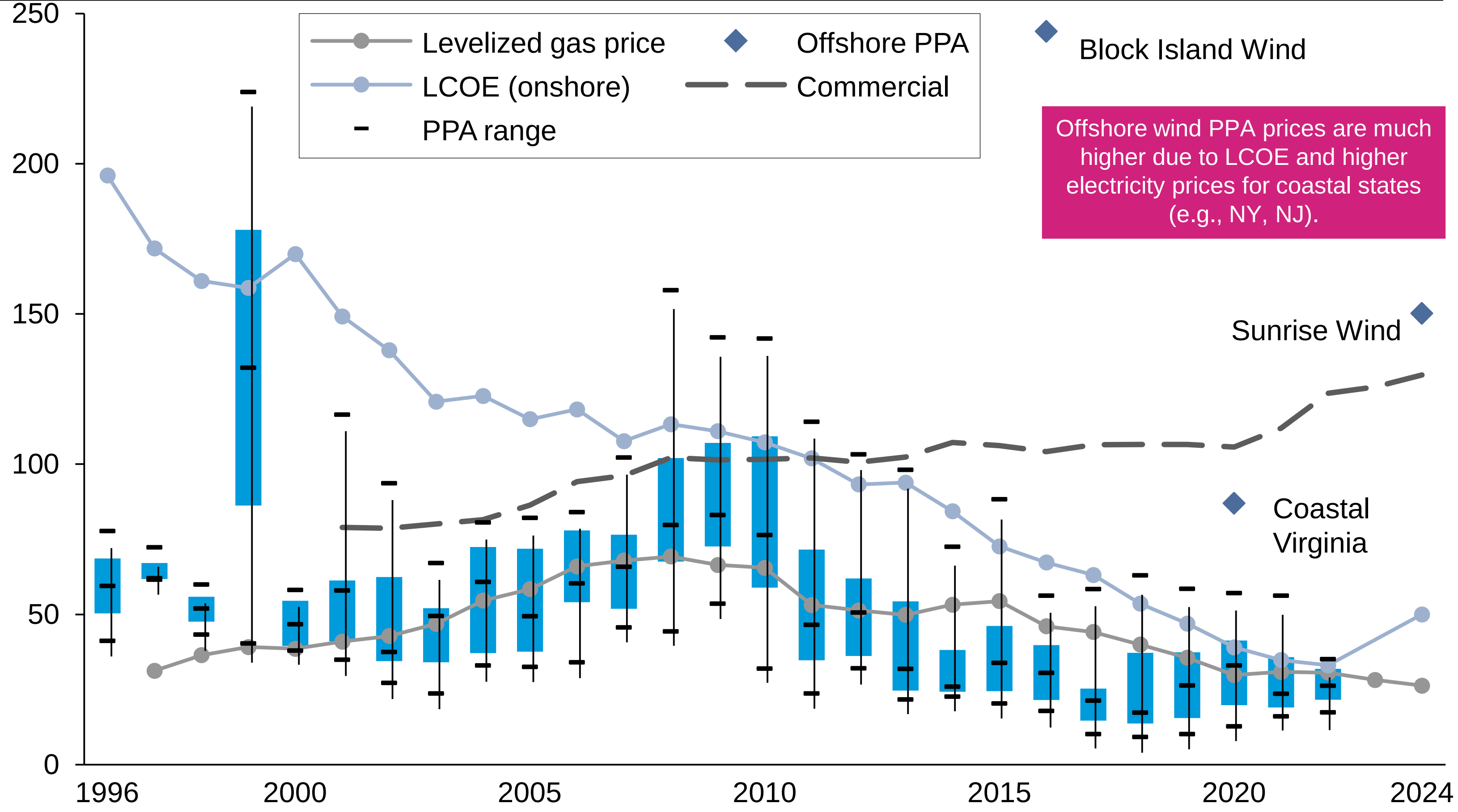
Observations

- **The recent rise in interest rates has a relatively large impact on the cost of debt for wind.**
- **The renewables sector is experiencing a higher borrowing cost than comparable sectors.**
  - Typically, renewables are funded through debt from bonds and project finance, which are secured against long-term power purchase agreements.
  - Given the high capital intensity of renewable energy projects, particularly wind, they are more exposed to interest rates.
  - Their high capital intensity and low returns indicate risk for future projects, which can impact investment sentiment for the sector.
  - China has lower interest rates, given its maturing economic development and lower growth, making it an exception.

Source: Wood Mackenzie, The cost of investing in the energy transition in a high interest-rate era (2024).
Credit: Abha Nirula, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

Average PPA prices have declined since 2009, but an increase in commercial electricity prices indicates increases in PPA trends

Power purchase agreement ranges, gas and commercial electricity prices, *1996-2024, $/MWh*



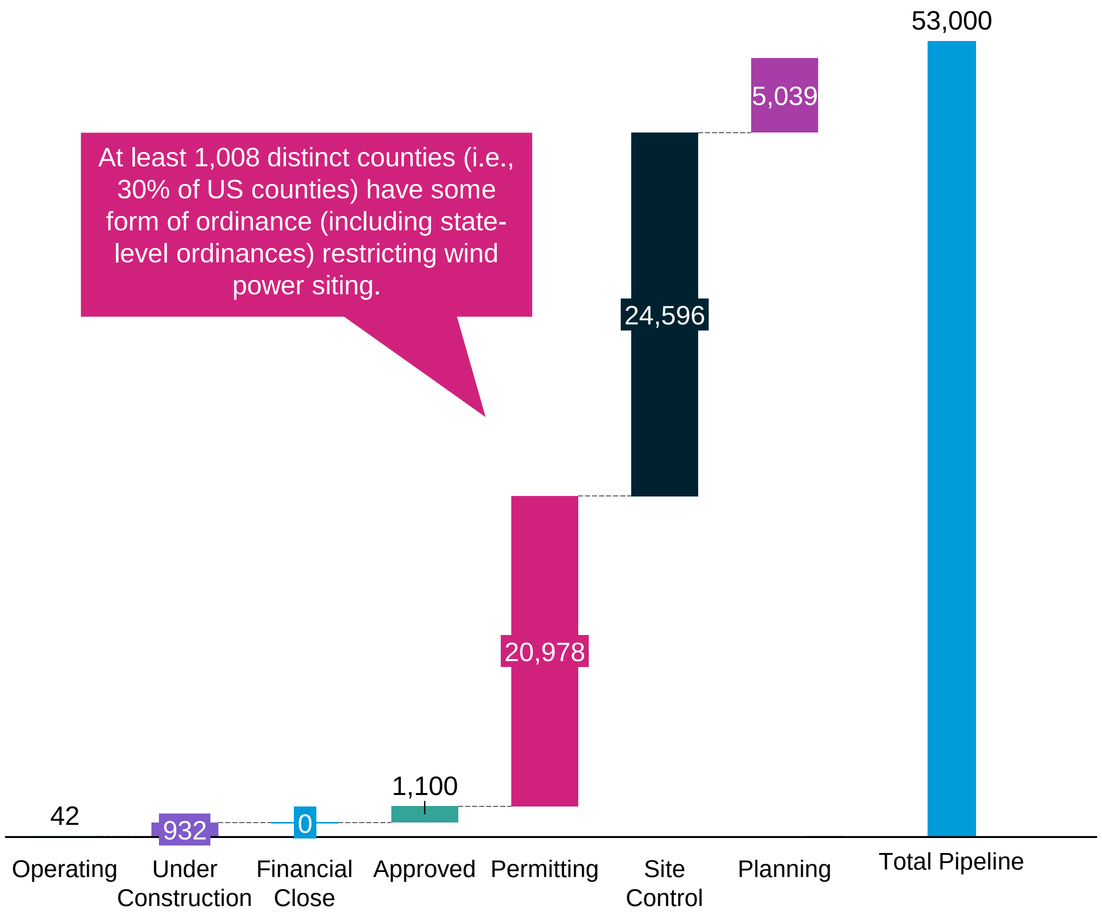
Observations

- **The lowest PPA prices were recorded in 2018,** due to the combined effect of declining capital and operating costs along with improved operating cost and improved performance.
- **The gas LCOE declined in 2023** and was lower than recent PPA prices in several regions.
- **PPA prices vary up to 3x by region.**
  - Typically, PPA prices in the Southwest are on the lower end while California and New York are on the higher end.
- **Electricity prices have increased across the US since 2022, indicating higher PPA prices for wind are likely.**
- **Offshore PPA prices are a recent phenomenon and much higher than onshore** due to the higher LCOE of offshore wind, with the difference paid by the regional system operators.

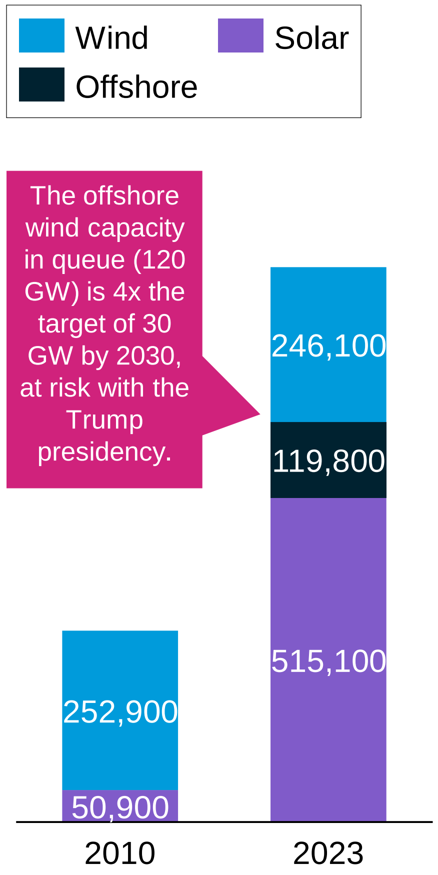
Sources: Berkeley Lab, Wind Power Purchase Agreement (PPA) Prices (2024); Our World in Data, Levelized cost of energy by technology (2023); Offshorewind.biz, LCOE for Coastal Virginia Offshore Wind Project Expected to Be Lower (2023); S&P, Dominion's Virginia offshore wind project cost rises to $10 billion (2021); DOE, Offshore Wind Market and Economic Analysis (2013).
Credit: Abha Nirula, Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

Permitting delays are slowing the deployment of offshore wind projects by 30%, compounded by interconnection queues

US project pipeline classification for wind by status, *MW*



RE capacity in queue in US, *MW*



Observations

- **The US ranks lowest in offshore energy deployment.**
  - Nearly half of US wind projects face significant delays in development, and almost 30% get canceled.
- The US finalized new rules **that are expected to reduce the permitting time by half and save offshore wind stakeholders around $1.9 billion over the next 20 years.**
- **The US Federal Energy Regulatory Commission adopted major interconnection reforms** in 2023. However, they have not taken effect in most regions.
  - Of projects that submitted a request for interconnection during 2000-2018, only 19% reached commercial operations by 2023.
  - The timeline from an initial connection request to a operational plant has increased from <two years for projects built in 2000-2007 to more than four years for those built in 2018-2023.

Sources: DNV, Energy Transition Outlook (2024); NREL, Offshore Wind Market Report (2024); US Department of the Interior, Interior Department Finalizes Rule to Streamline and Modernize Offshore Renewable Energy Development (2024); NREL, Database for wind siting (2022); Berkeley Lab, Generation, Storage, and Hybrid Capacity in Interconnection Queues (2024).
Credit: Abha Nirula, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

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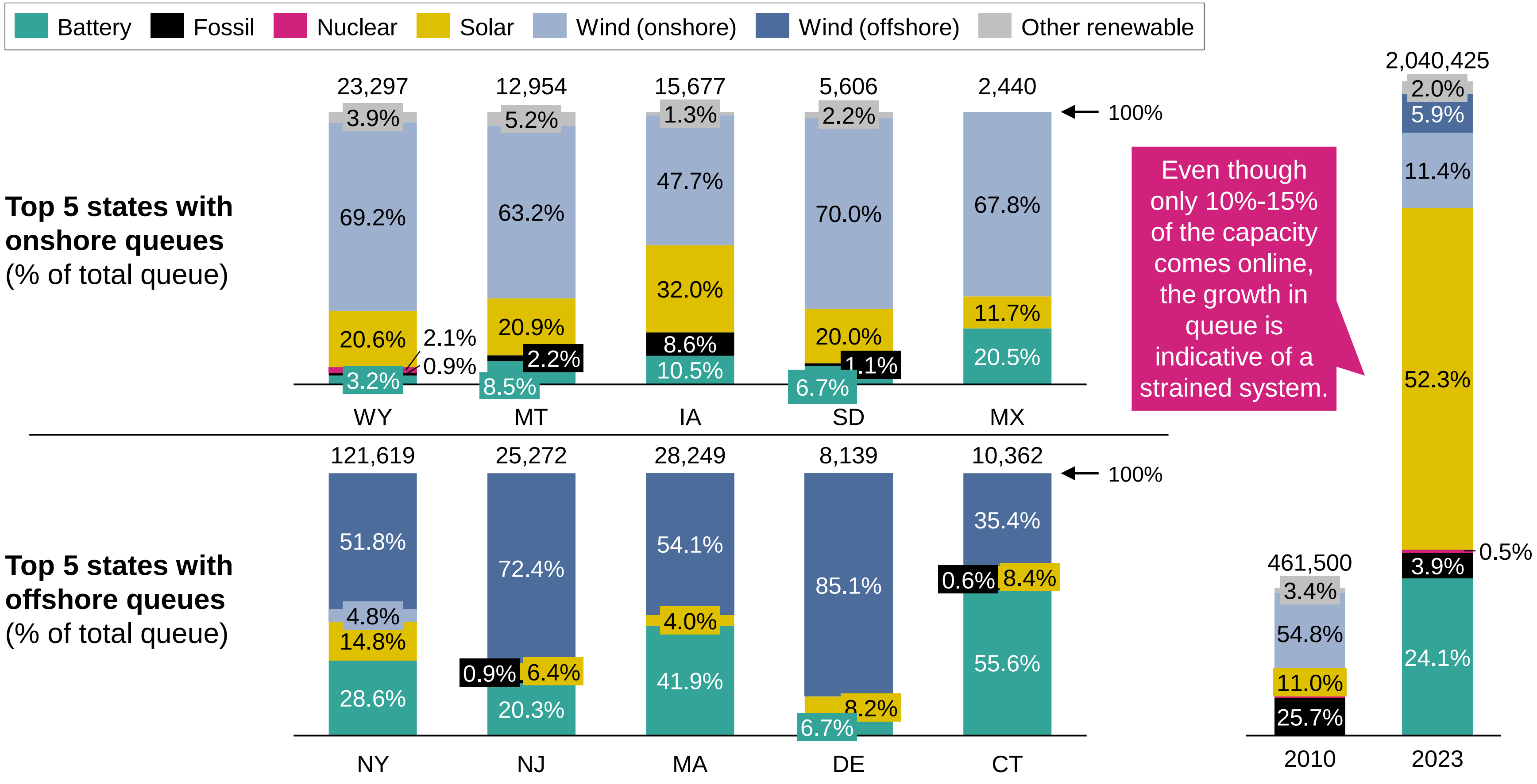
Wind represents 17% of the interconnection queue in the US; in some states, this is 70% for onshore and 85% for offshore wind

Interconnection queue by state and for US total, *2024,% of total MW*



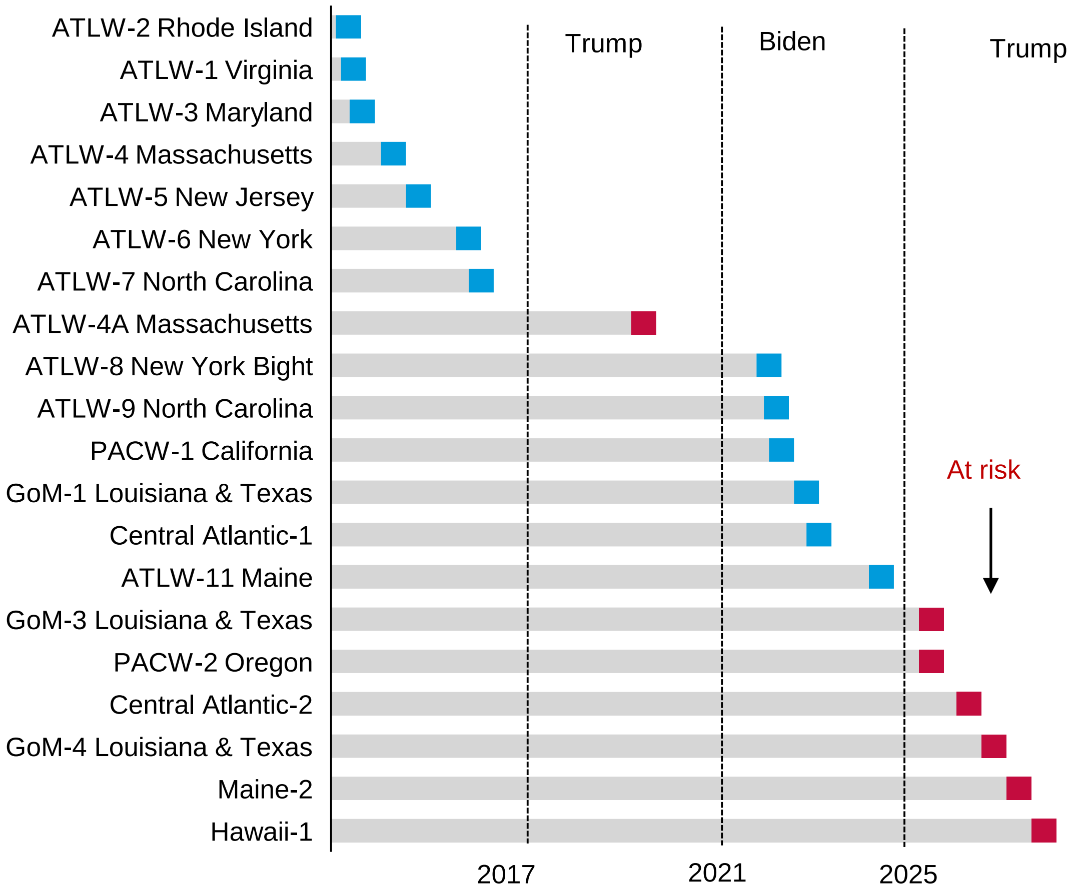
Observations

- **Interconnection queues are a large problem for wind adoption** – although the problem is even larger for solar and batteries (52% and 24% respectively in the US as a whole).
- **In Midwest states** (Wyoming, Montana, Iowa, South Dakota, and New Mexico), **the queues are dominated by onshore wind.** The largest is 13 MW in Wyoming.
- **In coastal** states (New Jersey, New York, Delaware, Connecticut, and Massachusetts) **the offshore wind waiting for interconnection is 35% to 85% of the total queue.** The largest is 65 MW in New York.

Sources: BCG, Offshore Wind: Future of logistic (2022); NY ISO, NYISO's 2024 Priorities Are Fueling New York's Clean Energy Future (2024); Berkeley Lab, Generation, Storage, and Hybrid Capacity in Interconnection Queues (2024).
Credit: Quint Houwink, Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Impact of Trump presidency on wind still uncertain; offshore wind at risk due to potential delay or canceling of offshore lease licenses

US leasing rounds



Risk	Impact
Offshore wind	• 30 GW target of offshore wind to be affected
Leasing	• 7 leases scheduled in 2025-2029 could be delayed or canceled
Permitting	• Expected budget reduction for BOEM; could slow process of applications and extend timelines
Inflation Reduction Act	• Uncertainty regarding IRA provisions; could increase costs, making projects unviable
Supply chain	• Potential of higher tariffs on imports (particularly Europe and China)

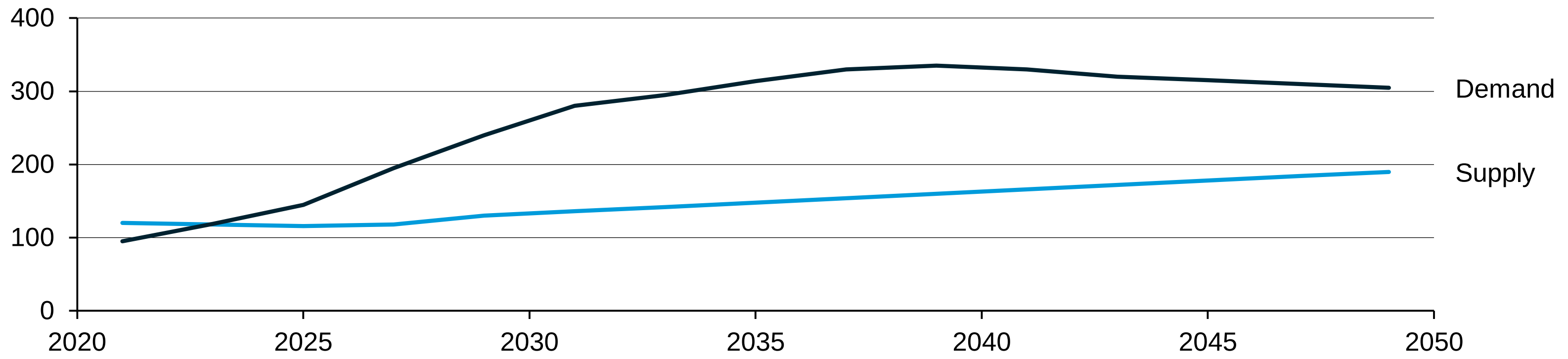
Observations

- The reelection of Trump can impact offshore wind in the short term in three different ways:
  - At the permitting level, by controlling the Department of Interior and the BOEM.
  - At the financial level, by killing parts of the Inflation Reduction Act.
  - By imposing tariffs on a supply chain reliant on foreign companies.
- However, state-level support and approved project pipelines might help mitigate some of the federal-level challenges.
- Progress is expected to slow down but unlikely to result in a complete halt.

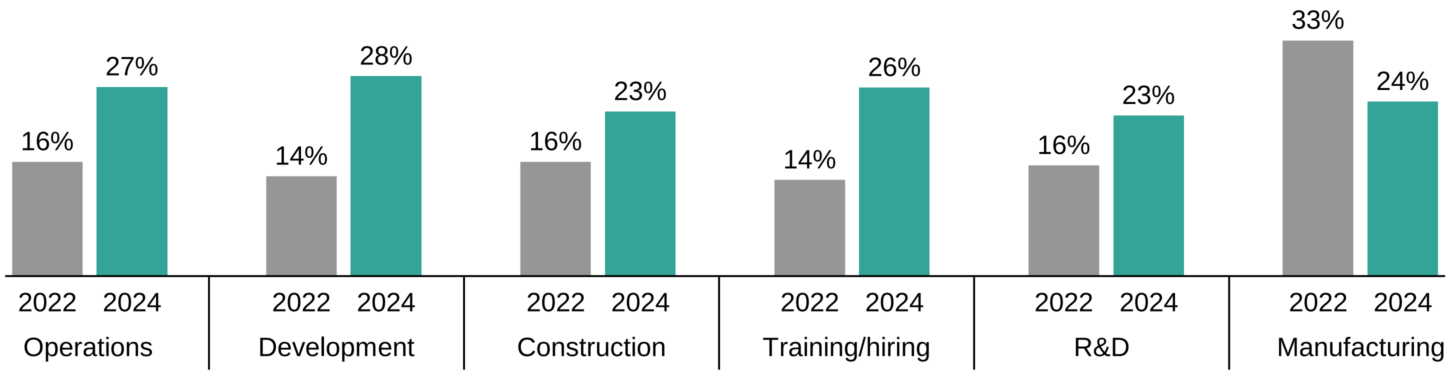
Source: Spinergie, Impact on Offshore Wind Sector (2024).
Credit: Abha Nirula, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

There is an expected gap of 125K workers in wind by 2030; the need most often unmet is wind development

US wind workforce supply and demand, *projected until 2050*



Employers indicating 'great difficulty' in hiring talent by segment, *% of employers*



Observations

- **There is a gap in wind workforce supply and demand that is projected to increase until 2035-40 in the US.**
- **Non-entry-level roles are especially hard to fill due to a lack of qualified applicants.** Applicants often indicate geography as one of the barriers to work in wind.
- More training is needed in practical engineering skills to increase the supply of talent and student awareness of the industry.

Sources: NREL, National Wind Energy Workforce Assessment: Challenges, Opportunities, and Future Needs (2024); NREL, Defining the Wind Energy Workforce Gap (2022).
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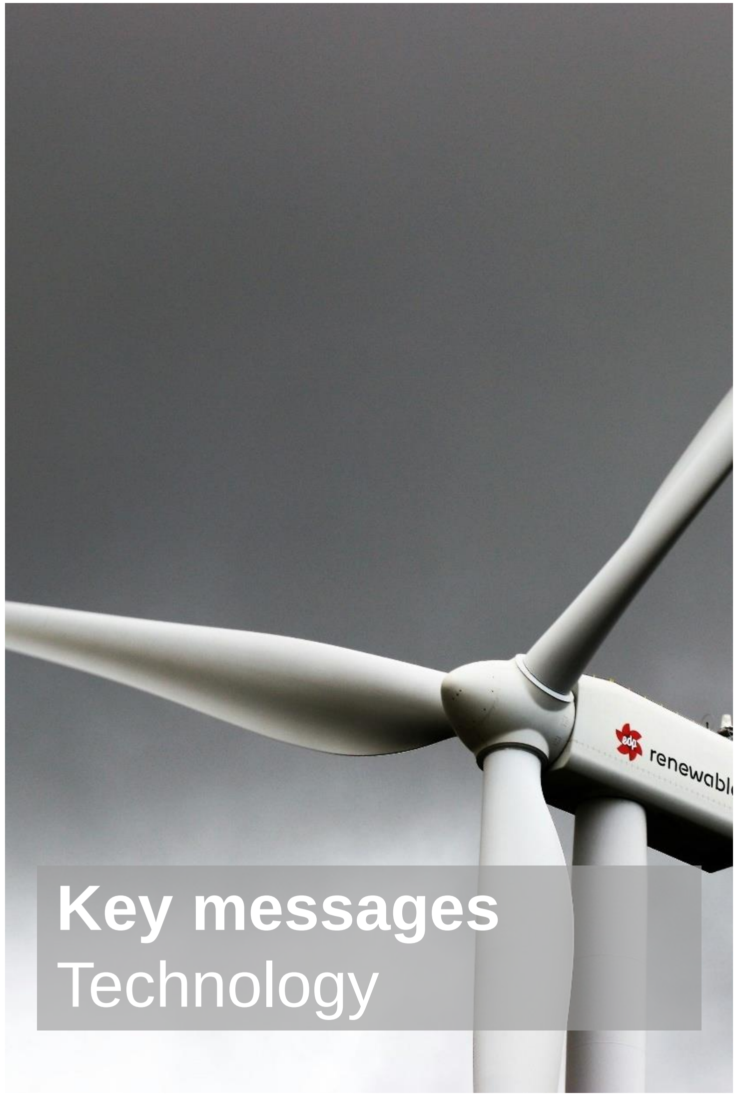
Wind Fundamentals: Technology



Key messages
Technology

There is a total 424 TW of potential wind energy resource around the world, of which less than 0.5% is used. A lot of that unused potential is in the US, Russia, and Australia.

Wind turbines **capture kinetic energy** from an airflow and convert, at most, 60% of it into electric energy.

- Although vertical-axis turbines exist in urban areas, **nearly all (>99%) modern wind capacity comes from horizontal-axis turbines.**
- **Most wind turbines use a gearbox to improve the efficiency of the generator** (~90% of onshore turbines), with **direct-drive gaining market share in the offshore segment** (~60% of offshore turbines).

Utility-scale onshore wind dominates the sector, with >90% of installed capacity. Fixed-bottom offshore represents ~7% of installed capacity.

Wind is the least CO2-intensive electricity source at ~11 gCO2e per kWh, caused by fossil fuels used in raw materials and construction.

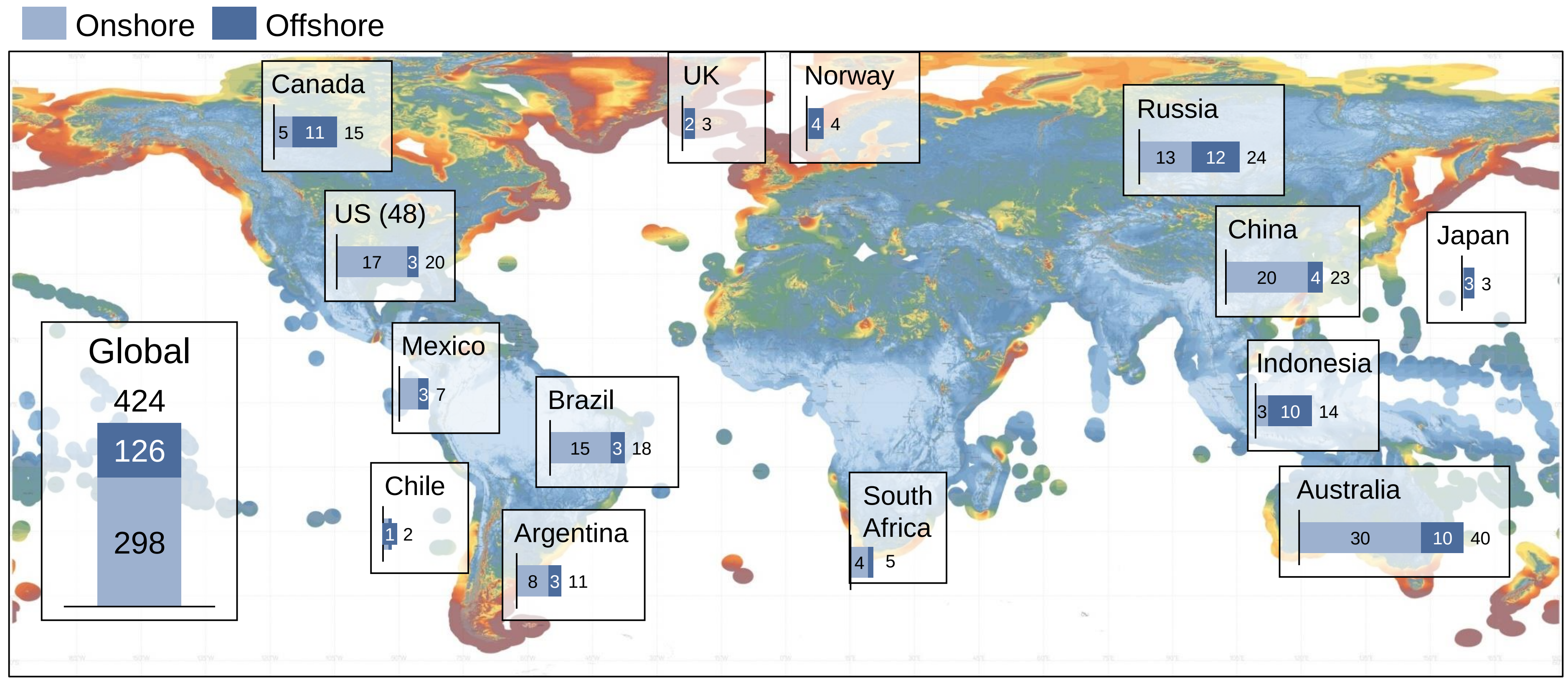
Wind energy faces **technical opportunities and challenges** that impact its cost and yield, as well as **communities' resistance** to new installations.

- Offshore wind offers a lot of additional capacity for wind energy, since it isn't limited by space. **Offshore has grown at >20% p.a. vs. 9% p.a. for onshore, but higher costs due to technical challenges** (in construction and maintenance) **prevent large-scale adoption.**
- **Nameplate capacity has grown 6x for onshore wind and 10x for offshore wind since 2000,** driven by higher wind speeds and a higher capacity factor (capacity per m^2) for larger wind turbines. Further growth is expected, helping to decrease the LCOE of wind energy.
- **Because turbines are increasingly large, physical limits** (e.g., road size, moving and construction equipment) **need to be overcome when deploying turbines.**
- Wind farms need to **maintain a capacity density of <3 MW/km2** to prevent wake loss. This trend has led to exponentially larger wind farms and concerns about the total availability of land suitable for wind turbines.
- **Wind farms increase local temperatures** by mixing air from higher altitudes with surface air. Global warming has a much larger long-term impact, but local warming could affect some of the agriculture in the areas with high turbine density (e.g., the Midwest and Texas).
- **Wind intermittency causes a mismatch in supply and demand** and thus a lower LCOE. One solution is smart-grid integration, whereby battery energy storage systems and hydrogen conversion are added to wind installations.

Sources: IEA, Net Zero Roadmap (2023); Our World in Data, Electricity generation from wind power (2024).
Credit: Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.,* "Reconsidering Wind" (5 March 2025).

Global wind energy resource is 424TW – enough to power the world 10x in a 2050 Net Zero scenario; US, Russia, and Australia most unused potential

Global wind capacity potential at 90-meter turbine hub heights*, *TW*



Observations

- **Global wind capacity potential is 424 MW**, of which ~75% comes from onshore potential.
- This is equivalent to **872,000 TWh of annual electricity production.**
- **The US currently uses only 2% of its potential wind capacity.**
- **China uses 4% of its potential wind capacity.**
- The model accounts for wind speeds, terrain elevation and slope (for onshore), and water depth and distance to shore (for offshore and protected areas)**.**

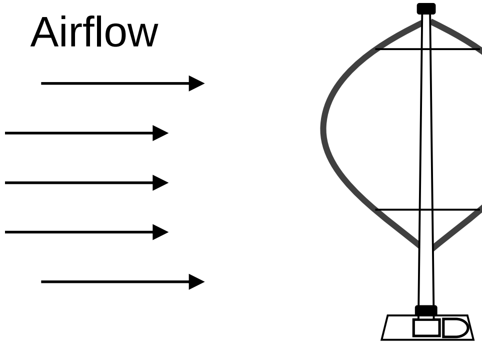
(*) Selection of countries based on wind potential and economic capabilities.
Sources: GWA, Wind Power Density (2019), data provided by The World Bank and funded by ESMAP; NREL, An Improved Global Wind Resource Estimate for Integrated Assessment Models (2019).
Credit: Taicheng Jin, Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Wind turbines convert kinetic wind energy into electricity using blades – typically around a horizontal axis, although vertical exists

Comparison of horizontal- and vertical-axis wind turbines

Global installed capacity, GW, 2024

Airflow



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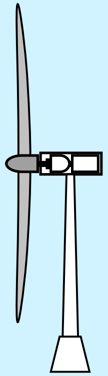
Focus of this document



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	Vertical-axis wind turbine (VAWT)	Horizontal-axis wind turbine (HAWT)
Considerations	+ Captures wind from any direction	+ High efficiency – up to 50%
	+ Easy to service due to lower heights	+ Captures stronger winds at greater heights
	– Constrained to lower heights due to structure	+ Long track record of reliability
	– Lower, uncertain efficiency (20%-40%)	– Difficult to service due to heights
	– Larger footprint	– Needs yaw system to track the wind
Applications	• Residential • Urban	• Commercial and utility scale • Onshore and offshore

Observations

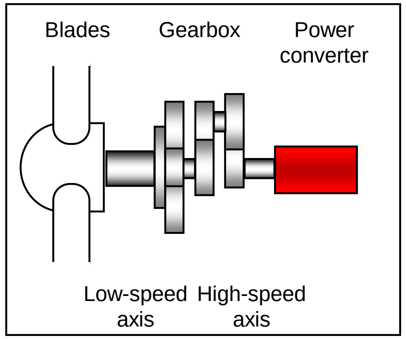
- The theoretical maximum efficiency of any turbine is ~59%, known as the Betz Limit. **HAWTs reach up to 80% of that limit in practice, compared to only half for VAWTs.**
- Because of their historic dominance in efficiency and reliability, **HAWTs have seen much more development and deployment** in the past decades. This has ultimately led to an even bigger technological and economic advantage.
- Some recent academic research has indicated that VAWTs could have superior efficiency and be more serviceable than HAWTs. Nevertheless, **it's unlikely that a big shift to VAWTs will occur in the near future.**

Sources: Trepka, Wind Energy; EPA, Renewable Energy Fact Sheet (2013); Our World in Data, Installed wind energy capacity (2023)
Credit: Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

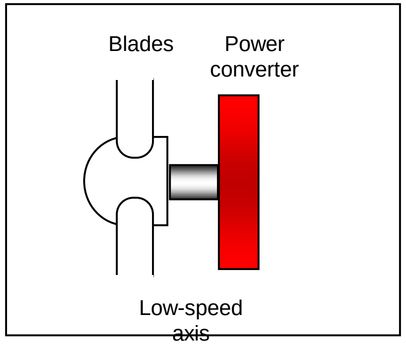
Blade rotation into electricity is either direct or through a gearbox, with direct drive growing offshore and geared dominant onshore

Trend in average US wind farm size

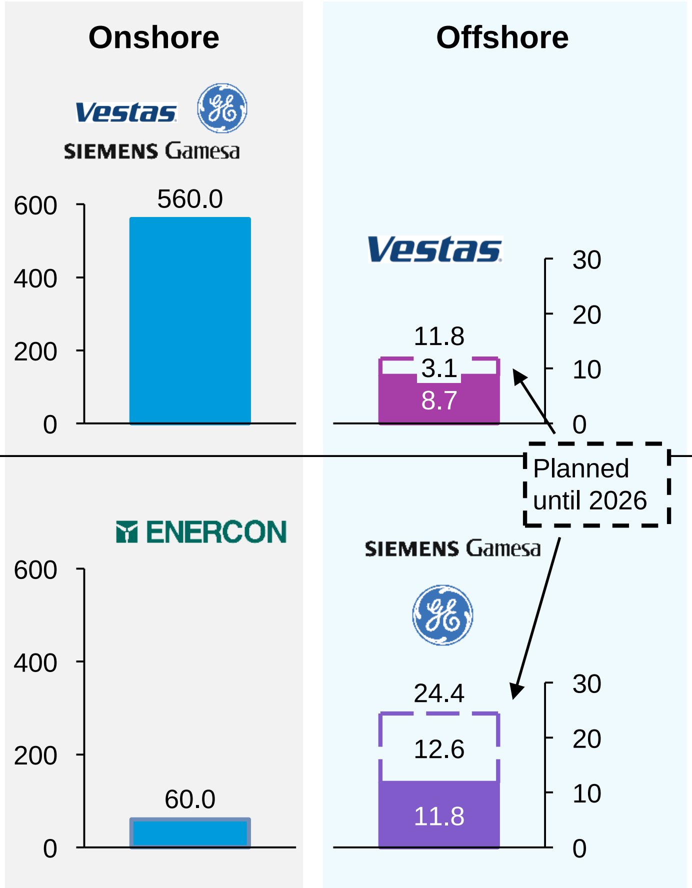
Geared



Direct drive



Global installed capacity, *excl. China, 1990-2024, GW*



Considerations

- Gearboxes change the speed and torque of a rotating shaft. This allows for a **smaller and cheaper** power generator in turbines, reducing cost and stress on the tower structure.
- **Gearboxes fail frequently** – one in every 145 turbine gearboxes fails annually. As such, they add to the maintenance of wind turbines, which is **especially costly offshore.**

- **A direct drive eliminates the need for a gearbox** and thus the complexity and maintenance cost associated with gearboxes.
- A direct-drive turbine can also **maintain its efficiency** across a range of wind speeds – if the total torque is large enough. **Wind turbines of >7 MW are therefore not suitable for direct drive.**

Sources: Enercon, Track Record (2024); Wikipedia, List of offshore wind farms (2024); GWEC, Global Offshore Wind Report (2023); Pall, The Consequences of Gearbox Failures in Wind Turbines (2023); Spinning Wing, Direct Drive Wind Turbines; Picture top: Paul Anderson; Picture bottom: DKViolet.
Credit: Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Onshore makes up >90% of global installed capacity; composition may shift toward offshore as cost declines

	DISTRIBUTED SCALE			UTILITY SCALE		
	ONSHORE				OFFSHORE	
	Residential*	**Commercial***	**Mid and large***	**Onshore**	**Fixed-bottom**	**Floating**
Benefits	• Serve **on-site energy demand** or support **local** electricity networks • Can cover part or entire utility demand			**Rapid** rollout and connection; **cheaper** installation, **easier O&M** once installed	Higher wind speed, **frequent** and **constant** wind input offshore; far from residential areas	
Description	• **Small systems**, most often on **rooftops of homes** • Produce electricity directly for the **homeowner's use;** could **export excess**	• **Midsize systems,** often **mounted close to the source demand** • Produce electricity **directly for the business' use;** could export excess to the grid	• **Industrial parks, factories**	• **Large, ground-mounted array** that **delivers power to the grid** • Often sells to a utility offtaker through a **power purchase agreement**	• **Larger turbines**, located off the coast in shallow water, often with platforms that are embedded into the **seabed**	• **Sited in deep ocean and complex seabed** • **Flexible anchors such as chains and steel cables** • **Less ecological impact**
Installed capacity, MW '24 2030	~2	~3	~7	977 1,773	70 250	0.2 12

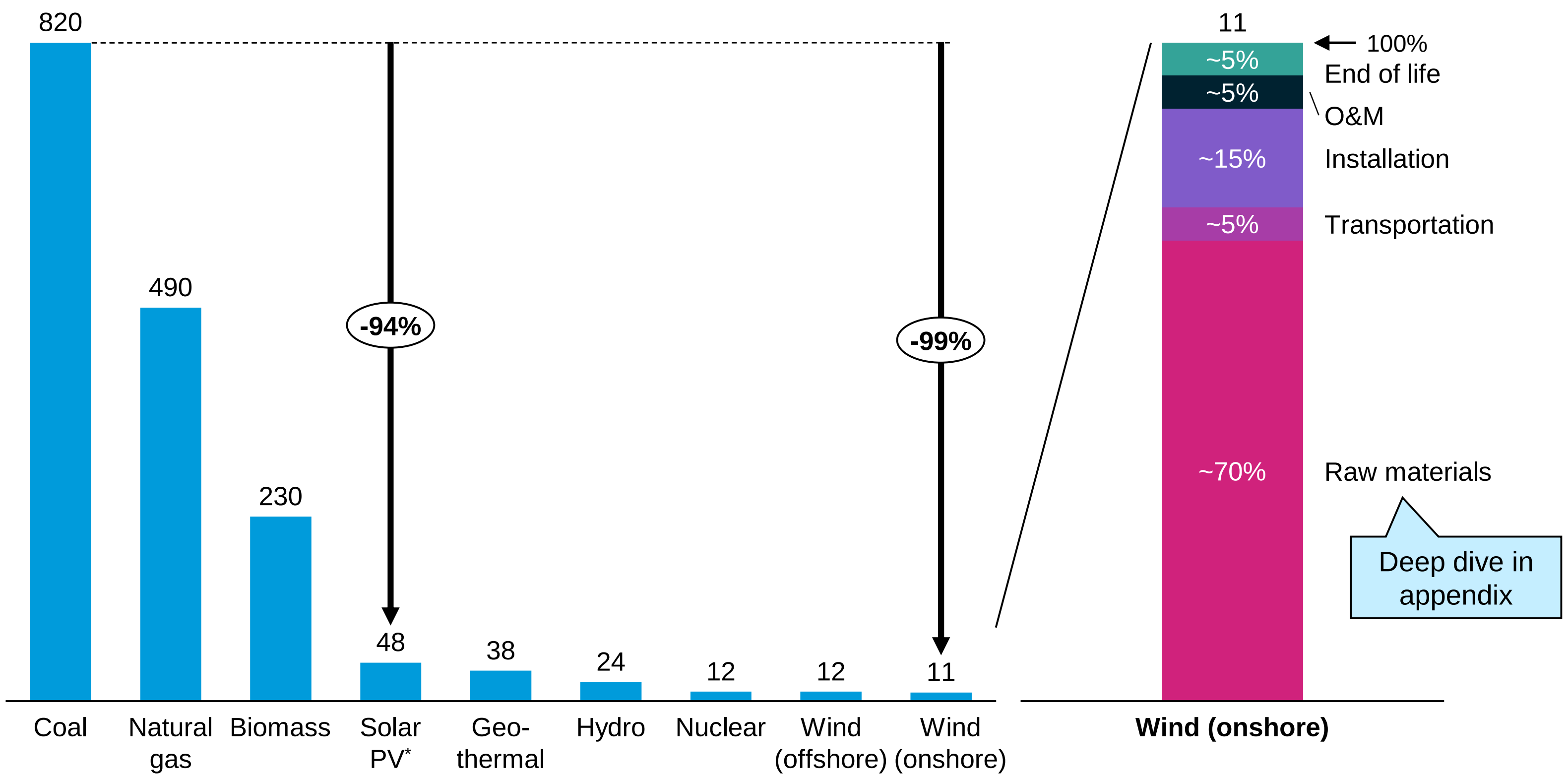
(*) Installed capacity for commercial and Mid & Large extrapolated based on U.S. numbers. CAGR based on 2016 projections

Sources: IEA, Renewables (2023); Energy.gov, Wind Energy Market Reports (2024); Nuveen, Infrastructure Energy Transition Update (2024); Incorrys, Wind Power Capacity Forecast 2022-2030 (2024); NREL, Assessing the Future of Distributed Wind: Opportunities for Behind-the-Meter Projects (2016).

Credit: Taicheng Jin, Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Wind is the least CO_2-intensive electricity source at ~11 gCO_2e/kWh due to fossil fuel use in raw materials and construction

Carbon intensity by electricity source, *gCO_2e/kWh* **By phase for wind**



Observations

- **Wind emits about 1% of CO_2e/kWh compared to coal (820 gCO_2e/kWh) and about 2% compared to natural gas (490 gCO_2e/kWh),** making it the best electricity source, even among other renewables.
- **Production of raw materials** (e.g., fiberglass and steel) are **responsible for ~70% of total emissions** generated over a power plant's lifetime. Emissions here mainly come from the usage of coal in the production of steel.
- **Installation is the second largest source of CO_2 for wind energy.** These emissions come from diesel fuel used by construction equipment and personnel transport.

(*) Utility-scale solar
Sources: World Nuclear Association, Carbon Dioxide Emissions From Electricity (2024); Sikdar and Princiotta, Advances in Carbon Management Technologies (2021).
Credit: Quint Houwink, Petr Jenicek, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Wind energy faces technical opportunities and challenges that impact cost and yield, as well as community resistance

Non-exhaustive overview of technological opportunities and challenges (including impact on deployment)

Focus of this deck

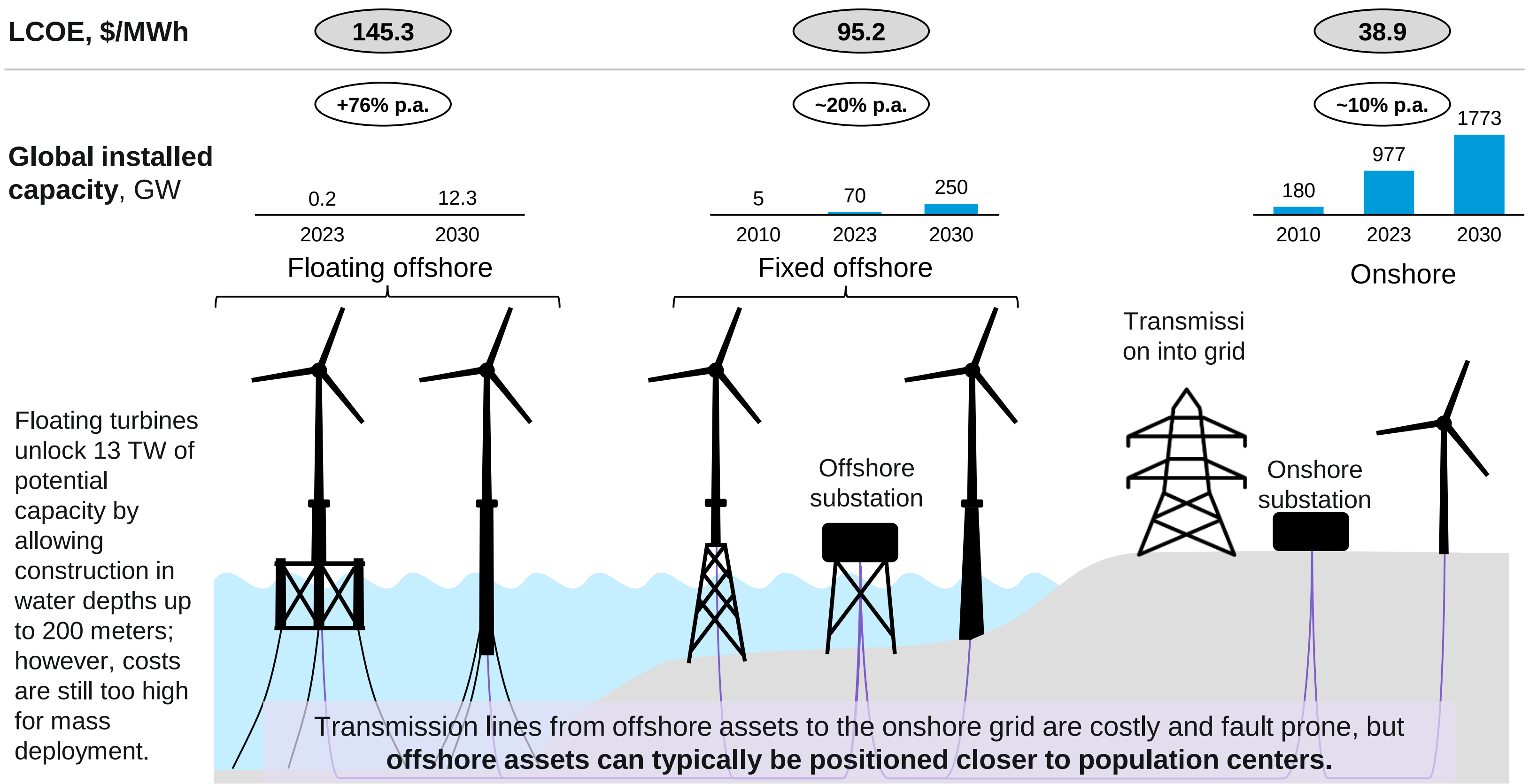
	Onshore	Offshore
Opportunities	**Increasing size** (lower CapEx/MWh)	
	Grid integration with hydrogen and solar (higher returns)	
	Predictive maintenance using AI (lower OpEx)	
	Low-specific-power turbines (more suitable areas)	**Floating turbines** (more space for wind)
		Direct-drive transmission (lower OpEx)
Challenges	**Logistical and manufacturing constraints due to turbine size** (delay)	
	Wake losses in larger farms (lower yield)	
	Bird and bat killings (more community resistance)	
	Long transmission lines (higher CapEx)	
	Local warming (more community resistance)	**Marine life influence** (more community resistance)
	Noise (more community resistance)	**Turbine scour** (higher OpEx)

Sources: EERE, Land-Based Wind Market Report (2023); EERE, Offshore Wind Market Report (2023); NREL, Technology Advancements Could Unlock 80% More Wind Energy Potential During This Decade (2023); NREL, Offshore Wind Market Report (2024)

Credit: Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Offshore wind grows at >20% p.a. vs. 9% p.a. for onshore, but higher costs due to technical challenges prevent broad adoption

Comparison of horizontal- and vertical-axis wind turbines



Observations

- Offshore wind has grown 14x in the past decade and is expected to grow an additional 4x by 2030. Nevertheless, the total installed capacity is still much smaller than onshore wind, which has steadily been growing at ~10% CAGR.
- Offshore wind turbines are appealing for multiple technical reasons, including:
  - Less impact on residential areas.
  - Higher average wind speeds and more consistent.
  - Larger constructions can be shipped rather than transported by road.
  - There is no competition with other space-consuming projects (e.g., industry, agriculture, housing).
- However, offshore wind comes with significant challenges compared to onshore wind:
  - Structures must overcome fatigue, erosion, and corrosion in tough ocean climates.
  - Structures need to be fixed to ocean bottoms at 30 to 50 meters depth.
  - Transmission lines need to connect offshore wind farms to the onshore power grid.

Sources: Ørsted, Advantages of offshore wind; Asim et al., A Review of Recent Advancements in Offshore Wind Turbine Technology (2022); Incorrys, Wind Power Capacity Forecast 2022-2030 (2024); Blackridge, Top 7 Upcoming Floating Offshore Wind Projects In the World (2024).
Credit: Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Hywind Scotland demonstrates the technical feasibility of floating wind, but the LCOE is 3x that of offshore wind (8x onshore)

Facts

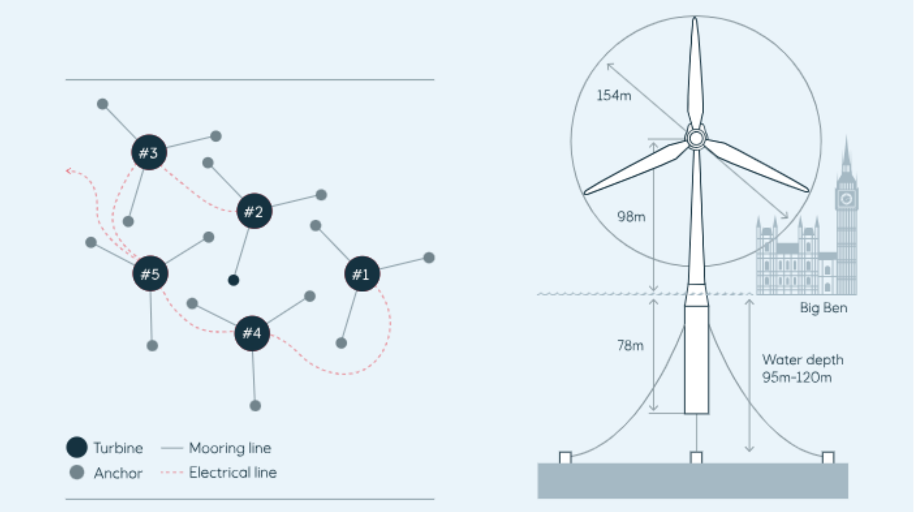
- Developer: Equinor
- Location: Scotland, Grampian, UK
- Status: Operating
- Commission date: October 2017
- Capacity: 30 MW
- Operator: Hywind Limited
- Units operational: 5 x 6 MW
- Make and model: Siemens Wind Power SWT-6.0-154 (direct drive)

Performance

- Cost: £8.8m/MW (~3x compared to fixed offshore wind farms)
- Average capacity factor: 54%
- Survived storms such as Hurricane Ophelia and Storm Caroline, which caused up to 10-meter waves

Future ambitions

- Hywind Tampen, an 88 MW floating wind farm, became fully operational in 2023, reaching a cost of £6.8/MW and an LCOE of $248/MWh.
- The US launched Floating Offshore Wind Shot to reduce the cost of floating wind turbines to $45 per MWh.
- Ørsted is working on two projects in Scotland: Project Salamander, with a capacity of 100 MW, and Project Stromar, with a capacity of 1 GW. Both should be operational by 2030.



Observations

- Hywind Scotland is the **first floating turbine wind farm**, demonstrating that floating wind turbines are technically feasible and can operate in extreme weather conditions.
- Unfortunately, its **LCOE of $248/MWh is 3x as high** as other offshore energy (~$80/MWh) and 8x that of onshore energy (~$33/MWh).
- The higher LCOE is mostly **driven by higher CapEx** for the substructure and foundation (~45% of cost compared to ~30% for fixed-foundation offshore wind). More **investments** in standardized technology for floating offshore wind should **bring this down by 80% by 2050.**

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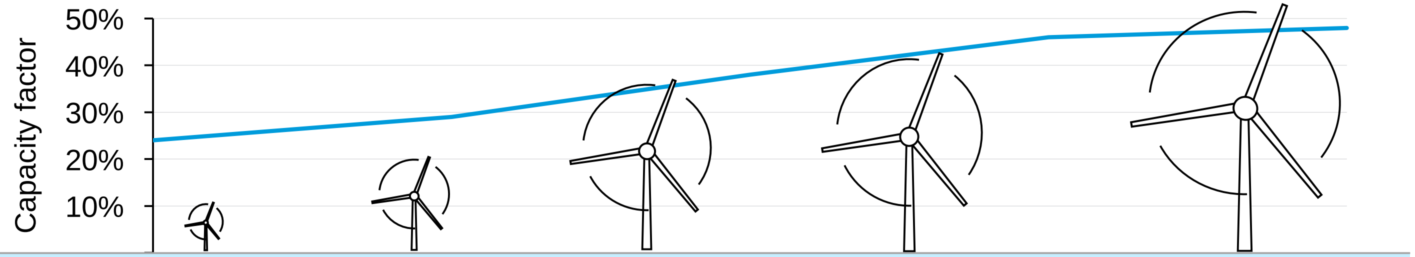
Sources: Equinor, Hywind Scotland; Equinor, Our Floating Offshore Wind Projects; NREL, Cost of Wind Energy Review (2022); DNV, Floating Wind: Turning Ambition into Action (2023).
Credit: Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Nameplate capacity increased 6x for onshore and 10x for offshore since 2000, driven by higher wind speeds and capacity factor

Overview of largest developed wind turbine in selected years, *in capacity and rotation diameter*

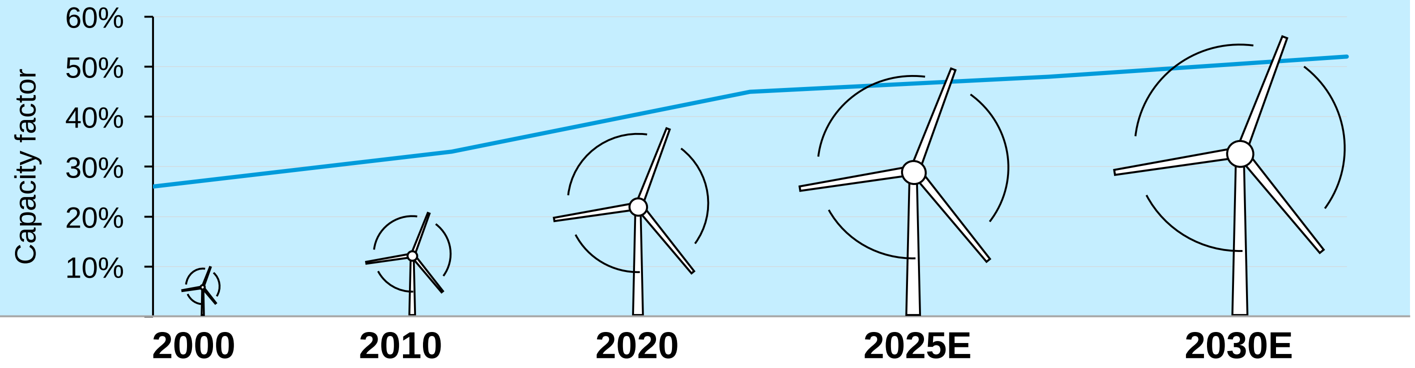
Onshore

	2000	2010	2020	2025E	2030E
LCOE	$170/MWh	$124/MWh	$49/MWh	$50/MWh	
Installed capacity	1.0 MW	1.9 MW	4.8 MW	7.2 MW	10 MW
Rotor diameter	50m	81m	158m	172m	~220m



Offshore

	2000	2010	2020	2025E	2030E
LCOE	$177/MWh	$197/MWh	$88/MWh	$75/MWh	
Installed capacity	1.6 MW	3.0 MW	10 MW	14.7 MW	22 MW
Rotor diameter	44m	94m	164m	222m	~270m



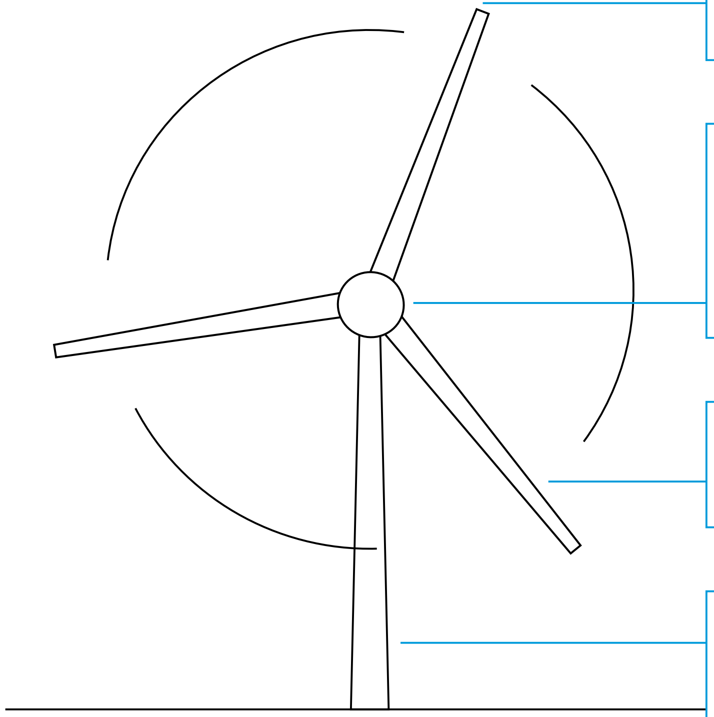
Observations

- Taller towers **benefit from higher wind speeds** (~0.5m/s increase per 30-meter altitude).
- Larger wind turbines have **proportionally lower costs** for construction of the tower (down to $200/kW from $500/kW).
- A larger disk area leads to lower specific power (W/m²), which typically **improves a turbine's performance in slower wind conditions, unlocking an additional 80% economically viable onshore wind energy capacity in the US.**
- The capacity factor, defined as the average. power output divided by its maximum power capability, **is higher for turbines with larger disk area and more altitude.**
- Currently, **transporting and constructing the foundation of wind turbines form the biggest challenge** in increasing turbine size further.

Sources: Berkely Lab, Land-based Wind Market Report (2024); NREL, Offshore Wind Market Report (2024); IRENA, Future of Wind (2019); NREL, Increasing Wind Turbine Tower Heights: Opportunities and Challenges (2019); NREL, Annual Technology Baseline (2023); NREL, Technology Advancements Could Unlock 80% More Wind Energy Potential During This Decade (2023).
Credit: Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Complex logistics of increasingly large components reduce the rate of adoption for bigger wind turbines

Challenges associated with the increasing size of wind turbines



Tip height is often limited by local regulations (e.g., in Poland, max 10% of distance to nearest housing).

Hoisting the 300t nacelle to a height of 120m is pushing the existing cranes to the limit. New crawler cranes must be developed to support the biggest contemporary turbines. Offshore, existing wind turbine installation vessels have maximum hoist heights of 125m. New vessels are being produced to reach 160m hoisting heights.

Blade size is limited by road transport. Traditionally, this was a maximum of ~60m (3.8 MW turbine). Modern blade lifter transport vehicles have extended this ~80m (7-10 MW).

Tower base diameter is limited by road transport, at ~4.3m due to underpasses and bridges, leading to less efficient tower designs.

Observations

- **Wind turbines become more efficient at larger sizes,** but logistical challenges in transportation and hoisting could cause delays in further growth.
- For onshore, size is mostly **limited by road transport.**
- For offshore, size is **limited by the existing wind turbine installation vessel.**
- **Technological innovations**, such as a blade lifter**, allow for larger blades** without changing road infrastructure.

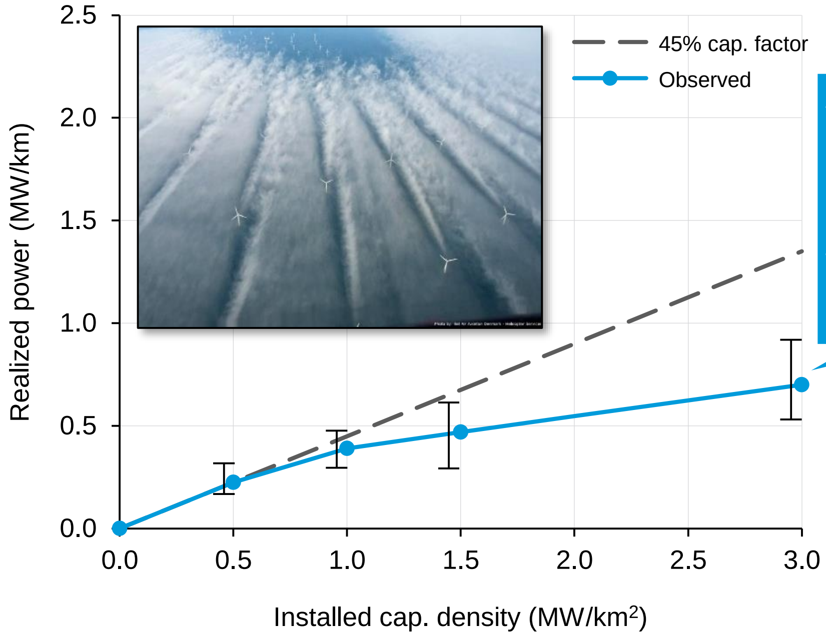
Sources: NREL, Analysis of Transportation and Logistics Challenges Affecting he Deployment of Larger Wind Turbines: Summary of Results (2014); EIA, Why are Midwest grid operators turning away wind power? (2024); Wind Europe, Only a setback distance of 500 metres will support onshore wind in Poland (2023); Cranes Today, Reaching the limit? (2021); NREL, Analysis of Ideal Towers for Tall Wind Applications (2018); Offshore Construction Associates, Larger Wind Turbines: What does this mean for offshore installation vessels? (2021).
Credit: Quint Houwink, Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Wind farms need to maintain a capacity density of <3 MW/km2 to prevent wake loss, leading to exponentially larger wind farms

Wake losses increase with larger turbines and decrease with more space …

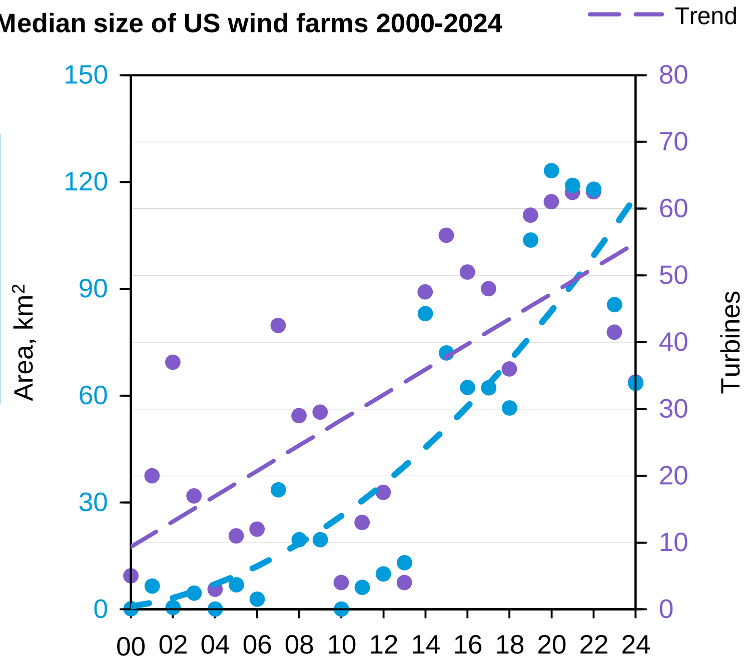
… leading to exponentially more area being taken up by wind farms in the US.

Observed realized power for various installed capacity densities



At a density of 3MW/km^2, **~80% of the US** would need to be covered in wind farms to cover the energy need of 86MWh/cap.

Median size of US wind farms 2000-2024



Observations

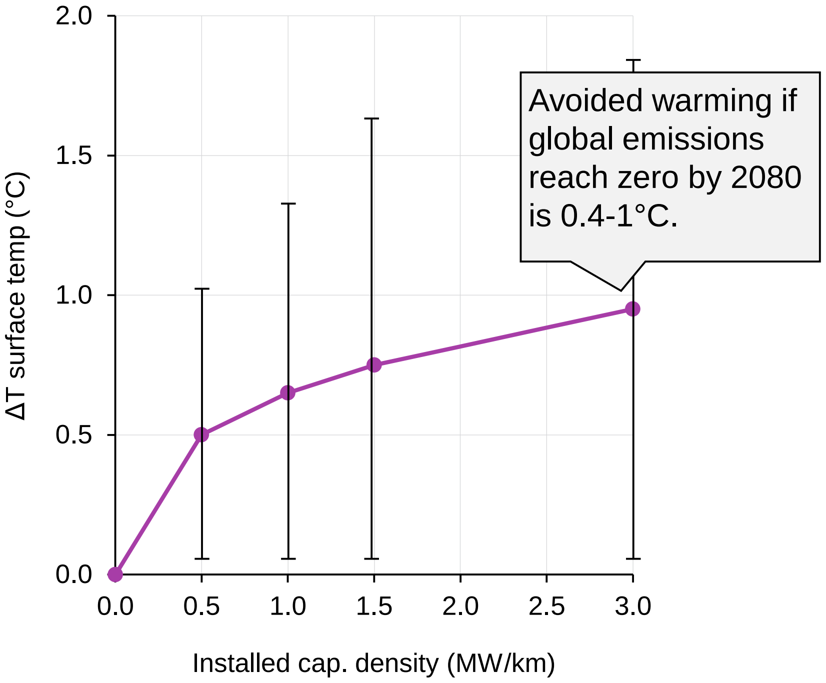
- As wind energy has become more competitive in LCOE, **wind farms have gotten larger.** The average number of turbines has increased from 30 to 80 in the past two decades. Similarly, **the average capacity has increased sevenfold from ~30 MW to ~210 MW** per farm.
- **This leads to wake losses**, where the interaction between turbines **reduces the production capacity by up to 50%.**
- New turbine designs **steer wake away from downwind turbines** and thus allow for slightly denser wind farms.

Sources: Baas et al., Investigating energy production and wake losses of multi-gigawatt offshore wind farms with atmospheric large-eddy simulation (2023); Miller and Keith, Observation-based solar and wind power capacity factors and power densities (2018); USGS, U.S. Wind Turbine Database (2024); Hasager et al., Wind Farm Wake: The 2016 Horns Rev Photo Case (2017).
Credit: Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

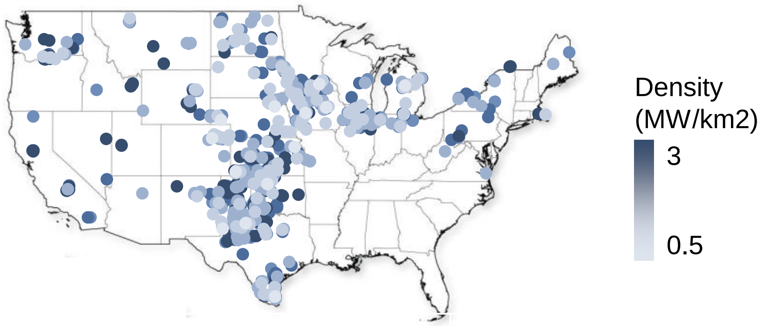
Wind farms have a significant impact on local temperatures, although global warming has a much larger long-term impact

Wind farms lead to local effects on the environment … ⇨ **… causing areas of the US to be up to 1°C warmer.**

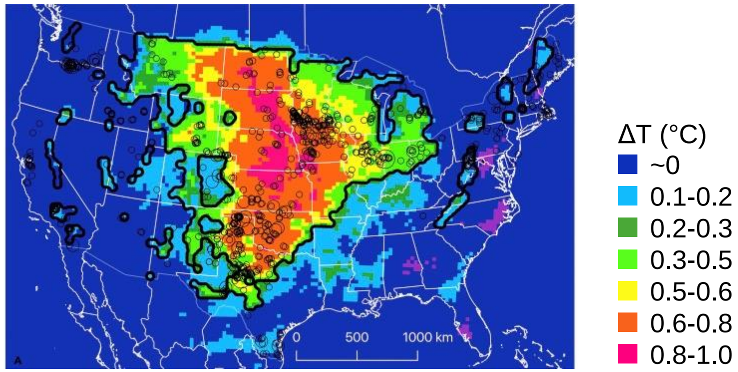
Effect of installed wind power on local surface temperatures



Installed power density of >100 MW wind farms in the US



Local warming due to wind farms



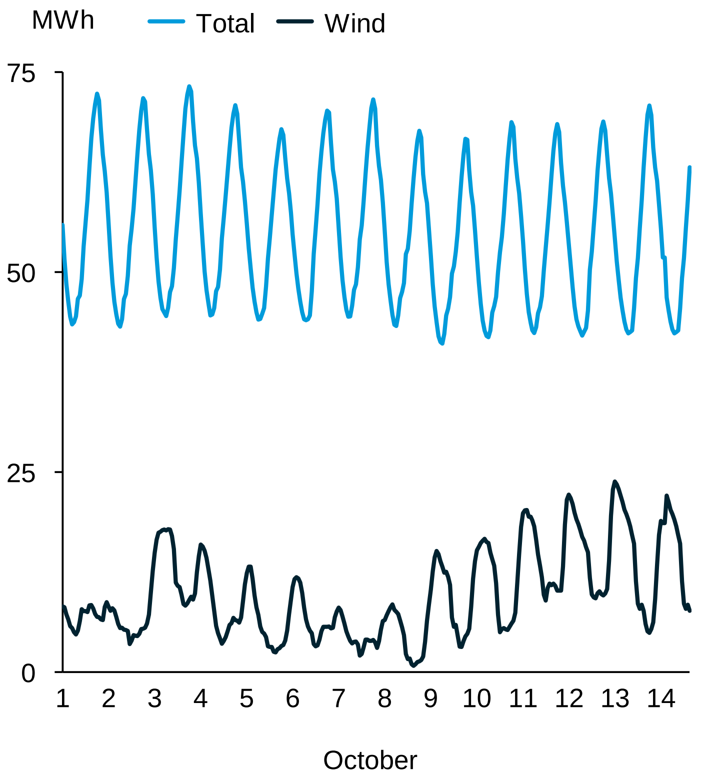
Observations

- Wind turbines create turbulence, vertically mixing air from higher altitudes with the surface-level air.
- The effect is largest during the night, when solar convection doesn't naturally mix the air.
- It is important to note that turbines do not add heat to the atmosphere as a whole, like global warming does, but instead redistribute the heat.

Sources: Miller and Keith, Climatic Impacts of Wind Power (2018); USGS, U.S. Wind Turbine Database (2024); EIA, How much energy does a person use in a year? (2023).
Credit: Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Wind intermittency causes a mismatch in supply and demand; a lower LCOE smart grid integration offers a solution

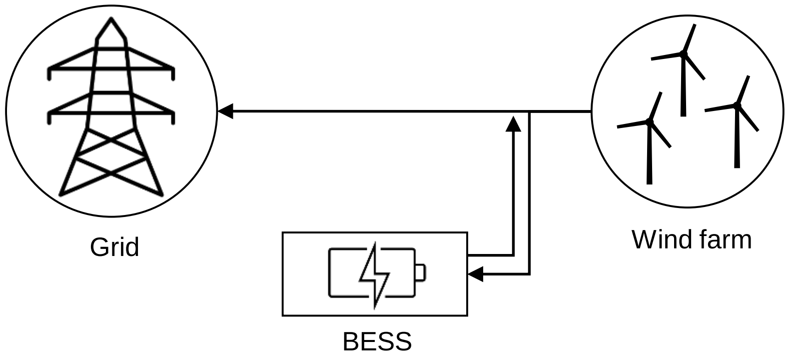
Hourly wind energy production in Texas, *October 2024*



Promising solutions for intermittency

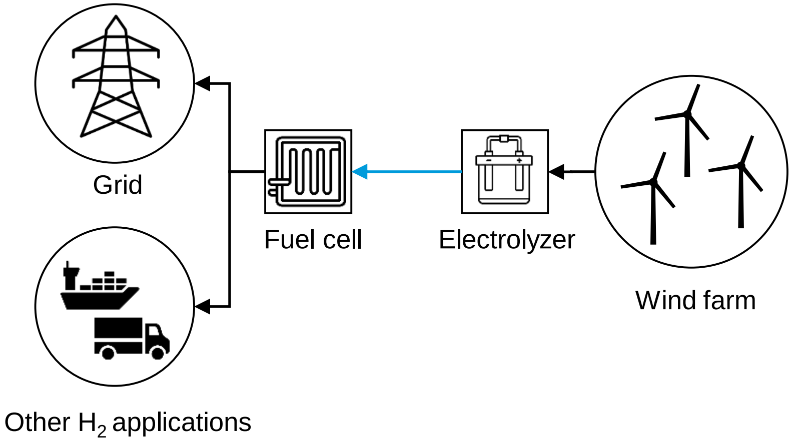
Battery energy storage system (BESS)

- A BESS can be charged during low grid prices and high wind speeds and discharged when prices are more favorable.
- A BESS can be integrated with a wind farm or as a standalone system.
- Theorized BESS's have an optimal storage capacity of ~30%-40% of the farm's capacity and have an IRR of 10%-20%.



Wind-hydrogen integration

- A wind-hydrogen integration allows for intermittency storage as well as cheaper transportation of energy from a wind farm to an energy demand center.
- Offshore wind farms in particular can benefit from more efficient energy transport.
- Although some European tenders require integrated electrolyzers, green hydrogen prices are insufficient to warrant a full system.



Sources: EIA, Hourly Electric Grid Monitor (2024); Hukkinen, Business Case Analysis of a Battery Energy Storage System Co-Located with a Wind Park (2024)
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Wind Fundamentals: Supply Chain

The wind turbine supply chain is divided into five tiers: raw materials, finished materials, subcomponents, subassemblies, and finished assemblies.

Uneven market concentration, particular in tier 3, creates pinch points and incentives for manufacturers to vertically integrate. The market for bearings, rotors, and blades represents the highest concentration with just a few players.

Despite making up 75% of the turbine weight, **steel represents only 25% of the cost**, whereas rare earth elements make up ~1% of weight but 25% of the cost.

The supply of rare earth materials is typically not in the manufacturing countries, leading to **dependencies** and a reliance on open borders.

Wind LCOE is therefore **sensitive to commodity prices** of rare earth materials (e.g., copper, nickel).

Most demand-supply dyads are healthy with pain points in **fiber, neodymium, and balsa wood** if deployment is high.

Working solutions include **vertical integration, localization of supply chain**, and improved risk management regimes.

China is leading wind tech manufacturing capacity with ~60% market share, and there is still a significant demand gap to be captured. **China is the only market with production expected to surpass domestic demand** in 2028; there are significant deficits in Europe and NAM.

Energy policy is largely in lockstep with **five-year plans**, with **institution, market**, and **tech** the three largest levers.

Energy bases in Inner Mongolia represent the largest strategic focus; most jobs are expected to come from supporting component manufacturing.

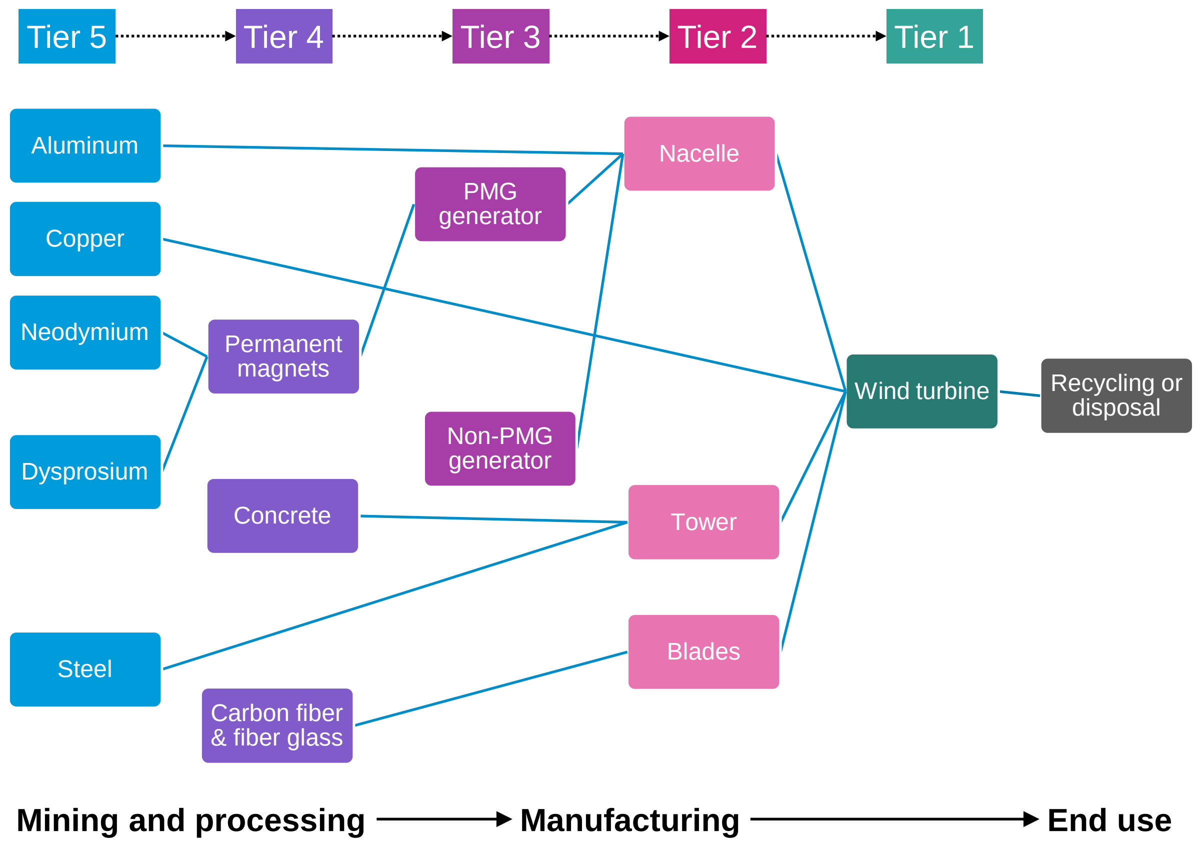
Trade in **raw materials also relies on open borders** due to a mismatch in mines and manufacturers.

An open-door trade policy is instrumental to a resilient global wind supply chain, with healthy margins and decreasing LCOE.

Image: Santeri Viinamäki
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

Wind supply chain is composed of five tiers, from raw materials to finished components

A simplified materials breakdown of the wind value chain



Observations

A complete wind farm is generally composed of five elements:

1. The generation unit (turbine and tower)
2. Roads for maintenance, transmission station
3. Collector line: collects electricity from dispersed turbines
4. A substation: transforms and transmits the power externally
5. A monitoring station

- **Tier 1** – **Finished components** are major products, such as the turbine, foundation, or cables, that are purchased by a developer. Tier 1 suppliers **contract directly with** the project developer.
- **Tier 2** – **Subassemblies** have a specific function for a tier 1 component and may include smaller parts, such as a pitch system for blades. Tier 2 manufacturers contract with tier 1 suppliers as a **subcontractor** or **vendor.**
- **Tier 3** – **Subcomponents** are commonly available items that are combined into tier 2 subassemblies, such as motors, bolts, and gears. Tier 3 manufacturers are typically vendors that provide components to tier 2 suppliers.
- **Tier 4** – **Primary processed materials,** including steel, fiberglass, and glass, is directly processed into tier 2 or 3 components.
- **Tier 5** – **Raw materials** include iron, chromium, copper, oil, acrylonitrile, etc.
- **Wind lead time:** 1-2 yrs. for blade, 1.5-2.5 yrs. for tower, 1.5-2 yrs. for nacelle.

Sources: NREL, A Supply Chain Road Map for Offshore Wind Energy in the United States (2023); Carrara S. et al., Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system (2020).
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

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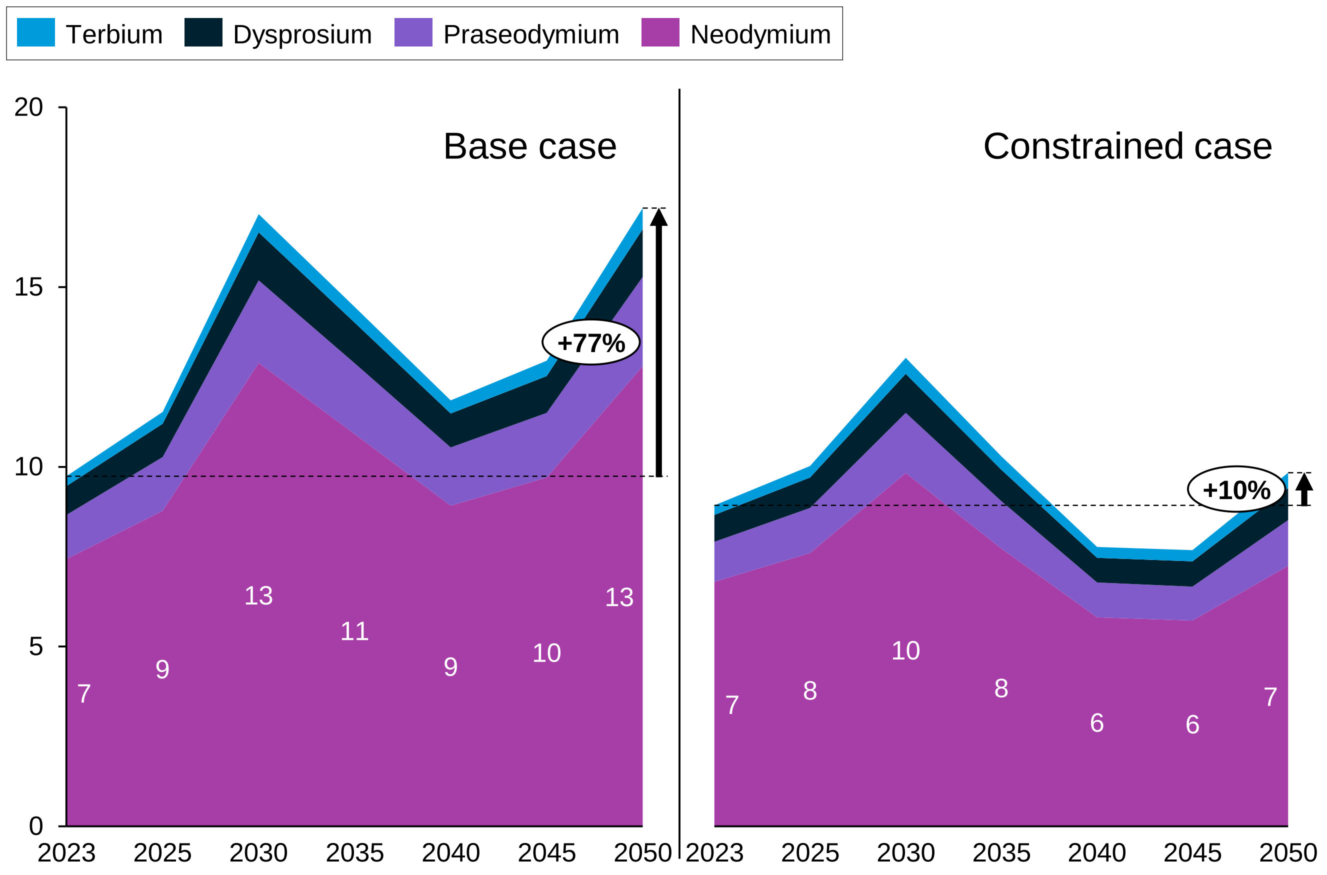
Efficient turbines need rare earth elements; adaptation may cut neodymium use by ~12%, but supply constraints persist

Mineral demand for wind in the Stated Policies Scenario, *kt*



Observations

- Wind turbines require **concrete**, **steel**, **iron**, **fiberglass**, **polymers**, **aluminum**, **copper**, **zinc**, and **rare earth elements.**
- Mineral intensities depend on both **turbine size** and **turbine type.**
  - Turbines based on **permanent magnet synchronous generators** dominate the offshore market due to their **lighter weight, efficiency, and lower maintenance costs**, but they require **rare earth elements** (REEs).
- Constrains capture tensions on these supply chains, possibly caused by **rising demand** or **geopolitical events.**
- In constrained REE supply, manufacturers may:
  - Switch to **non-magnet technologies**
  - Adopt **hybrid configurations** with a gearbox and smaller magnets
- Despite constraints, **rare earth magnet technologies** are expected to remain preferred for **offshore wind** due to higher performance.
- In a constrained supply scenario, **neodymium demand** in 2030 could be reduced by about **12%** under the **Net Zero Scenario.**

Sources: NREL, A Supply Chain Road Map for Offshore Wind Energy in the United States (2023); IEA, Critical Minerals Data Explorer (2024).
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

Uneven market concentration (tier 3) leads to bottlenecks and motivates manufacturers to pursue vertical integration

Market for bearings, rotors, and blades represents highest concentration with few players

	Towers	Castings	Generator	Controls	Gearbox	Bearings	Rotor/Blade
Concentration	**Highly fragmented:** Several metal works firms involved; localized sourcing		**Highly fragmented:** Dozens of sub-5-MW suppliers, at least a dozen supplying 1 MW or larger	**Highly concentrated:** Among independent suppliers, nearly half sourced in-house	**Somewhat concentrated:** 3 leading multi-MW players, 12 other competitors	**Highly concentrated:** Just 3 players supplying all segments, few multi-MW providers	**Highly concentrated:** One independent supplier of 2,000 MW or greater, half of OEMs supply internally
Typical sourcing approach	In-house supply strategic models, outsource older models and non-core markets	Maximize quality, vetted supply partners to avoid shortage	Heavy reliance on 1-2 major players for larger models; open to new, reliable suppliers	Single supplier sourcing, highly sensitive to turbine design	3-4 qualified external suppliers, usually 1-2 suppliers for larger turbines	Multiple suppliers selected by region	
Select leaders	SIEMENS Gamesa RENEWABLE ENERGY; Vestas; NTN; NORDEX We've got the power.; winergy; KK Wind Solutions; ABB; SAKANA group; Goldwind; GE; KAYDON; Envision; ZF GROUP; DANA BREVINI Motion Systems; TRINITY TURBINE TECHNOLOGY, L.P.						

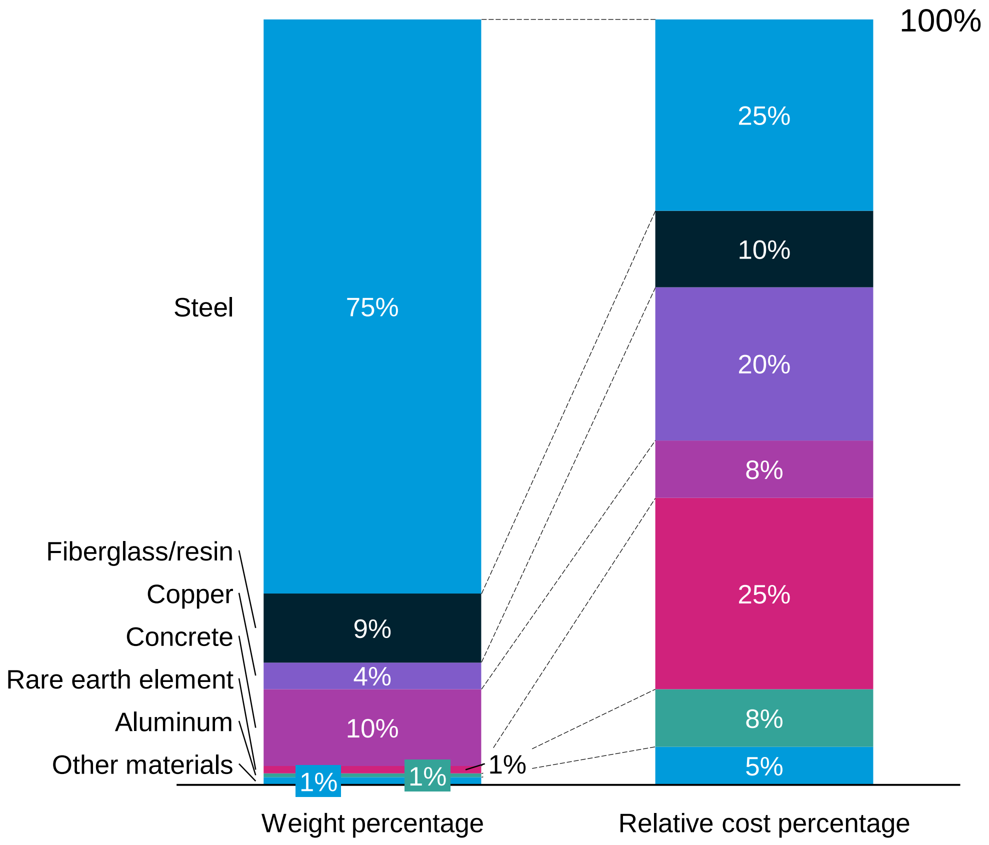
Observations

- Procurement trends have led to **distinct market structures** within each component segment.
- **Major pinch points** exist in the **blade, bearing, and gearbox** segments, where high market concentration and a limited number of suppliers constrain availability.
- As pinch points ripple through the supply chain, component disparities intensify shortages. Ultimately, **turbine assembly volumes are dictated by the component segment with the tightest pinch point** in supply, limiting the total units available for production.
- **Lower entry barriers** in segments such as **controls, generators, castings, and towers** have resulted in a more diversified and competitive supplier base.
- Structural dynamics create a highly uneven market, incentivizing manufacturers to explore **vertical integration** as a risk mitigation strategy.

Source: Wind Energy - the Facts, Emering Energy Research, Supply Chain Key to Delivery (2023).
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Cost-to-weight ratios of key materials influence wind’s economic viability and supply chain resilience

Steel makes up the bulk of input, but rare earth is very cost intensive



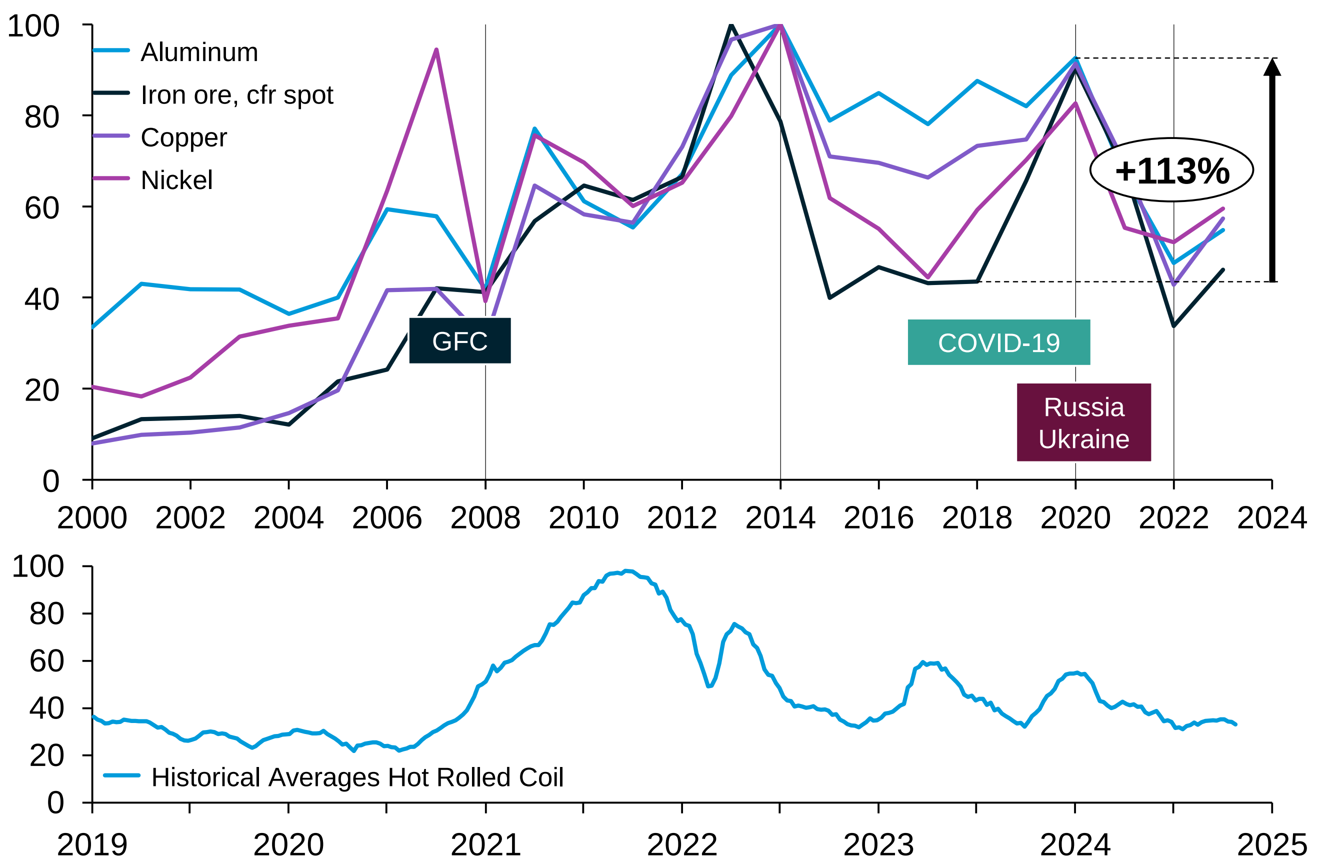
Observations

- **Cost-to-weight ratios**
  - **Rare earth elements:** A high cost-to-weight ratio (22.50) signifies vulnerability to supply chain disruptions, impacting turbine costs significantly.
  - **Copper:** An elevated ratio (3.57) highlights its critical role in electrical systems, suggesting potential cost pressures as demand for renewable energy grows.
- Offshore wind turbines demand significantly more **copper (7,500 kg/MW)** than onshore turbines (**3,000 kg/MW**) due to greater electrical system needs, while onshore turbines use slightly more **steel (130,000 kg/MW vs. 125,000 kg/MW)** and require more **cement (55,000 kg/MW vs. 35,000 kg/MW)**, reflecting differing structural and foundational requirements.
- **Other critical materials** remain constant across both types at **6,000 kg/MW**, highlighting consistent ancillary material needs regardless of the installation type.
- There have been minimal price increases for clean energy products (e.g., electric cars +0.5% from steel hike). Decarbonization costs: heat pumps (<0.3%) and offshore wind farms (+0.6%).
  - Competitive markets challenge manufacturers in passing on costs.
  - Wind turbine and solar PV producers are better positioned due to rising wholesale prices.
  - There is consumer interest in premium clean products, e.g., automotive companies committing to “green steel” by 2025.

Sources: IEA, Energy Technology Perspectives (2023); Sikdar and Princiotta, Advances in Carbon Management Technologies (2021).
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

Wind is more sensitive to volatility in bulk material cost such as steel, aluminum, copper, and nickel than energy cost

Prices for commodities like steel have experienced high volatility, fueling uncertainty



Observations

- **Levelized cost of production (LCOP):** the total cost of producing one unit of output, such as 1 MW of solar modules, 1 MWh of battery cells, or 1 Mt of steel, considering all the up-front and ongoing costs incurred over the lifetime of the investment.
- At high utilization rates, component and material costs are the main contributors to the LCOP of the clean energy technologies examined in this report, typically accounting for upward of 50% of total production cost.
- Approximately **80%** of the total cost of producing wind turbines (including nacelles, blades, and towers) is derived from **materials and upstream components.**
- With an 85% utilization rate and financing costs between 5% and 20%, the CapEx contribution to total cost is between 5% and 15% for wind turbines, showing a moderate impact on LCOP when facilities are fully utilized.
- Under high utilization, **energy and labor costs drive LCOP regional variation** in variable OpEx.

Sources: Unarco, Steel Averages (2024); InfoLink Consulting, How raw materials turbulence in past two years impact wind energy system suppliers? (2023).
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Most demand-supply dyads are healthy, except for pain points in fiber, neodymium, and balsa wood if deployment is high

Average US wind energy demand, *2020, % of US production*

<table>
<tr><th>Materials</th><th>Recent past</th><th>Current policies</th><th>High deployment</th></tr>
<tr><td>Carbon fiber</td><td rowspan="6"><2%-20%</td><td>21%-100%</td><td>>100%</td></tr>
<tr><td>Electric steel</td><td rowspan="5"><2%-20%</td><td rowspan="5">21%-100%</td></tr>
<tr><td>Aluminum</td></tr>
<tr><td>Cobalt</td></tr>
<tr><td>Dysprosium</td></tr>
<tr><td>Neodymium</td></tr>
<tr><td>Nickel</td><td colspan="3" rowspan="2">>100%</td></tr>
<tr><td>Balsa</td></tr>
<tr><td>Glass fiber</td><td colspan="2">21%-100%</td><td>>100%</td></tr>
</table>

Balsa wood

- **Key benefits:** Lightweight and strong; ideal for turbine blades
- **Source**: Fast-growing trees from tropical Americas, including Ecuador (20.3%), Chile (3.92%), Brazil (3.77%)
- Enhanced with glass or carbon-fiber composites
- Illegal deforestation and pollution, especially around **Pastaza, Bobonaza, Curaray,** and **Villano** Rivers

Sintered NdFeB magnets

- **Key benefits:** High magnetic strength relative to size → compact generators in high-capacity wind turbines
- **Thermal limits:** Operates optimally up to **310°C (590°F);** exceeding Curie temperature compromises magnetic properties
- **Performance consistency:** Uniformity in size and magnetic strength is essential to system efficiency; variations can disrupt turbine performance

Nickel in steel alloys

- **Key benefits:** Improves toughness (absorbs mechanical energy, prevents fractures), which is important for turbine durability
- **Weight reduction impact:** 1 kg nacelle weight reduction can save 10 kg in the support structure
- Critical for scaling up to larger turbines (20 MW)
- **Trends:** Current gearbox steel: up to 2% nickel
- Future designs may add 0.5% nickel in components to reduce weight and increase reliability

Sources: UNAV, Wind turbine propellers boost balsawood sales (2021), USITC, From Balsa Wood to Polymer Foam in Wind Turbine Blades: Material Input Substitutes in Low-Carbon Technologies (2022); Stanford Magnets, Application of Neodymium Magnets in Wind Turbine Generators (2024); Nickel Institute, Wind and water - Nickel in clean energy (2021).
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Working solutions like vertical integration and localization of supply chain improve risk management regimes

Strategy	Description	Effectiveness	Challenges	Case example
Vertical integration	Developers directly control the supply of turbine blades, nacelles, and gearboxes; enables in-house R&D and customization for performance and durability.	Predictable project budgets, long-term savings, and enhanced component customization suited to project locations.	Requires significant capital investment and expertise in upstream operations.	**Ørsted and Salzgitter AG (2022):** Collaboration to produce green steel using wind power, promoting circular economy.
Localization	Reduces dependency on global supply routes, minimizes logistics disruptions, and reduces transportation costs.	Accelerates project timelines, reduces costs, and fosters local economic growth through job creation.	High **up-front costs** for setting up localized manufacturing and potential dependency on regional policies and infrastructure.	**Enel and Comal:** Increased solar PV module production in Sicily fifteenfold, building local manufacturing capacity.
Price hedging	**Long-term agreements** through future and options contracts.	Helps stabilize costs and secure supply chain predictability.	**Insufficient** industry-wide adoption; requires **proactive supplier evaluations** and robust partnerships to identify and manage risks.	Price **hedging** using **futures** locks in **stable steel costs**, ensuring cost predictability and **mitigating volatility** for key raw materials like steel.

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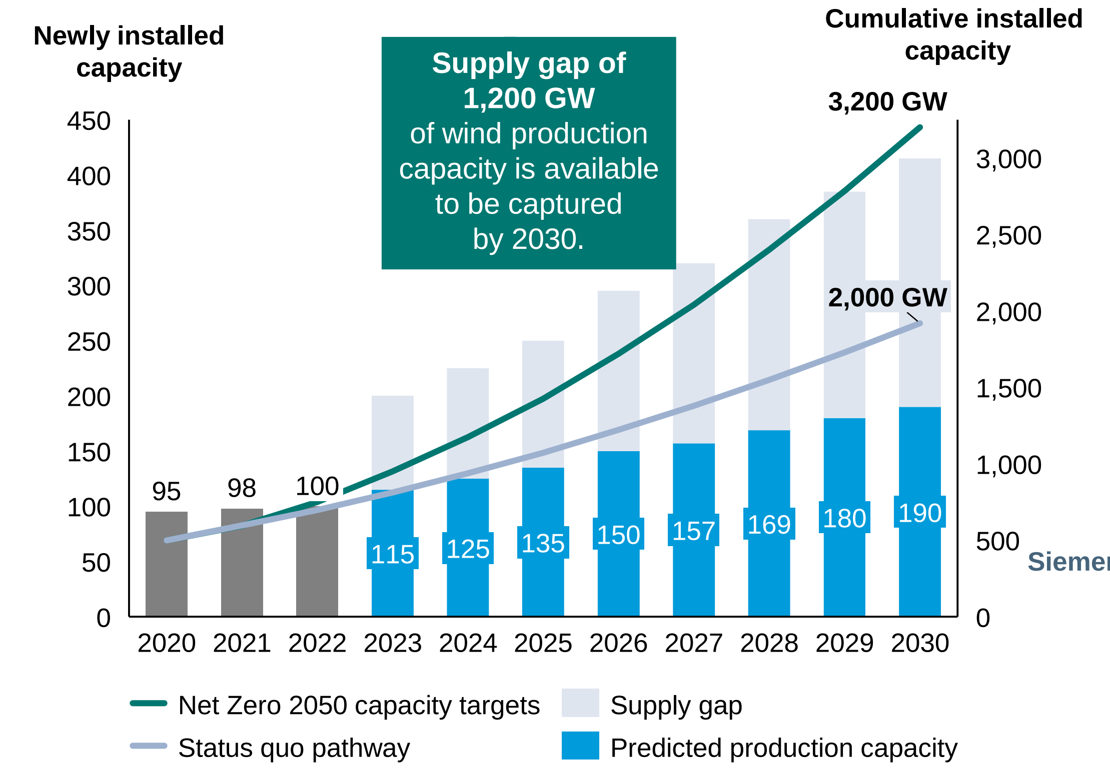
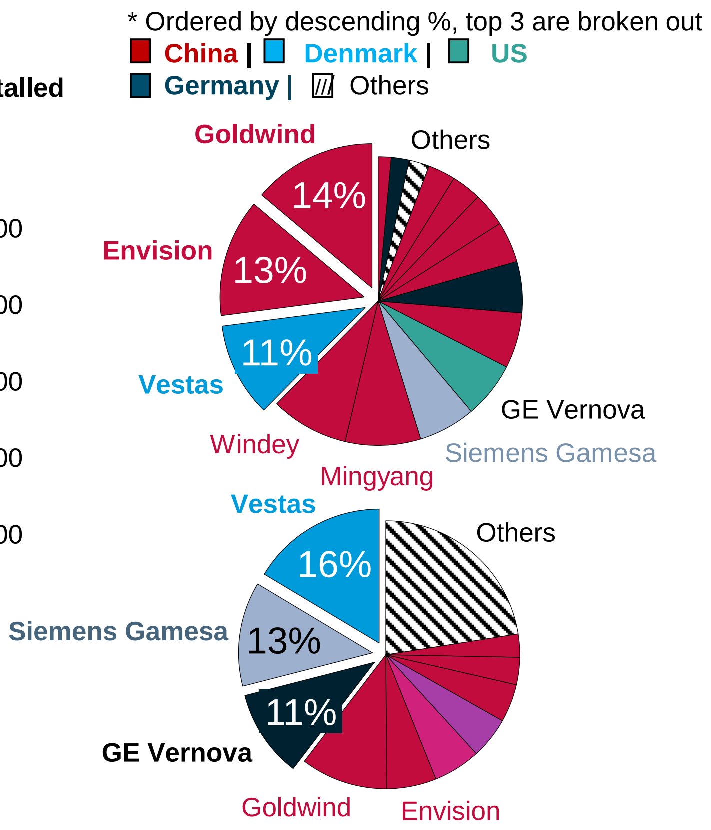
Source: McKinsey, Renewable-energy development in a net-zero world: Disrupted supply chains (2023)
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

China is leading wind tech manufacturing capacity with ~60% market share; a significant demand gap can still be captured

Current production capacity and gap to 2050 Net Zero targets, *GW*



World vs. Europe market share, *2023*

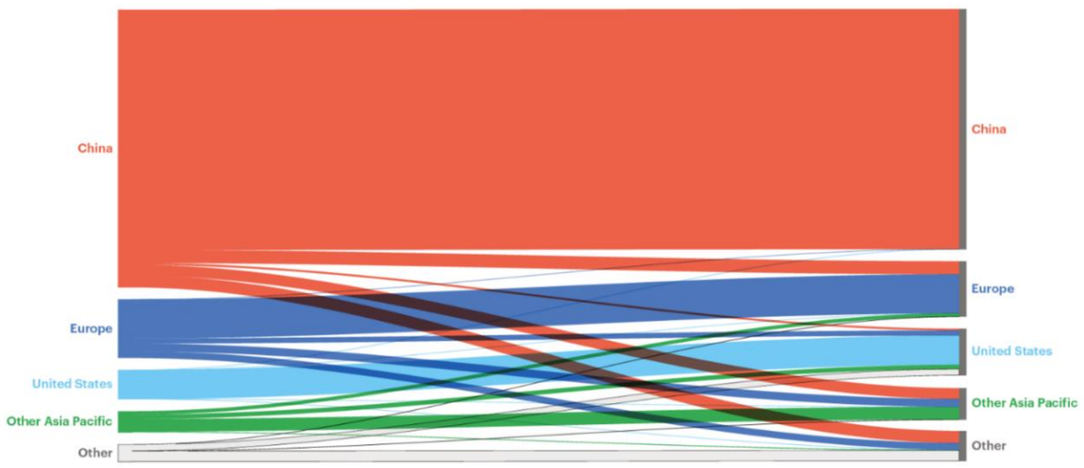


Observations

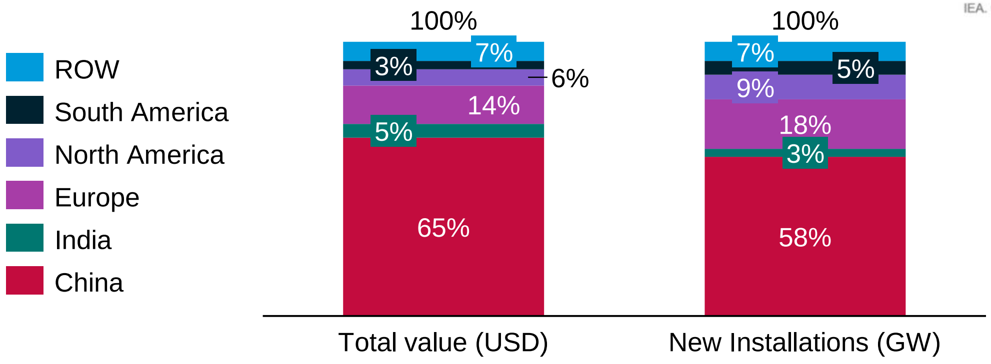
- Currently available wind production capacity and its predicted growth is **not enough to meet 2050 Net Zero targets.**
- A total **supply gap of 1,200 GW of capacity** is available to be captured by OEMs until 2030.
- EU and US OEMs should invest significantly to capture a part of the 1,200 GW supply gap.
- Currently, China dominates the OEM market with ~60% market share, reaching up to ~80% in selected components.
- China: 81.6 GW of installed capacity, ranking 4th among the top 5 and 6th among the top 10 globally.
- In 2023, Vestas, Siemens Gamesa, and Nordex Group were the top three companies in Europe. Globally, Vestas ranked between 1st and 3rd, continues to supply to 36 countries.

China is mostly self-sufficient; India is eager to position itself as a production hub along the supply chain

I. Trade flows of wind components | II. Manufacturing value vs. installation



IEA. CC BY 4.0.



Observations

- **China** holds a positive trade balance for 2023-2025. Some **97%** of Chinese wind turbine manufacturers' installed capacity in 2023 is in the **domestic market**, which is basically the same as the previous year. In 2023, Chinese manufacturers installed 2.3 GW outside the domestic market, of which **63% was in the APAC market.**
- **India's trade balance surpasses China**, reflecting its growing strength as a **production hub.**
- **India's growing role** is driven by large conglomerates investing in **cleantech** and the "Make in India" policy. The country is positioned to become a **global export hub** for the wind industry.
- The EU and US generate the most wind component value from and to **internal markets; China receives very little wind components,** in USD terms, from foreign markets.
- **The US and Japan run a wind turbine deficit** that is even more significant compared to their trade position across other **energy tech**; all depend on the **free flow of minerals.**
- **Trade policy goals: Competitive industries** without higher costs for end users.
  - Enable **resource sharing** across regions for **cost reduction via supply chain capacity utilization.**
  - Develop **workforce skills and infrastructure.**
  - Avoid **prescriptive regulations** that restrict cross-border trade.

Sources: GWEC, Global Wind Report (2024); IEA analysis based on Eurostat, US DOE (2022a), the US ITA; IEA investment data (2022e), IEA – Solar PV Global Supply Chains (p. 28).
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

US has a large deficit in turbines and is especially weak in refined nickel; China, Japan, and Korea are weak across ores

Trade balance (%) along supply chains in select countries, *2021*

China: modest surplus in turbine but depends on foreign ore and refining; EU weak on ore; US good on ore but weak in refining

	China	EU	US	Japan	Korea
Wind turbines	**14%**	**6%**	**-38%**	**-46%**	**80%**
Cobalt ore	-98%	-100%	100%	-100%	0%
Nickel ore	-88%	-66%	100%	-100%	-100%
Copper ore	-80%	-40%	30%	-100%	-100%
Nickel refined	-51%	-22%	-100%	23%	-58%
Copper refined	-25%	-11%	-45%	41%	-1%
Iron and steel	5%	2%	-24%	31%	17%
Aluminum	-7%	-53%	-80%	-100%	-100%
Energy tech average	15%	-38%	-16%	6%	26%
CE average	-85%	-52%	33%	-74%	-50%
Refined average	-43%	1%	-43%	35%	2%
Bulk average	-8%	-20%	-28%	-21%	-13%

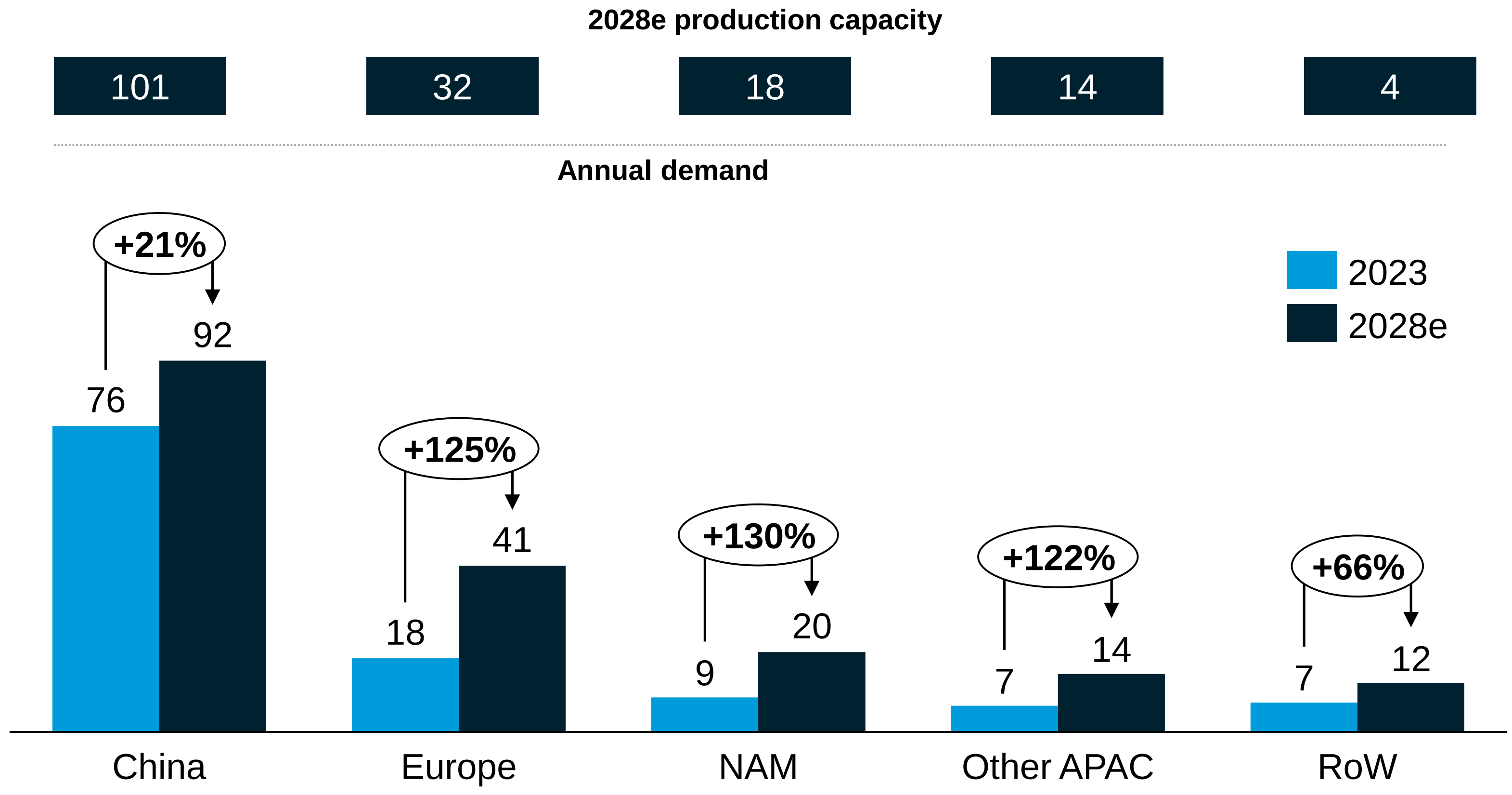
Observations

- **Nickel exports:** Russia's main nickel exports are unwrought refined nickel and nickel matte; nearly all matte is processed at Nornickel's Finland plant, with refined nickel sold globally.
  - **Post-2022 shifts:** Imports of refined nickel from Russia dropped 41% in 2023 due to lower prices; US imports fell by 93% ($19M vs. $264M in 2022), with Germany and the Netherlands also declining.
  - **China's role:** China, the Netherlands, and Taiwan accounted for 91% of Russian refined nickel imports in 2023; many Chinese firms shifted to cheaper nickel from Indonesia.
- **Balsa wood demand:** Lightweight balsa is essential for wind turbine blades, with global demand at **400,000 to 465,000 m³/year.**
  - **China:** Accounts for 50% of global balsa imports, driven by rapid wind energy expansion (60% capacity growth in 2020).
  - **Key markets:** The EU (20% of global imports, led by Denmark, Poland, and Germany) and the US (7.6%, top tropical wood species, 23% of imports in 2018).

Note: Data for wind-power generating sets were used as a basis to estimate trade for wind nacelles and blades.
Sources: USITC, Impact of the Russian Invasion of Ukraine on Global Nickel Trade (2024); Eurostat, US DOE (2022a); US ITA, and analysis based on IEA investment data (2022e), Forest Trends, Forest Policy Trade and Finance Initiative (2022).
Credit: Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

China the only market with production expected to surpass domestic demand in 2028; significant deficits in Europe and NAM

Predicted production capacity and forecasted annual demand for wind generation tech, *GW*



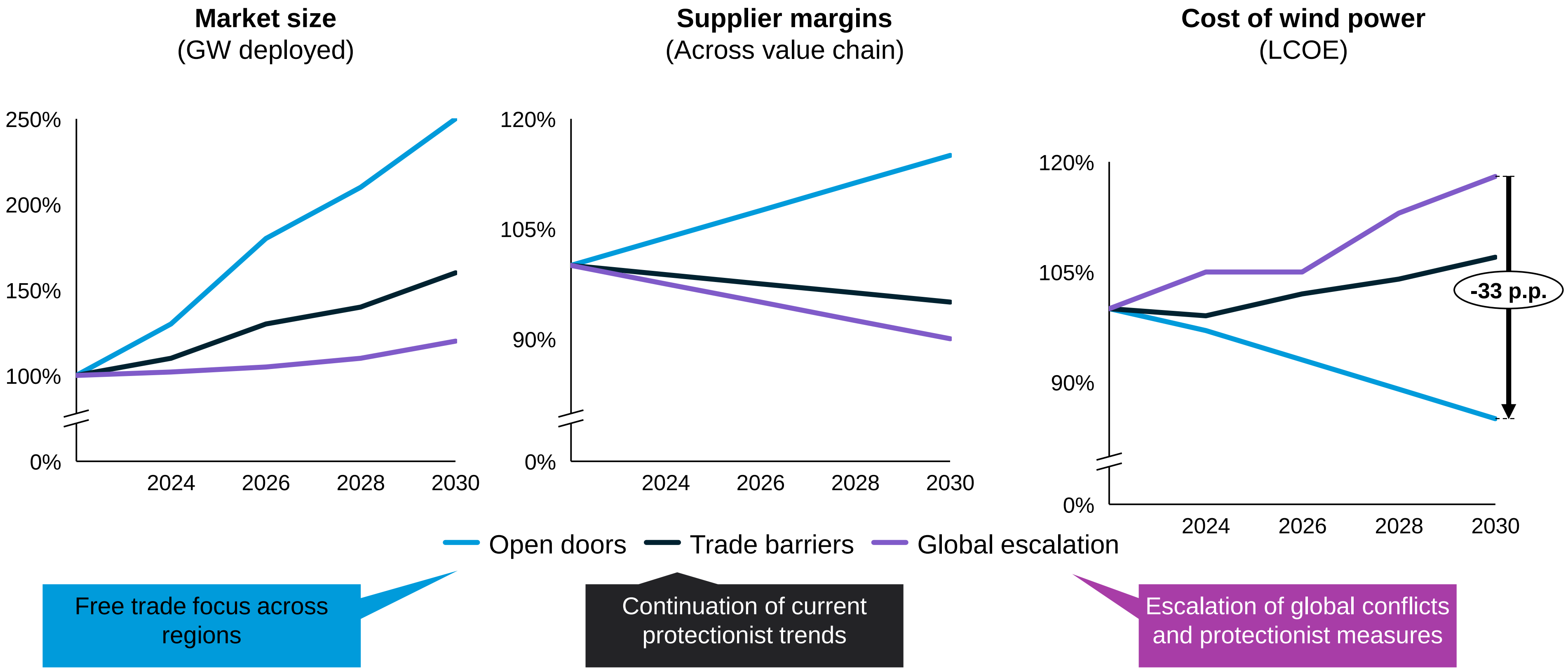
Observations

- **China represents the largest market for wind generation technology worldwide,** rapidly expanding its renewable generation capacity.
- The trend is expected to continue into 2025 and onward, with a **21% increase in demand** for wind generation technology within China, comfortably covered by domestic supply. This **solidifies China as a key exporter in the market.**
- A significant demand increase for wind generation technology is expected in Europe (+125%), North America (+130%), and wider APAC, including India (+122%), driven by global decarbonization efforts.
- **Europe and the US will require significant imports of wind generation technology** to cover expected demand in 2028 unless massive investments in production capacities are made within the coming years.

Sources: IEA, Energy Technology Perspectives (2023); GWEC, Global Wind Report (2024).
Credit: Petr Jenicek, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

Open doors trade policy is instrumental to building a resilient global wind supply chain with healthy margins and decreasing LCOE

Market size, supplier margins, and LCOE under three scenarios, *indexed to 2023 levels*



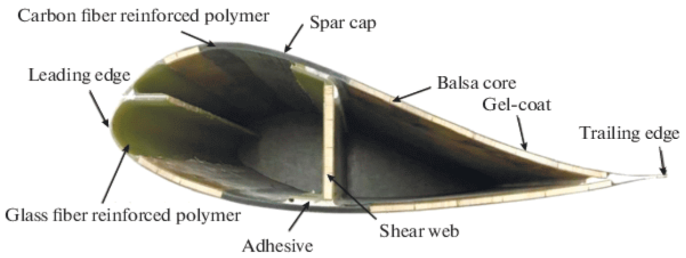
Observations

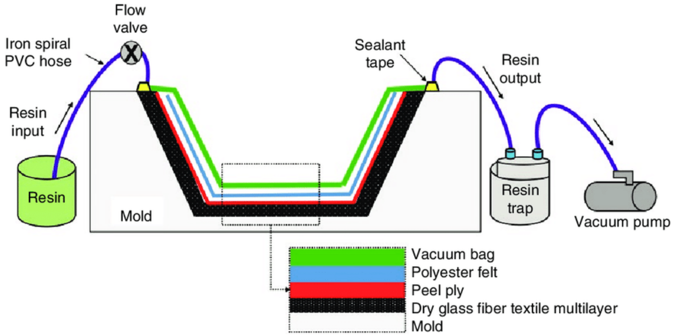
- Due to the overall production-demand imbalance between regions and the EU's and NAM's reliance on China's production capacity, **open-door policies are required to guarantee stable wind generation and deployment.**
- Any trade barriers (as is the current trend) and **attempts to forcefully onshore production will stifle deployment and negatively impact margins** across the value chain, eventually increasing LCOE.
- Escalation of protectionism or war efforts will have a catastrophic effect on the wind market.

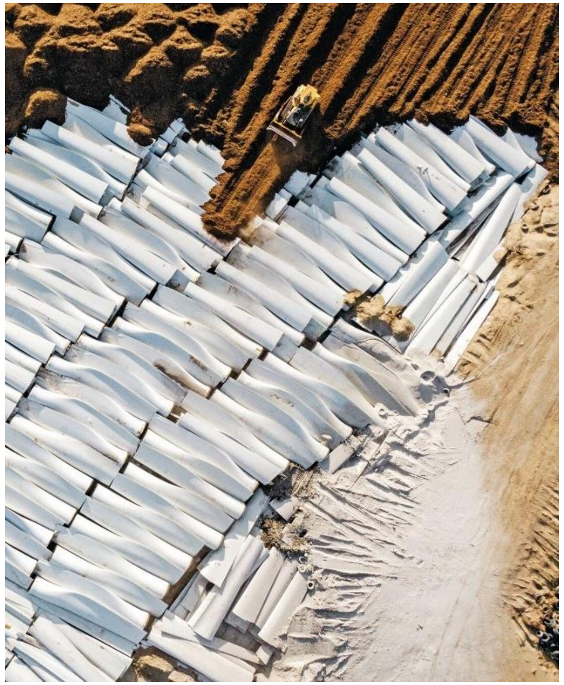
Sources: GWEC, Global Wind Report (2024); BCG, The Hidden Dynamics of the Energy Transition (2024).
Credit: Petr Jenicek, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Resin infusion technique used to produce turbine blades and the large size of the blades complicate end-of-life recycling

The turbine involves some form of infusion of resin to a frame







Top left: A cross-sectional illustration of component parts of a wind turbine
Bottom left: A diagram of the resin infusion technique
Right: Photo of cut turbines being shoveled into a landfill and buried (C&EN)

Observations

- **Resin infusion mechanism:** Fibers placed in molds; resin injected (under pressure or vacuum) to saturate fibers and then cured to form strong, durable blades
- **Prepreg technology:** Aerospace-inspired; pre-impregnated fibers for complex shapes; used by Vestas and other turbine manufacturers
  - **Resin infusion methods:** Common for long blades
  - **RTM:** Resin injected at high pressure
  - **VARTM:** Resin injected under vacuum; widely used for rotor blades
- **EOL blade recycling challenges:**
  - **Composite complexity:** Towers and generators recyclable; harder for blades due to thermoset resins (epoxies, polyesters)
  - **Material waste:** Projected global decommissioned blade material: 400,000 tons per year by 2030 and 2 million tons per year by 2050
  - **US forecasts:** 1.2 million tons by 2040; 2.1 million tons by 2050, with an annual potential of 50,000 to 300,000 tons by 2050
  - **Alternative uses:** Fiberglass in concrete, balsa wood applications, PVC/PET foams for various products

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AT THE VERY CENTER OF BUSINESS

Wind Fundamentals: Global Policy & Finance

Governments worldwide have set 2030 targets for wind energy and provided policy incentives, including auctions, feed-in tariffs, and contracts, which have been the key drivers for deployment.

- However, **wind projects have been delayed** due to inadequate permitting and licensing rules.
- **Regional collaboration and favorable trade policy are required** for a continued attractive market environment.

Wind energy attracts the second largest share of renewables investments.

- **Onshore wind constitutes 80% of the investments.** Meanwhile, **global offshore wind investment reached a record $76.7 billion in 2023.**
- While the share of equity has fallen from 77% in 2013 to 43% in 2020, the **share of debt financing has more than doubled given the increasing maturity of the technology.**

In response to China's market dominance, the US has introduced **advanced manufacturing tax credits**, put **tariffs on imported wind towers**, and included a **domestic content bonus in the wind tax credits** for businesses to encourage domestic production.

- By extending and increasing tax credits for wind projects, the **US Inflation Reduction Act of 2022** is **expected to increase land-based wind deployment by 171 GW by 2030.**
- Since 2022, companies have announced **42 new projects, creating a total of 15,339 new jobs and $14.38 billion in new investments.**

The EU has been caught in the cross-wind between the US and China. While it boasts of a mature renewable energy market, it is pushing toward a regulatory environment that ensures a resilient supply chain and faster permitting processes.

Policy on wind is shifting from subsidies to market mechanisms

Key policy drivers across select countries

	1 US	2 EU	3 China
Main policies	**Federal: Inflation Reduction Act (IRA)** **State: Renewable Performance Standard**	**Green Deal Industrial Plan;** **Fit for 55 package**	**14th Five-Year Plan;** **Wind Energy Development Roadmap 2050**
Policy focus	Boost domestic manufacturing, create jobs, and build more resilient supply chains	Facilitate improved auction design; provide dedicated funding support, enhanced skills, and open trade for clean energy projects	Reduce the carbon intensity of the economy and peak carbon dioxide emissions before 2030
Target for renewable energy (RE)	No explicit target; expected to achieve 938 GW RE by 2030	RE target 2030: **At least 42.5% of RE** Total: 1,236 GW; solar 592 GW; wind 510 GW; offshore 111 GW	RE target 2030: **1.2 TW (achieved)** (No offshore wind target)
Investment	**$400 million** for onshore wind and **$6.9 billion** for offshore wind manufacturing	**Innovation Fund:** Dedicated **RepowerEU** funding windows **InvestEU programme:** €1.8 billion (approved)	**Investment in R&D** for clean energy technologies and fiscal incentives to attract private investments
Incentive for onshore and offshore wind	**Tax credits** on production, investment, and manufacturing	**Electricity Market Design (proposal)** to improve power purchase agreements and contracts for difference; **cross-border cost sharing** and **regional development** to coordinate planning for offshore wind and other RE projects	**National and regional subsidies and tax breaks;** Industrial wind policy and market mechanisms such as green power trading
Manufacturing	**Advanced manufacturing production tax credit** for wind components; bonus credit for domestic content threshold	**Net Zero Industry Act (proposal)** and Critical Raw Materials Act to scale up manufacturing facilities for clean energy	**Direct and Indirect subsidies for manufacturing** (including steel)**;** tax incentives and custom duties
Permitting reforms/grid Integration	Outside of IRA, finalizing **new rules that streamline regulations** for wind permitting	**Digitalizing permitting processes** and technical assistance to members under the Accele-RES initiative	**Creating spot markets** among multiple province and interprovincial transmissions

Sources: ADB, China 14th Five-Year Plan (2021); EU, European Wind Power Action Plan (2023); Office of Energy Efficiency & Renewable Energy, Inflation Reduction Act Spurs Breakthrough in Domestic Wind Production (2023); Ember Energy, Global Renewable Energy Target Tracker 2030; S&P, China's 14th Energy Five-Year Plan: Pivoting toward a 'modern energy system' (2022).
Credit: Abha Nirula, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

US Inflation Reduction Act extends and improves wind investment and production tax credits

The residential and commercial wind investment tax credits aim to ease the cost inflation for wind power projects in the US

Homeowners

Residential Wind Energy Credit

30%

of the expenses of an installed wind system (100 kW or less) can be **subtracted from federal income taxes.**

- **Expenses covered by the tax credit include:**
  - Labor costs for on-site preparation, assembly, or original system installation
  - Piping or wiring to interconnect a system to a home
- The tax credit applies to existing homes, newly constructed homes, principal residences, and second homes. It is not applicable for rental properties.

Businesses

Wind Investment Tax Credit (ITC)

30%

of the expenses of an installed wind system can be **subtracted from federal income taxes** *(up to **50%** if certain conditions are met).*

- **Expenses covered by the tax credit include:**
  - Cost of installed equipment

Advanced Manufacturing Credit

30%

for companies that domestically manufacture and sell clean energy equipment.

Wind Production Tax Credit (PTC)

¢2.60 per kWh

of produced wind energy can be **subtracted from federal income taxes.**

- The tax credit **begins phasing out in 2032** and **ends by 2035**, or when the US treasury secretary determines there has been a 75% reduction in annual greenhouse gas emissions.
- The **inflation-adjusted PTC** for projects sold in 2023 was **¢2.75 per kWh.**

- **Business owners cannot claim the ITC and PTC for the same wind installation.**
- **Components produced in facilities that received the manufacturing ITC are not eligible for the advanced manufacturing production credits.**

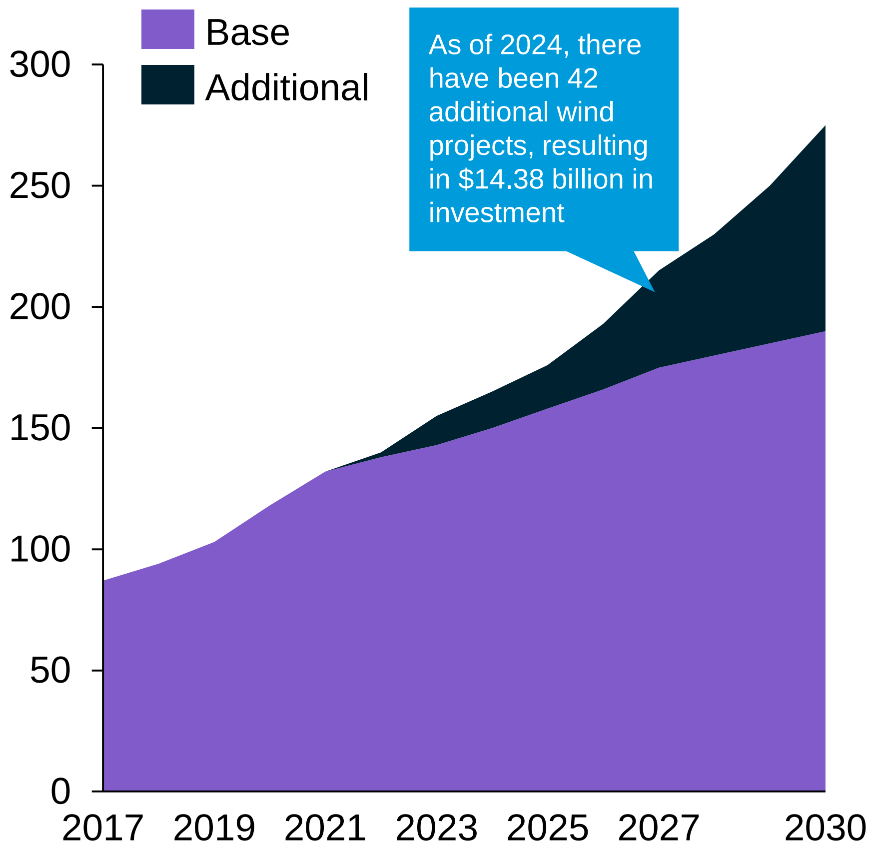
Columbia Business School

Source: Office of Energy Efficiency & Renewable Energy, Production Tax Credit and Investment Tax Credit for Wind Energy (2024)
Credit: Abha Nirula, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

IRA expected to mobilize ~85 GW of additional wind capacity and ~$160 billion in investments by 2030

Post-Inflation Reduction Act wind projections

Annual installations for wind capacity (GW)



Top 10 states benefitting from IRA for wind projects

State	Project	Est. Inv. ($B)	Est. Jobs
Georgia	33	15.42	16,703
Michigan	33	12.10	12,205
South Carolina	29	15.46	14,087
Texas	26	8.00	9,602
North Carolina	23	21.09	11,633
Tennessee	19	5.44	4,921
Ohio	18	7.07	4,854
California	14	1.60	160
New York	13	0.79	3,079
Indiana	12	8.32	5,262

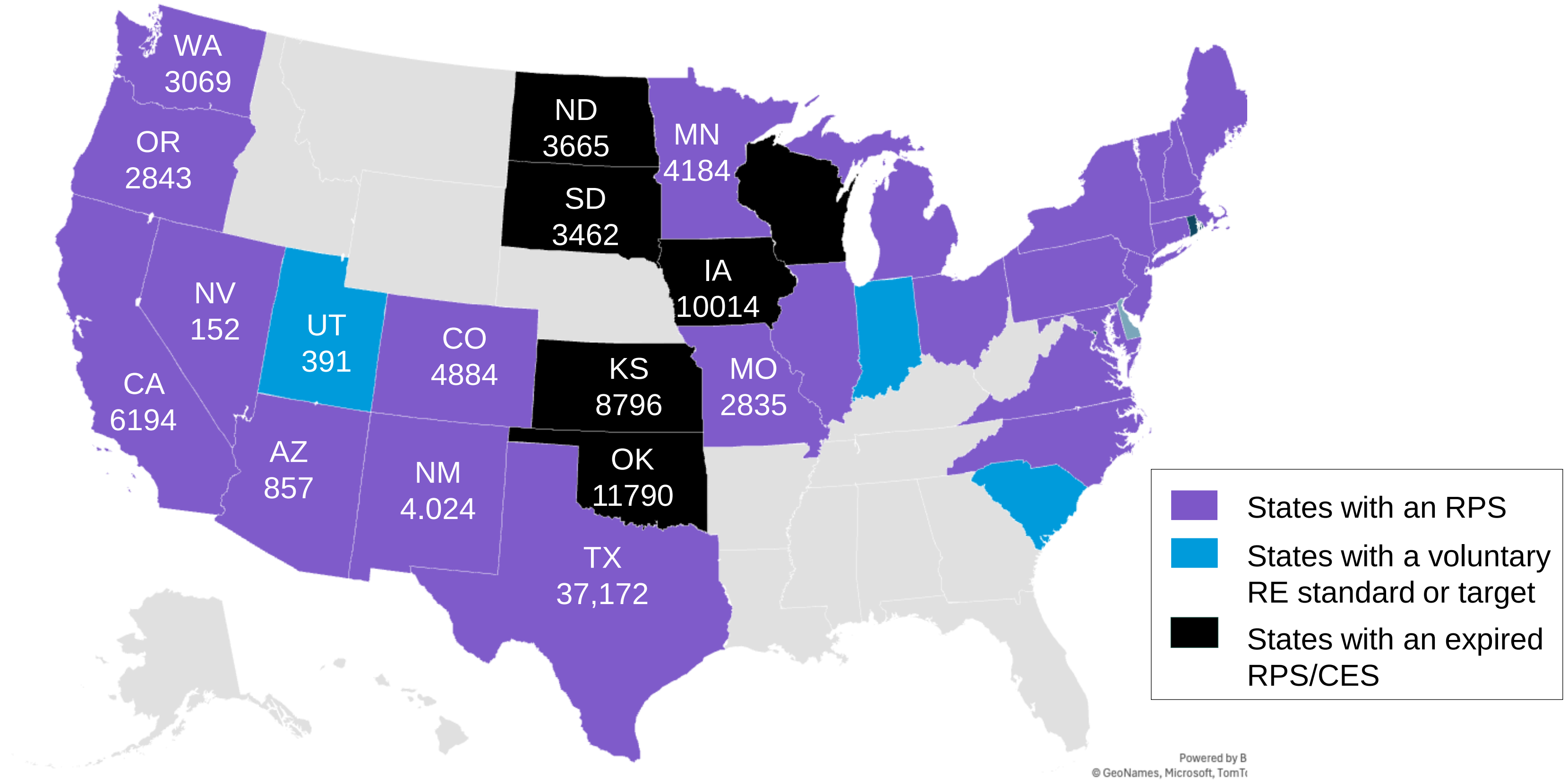
Observations

- The IRA is expected to add 85 GW to existing onshore wind projects, with cumulative capacity likely to reach 280 GW by 2030.
- **Increased investments and jobs:**
  - These new wind developments are estimated to result in an additional investment of $160 billion.
  - The IRA is expected to create 250,000 additional wind-related jobs by 2035. This includes domestic demand for 55,000 jobs in wind manufacturing.
- **Building supply chain and manufacturing:**
  - The 45X tax credits under the IRA are estimated to make US-manufactured onshore and offshore wind components less expensive to produce than imported products.
  - The IRA is also contributing to supply chain expansion with 15 new, reopened, or expanded land-based wind manufacturing facilities.

Sources: Wood and Mackenzie, The Inflation Reduction Act and its impact so far (2023); Berkeley Lab, Land-based Wind Market Report (2024); Blue Green Alliance, Effects of Renewable Energy Provisions of the Inflation Reduction (2023); E2, Clean Economy Works: Inflation Reduction Act Two-Year Analysis (2024); Rystad Energy.
Credit: Abha Nirula, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

29 US states have a Renewable Portfolio Standard, increasing wind capacity by 44%

States with renewable energy performance standards or voluntary targets



Observations

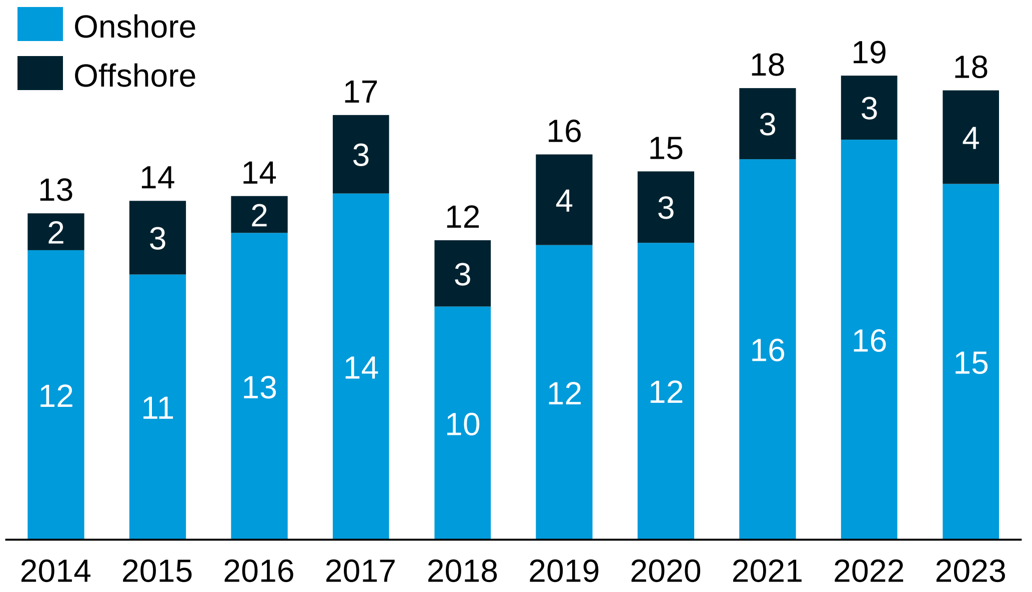
- In the US, **29 states and Washington, D.C., have a Renewable Portfolio Standard (RPS) and 16 states have a Clean Energy Standard (CES).**
- Among those with an RPS, **16 have RPS targets of at least 50% of retail sales and 4 states have a 100% RPS.** Sixteen states have adopted a broader 100% CES, most of which also have an RPS.
- Several states in the Northeast and MidAtlantic have established **procurement targets for offshore wind.**
- **RPS policies increased wind generation capacity by between 600 and 1,200 MW,** an increase of about 44% relative to the installed wind capacity.
- **13 states have policies that collectively support 115,130 MW of offshore wind by 2050.**

Sources: NBER, Causal Effects of Renewable Portfolio Standards (2023); NCSL, State Renewable Portfolio Standards and Goals (2021).
Credit: Abha Nirula, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

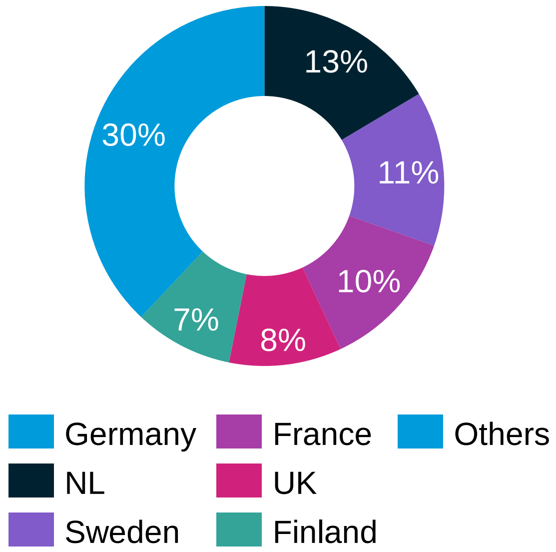
EU Green Deal sets ambitious targets for expansion of renewable energy

RE share in energy mix	Accelerate deployment for offshore wind	Increased investment and focus on R&D	Interconnected energy systems	Focus on R&D
• At least 42.5% renewable energy by 2030, with an **ambition to reach 45% renewables**	• Expected to increase the EU's offshore wind capacity from its current level of 12 GW to **300 GW by 2050**	• Investment of almost **€800 billion between now and 2050** in offshore energy infrastructure	• Build **inter-connected, digitized and integrated grids** to support RE sources	• 35% of the EU's research and innovation program ring-fenced for new clean technologies

Trend in installed capacity of wind energy in Europe (GW)



New installation by countries (%)



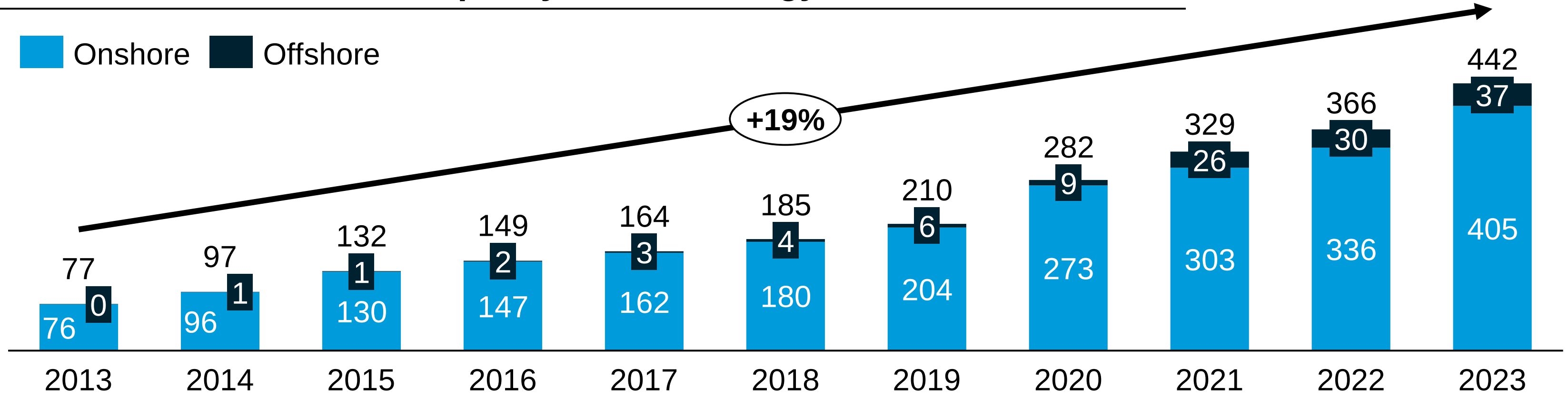
Observations

- Europe now has **272 GW of installed wind power capacity**: 238 GW onshore and 34 GW offshore.
  - Germany led the new installation of wind capacity in 2022 due to rapid wind expansion.
- Wind energy was **19% of all the electricity consumed in the EU 27 in 2023.**
  - It was 56% in Denmark, 36% in Ireland, 31% in Germany, 29% in the UK, and 27% in Spain and the Netherlands.
- To meet its 2030 climate and energy targets, the **EU now needs to build 33 GW per year** on average.
- The new EU rules on permitting have already boosted permitting volumes for new wind farms.
  - Germany and Spain both permitted 70% more onshore wind in 2023 than in 2022, with Germany reaching 7.5 GW.

Source: Wind Europe, Statistics and Outlook for 2024-2030 (2023).
Credit: Abha Nirula, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Energy policy is largely in lockstep with five-year plans, with institution, market, and technology the three largest levers

Trend in cumulative installed capacity of wind energy in China, *GW*



2006-2010 (11th 5-year plan)	2011-2020 (12th and 13th 5-year plan)	2021-2030 (14th and 15th 5-year plan)	2031-2040 (16th and 17th 5-year plan)
• **Prioritize wind power** with financial incentives, setting wind power as a priority. • Focus on **cleaner coal**, large plants, new hydro, nuclear, and grid capacity, along with building **west-east transportation corridors.** • Implement a **regional fixed electricity price system** with grid-connected prices above the coal benchmark covered by a surcharge and a **distance-based subsidy** for wind farms (0.01-0.03 yuan/kWh).	• **Align onshore wind pricing with coal,** expand both onshore and offshore wind power, and increase subsidies (210-300 billion yuan), with a focus on **offshore** wind development. **Subsidies reach peak around 2020.** • Wind power costs reach **parity with coal**, with a **large-scale market** and an **industrial system** that incorporates advanced **technology standards.** • Focus on wind power development in **Inner Mongolia** and **distributed** wind in **central and eastern** regions, supporting **expansion and electrification efforts** across the country.	• Achieve **lower wind costs** than that for coal (excluding transmission); push **onshore and offshore projects.** • Promote **transmission infrastructure** and flexible systems; accelerate **power system reforms** and direct subsidies mainly to **offshore wind power.** • Develop **integrated, smart energy management systems** with a target of **20% energy from renewables,** ensuring **wind power development** accelerates across the country.	• Advancements in wind power, **energy storage**, and **grid integration,** to ensure stability and efficiency in power delivery. • Wind power will reach **saturation by 2040**, achieving balanced development while **pushing for 20% of energy demand** from renewables, transitioning to electrification with a gradual reduction in coal reliance.

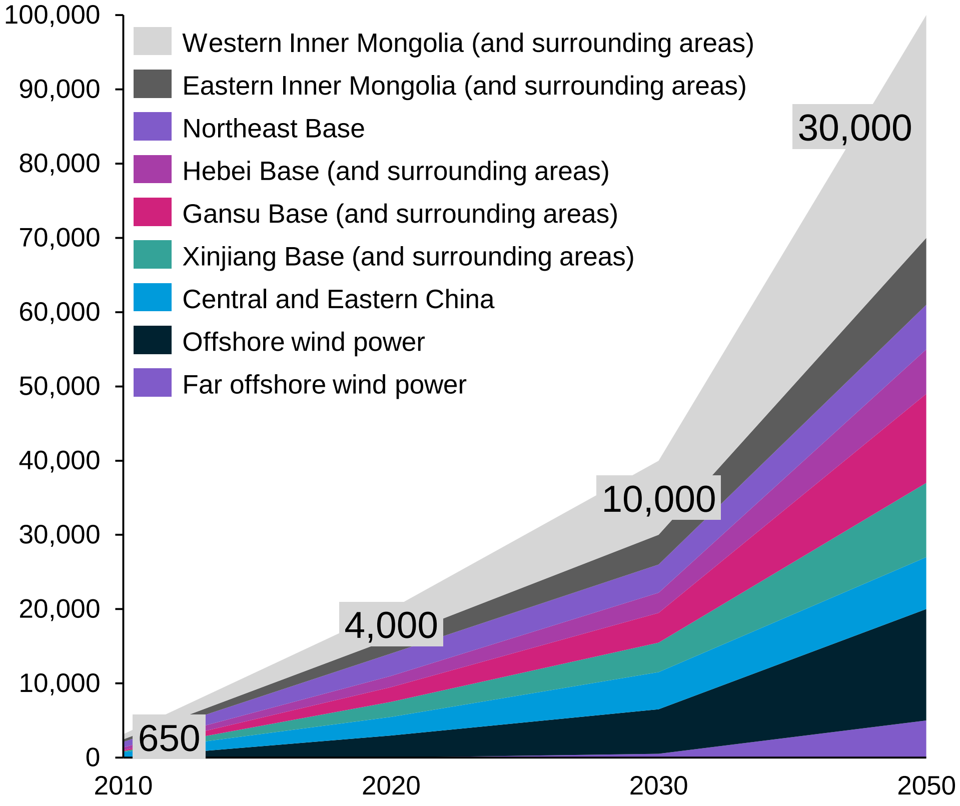
Observations

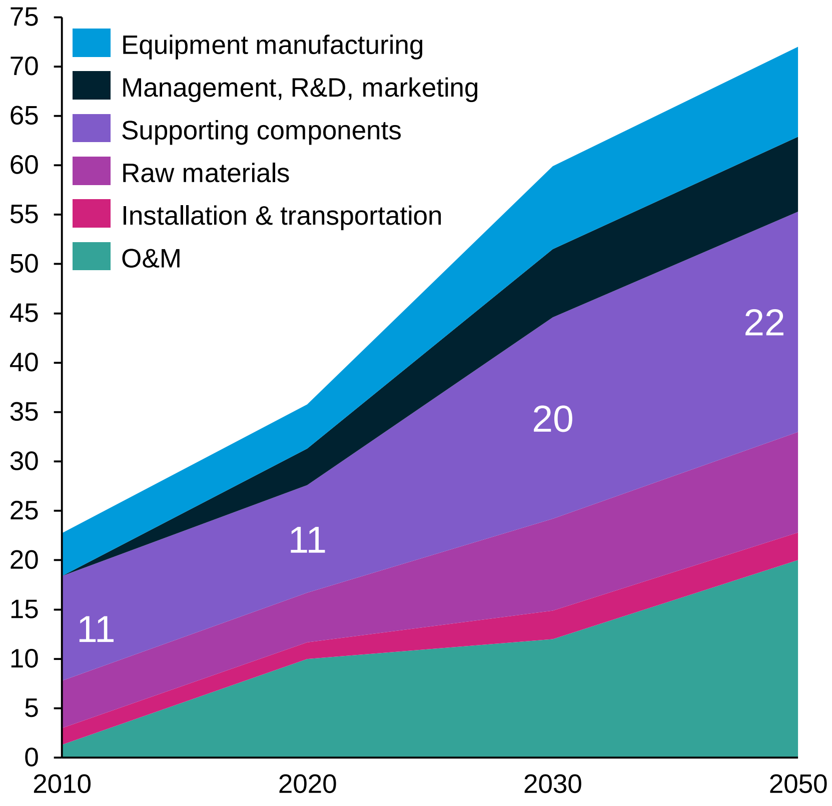
- **China maintains a lead globally** with a total cumulative wind capacity of 442 GW.
- Grid expansion strategy:
  - China has budgeted **$455 billion for grid investment from 2021 to 2025**, including long-distance transmission lines.

Sources: China Power, 2023-2024 National Electricity Supply and Demand Situation Analysis and Forecast Report (2024); IRENA, China (2024).
Credit: Abha Nirula, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

China’s wind goal relies on energy bases in Inner Mongolia; most jobs are expected to come from supporting component manufacturing

China focuses on a select few energy bases, plus transmission from high-potential to high-intensity areas





Observations

- **Subsidies and incentives have been the backbone of China’s RE expansion:**
  - China introduced FiTs to support onshore wind development in 2009 and subsequently expanded them to support offshore wind projects.
  - With the declining cost of wind projects, the government withdrew FiTs for RE projects in 2022 to move toward a market-based mechanism and reduce the subsidy burden for the government.
  - The wind sector continues to receive indirect support from state banks.
- **Domestic manufacturing of turbines:**
  - China introduced FiTs to support onshore wind development in 2009 and subsequently expanded them to support offshore wind projects.

Sources: IEA, Energy system of China (2022); Wood Mackenzie, China leads global wind turbine manufacturers’ market share in 2023 (2024); GWEC, China Wind Power (2024).
Credit: Petr Jenicek, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

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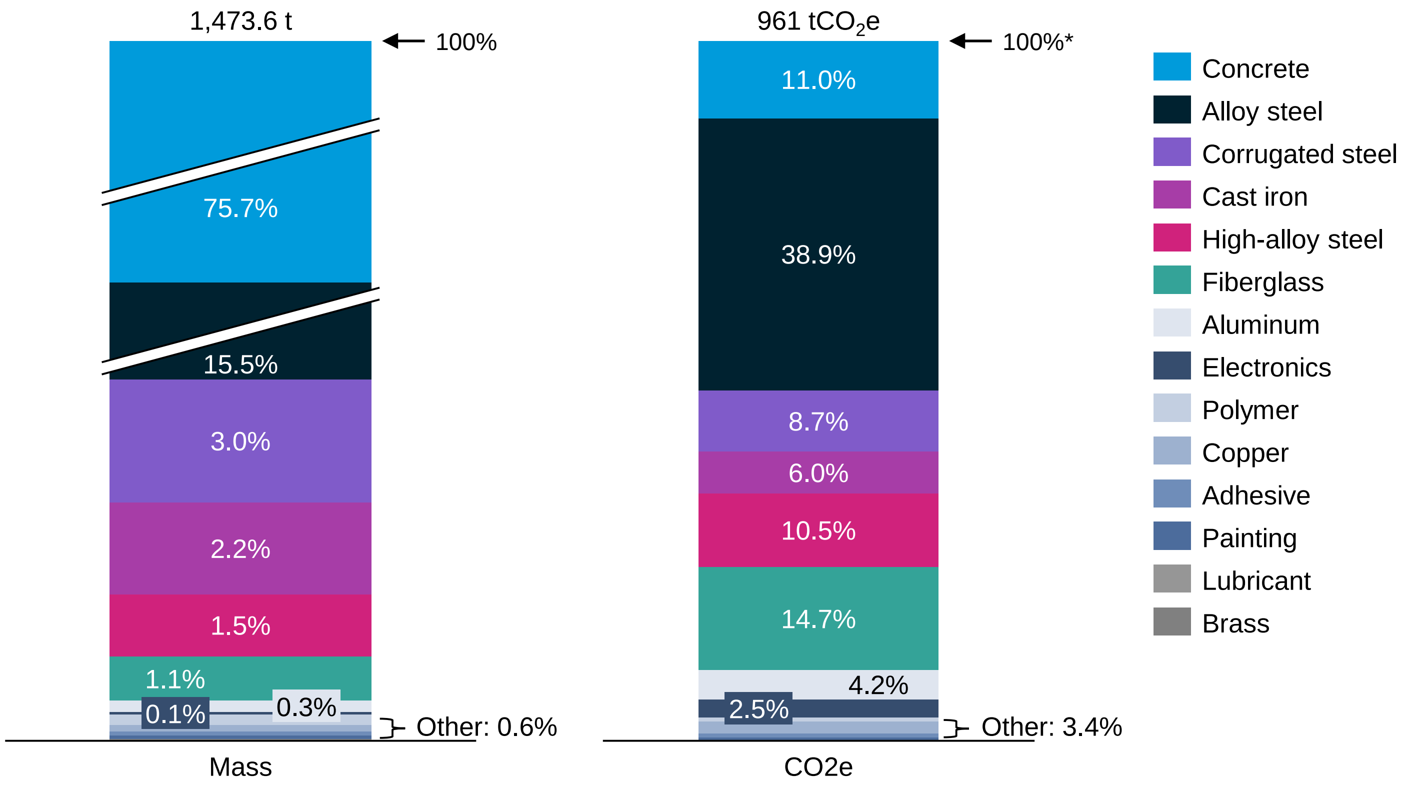
Appendix

The steel tower represents ~40% of wind energy raw material CO_2e emissions; fiberglass is the most emission-dense raw material

Mass and respective CO_2e emissions for raw materials in a Gamesa 2 MW turbine



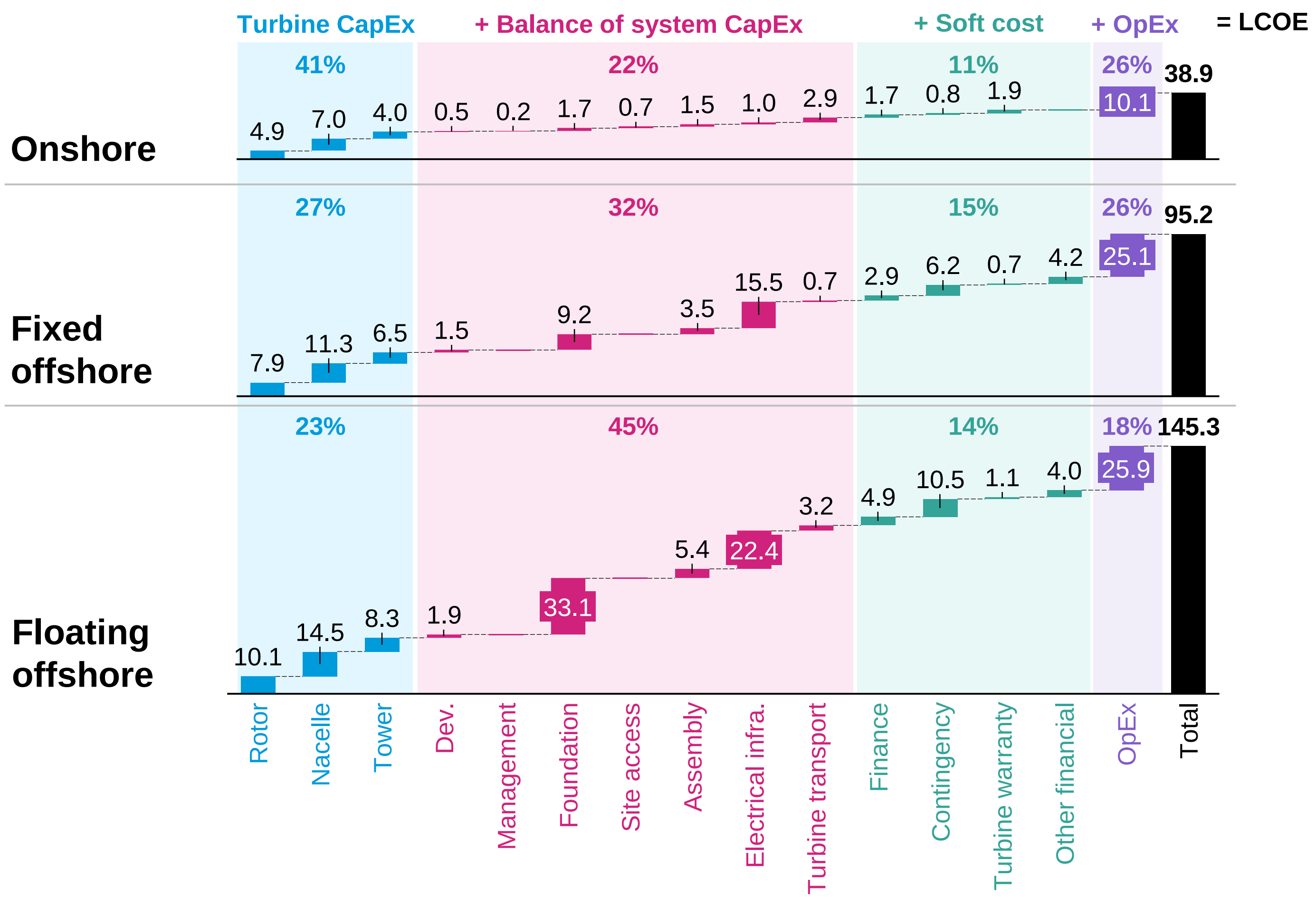
Observations

- **Concrete makes up three-quarters of the weight of a wind turbine but represents only 11% of emissions.**
- **On the flip side, alloy steel makes up only 15.5% of the weight but represents 38.9% of the emissions.**
- **Fiberglass has the highest emission density, as it represents only 1.1% of the weight but 14.7% of the emissions.**
- **Steel offers the largest opportunity to reduce total emissions from wind energy.** This can be achieved by using recycled steel and renewables in the steel production process.
- Replacing the steel tower with a reinforced cement tower would decrease emissions by ~6% overall.

(*) Percentages may not add up to 100% due to rounding
Sources: ICF, Recycling initiatives and carbon considerations that propel wind energy past other renewable sources (2021); Sikdar and Princiotta, Advances in Carbon Management Technologies (2021).
Credit: Quint Houwink, Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

Turbine and BoS CapEx compose most of the LCOE, with OpEx representing around ~15% to 25% of cost

LCOE breakdown by deployment type, *$/MWh, 2023*



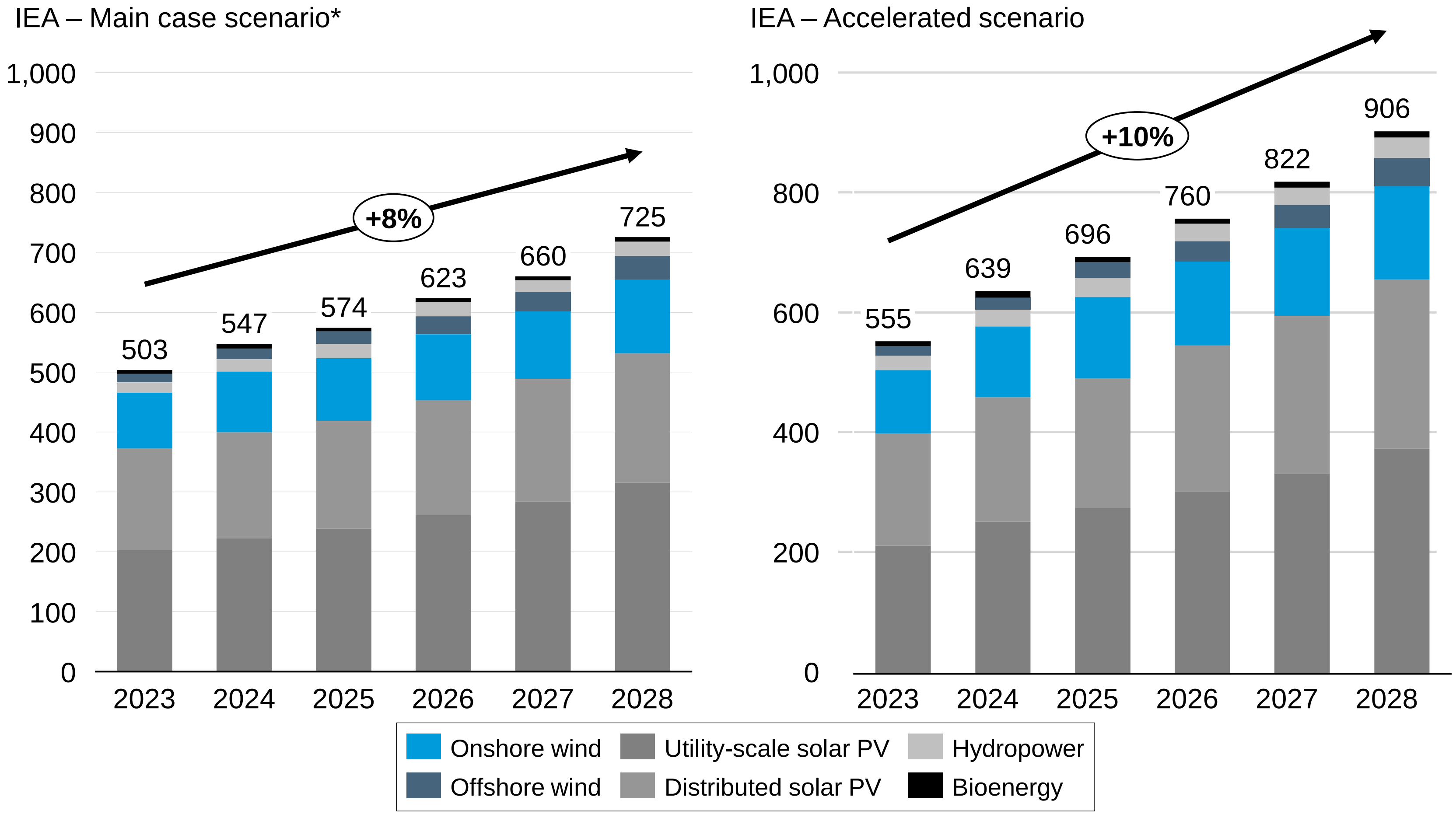
Observations

- **Among utility-scale wind projects:**
  - **Onshore** represents the **most capacity (~90%).**
  - **Offshore floating** is the **most expensive** ($145/MWh) due to the elevated cost of the foundation and electrical infrastructure.
- **Capital expenditure** includes the turbine structure as well as **balance of system (BoS)** components.
  - The **turbine/rotor, tower, and nacelle** represent anywhere from ~20% to 40% of total cost.
  - **BoS** similarly is around ~20% to 40% of cost; the **foundation** and **electrical infrastructure** represent the largest contributor to BoS CapEx.
  - **Turbine CapEx and BoS CapEx** collectively represent roughly 60% of total cost**.**
  - Financial CapEx is relatively stable (~11% to 14%); **O&M expenses are anywhere from ~17% to ~26%.**
- **Among distributed projects, BoS represents an increasingly smaller portion of the total project cost as the system size (in kW) increases:**
  - Residential (>50%), commercial (30%), industrial (~20%).

Source: NREL, Cost of Wind Energy (2023).
Credit: Taicheng Jin, Quint Houwink, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

Among renewables, wind is forecasted to make up ~20% of capacity additions from 2023 to 2028; solar makes up ~70%

Renewable global net capacity additions, *GW/yr, 2023-28*



Observations

- In absolute capacity terms, onshore **will still lead in scenarios, but offshore will play an increasingly important role, reaching 30% of added capacity by 2028.**
- **Solar has taken the lead in renewables** due to its significantly lower LCOE and fewer obstacles in manufacturing capacity.
- **APAC (including China) will lead capacity expansion:**
  - **Onshore:** 50% of capacity addition in 2050, followed by North America (23%) and Europe (10%).
  - **Offshore:** 60% of capacity addition in 2050, followed by Europe (22%) and North America (16%).
- **Investment needs to significantly scale:**
  - **Onshore needs to triple by 2050:** $67B (2018) to $146B (2030) to $211B (2050).
  - **Offshore needs to increase 5x by 2050:** $19B (2018) to $61B (2030) to $100B (2050).

(*) IEA's "main case" is based on current policy and market conditions, while the "accelerated case" assumes changes in the policy or market to address current challenges.
Source: IEA, Renewable Energy Progress Tracker (2024).
Credit: Quint Houwink, Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Scenarios

ETS

The Economic Transition Scenario reflects a world where policymakers pursue an energy transition relying only on **historical efficiency trends** and **economically competitive, commercially at-scale clean energy technologies.**

The ETS requires no further support for clean technologies beyond existing measures, although it does hinge on a level playing field that allows these solutions to access markets and compete with incumbent technologies.

NZS

The International Energy Agency's Net Zero Scenario reveals the sheer scale and scope of the challenge of remaining within 1.75°C of global warming and achieving the goals of the Paris Agreement.

Source: BloombergNEF, 2024 Outlook (2024).
Credit: Quint Houwink, Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, “Reconsidering Wind” (5 March 2025).

Balance-of-system components (ref. slide 63)

BoS component	Description
Inverters	Solar panels produce direct current (DC), while power grids are alternating current (AC). The inverter converts the DC power generated by the panels to AC. The most crucial component of a PV system after solar panels.
Wiring	Connects the solar panels and other electrical parts of the PV system.
Switches	Used for safety reasons (can disconnect the panels from the grid in case of a power surge or emergency) and to direct the flow of power (for example, either to the grid or to a battery).
Junction boxes	Metallic or plastic boxes used as meeting points for electrical connections.
Mounting systems	Provides support for the panels and fixes them in place.
Metering systems	Measure the amount of electricity flowing through them.
Batteries	*Optional item:* Store energy generated by the panels. Can provide power when the sun is not shining.
Charge controllers	*Optional item:* Devices that manage the electricity flow to and from batteries and protect them from overcharging.
Sensors	*Optional item:* More common in utility-scale projects. Help to keep track of environmental variables like panel temperature and solar irradiance. Used for monitoring and maintenance purposes.

Sources: NREL, U.S. solar PV system cost benchmarks Q1 2023 (2023); SolarEdge, Balance of System and Energy Production Comparison.

Glossary

AD/CVD	Antidumping and countervailing duties
APAC	Asia Pacific
ASEAN	Association of Southeast Asian Nations
BIPV	Building-integrated PV
BoS	Balance of system
BSF	Back surface field
c-Si	Crystalline silicon
C&I	Commercial and industrial
CAGR	Compound annual growth rate
CapEx	Capital expenditures
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CPV	Concentrator PV
CSP	Concentrated solar power
EMEA	Europe, Middle East, and Africa
EPC	Engineering, procurement, and construction
ESP	Energy service provider
EVA	Ethylene vinyl acetate
FiT	Feed-in tariff
FBR	Fluidized bed reactor
FPV	Floating PV
HJT	Silicon heterojunction cells
IRA	Inflation Reduction Act
IRR	Internal rate of return
ITC	Investment tax credit
LID	Light-induced degradation
LULCF	Land use, land-use change and forestry
MOIC	Multiples of invested capital
mono-Si	Mono-crystalline silicon
NAM	Non-Aligned Movement
NPV	Net present value
OpEx	Operating expenses
O&M	Operations and maintenance
PAY	Pay as you go
PERC	Passivated emitter and rear cell
Poly-Si	Poly-crystalline silicon
PPA	Power purchase agreement
PTC	Production tax credit
PV	Photovoltaic
REC	Renewable energy credit
RPS	Renewable Portfolio Standard
SG&A	Selling, general, and admin. expenses
SiO_2	Quartzite
SPV	Special purpose vehicle
TCO	Transparent conductive oxide
VIPV	Vehicle-integrated PV
VOST	Value-of-solar tariffs
WACC	Weighted average cost of capital

Credit: Quint Houwink, Taicheng Jin, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Kim *et al.*, "Reconsidering Wind" (5 March 2025).

Units, calculation, and references

- One watt equates to one **joule** of energy per **second**.
- In electrical systems, power (**watts**) is calculated by multiplying voltage (**volts**) by current (**amps**).

Kilowatt (kW)	1,000 (one thousand) watts
Megawatt (MW)	1,000,000 (one million) watts
Gigawatt (GW)	1,000,000,000 (one billion) watts
Terawatt (TW)	1,000,000,000,000 (one trillion) watts