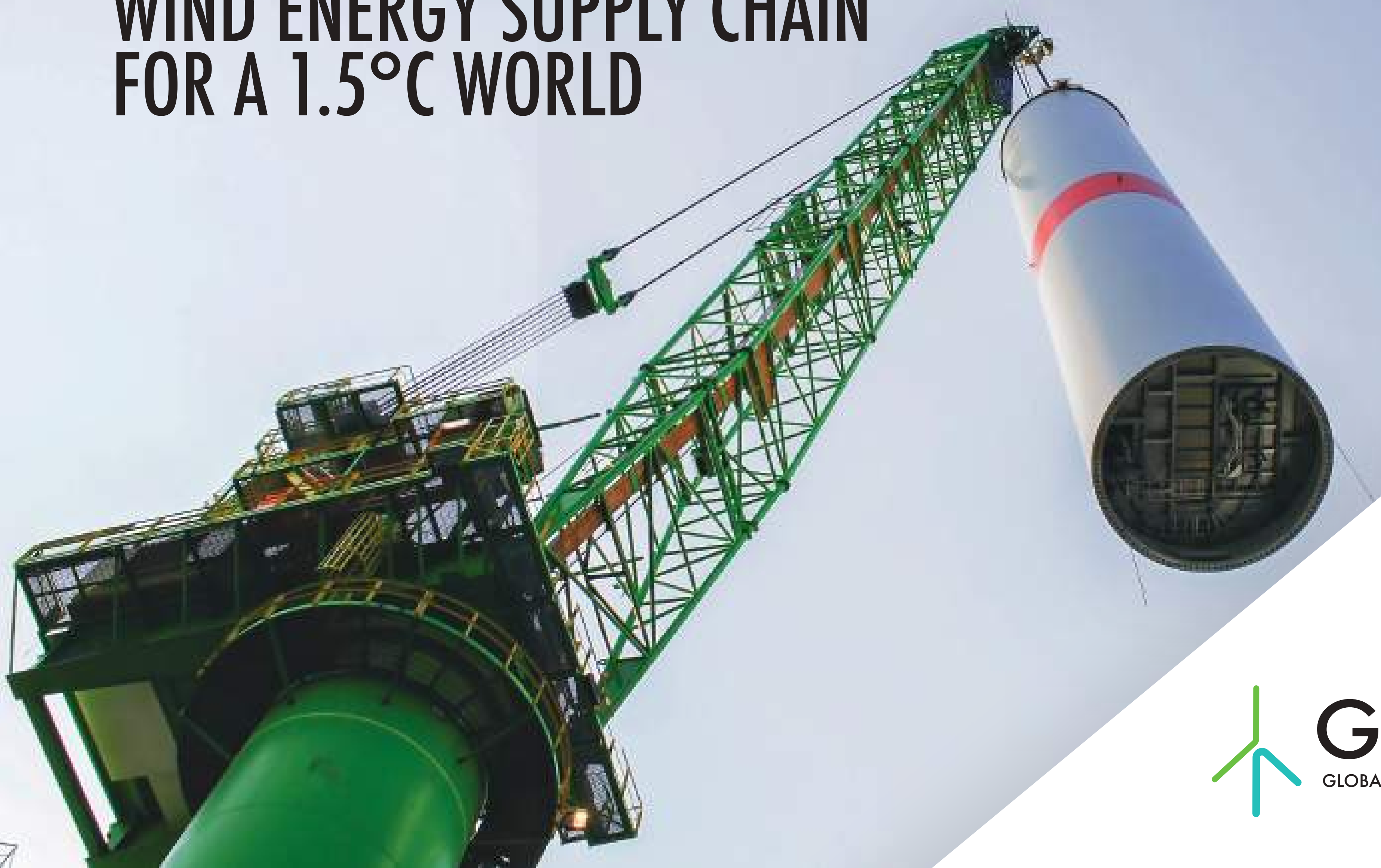
MISSION CRITICAL: BUILDING THE GLOBAL WIND ENERGY SUPPLY CHAIN FOR A 1.5°C WORLD



GWEC
GLOBAL WIND ENERGY COUNCIL

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Citation

Global Wind Energy Council and Boston Consulting Group (2023), Mission Critical: Building the global wind energy supply chain for a 1.5°C world.

Acknowledgments

This report was produced by the Global Wind Energy Council and co-authored by the Global Wind Energy Council and Boston Consulting Group. The lead authors of this report were Feng Zhao, Joyce Lee and Ben Backwell (GWEC) and Jens Gjerrild and Lars Holm (BCG).

The authors wish to thank Carsten Brinck, Shashi Barla and Christos Chronopoulos (Brinckmann), Haoran Li, Jieying He and Guiyong Yu (Chinese Wind Energy Association), Maf Smith (Lumen Energy & Environment) and Jianrong Zhou (ELKEM) for providing data for selected components and materials, as well as Matthew Watkins, Aisling Hubert, Chenfei Wang (CRU), Shashi Barla (Brinckmann) and Daan De Jonge (Benchmark Mineral Intelligence) for providing additional content for selected materials.

Published

1 December 2023

Design

Lemonbox
www.lemonbox.co.uk

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The world today is confronting a series of macro challenges, among them climate change, the lack of energy security and energy access, and rising inflation and unsustainable debt levels, particularly in developing economies. Scaling up renewable energy will go a long way to mitigate these challenges. If well managed, the global energy transition can bring prosperity, justice and resilience to communities around the world.

To support the transition, political momentum is gathering around a target of tripling global renewable energy capacity by 2030, which would translate to growing the installed wind fleet by roughly 3 times to reach at least 2.7 TW by the end of the decade. Achieving this leap in wind capacity will require a rapid and sustained ramp-up in investment in order to build a stronger global supply chain for the wind industry.

This is a watershed moment for getting trade and industrial policy in shape for a 1.5°C world. The wind supply chain is highly global in nature, with a strong focus in China given its sizeable domestic demand. But from Europe to the Americas, the supply chain in some key regions of the world has been insufficient in recent years, and has seen setbacks in its ability to make forward-looking investments in supply, due to insufficient market volume caused by policy and regulatory challenges.

This report, delivered by GWEC in partnership with Boston Consulting Group, is the first comprehensive study of its kind which performs a deep dive across the wind energy supply chain, from nacelles to components to materials to offshore wind balance of plant. The report assesses the implications for energy transition policy across four future macroeconomic scenarios by 2030, and the broader wind supply chain landscape, market size and returns.

Our analysis reflects key action areas for policymakers and industry, and outlines the need for stronger collaboration to ensure the wind supply chain is in place for a net zero future. Above all, action must focus on: scaling up volume and predictability in the wind pipeline; industrialising the wind sector with more global and modular designs; balancing regional supply chain security with continued and enhanced global interlinkages, ensuring markets can provide clear and bankable demand signals; shaping trade policy to build competitive industries, rather than pursuing defensive mechanisms; and undertaking power market reform to boost investment certainty and reflect the broader societal benefits of wind power.

Clean technology manufacturing is one of the most pressing challenges and opportunities of the current climate and energy debate. We need collaborative thinking and action on trade, finance and policy measures that can effectively respond to the climate emergency. Working with key partners, governments and the industry, GWEC will continue building upon the work contained in this report to secure the global wind supply chain for a 1.5°C pathway.

EXECUTIVE SUMMARY

Mission Critical: Building the global wind energy supply chain for a 1.5°C world

The global wind energy supply chain is exposed to many internal and external challenging factors. This comes at a time when political momentum is growing to set a target for the tripling of renewable energy capacity by 2030, to support the delivery of 1.5°C scenarios which see wind energy as the backbone of a future power system.

International energy agencies and net zero roadmaps agree on the primary role of wind energy on the road to net zero. IRENA's World Energy Transitions Outlook foresees 3,040 GW cumulative onshore wind by 2030 and 494 GW of offshore wind by 2030, or about 3.5 TW of total wind installed by 2030.[1] The IEA's Net Zero by 2050 Scenario calls for 2.75 TW of cumulative wind installations in 2030, with 320 GW installed in 2030 alone.[2] This would require today's global installed wind fleet to scale up by 3-3.5 times over the next 7 years to 2030.

However, deployment of wind energy, and the manufacturing and production capacity required to deliver it, is still lagging far behind these levels. By 2030, the Global Wind Energy Council (GWEC) forecasts that we will reach just more than 2 TW of installed wind capacity worldwide, leaving a sizeable gap of 650-1,500 GW between growth under current policies and a 1.5°C pathway.[3]

This report outlines the status of the global wind supply chain under business-as-usual (BAU) and net zero scenarios for growth to 2030, investigates future macro geopolitical and economic outlooks impacting the supply chain, and presents the priorities for industry and policymakers to put the industry back on track to deliver on global decarbonisation goals.

Volatile policy and market demand have led to scaling hesitancy, under-intdustrialisation and localisation pressures

The wind industry is increasingly experiencing high demand-side volatility, hesitation towards scaling on the supplier side, and rapid technological innovations. These factors have fuelled a 'race to the bottom' approach to costs combined with a 'race to the top' thinking on turbine size, leading to growing technical risk and a low level of serial production.

From Europe to the Americas, supply chain investment in some of the world's key regions has been insufficient in recent years, mainly due to stop-start government policies, permitting bottlenecks and a lack of clarity and regular cadence for tenders. Market design and policy frameworks overly focused on power cost have unintentionally led to razor-thin or negative margins while failing to account for higher financing and material costs, making investment in supply chains unviable.

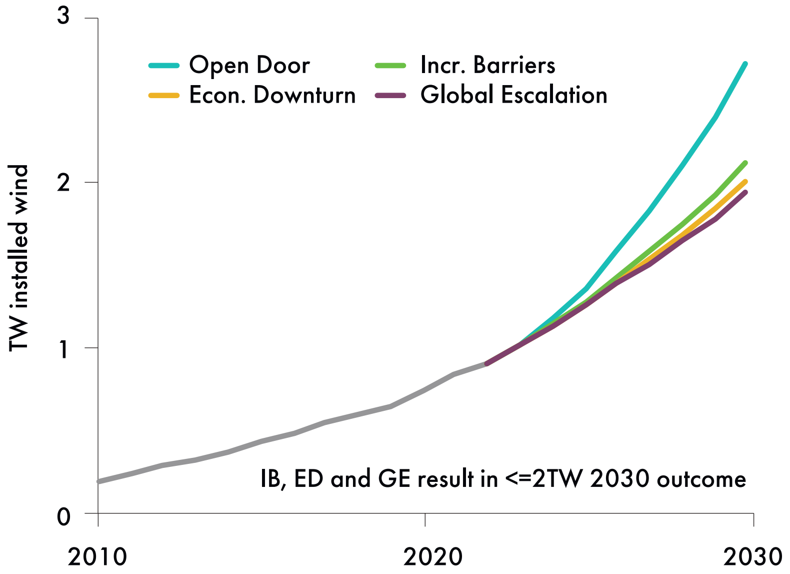
In China, India, Europe and the US – home to existing production hubs for the wind supply chain – governments are aiming to increase manufacturing capacity as part of national industrial strategy. This is also reflective of the anticipated growth of wind deployment in their home markets and the wider APAC, Europe and Americas regions. Increasingly, policymakers have focused on ensuring resilience at the national level not simply in terms of power flows, but also in the ability to expand generating and production capacity.

Four broader challenges impacting global wind supply chains are explored in this report:

- **Market volume and power price volatility is increasing in many markets.** Failed auctions, project cancellations, inflationary impacts on supply chain components, shipping and logistics – as well as the rising cost of capital – are all impacting the investment case for wind energy.
- **Policy signals are preventing the industry from adjusting and scaling production capacity.** Supply chain actors in many areas of the world have been rightly hesitant to adjust their capacity downwards given the anticipated uptick in wind demand – a growth

1. IRENA, World Energy Transitions Outlook: 1.5°C Pathway, 2023.
2. IEA, Net Zero Roadmap: A global pathway to keep the 1.5 °C goal in reach - 2023 Update, 2023.
3. GWEC, Global Wind Report, 2023.

Only the Open Door scenario is sufficient for net zero; the Increased Barriers scenario is most likely to materialise and falls 650 GW short



Note: Interpolated 2024-2030 forecasts, assuming higher demand can have impact on installations from 2025 onwards.
Source: GWEC, IEA Net Zero scenario (released September 2023), BCG analysis

that is desperately needed from a climate perspective. Meanwhile, local content and industrial policies are preventing consolidation in some markets like China, which would allow for a more efficient supply chain. Maintaining this overcapacity is putting tremendous pressure on the P&L of wind industry players.

- **The industry is hit by a rapid innovation curse.** The industry has reached a stage where ever-larger turbines are specialised for specific markets but less suited to the global market. At the same time, the core industry challenges created by the rapid increase in turbine sizes are becoming increasingly evident, including a shortened product development lifecycle that can lead to defects stemming from untested new technology deployments, large R&D spend for OEMs that they have not been able to recuperate, and a lack of industry standardisation pushing up costs.

- **A focus on resilience and political pressure around job creation makes regulators push for localisation.** The energy crisis of 2021 made energy resilience a core political theme, placing the focus on energy supply. Since then, the resilience agenda has expanded to encompass supply chains and industry. This has prompted varying industrial strategies from new wind markets, countries/regions with a fragmented supply chain footprint and countries with an at-scale supply chain.

These factors have converged to make the outlook for global wind supply chains challenging – but one that can be greatly improved.

The future outlook for wind supply chains is uncertain and likely to become more challenging

Looking to the future, there are different elements that can impact the outlook for the global wind supply chain. We foresee four scenarios:

1) **Open Door,** with growing regional collaboration on both supply and demand.

2) **Increased Barriers,** where markets increase trade barriers and turn their attention to domestic investment.

3) **Economic Downturn,** where investments dry up and attention focuses towards low-cost rather than low-emissions technology.

4) **Global Escalation,** where increasing cross-border conflict reduces trade and shifts the focus from decarbonisation towards ensuring access to energy.

An Open Door scenario would have the highest net-positive climate and wind industry impact, with wind growth sufficient for reaching a net zero pathway. However, we currently see a higher likelihood for the Increased Barriers scenario to materialise. Under current policies, we are likely to install just more than 2 TW of global wind capacity by 2030, which means a roughly 650 GW shortfall from a 1.5°C pathway.[4] This current growth trajectory is in line with the Increased Barriers scenario, and reflects a low-demand

4. Comparing GWEC's BAU outlook (Global Wind Report 2023) to IEA's Net Zero by 2050 scenario (2023).

picture in Europe and other key regions that provides insufficient signals for the supply chain to scale.

It is also likely that elements of the other two scenarios, Economic Downturn and Global Escalation, will resonate in global markets to some extent. The body of this report details how each scenario would impact the global wind supply chain.

In the current macro environment, the wind industry must be ready to navigate these scenarios and prepare for growth, while at the same time guarding itself against the adverse effects of an economic downturn and escalation of global trade tensions.

The wind supply chain must address specific bottlenecks

Current supply chains only have enough capacity to deliver on growth scenarios that fall short of net zero. To allow the industry to achieve the necessary 2.75 TW of installed capacity by 2030, supply chains must scale across all activities and markets. It is essential to directly address the key challenges within the wind supply chain, or they will pose likely bottlenecks before 2030.

- **The wind supply chain is currently highly globalised, with a strong focus in China.** China represents approximately 64% of global value and an expected 58% share of planned near-term (2023–2025) global wind installations.[5] Concentration is strongest for rare earth element refining and the manufacturing of gearboxes, converters, castings and generators, for which the rest of the world is heavily dependent on continued imports. There are clear signals that China intends to keep growing its role as the leading component manufacturer for the global wind industry, and further extend its involvement to providing finished wind turbines to international markets.

- **Mining for the most important raw materials such as iron, zinc and copper is heavily centralised in a handful of countries,** while the refining of critical rare earth minerals for wind turbine permanent magnets is handled almost exclusively by China. The natural resources and refining capacity for these materials are plentiful, but their heavy centralisation makes trade restrictions a major risk for the global industry.

- **While concentration risk in China is not as high in the wind industry as it is in the solar PV industry,[6] concentration of component manufacturing is a significant concern** due to a historical tendency in Europe – and to an even higher extent in the US – to outsource gearbox, converter and generator manufacturing. For resilient wind scaling, we need to see efforts to ensure local supplies of these components. Europe must at least double its existing capacity by 2030, while the US needs to establish local industries from scratch to meet domestic demand.

- **Nacelle assembly capacity will be insufficient in all regions except China and India,** with the thin margins currently experienced in the industry deterring the necessary capacity expansion. The underlying challenges threatening the profitability of first-line suppliers must be addressed to ensure sufficient capacity, especially for offshore wind.

If we are to ensure a sufficiently large and stable demand for a net zero future, delivered at a highly competitive cost, industry and policymakers must actively collaborate on immediate action. Six key recommendations for action to secure the global wind energy supply chain for a 1.5°C are listed below:

Recommendation 1: Address basic barriers to wind industry growth in land, grids and permitting to increase volume and predictability

Parts of the supply chain are now loss-making and unable to commit to future production capacity, largely due to policy and regulatory barriers that lead to heightened uncertainty for project investments. These barriers include overly complex permitting procedures, grid bottlenecks and impractical pricing signals at auction. In many places, policy and financing environments are not fit for purpose for a 1.5°C pathway that culminates in wind generating one-fifth of the world's electricity by 2030 and one-third of electricity by 2050.[7]

As a key energy and political

5. Value-add based on estimated share of mining, refining, manufacturing, assembly and services with calculation done based on activity location. Installation outlook covering 2023-2025 is from GWEC's wind growth forecast (Q2 2023 Outlook).
6. China has more than 80% share of all key solar panel manufacturing stages, and manufacturing for components like polysilicon and wafers is set to rise to 95% in the next few years, according to the IEA. See: IEA, Solar PV Global Supply Chains, 2022.
7. IRENA, World Energy Transitions Outlook: 1.5°C Pathway, 2023.

Theme		Critical materials					Key components								Assembly		Offshore wind enablers		
Subject		Rare Earths*	Steel Plate*	Copper	Concrete	Carbon Fiber*	Gearboxes*	Generators*	Blades*	Power Converters*	Castings*	Towers*	Foundations*	Cables*	Onshore nacelles*	Offshore nacelles*	Installation vessels*	Ports*	Workforce
Global level criticality		●	◔	◔	○	◑	◕	◑	◑	◔	◕	◑	◑	◔	◔	◑	◑	◑	◕
Time to action **	Europe	2023	-	-	-	2025	2024	2024	2024	2024	2023	2025	2025	2025	2024	2024	2025	2023	2023***
	North America	2023	-	-	-	2025	2023	2023	2023	2023	2023	2023	2023	2023	2024	2023	2023	2023	2023***
	China	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	***
Key findings		• General availability of needed materials at the global level, with copper mining/refining and concrete production available for all major regions • Major centralisation for refining of rare earth materials, with close to no capacity outside of China today. First alternate refineries expected to be ready by 2028 • Carbon fiber production currently experiencing undercapacity; major capacity expansion has been announced in particular in China, with Europe and North America likely becoming reliant upon imports					• Risk of manufacturing bottlenecks before 2030 for multiple components at regional level, in particular gearboxes, generators, blades as well as offshore wind size compatible metal castings, towers and foundations • Strong centralisation for some key components, especially gearboxes and castings. North America is generally fully dependent on imported components and is already today experiencing undersupply of especially components for offshore wind including offshore towers, foundations and subsea cables • Supply chains will generally benefit from building out regional manufacturing hubs to ensure more resilient access to needed components while ensuring continued trade and global interlinkages to enable flexibility and address demand volatility								• Onshore challenge expected only if trade exports from India/China are restricted • Offshore assembly risks undersupply as uncertain industry outlook may lead to plant cancellations		• Offshore wind needs to scale both port capacity and wind turbine installation vessels with sufficiently large crane capacity • US critically lacks vessels and ports while announced expansion plans and orders in other markets can address need to 2030; any cancellations will pose risks		

Recommendations

- Address basic barriers to wind industry growth in land, grids and permitting to increase volume and predictability
- Regionalisation will be needed to support growth and resilience, while maintaining a globalised supply chain
- Trade policy should build competitive industries, not push higher costs onto end users
- The wind industry must standardise and industrialise
- The market must provide clear and bankable demand signals
- Fundamental reform of the power market underpins further wind growth

○ No global bottleneck risk ● Immediate global bottleneck

* Deep dive analysis provided ** Time to action denotes time when new capacity construction must be started to avoid bottlenecks in each region without trade

*** Workforce with major challenges, addressed in GWEC & GWO: *Global Wind Workforce Outlook 2023-2027* priority, the wind energy industry must work with government and civil society to urgently address policy and regulatory barriers, in order to help improve its outlook.

Recommendation 2: The wind industry must standardise and industrialise

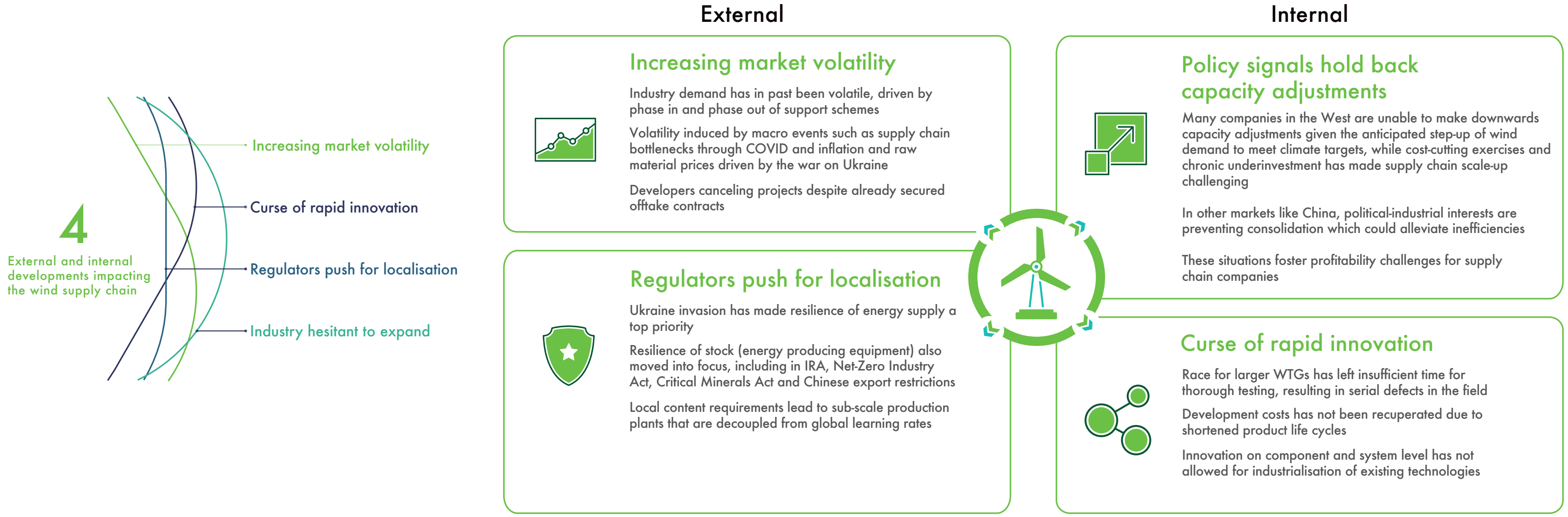
The wind sector must industrialise and scale, with designs becoming global and modular. To achieve this, turbine platform growth will need to slow down towards 2030 to the extent needed to avoid serial damages in the field, ensuring that OEMs can capitalise on their R&D investments while allowing for the supply chain to use equipment for more than a few years and achieve economies of scale.

Recommendation 3: Regionalisation will be needed to support growth and resilience, while maintaining a globalised supply chain

With a growing push towards diversification, reshoring and regionalisation, the industry will profit from building out regional supply hubs to provide alternative sources for the materials and components needed to deploy additional wind capacity. But this must be accompanied by measures to keep trade flowing within and between regions, supporting individual nations in enhancing their capacity to deliver at scale, ensuring flexible access to needed materials, components and services, and providing stronger wind demand drivers across borders. This will be particularly important for the future growth of the offshore wind sector, where manufacturing, installation and O&M services all benefit greatly from regional collaboration and cross-border learning.

Governments should adopt a balanced approach between fostering regional supply chain security and accounting for the global interlinkages of the wind energy supply chain. Regions will need to pursue supply diversification strategies, reshore/onshore some segments and grow their own capacities. But this should not manifest in measures that outright block current trade flows and interrupt or delay deployment. Particular attention should be paid to gearboxes,

External and internal developments impacting the wind supply chain



generators, power converters, castings and rare earth materials where global resilience is currently low and concentration risk in China is high.

Recommendation 4: The market must provide clear and bankable demand signals to reach net zero

Markets must develop credible build-out trajectories in the shape of concrete and transparent targets, as they will be key to supply chain investment. These must be stable, bankable and much stronger than they are today. By stating clear targets and roadmaps over a long horizon stretching beyond 2030, policymakers will be able to grow wind power demand as needed through communicated targets for electrification, decarbonisation, sector coupling and storage, involving the broader industry in building renewables ecosystems.

Recommendation 5: Trade policy should aim to build competitive industries, not push higher costs onto end-users

Supply chain capacity utilisation remains key to cost reduction, and is only possible if resources can be shared across regions, with competitive cost positions and limited trade barriers. Markets will benefit from public investment into workforce skills and infrastructure, while prescriptive regulation against cross-border trade could reduce industry growth and increase costs. This will ultimately be paid for by households, commercial and industrial consumers, cities and other consumers of electricity.

Rather than pursuing defensive mechanisms which could enhance trade barriers, governments should focus on incentivising strategic segments of the domestic industry, creating a more attractive market environment by ensuring adequate pricing and returns, making competitive finance available and removing bureaucratic barriers.

Recommendation 6: Fundamental reform of the power market underpins further wind growth

In order to provide the certainty needed to attract investment, power market reform should be introduced to better address the requirements of renewable generation. Long-term operating margins must be ensured through awards based on solutions with higher system value – such as a better production profile – rather than strong competition for the lowest price per MWh. The broader societal benefits of wind energy could also be considered to further stimulate innovation and domestic value creation.

As one of the most innovative, scalable and cost-effective renewable energy sources, the global wind industry is prepared to continue making large and long-term investments in technology, supply chains and people. Through a coordinated global effort from industry and policymakers, we firmly believe that the challenges in the global wind supply chain can be resolved over the course of this decade. Actions taken now will help to foster a highly resilient and even more cost-efficient solution to decarbonise the world. This would provide incredible value from a socioeconomic and, not least, a climate perspective.

Actions taken now will help to foster a highly resilient and even more cost-efficient solution to decarbonise the world.

CHAPTER 1: GLOBAL STATUS AND OUTLOOK OF THE WIND SUPPLY CHAIN

Global findings on the wind supply chain

Macro trends in wind are challenging the global supply chain

Numerous global trends are impacting the wind supply chain. Since the COVID-19 pandemic in 2020, the world has shifted to a period of high uncertainty and rapid change.

Overall, the potential for disruptive shocks in 2024 remains, including impacts originating from the US election cycle, the ongoing wars in Ukraine and the Middle East and possibly a further slowing down of Chinese economic growth, alongside continued food and energy price volatility.

As governments put plans in place for 2024 to shore up economic security while progressing the energy transition, leaders will need to embrace a more adaptive mindset and embed processes that monitor and respond to major changes in the macro environment. Building those muscles before they are needed will be a differentiating factor in this decade, determining how well countries can navigate uncertainty and change.

By 2030, GWEC forecasts that we will surpass the 2 TW milestone of installed wind capacity worldwide under current policies.[1] However, growth is still lagging far behind the levels required for a 1.5°C pathway.

International energy agencies and net zero roadmaps agree on the primary role of wind energy on the road to net zero. IRENA's World Energy Transitions Outlook foresees 3,040 GW of cumulative onshore wind by 2030 and 494 GW of offshore wind by 2030, or about 3.5 TW of total wind installed by 2030.[2] The IEA's Net Zero by 2050 Scenario calls for 2.75 TW of wind installations in 2030, with 320 GW installed in 2030 alone.[3]

In either scenario, global wind growth must rapidly accelerate to meet 2030 targets for a 1.5°C pathway. This would mean ramping up annual global wind installations from the current 110 GW by roughly 3-3.5 times by the end of the decade. Against this backdrop, a number of macro trends are challenging the wind industry's capacity to forward-plan and invest in production and manufacturing capacity to meet these growth targets.

1. Market volatility is increasing

Wind has historically experienced high volatility, triggered by the introduction or expiry of support schemes. While damaging to the industry, this type of volatility was predictable. Today's volatility is increasingly due to new, less-anticipated drivers such as failed auctions, serial defects triggered by the rapid growth in platform size, and raw material price increases. These factors are leading to wind project delays or even cancellations of wind projects that have secured offtake contracts. This is impacting buyers and sellers of wind power and components alike.

Since COVID-19, inflationary impacts on supply chains, shipping and logistics have pushed up capital costs (CAPEX) of wind and other forms of electricity generation. Labour expenses have also increased, while the prices of key commodities like iron and steel remain well above pre-pandemic levels. Developers that secured offtake contracts between two and four years ago are experiencing a dramatic shift in total project costs, undermining future revenue certainty and their ability to reach final investment decisions.

In response to increasing inflation, central banks have embarked upon a series of interest rate rises, leading the cost of capital to also increase. Higher cost of capital leads to increased costs for all investments. Tightened monetary policy combined with historically high commodity prices in the last two years has impacted lending for energy sources worldwide.

2. Policy signals are preventing the industry from adjusting and scaling production

The global wind supply chain has historically carried a degree of overcapacity, and this is even sensible given the tendency for market upswings and downswings. However, varying policy signals are preventing supply chain actors from making necessary adjustments in capacity to meet current demand and anticipated demand more efficiently.

In many areas of the world, companies are unable to make decisive downwards capacity adjustments given the anticipated step-up of wind demand growth in this decade and beyond – growth which is desperately needed from a

1. GWEC, Global Wind Report, 2023
2. IRENA, World Energy Transitions Outlook: 1.5°C Pathway, 2023.
3. IEA, Net Zero Roadmap: A global pathway to keep the 1.5 °C goal in reach - 2023 Update, 2023.

climate perspective. In terms of upwards adjustments, a strain on profitability is pronounced among Western companies, where cost-cutting exercises and chronic underinvestment has made supply chain scale-up to meet a net zero pipeline equally challenging. Maintaining overcapacity is putting tremendous pressure on the P&L of wind industry players, especially those that are purely wind focused and have a regional scope. Less affected are players with a broader client base, such as bearing manufacturers, foundries for cast iron, or cable suppliers.

In China, there is adequate investment for scaling up to meet the huge growth projections of the domestic market. However, political-industrial interests and competing priorities are preventing industry consolidation, which would alleviate the cost pressures and inefficiencies in the supply chain fostered by a crowded market. This situation similarly imposes a squeeze on profitability of wind industry companies in China.

3. How the rapid innovation curse has hit the industry

In the past, Europe developed the leading and largest WTG technology, which was then replicated at multiple regional production hubs, leading to the exit or consolidation of local players that had been producing less advanced WTGs.

There was an expectation in the industry that this trend would persist and lead to globally standardised wind turbines that could be produced at scale in various locations. However, with continuous technological progress, the industry has reached a new stage with turbines so large and specialised for a specific market that they have become less suited for the global market.

We are now seeing market-specific WTG designs to match physical limitations such as payload on highways (USA), environmental requirements (EU), climate conditions (Middle East), co-located plant planning (China) or grid limitations (Australia). At the same time, the rapid increase in turbine sizes has resulted in several core industry challenges becoming increasingly evident, including a shortened product development lifecycle that can lead to defects stemming from untested new technology deployments, large R&D spend for OEMs that they have not been able to recuperate, and a lack of industry standardisation pushing up costs.

4. A focus on resilience and job creation makes regulators push for localisation

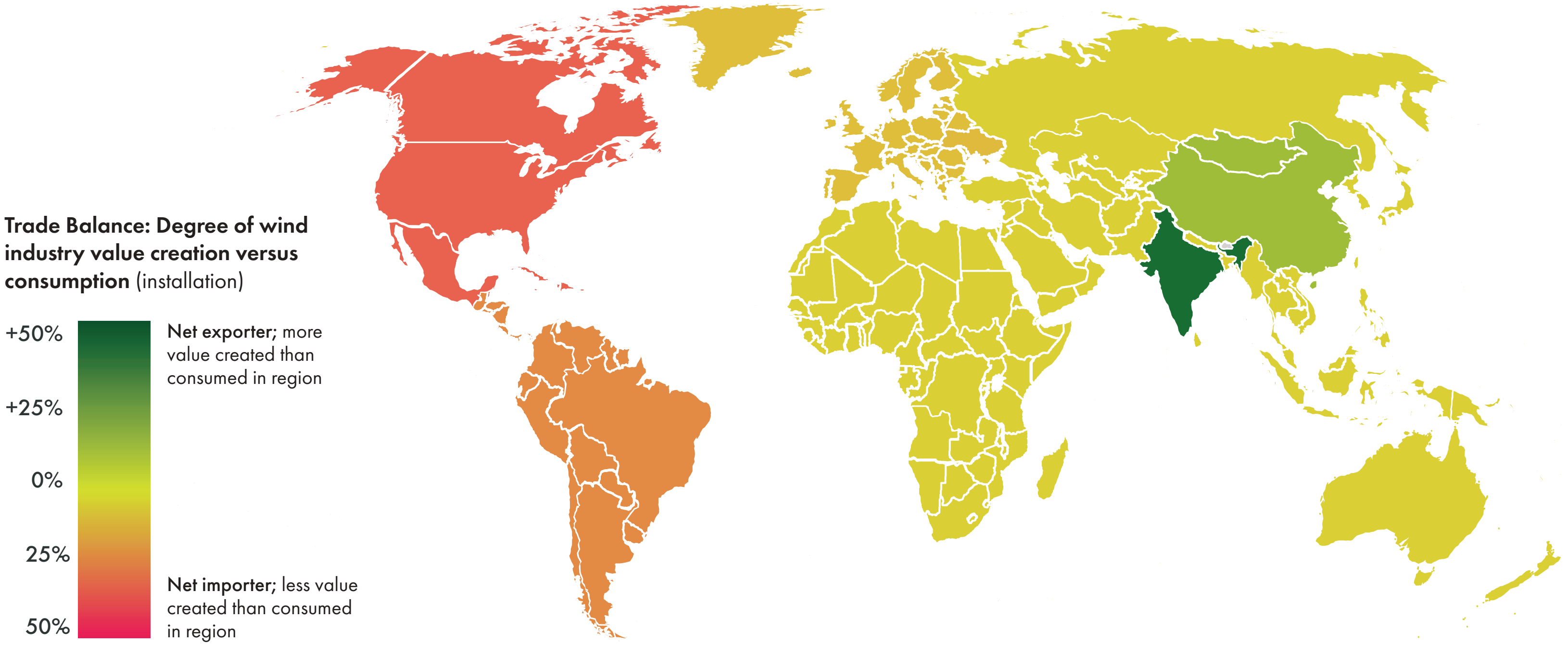
The global energy crisis and Europe's reliance on Russian gas at the advent of the Ukraine invasion immediately made energy resilience a core theme for politics and the energy industry, while energy prices had been rising due to drought and coal price volatility in Asia. The initial focus in Europe was on resilience of energy supply (the flow), both by diversifying sources of fossil fuel generation (e.g. building new LNG terminals in record time, or temporarily switching coal back on) while assembling medium-term plans to accelerate renewable energy deployment. China responded to the energy crisis by accelerating its renewables buildout and speeding up coal plant approvals.

Since then, the discussion around resilience in Europe and the US has expanded to encompass supply chains in the energy sector (the industry). Today many decisions are influenced by the desire to also be resilient with regards to equipment manufacturing, translating into prioritising not only the ability to produce the energy but also the generation technology itself in the market or region (local for local).

Countries are responding to this trend in different ways.

- **New markets** often set local content requirements to localise some manufacturing. This comes at the expense of higher CAPEX and ultimately higher power prices. We have observed this in the nascent offshore wind sectors in the Chinese Taiwan area and the US. The sustainability of such a model depends on stable local demand for wind turbines (as seen in Brazil) or on local players reaching a critical scale as support is being phased out (e.g. blade production in Turkey). Equally, there are examples of the local installation volume protected through local content declining. Local players that had not reached a globally competitive level became distressed, such as the gearbox manufacturing industry in Spain, or manufacturing in Brazil for WTGs smaller than 2MW. Local content requirements do not necessarily improve resilience of the stock as the market will likely continue to depend on the import of critical components. The Inflation Reduction Act (IRA) in the US, for example, omits certain components from its scope, leaving local assembly plants

Supply chain has major trade imbalance* with greater exports from Asia



* Represents local mining, refining, manufacturing, assembly and services compared to local consumption. Calculation at regional level for North America, South America, Europe, India, China and Rest of World. Value based on location of activity.

Source: GWEC, IEA, BCG analysis.

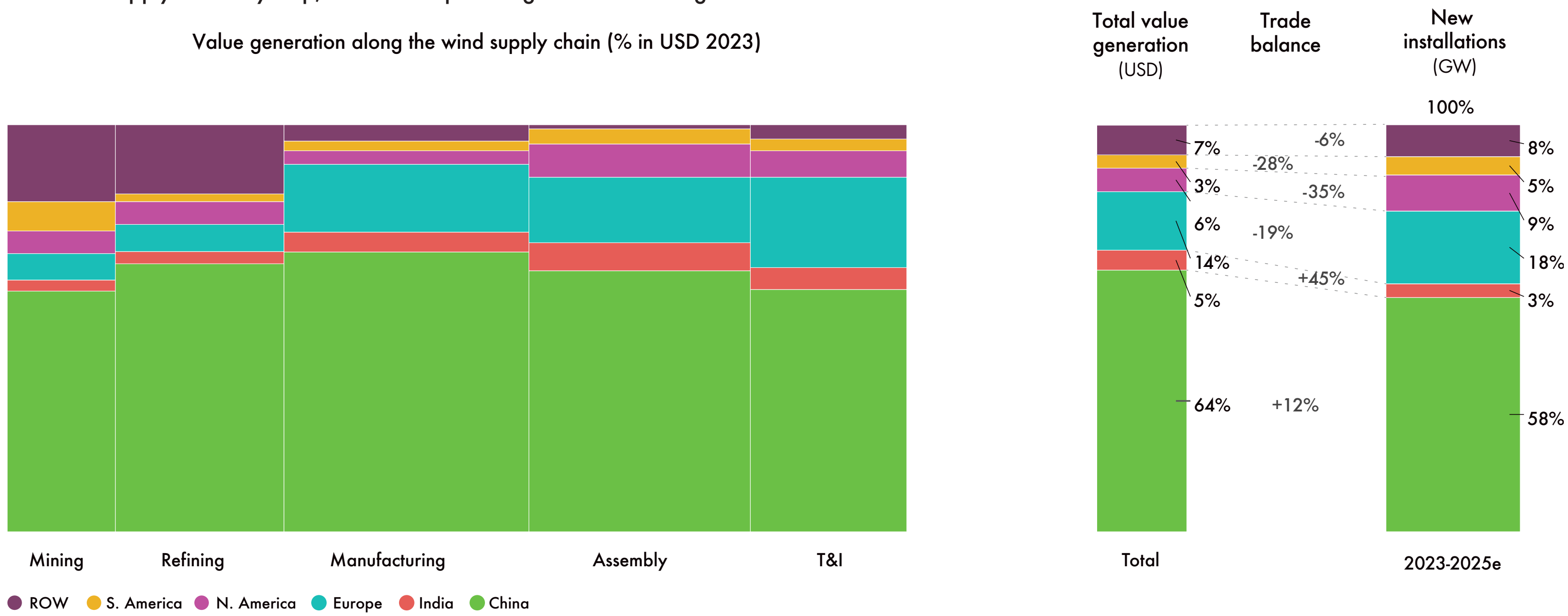
reliant upon imports. Local content may well result in greater supply and demand imbalances – as in the European offshore nacelle assembly sector.

- **Countries or regions with a fragmented footprint** are applying non-price criteria (NPC) in their auctions in order to support local industrial development and supply chain investment, as is increasingly seen in the European and Japanese offshore wind industries.

- **Countries with an at-scale supply chain** try to leverage their cost advantage to make the best use of their production capacity by serving both the domestic and an increasingly diversified export customer base. This approach allows for export orders to be calculated at a marginal price and creates resilience for domestic production, but comes at costs for other players in the market and can prompt protective trade measures.

Resilience strategies generally apply a growing focus on local supply chains. For countries without existing at-scale supply chains this will lead to higher local wind technology costs due to sub-scale production levels and a decoupling of local wind industry from global industry learnings. For countries with an at-scale supply chain there will be a

Value add from supply varies by step; EU and US punching below their weight



Note: Analysis on location of value-add, not nationality of producer. Mining, refining and production split for wind use estimated based on national capacity, sourcing policy and trade patterns, and do not include major Chinese ownership in major mining markets such as Indonesia and Chile. Manufacturing includes sub-suppliers for towers and blades. Assembly includes OEM R&D.

Source: GWEC, IEA, BCG analysis.

high risk of overcapacity, with an adverse impact on both costs and industry margin outlook.

The IRA currently represents a strong example of the use of targeted incentives and industrialisation policy driving supply chain regionalisation in response. Rising US-China trade tensions and a shift of manufacturing capacity into China over the last decade have led to falling US manufacturing capacity of components such as gearboxes and blades. To reduce reliance upon imports and revive domestic manufacturing capacity growth, the IRA provides production-based tax credits for domestic wind component manufacturing such as towers and nacelles, as well as for nacelle assembly. It also provides a demand incentive through a 10% bonus for wind projects meeting domestic content requirements. The full impact of the IRA is still to be seen, but there are signs of a coming industry revitalisation, with at least 11 announcements made recently around wind manufacturing plant capacity expansion.[4]

China has built a strong supply chain, but is also the market with largest annual installations

The wind supply chain in China has benefited from growing annual new installations, allowing scale and experience to advance while driving down costs. The manufacturing footprint is concentrated in a few building hubs capable of supplying other markets.

The depth of value creation at most OEMs has decreased over time, with

4. US Department of Energy: Land-Based Wind Market Report, 2023 Edition.

an increasing focus on core competencies such as design, engineering and assembly. A large part of the wind industry value-add (58%) comes from OEMs' supply chains (Tier 1 and Tier 2 players) and the upstream industry. Around 10-15 years ago, the supply chain was typically in the direct vicinity of the OEM, but over time cost has become more important than proximity. Consequently, many supply chain players have moved some or all of their production to LCCs (Low Cost Countries).

OEMs' assembly and supply chain today are mainly located in China and increasingly India. The relative domestic value-add in the US has declined since 2012 due to a high cost base and a massive drop in new installations after expiry of the Production Tax Credit. However, growth is expected to pick up in the US in this decade, buoyed by incentives in the IRA. Europe has been able to maintain considerable domestic manufacturing capacity through regulatory effort but is heavily reliant upon imported materials, and hampered by slower market expansion.

While China remains the world's main wind installer with approximately 58% of expected global installations, it is currently procuring a 64% share of total industry value.[5] India also has a higher share in domestic value-add (5%) compared with its share in global installations (3%). Given the stated ambitions of Indian conglomerates such as Adani, this surplus is likely to increase. This leaves other regions with an under-proportional value-add in Europe (-4%) and North America (-3%), while the rest of the world has a slight surplus (less than 1%) driven mainly by raw material mining.

Over the last decade, China has built up a scale-driven and backwards-integrated industry through steady market expansion. China has been the strongest example of a growing production wind hub. The new installations in China due to come online by 2025 (comprising around 58% of global new installations) are almost exclusively supplied by domestic players; on top of that, many supply chain players serving global OEMs maintain production lines in China.

Today China is the only market with an almost fully backward integrated wind supply chain serving the domestic and export markets.

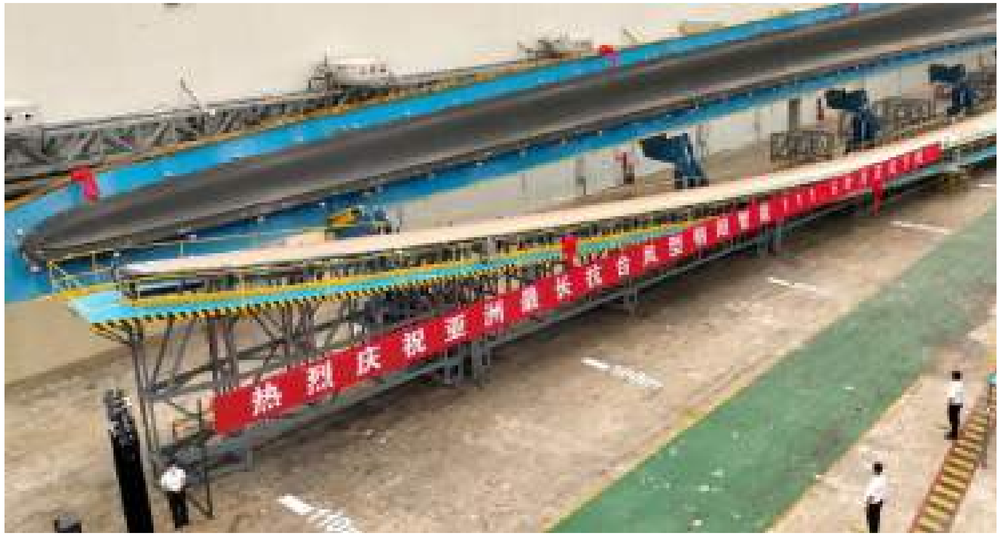
- China has built up its own mining – or secured access to mines elsewhere – for the vast majority of the materials it needs. Excavations are either within China or supported by Chinese investment in regions such as South America, Asia-Pacific or Africa, where reserves are concentrated.

- China has built a leading role in material refining, covering the majority of steel and aluminium as well as the rare earth materials of crucial importance to the wind industry. China dominates the refining of neodymium (100% global market share) and dysprosium (88%), both of which are critical to the manufacture of permanent magnets for wind and difficult to refine due to environmental concerns.

- China has developed an export industry for WTG components. It dominates the manufacturing of gearboxes (80%), wind power converters (82%), wind power generators (73%) and castings capable of supplying wind (82%). The picture is more evenly spread out across markets for tower manufacturing and blades, driven by a combination of active retention policies and logistics.

- China's share of the global market of finished WTGs remains limited but is likely to grow. Out of the 89.9 GW of new global wind installations in 2022, 56.6 GW was produced and assembled in China, according to GWEC Market Intelligence. Of this Chinese production, 88% was made by Chinese OEMs for the domestic Chinese market, less than 0.2% was made by Western OEMs in China for the Chinese market, close to 9% was exported by Western OEMs from China for the global market and less than 3% was exported by Chinese OEMs for the global market. While the absolute number of Chinese turbines exported on an annual basis has grown from 545 MW in 2016 to 1,590 MW in 2022, the relative share of Chinese-produced turbines in the global market remains low. However, taking into account the current scale of Chinese turbine assembly, as well as capabilities in cost control and project expectation, we expect this global market share to grow in this decade.

5. Value add based on estimated share of mining, refining, manufacturing, assembly and services with calculation done based on activity location. Analysis applied to regions (Europe, North America, South America, China, India and Rest of World). Installation outlook covering 2023-2025 GWEC wind forecast (Q2 2023 Outlook).



China is moving from local-for-local to regional-for-global

Although China is a dominant player across the global wind supply chain, the country's initial focus was to ensure it could deliver on its high wind installation ambitions. In the past, Chinese wind turbine OEMs mainly focused on competing with each other for domestic projects.

This has changed over time. In broad terms, the change took place in three phases. In the first phase, global component suppliers built manufacturing sites in China to serve both Chinese OEMs and their traditional customer base. Then, Chinese suppliers began to increasingly qualify as suppliers to the global market, although mainly as component sub-suppliers. Now, we are increasingly seeing Chinese OEMs supplying complete WTGs to overseas markets.

This growing export focus is supported by four independent developments:

- China has built the most modern manufacturing base and many of its manufacturing and assembly sites have favourable access to infrastructure such as roads and ports.
- Developers' buying decisions are to a large extent price-driven, leaving very little room for differentiation. This commoditisation trend first impacted component suppliers and is now increasingly impacting OEMs.
- Growing exports aligns with China's Belt and Road development and lending initiative. Since 2013, it is reported to have supported more than 68 countries, mostly developing, with infrastructure such as roads, ports and grids with the stated goal of achieving stronger connectivity and trade.
- The coming EU energy market reform is introducing frameworks that may impact competitiveness of Chinese turbines in Europe. Under the reform, governments will support projects through Contracts for Difference (CfDs), with all power produced under them sold in the day-ahead markets. European wind projects entering operation now will exit the subsidy scheme after approximately 15 years, when Europe is targeting renewables to achieve a share of more than 60% of the energy mix. This high share of variable renewable energy (VRE) in the merit order markets will lead to higher volatility and very low price capture rates. These will have a negative impact on all renewable generation that needs to sell on the merchant market or wants to secure commercial and industrial (C&I) power purchase agreements (PPAs). With no more 'golden tail' of post-CfD generation, there may be a reassessment of pricing for WTGs, as longer technical lifetimes could be less valuable under this reform. However, the introduction in parallel of non-price criteria in auctions in Europe and other parts of the world will introduce new value factors to WTGs, such as supply chain traceability and ESG assurance, which may also impact competitiveness of Chinese WTGs.

China is also expanding its supply chain, largely to serve the anticipated leap in domestic wind energy growth. Our study has found that the Chinese wind industry is planning to add 17 onshore nacelle assembly plants and 47 offshore nacelle assembly plants in China, compared with a total of 2 onshore and 8 offshore for the rest of the world combined. On the installation side, Chinese installation providers are planning to construct 20 new wind installation vessels compatible with the largest new turbines, compared to a total of 18 for the rest of the world.[6]

6. GWEC: Global Offshore Wind Report, 2023

Looking ahead to 2030

1. The wind supply chain looks different depending on global developments

In order to assess the prospects for the global wind supply chain, we analysed its capacity in the context of net zero and GWEC's current projections under BAU conditions. We also looked at the macro trends that would impact and support the different scenarios. This is critical, since the ability for the global wind supply chain to deliver low-cost capacity at the scale needed for addressing climate change will in the end largely be driven by macro trends and the policies introduced in response.

GWEC's BAU growth forecast indicates wind capacity in 2030 to fall around 650 GW short of what is needed for wind to make its full contribution to a net zero future. In the BAU scenario, the annual installed capacity in MW is almost entirely supplied by growing turbine sizes under existing production capacity. Therefore, no further WTG production capacity would be required to achieve forecast BAU growth.

We would still expect investments into larger equipment for manufacturing and assembly (larger castings, foundations and blades), as well as for installation (cranes and vessels), in order to accommodate the expected growth in turbine platform sizes both onshore and offshore.

The IEA's Net Zero by 2050 scenario would require both larger equipment and greater investment into production capacity to close the 650 GW gap. The prospect of higher growth would provide the critical demand volume to build more regional supply chain centres and improve industry resilience.

It is important to note that industrial policies and the resulting future supply chain dynamics are uncertain. Large markets such as the EU and the US are trying to rebalance value generation in their markets to match the deployment of wind power through a combination of support programmes with a domestic focus and higher import barriers, as well as potential policy coordination via the EU-US Trade and Technology Council. At the same time, China has been expanding its list of restricted renewables-critical materials for export.

Depending on future macro geopolitical and economic trends and policy decisions, the global supply chain environment for wind energy will move towards one of four macro scenarios. Each scenario will have different implications for the wind industry, impacting its ability to deliver on the energy transition and the costs of doing so.

- **Open Door,** where major powers see the benefits of global cooperation based on established norms for trade and build regional supply chains that are competitive and resilient.
- **Increased Barriers,** where domestic investment focus, trade wars, conflicts and alliances lead economies to implement unilateral policies and trade barriers, reducing cross-border supply chain flows.
- **Economic Downturn,** where the world is hit by the severe knock-on effects of an economic downturn with hyper-inflation, defaults and investment dry-up. A global recession and Chinese growth slowing down lead to a supply chain crisis and consolidation.
- **Global Escalation,** where global markets are impacted by territorial, cyber or proxy war conflicts, resulting in powers pushing to restructure influence, fragmenting global supply chains.

While an Open Door scenario would have the highest net-positive climate and wind industry impact, we currently see a higher likelihood for the Increased Barriers scenario to materialise. An Increased Barriers scenario would deliver roughly the level of installations forecast by GWEC under current policies and BAU conditions. It is also likely that elements of the other two scenarios, Economic Downturn and Global Escalation, will resonate in global markets to some extent.

The wind industry must be ready to navigate these scenarios and prepare for growth, while at the same time guarding itself against the adverse effects of an economic downturn and global escalation. To better understand this, we have explained in detail what it means for the wind power supply chain.

1.1. Open Door will deliver larger, resilient supply chains and higher demand for wind power

In an Open Door scenario, growing climate change concerns and wind

Four potential future scenarios impacting supply chain priorities

	Open Door	Increased Barriers	Economic Downturn	Global Escalation
	Push for collaboration facilitates more global approach to ensure resilient supply chainss and strong, stable demand Social and power market transformation delivering against 1.5° target with large global coverage	**More regional crises** lead gov. to focus on short term aids targeting consumers and industry Continued progress towards net zero in developed markets with focus on local production and investment; emerging markets see little progress	**Economic crises** shift focus away from decarbonisation and makes investment into wind challenging Affordability prioritised over sustainability, minimises investments in mitigation; inability to pay cost of adaptation	**International economic and conflict crises** lead to restructured areas of influence; net zero efforts largely cease Availability is highest priority in energy. The world reduces efforts to tackle climate change; rich economies focus on adaptation
Policy	Free trade focus, building multiple price-competitive regions with backward integration	Focus on protecting domestic players and limiting imports; trade conflicts lead to less decarb. focus	Low industrial activity leads to select player support, insolvencies and likely consolidation / mergers	High domestic resilience focus; only larger economies perform well while conflict limits trade
ET focus	Renewable demand growth due to emission taxes and fossil tech phase out; shared standards for trade	More focus on local quick-win solutions and energy flow resilience rather than decarbonisation	Focus on power access and price rather than decarbonisation; less investment into CAPEX-heavy tech	Availability risk from unreliable trade. Chinese mineral restrictions and price uncertainty raise costs

ET = Energy Transition

industry collaboration make major world powers see the value in global cooperation to ensure a rapid, secure and low-cost energy transition.

This will lead global supply chains to deepen, focused on low-cost locations, such as China and India, that can supply fast-growing demand, while efficient capacity utilisation in rising regional hubs will deliver margins that are 3-4 percentage points higher, as well as improved resilience.

As a result, international supply chains combined with cross-border demand stimulation will ensure both more resilient supply chains and a stronger, less volatile demand outlook. We foresee an installation growth increase commensurate with the levels needed for the world to reach its net zero targets. This will be driven by a large increase in the number of turbines, allowing for growth even if better aligned platforms lead to a more moderate growth in turbine size, reaching 9.0 MW on average in 2030, up from 5.2 MW in 2023.[7]

1.2. Increased Barriers will lead to more domestic supply and demand

In an Increased Barriers scenario, the tendency for countries to introduce local content requirements deepens, even in early-stage markets, the US and EU introduce barriers to imports (especially from

7. Turbine scaling following GWEC Wind Turbine Drive Train Outlook 2023-2030

Global developments will impact the wind energy supply chain

	Open Door	Increased Barriers	Economic Downturn	Global Escalation
	Social and power market transformation delivering against 1.5° target with large global coverage	Continued progress towards net zero in developed markets with focus on local production and investment; emerging markets see little progress	Affordability prioritised over sustainability, minimises investments in mitigation; inability to pay cost of adaptation	Availability is highest priority in energy. The world reduces efforts to tackle climate change; rich economies focus on adaptation
Suppiler landscape	Fragmentation – Consolidation Deeper regional and global collab., with open trade policy; long-run consolidation by strongest players	Fragmentation – Consolidation Local content leads to localisation of critical parts, industry fragmentation and low resilience	Fragmentation – Consolidation Low cost, integrated conglomerates dominate; eventual consolidation as governments cannot afford support	Fragmentation – Consolidation Country blocs build own supplier base for all supply chain leading to fragmentation and low learning rate
Market size	Recession – High growth Supply/demand drivers open new markets and grow established ones	Recession – High growth Local market green growth focus; wind competitive with all renewables impacted by local content	Recession – High growth Little CAPEX available for mitigation; more focus on using less CAPEX-heavy fossil infrastructure	Recession – High growth Regions invest in renewables for resilience when best option, if not in tech with best short term business case
Suppiler margins	Low – High Sourcing from cost-efficient hubs with low costs and high capacity utilisation	Low – High Trade barriers lower competitive pressure but low capacity utilisation aggravated by local demand volatility	Low – High Global competition for low volume means low margins; over time, industry consolidates into strong players	Low – High Lack of scale and mainly local sourcing due to wartime policies lead to moderate margins

SC = Supply Chain VC = Value Chain

China), and China potentially expands its list of export-restricted energy transition minerals. As a result, decarbonisation efforts are re-focused towards domestic outcomes in developed markets, while emerging markets see little progress due to cost/supply barriers.

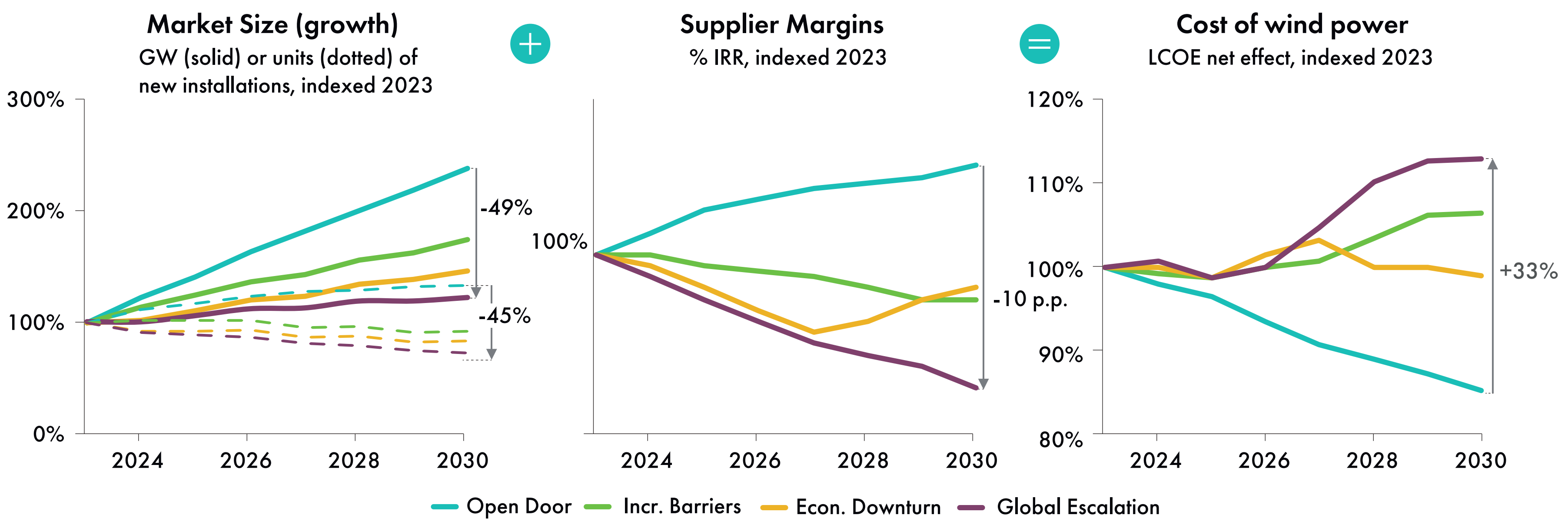
This will lead to greater supply chain regionalisation in response to subsidy conditions and industrial policy packages (e.g. the Inflation Reduction Act in the US), as well as wind growth driven by local demand, with protected margins 1-2 percentage points lower than in the past. Deployment would be policy-based and the industry would experience volatile revenue growth.

This scenario will see prices increase considerably as a result of over-replication of supply chain capacity at scales that would operate at overcapacity, given insufficient demand to cover the expanded supply chain. We foresee wind growth falling 20-25% short of the needs for net zero, following GWEC's BAU outlook and being driven by scaling in turbine size (reaching 9.2 MW average size in 2030) rather than number of installed turbines.

1.3. Economic Downturn will lower demand and lead to industry consolidation

In an Economic Downturn scenario, high inflation and interest rates continue to make investments

Global developments will impact wind market size, sustainable returns and cost curves



challenging, while some markets see hyperinflation and a growth in loan defaults. A global recession spreads and Chinese growth may significantly decline. Energy policy shifts quickly from decarbonisation and energy security towards a low-cost focus. More investment is made into OPEX-driven generation technology where costs can be delayed.

As a result, regional supply chains (including China) will struggle with low demand, leading to industry consolidation that, over time, benefits the survivors. This would drive wind sector margins down by 3-4 percentage points, until consolidation raises them again to a net 1-2 percentage points reduction.

A faltering focus on decarbonisation and reduced access to investments will lead to lower demand. We foresee wind growth to be 25–30% below the needs for net zero, driven by a major slowdown in turbine size scaling (reaching an average size of 8.4 MW in 2030) and a stagnating number of installed turbines per year.

1.4. Global Escalation will halt global trade as well as wind demand growth

In a Global Escalation scenario, growing territorial, cyber or proxy war conflicts in multiple regions lead to a polarisation of markets, with attention shifted from decarbonisation to securing local interests as trade falters and some markets look to expand borders of influence.

We see global supply chains largely collapsing due to lower demand and geopolitical tensions. With less trade, supply chains will be focusing on local, more volatile demand, depressing margins by up to 5-6 percentage points due to uneven capacity utilisation.

In this scenario, demand will focus on solutions to improve resilience while attention will be largely redirected away from decarbonisation. We foresee wind growth falling 30–35% below the needs for net zero, driven by a slowdown in average turbine size scaling (reaching an average of

8.8 MW in 2030) and a decline in the number of turbines installed per year.

2. The wind supply chain can profit from broadening to regional hubs, while maintaining global interlinkages

The wind industry is facing considerable uncertainty but is under pressure to increase its local focus in both the Increased Barriers and Global Escalation scenarios. With today's highly global supply chain, moving towards more regional supply chains will produce two possible outcomes, with the second a much more desirable prospect for the wind industry and society at large.

- A high degree of localisation combined with trade barriers would result in sub-optimal scale, limited flexibility for meeting demand fluctuations and a lack of opportunities for global industry learnings.

- A more regionally distributed supply chain with multiple, strong regions capable of covering the greater part of their own demand – albeit with the continued existence of globalised supply chains to ensure flexibility and competition – producing at similar cost levels and connected through open, mutually beneficial trade. This would avoid heavy reliance upon any market, allowing the creation of efficient regional hubs supporting wind industry growth and allowing more regions to derive value from it. As our study shows, regionalisation will be particularly important for the offshore wind sector, which is affected by annual demand fluctuation and has a higher potential for sharing port and vessel infrastructure for installation and O&M.

3. The supply chain is at risk of bottlenecks

This report has unveiled the potential for large global supply chains to support 2030 net zero targets, but only on the condition that markets are able to efficiently share excess production capacity.

In a future scenario with either trade barriers or an ambition to reach 1.5°C targets, the wind industry will quickly run into major bottlenecks, especially in Europe and North America, where reaching stated targets becomes extremely challenging and a net zero future impossible.

- The raw materials needed for wind include iron, copper and rare earth minerals. All of these are sufficiently abundant today to meet the future demand of a wind industry that only represents a fraction of their end uses. However, there is a concern that the heavy centralisation of mining activity will lead to low resilience. The same applies to refining, where capacity is abundant but heavily centralised in markets such as China, in particular for rare earth materials, where environmental concerns and necessary scale pose a roadblock for other markets.

- Component manufacturing capacity is at risk of undersupply in the coming years. Challenges are particularly high in North America and Europe where manufacturing capacities for iron castings, gearboxes, converters and generators are low and reliant upon imports. Both regions will need to grow their own major manufacturing industries over the coming years to ensure they can meet stated wind targets, with an additional risk for blades, offshore towers and monopile foundations in North America. To meet the demand of a more ambitious future industry, component manufacturing must be scaled up by at least 50% globally by 2030. Markets such as the EU and the US will need even higher growth to meet local demand. It is critical to retain a global flow of components, investments and know-how, since not only current production but also scaling expertise is heavily concentrated in China.

- Nacelle assembly capacity is under pressure in all markets except China and India. This activity is particularly reliant upon attractive financial outlooks for OEMs if critical investments are to be made into future assembly plants. If these additional investments are not made, bottlenecks will form by 2026, especially in the US market for onshore and offshore wind and in Europe for offshore wind. Resolving nacelle assembly supply chain challenges will require addressing the policy and regulatory barriers that are hampering predictability and volume in wind pipelines.

Building out regional supply chains while maintaining global open trade would address these bottleneck challenges and simultaneously support the expansion of wind supply and demand.

CHAPTER 2: DEEP DIVE INTO THE GLOBAL WIND SUPPLY CHAIN

While 2022 saw only 78 GW of new capacity connected worldwide, the market is ready to bounce back in 2023, primarily driven by expected growth in China. Cumulatively, nearly 940 GW of wind power was installed globally by the end of 2022. GWEC Market Intelligence forecast that the 1 TW milestone would be reached in mid-2023.

What is the expected demand in this decade?

Compared with the 2030 global outlook released alongside last year's Global Wind Report, GWEC Market Intelligence has increased its forecast for total wind power capacity additions for 2023–2030 by 143 GW (13% year-on-year). The main reasons behind this upgrade include:

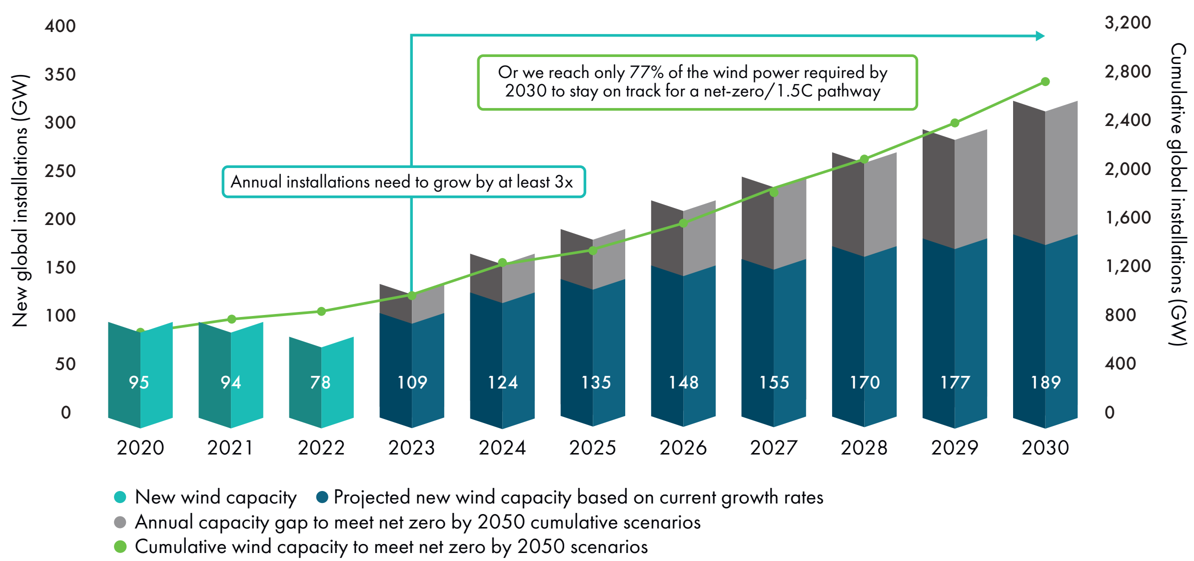
- Energy system reform in Europe, replacing fossil fuels with renewables to achieve energy security in the aftermath of Russia's invasion of Ukraine;
- China's commitment to further expand the role of renewables in its energy mix;
- An anticipated ten-year installation uplift in the US, driven by the passage of the IRA.

Although the revised rate of wind growth is still not rapid enough to enable the world to achieve its Paris Agreement targets or net zero by 2050, GWEC believes the milestone of a second terawatt is likely to be passed before the end of 2030 – provided the anticipated growth materialises in the three key wind markets of China, Europe and the US.

What is the state of the global wind supply chain? Where will there be enough supply chain capacity to feed growth?

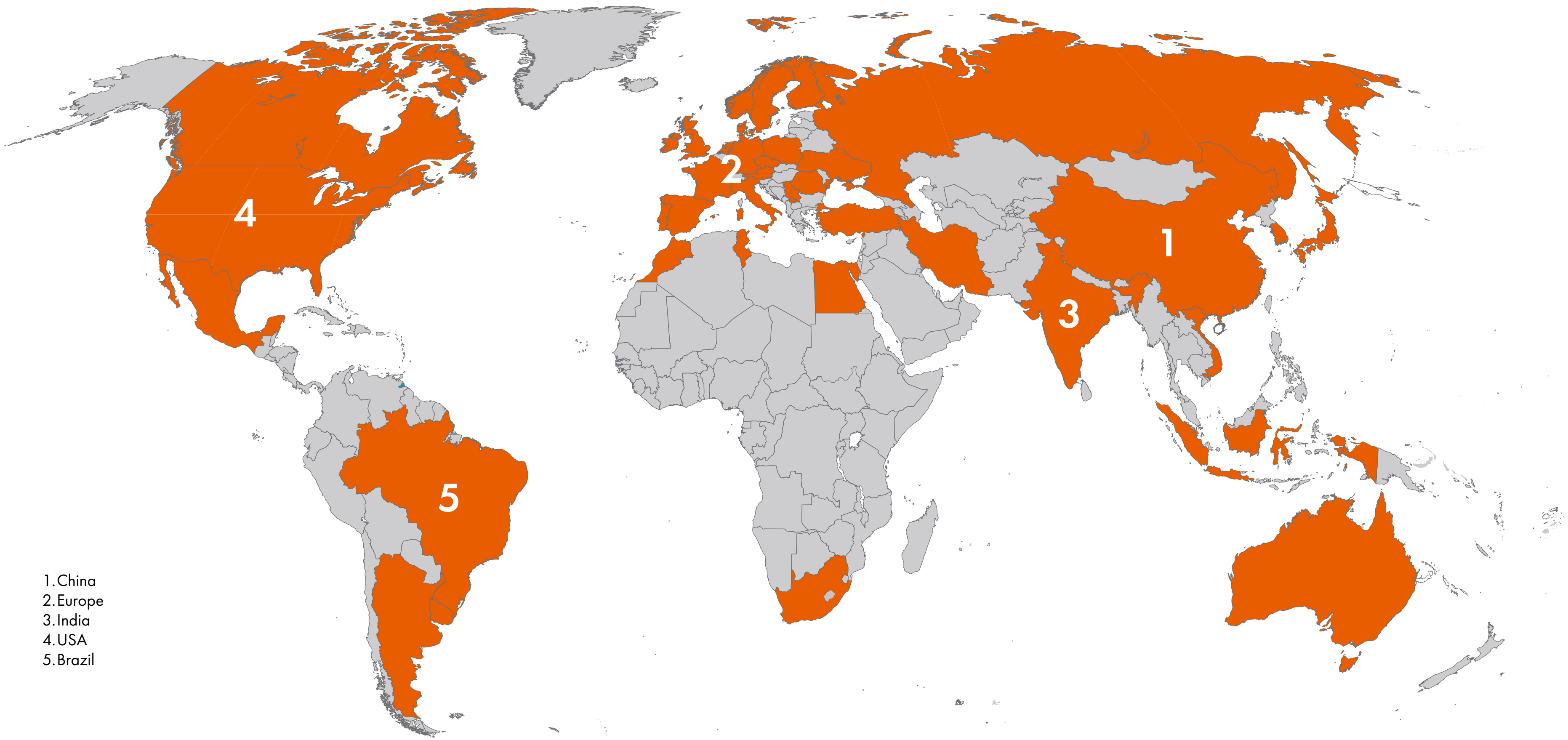
As the birthplace of the wind industry, Europe enjoys a mature supply chain spanning turbine nacelles through to key components and materials. However, since establishing a local wind supply chain in 2008–2010, China has not only become the world's leading wind turbine manufacturing base, but also the largest production hub for key components and materials.

Wind power installations need to triple by 2030 in order to achieve a 1.5°C pathway



Source: GWEC Market Intelligence; IEA Net Zero by 2050 Roadmap (2023); projected new wind capacity from 2023-2030 assumes a ~11.7% CAGR, which is based on GWEC's Q2 2023 Global Outlook; capacity gap figures are estimations based on the IEA Roadmap milestone for 2030. This data represents new and cumulative capacity and does not account for decommissioned projects.

World's top five wind turbine and component production hubs by annual output



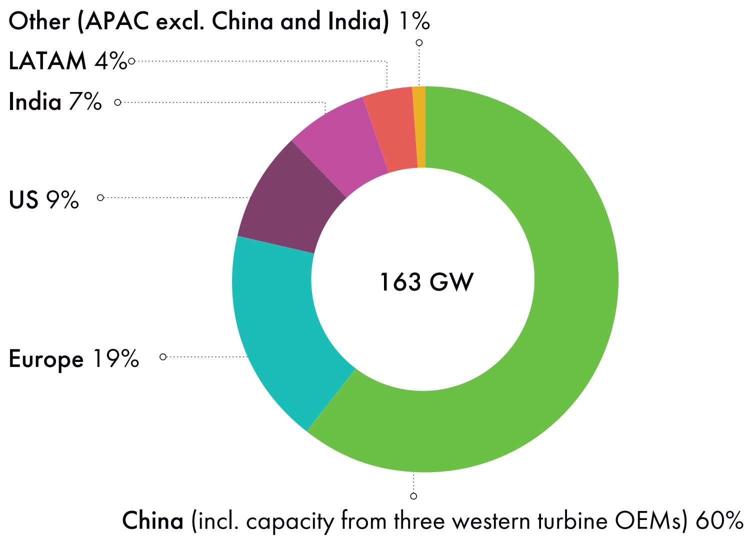
Source: GWEC Market Intelligence, February 2023

Since European and American turbine OEMs decided to diversify their supply chains to ensure security of supply, in the aftermath of the COVID-19 pandemic, India, the second-largest Asia-Pacific (APAC) hub for turbine assembly and key components production, has gained an increasingly prominent role in the global wind supply chain.

While most of the suppliers to the wind industry are still based in APAC, Europe and the Americas, new entrants have also emerged in the Middle East and North Africa (MENA) region.

TURBINE NACELLES

Global wind turbine manufacturing capacity in 2023



Note: Wind turbine manufacturing capacity refers to wind turbine nacelle assembly capability and doesn't represent actual nacelle production in 2023.

Source: GWEC Market Intelligence, February 2023

Globally, there are 153 turbine assembly plants currently in operation, with another 74 facilities either under construction or in the planning stage. China has more than 100 nacelle assembly facilities in operation and another 64 under construction. With a turbine nacelle production capacity of 98 GW per year, the country accounts for 60% of the global market, making it by far the world's dominant turbine nacelle manufacturing hub.

Europe is the world's second-largest turbine nacelle production base, with assembly facilities mainly located in Germany, Denmark, Spain, France, Portugal and Turkey. The US is the world's third-largest wind nacelle manufacturing hub, followed by India and Latin America (LATAM) – primarily Brazil.

Our data shows that 163 GW of nacelle production capacity is available worldwide in 2023. At first glance, the wind industry appears to have enough nacelle assembly capacity to meet the projected global demand up to 2027. However, the picture is different if separate benchmarks are applied for onshore and offshore wind, especially at a regional level.

Challenges in the supply chain for onshore wind nacelles

China dominates global onshore wind turbine nacelle assembly with 82 GW of identified annual capacity. Out of this total, 12 GW is from the three western OEMs: Vestas, SGRE and GE Renewable Energy.

With 21.6 GW of annual assembly capacity per year, Europe is the world's second-largest onshore turbine nacelle production base, followed by the US (13.6 GW), India (11.5 GW) and LATAM (6.2 GW).

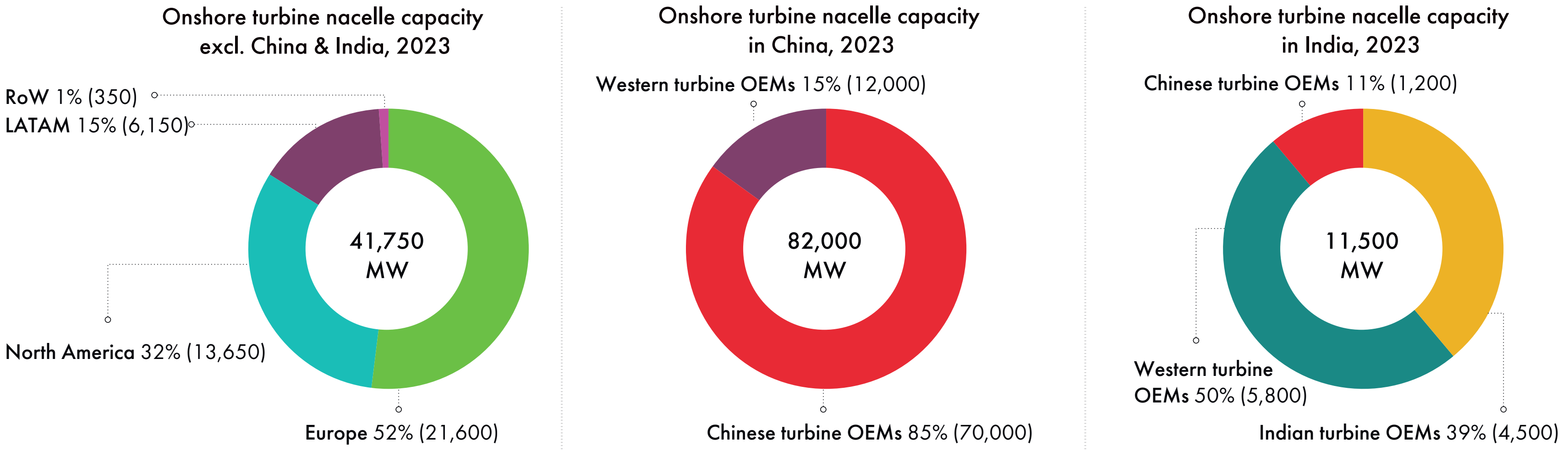
When we compare these production capacities with the onshore wind demand projected for this decade, we conclude that the supply chain in China, India and LATAM will have enough nacelle production capacity to accommodate demand, while the rest of the world, in a business as usual scenario, will continue to rely

Overview of global wind turbine nacelle facilities

	China	Europe	India	USA	LATAM	Asia Pacific	Africa & ME	Total
Total number of nacelle assembly facilities (onshore)	77 (4)*	16	13	4	6	3	1	123
Total number of nacelle assembly facilities (offshore)	20 (1)*	5	0	0	0	4	0	30
Number of announced nacelle assembly facilities (onshore)	17	0	2	0	0	0	0	19
Number of announced nacelle assembly facilities (offshore)	47	1	0	3	0	4	0	55

* facilities owned by western turbine OEMs

Onshore wind demand and supply benchmark, 2023–2031 (MW)



	Demand vs supply analysis 2023-2030 (MW)							
	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
Europe	14500	17700	18900	21000	23300	23500	24000	25000
US	7000	9000	10000	13000	15000	17000	18000	20000
LATAM	5900	5400	5200	5100	5000	5000	5000	5000
China	57000	60000	60000	60000	60000	65000	65000	65000
India	3400	3900	5100	5000	4500	4500	5000	5000
RoW	5600	10100	10100	13200	13400	14000	14300	15000
Global	93400	106100	109300	117300	121200	129000	131300	135000

Source: GWEC Market Intelligence, September 2023

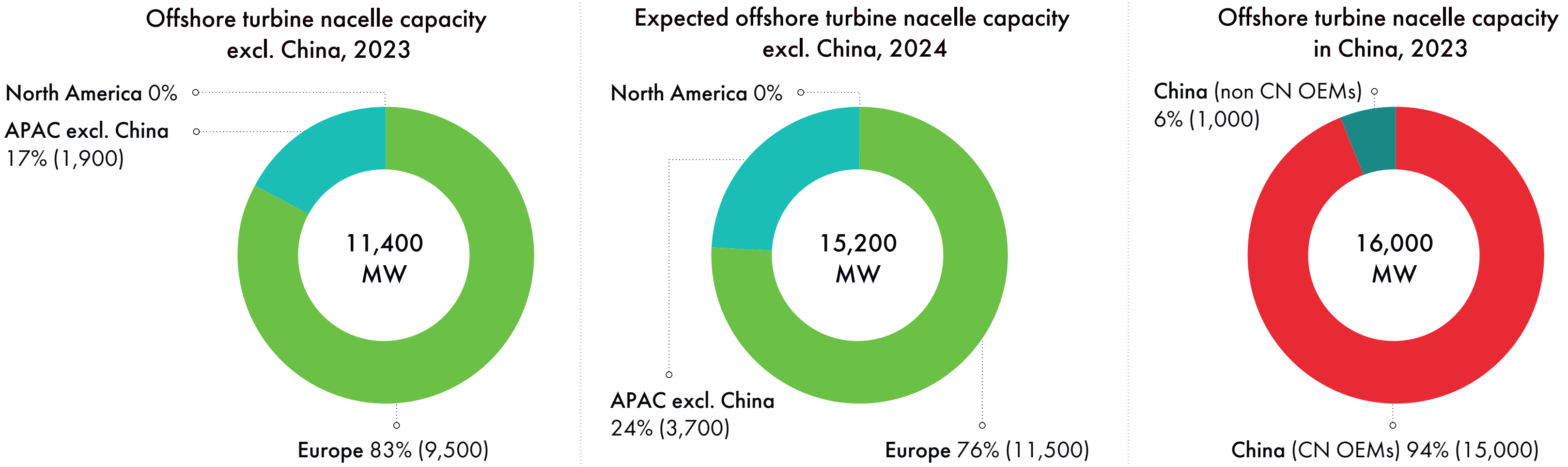
● Sufficient ● Potential bottleneck

on imported wind turbines to cope with the anticipated growth.

For Europe and the US, we expect sufficient supply throughout this decade if western turbine OEMs can smoothly mobilise the capacity they own in China and India. However, if the free flow of the global wind supply chain is interrupted by proposed regional initiatives such as 'Made in Europe' and 'Made in the USA' – and no new nacelle assembly capacity is built at the same time – we expect to see supply chain constraints in both regions by the middle of this decade.

Even assuming that all of the existing nacelle production capacity in Europe and the US can be fully utilised – an unlikely occurrence as buffer room is normally required to ensure the supply and production capacity will be impacted by the introduction of new turbines with greater power rating – we foresee bottlenecks occurring from 2026.

Offshore wind demand and supply benchmark, 2023–2030 (MW)



	Demand vs supply analysis 2023-2030 (MW)							
	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
Europe	5148	2916	6527	9598	10808	16225	20465	26400
China	8000	12000	14000	15000	15000	15000	15000	15000
APAC excl. China	1769	1559	2884	2695	3256	5030	5535	6995
North America	533	955	2335	3535	4500	4500	4500	4500
LATAM	0	0	0	0	0	0	0	1350
Global	15450	17430	25746	30828	33564	40755	45500	54245

Source: GWEC Market Intelligence, September 2023

● Sufficient ● Potential bottleneck

Challenges in the supply chain for offshore wind nacelles

Compared with onshore wind, the supply chain for offshore wind turbines is more concentrated, due to the fact that more than 99% of global offshore wind installed capacity is located in Europe and the APAC region.

China is the world's number-one offshore turbine nacelle production centre, with annual assembly capacity of up to 16 GW, of which 1 GW is owned by one western turbine OEM. Excluding China, the APAC region has an offshore turbine nacelle capacity of 1.9 GW, mainly located in the Taiwan area and South Korea.

In Europe, the current nacelle assembly capacity for offshore wind is about 9.5 GW, with 11.5 GW anticipated next year when a new nacelle facility comes into operation in Eastern Europe.

No offshore turbine nacelle assembly facility is currently in operation in North America, although GE Renewable Energy, SGRE and Vestas announced nacelle investment plans in New York and New Jersey in Q1 2023. Similar to North America, LATAM has no offshore nacelle assembly facilities despite Chinese turbine OEM Mingyang looking for offshore wind investment opportunities in Brazil since 2020.

Looking at the demand and supply situation for this decade, our benchmark results show more challenges for offshore wind than for onshore wind. GWEC Market Intelligence does not see any problems arising in the near term, given that European OEMs are able to share spare offshore nacelle assembly capacity with emerging markets in APAC and North America in 2023–2024.

However, the situation is going to change. Starting in 2026, we expect Europe's existing offshore turbine nacelle assembly capacity to no longer be able to support growth outside of Europe.

In fact, we expect that from 2028 Europe's offshore wind turbine nacelle assembly capacity will struggle to cope with the growth anticipated in Europe alone. Existing capacity needs to double in order to meet the projected demand for this region in 2030.

Looking at APAC (excluding China), although offshore turbine nacelle capacity is likely to increase to 3.7 GW after expansion work is completed at one of the existing facilities in 2024, it will still be insufficient to meet demand in this region from 2027. Taking into account estimates that demand for offshore wind turbines in this region will reach 7 GW in 2030, it is imperative that the investment plans announced by western OEMs in partnership with Japanese and Korean firms materialise in time.

In the US, considering the IRA's domestic content requirements and the two-year lead time needed to build a new offshore wind nacelle production facility from scratch, it is of the utmost urgency that GE Renewable Energy, SGRE and Vestas turn their investment plans into real action.

There are no plans for offshore wind projects to be built in LATAM until the latter part of this decade. However, early investment is needed to avoid bottlenecks. This is especially true of Brazil, where 71 offshore wind projects, totalling more than 170 GW, had filed environmental investigation licences by the end of 2022, according to the country's Ministry of Mines and Energy.

KEY COMPONENTS

Gearboxes

Three types of drivetrain technologies are in use in the wind industry today: the conventional high-speed gear drive, the medium-speed gear drive (or hybrid drive) and direct drive (without gearbox).

Both conventional high-speed wind turbines and medium-speed wind turbines use gearboxes to convert rotational energy into electrical power. The conventional high-speed geared system has been the mainstay of wind turbine technology with a 68.2% market share in 2022, followed by direct drive (22.1%) and hybrid drive (9.7%).

The gearbox is one of the most critical and expensive components of a conventional wind turbine.

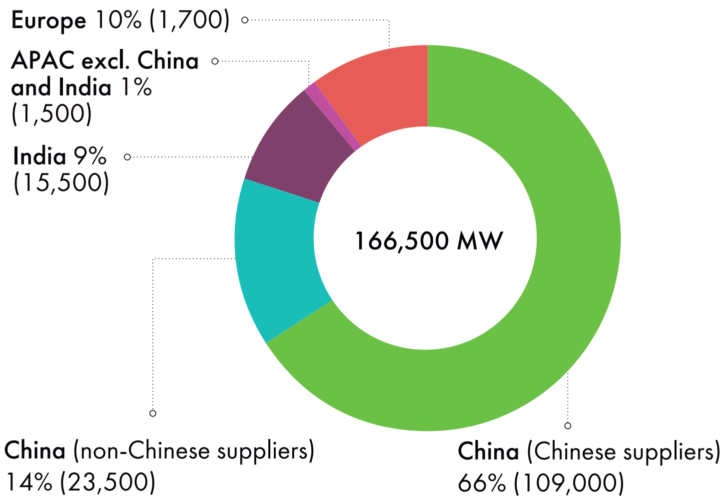
Although the gearbox is not the biggest contributor to wind turbines' overall failure rates, it leads to the most significant downtime experienced by turbine owners once it fails.

Today, there are 18 sizeable turbine gearbox suppliers (including two wind turbine OEMs, SGRE and Envision) active in the global wind supply chain. Based on their announced annual manufacturing capacity, collectively they can provide more than 165 GW of wind gearbox capacity per year.

As for geographical distribution by region, 90% (or 150 GW) of the identified new gearbox manufacturing capacity is located in

Wind gearbox demand and supply benchmark, 2023–2030 (MW)

Global wind gearbox production capacity in 2023



	Gearbox demand vs. supply analysis, 2023-2030 (MW)							
	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
North America	8000	10000	11000	14000	19240	19710	20125	22125
Latin America	5605	5130	4940	4845	4750	4875	4875	5213
Europe	13794	15555	18291	20630	25113	26820	27323	29865
Africa & ME	950	3040	3135	4560	4750	5225	5225	5700
China	51600	63600	65200	66000	66750	72875	74500	74500
India	3400	3900	5100	5000	4500	4750	5250	5500
Other APAC	4161	6587	6446	7998	8304	8562	9286	9898
Total	87510	107812	114112	123033	133407	142817	146584	152800

Source: GWEC Market Intelligence, September 2023

● Sufficient ● Potential bottleneck

APAC, with the remainder (17 GW) in Europe. By country, 80% (or 133 GW) is located in China, of which 82% (109 GW) is owned by Chinese local gearbox producers and the rest (or 24GW) is owned by European manufacturers based in China, followed by India (9%), Germany (6%), Belgium (3%), Spain (1%) and Japan (1%).

are the world's two largest wind gearbox manufacturing bases, so both markets have sufficient capacity to accommodate demand in 2023–2030.

Europe currently has an annual wind gearbox production capacity of 17 GW, which is sufficient for the predicted market growth in the

China and India are the world's two largest wind gearbox manufacturing bases, so both markets have sufficient capacity to accommodate demand in 2023–2030.

Demand and supply analysis

Based on GWEC Market Intelligence's turbine drivetrain outlook, annual global wind gearbox demand will grow from 87.5 GW in 2023 to 152.8 GW in 2030. Collectively, with 166.5 GW of annual wind gearbox manufacturing capacity being available, we don't expect bottlenecks in the global wind gearbox supply chain for the rest of the decade.

However, the situation is different at the regional level. China and India near term (2023–2024). Although European gearbox manufacturers will have huge production capacity available in Asia, deficits are possible from 2025, depending on whether European suppliers such as Flender and ZF will be able to freely move to Europe the wind gearboxes they produce in China and India.

In APAC excluding China and India, only 1.5 GW of gearbox production capacity is available, which is insufficient to cover the growth projection in 2023–2030. Thus,

imports are needed to fill the gap in this region.

In North America, LATAM and Africa & Middle East, no new wind gearbox manufacturing capacity is available, which means that gearbox demand must be entirely satisfied through imports. Bottlenecks will occur if restrictive trade policies and local content requirements come into play.

Generators

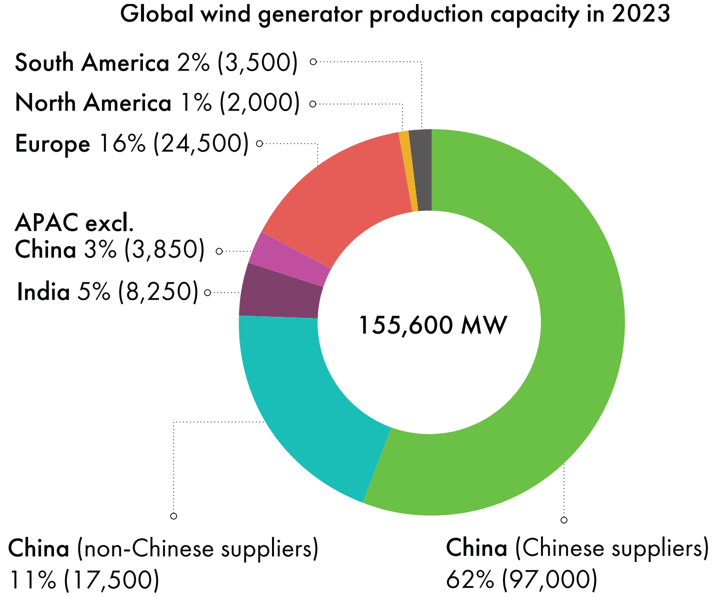
The generator makes up approximately 4-6% of the cost of a conventional turbine and up to 40% of the cost of a direct-drive turbine. The generator is crucial to producing electricity from wind, as it converts mechanical power into electrical power. As key components, generators are both manufactured in-house by wind turbine vendors and sourced from independent generator suppliers (third parties).

Worldwide, 27 turbine generator manufacturers are active in the global wind supply chain, of which 22 are independent generator producers and five are wind turbine OEMs with in-house wind turbine generator production. These 27 suppliers claim to be capable of manufacturing more than 156 GW of wind turbine generator capacity per year.

In terms of regional distribution, 81% (or 127 GW) of the identified wind turbine generator production capacity is located in Asia Pacific, 16% (or 25 GW) in Europe, 2% (or 3.5 GW) in South America and 1% in North America.

By country, 73% (or 115 GW) of the identified wind generator manufacturing capacity is located in China, of which 85% (97 GW) is owned by Chinese local wind generator producers and 15% (18 GW) comes from European OEMs. This makes China the world's largest wind generator manufacturing hub,

Wind generator demand and supply benchmark, 2023–2030 (MW)



	Generator demand vs. supply analysis, 2023-2030 (MW)							
	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
North America	8533	10955	13335	17535	20500	22500	23500	25500
Latin America	5900	5400	5200	5100	5000	5000	5000	6350
Europe	19648	20616	25427	30598	34108	39725	44465	51400
Africa & ME	1000	3200	3300	4800	5000	5500	5500	6000
India	3400	3900	5100	5020	4500	5000	5500	6000
China	65000	72000	74000	75000	75000	80000	80000	80000
Other APAC	5369	7459	8684	10075	10656	12030	12835	13995
Total	108850	123530	135046	148128	154764	169755	176800	189245

Source: GWEC Market Intelligence, September 2023

● Sufficient ● Potential bottleneck

followed by India (5.3%), Germany (4.8%), Finland (4.2%), Vietnam (2.4%), Brazil (2.2%), Spain (1.9%), Serbia (1.9%), Bosnia (1.3%), United States (1.3%), France (1%), Austria (0.6%) and South Korea (0.1%).

Demand and supply analysis

Based on GWEC Market Intelligence's Q2 Global Wind Market Outlook, annual global wind turbine generator demand will grow from 109 GW in 2023 to 189 GW in 2030. Because 156 GW of wind generator manufacturing capacity per year is available at present, we don't expect bottlenecks in the global wind generator supply chain before 2028.

At a regional level, China and India – the world's two largest wind generator manufacturing hubs – have sufficient capacity to accommodate demand in 2023–2030.

In Europe, current annual wind generator production capacity is 24.5 GW, which is sufficient to satisfy the predicted market growth in 2023–2024. As European generator producers have 17.5 GW of wind generator production capacity available in China and 6.5 GW in India, no bottlenecks are expected for Europe from 2025 if they can bring in generators from Asia without any disruptions.

Some wind generator production capacity is available in North America, LATAM and APAC excluding China and India, but the volume identified in each region can only meet 20%, 60% and 70% of their current demand, respectively. These regions, alongside Africa and the Middle East, need imports from China, India and Europe to fill the gap in 2023–2024, and from China and India from 2025 if no new investment is made locally.

Blades

Turbine blades connect to the rotor hub, which then connects to the drivetrain through the main shaft. As the wind blows, this interconnected system converts wind energy into rotational energy. Rotor blades account for approximately 15% of a wind turbine's costs.

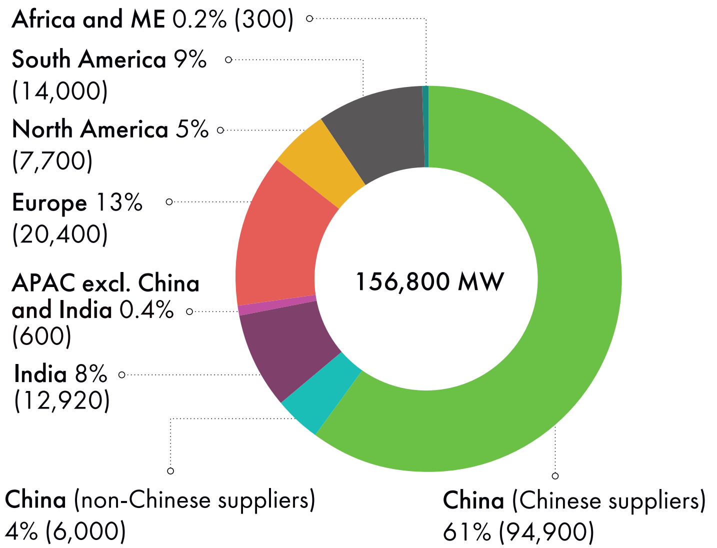
Typically, most utility-scale wind turbines have three blades with an upwind design made of fibre-reinforced epoxy composite material. Other blade options are available, but this symmetrically balanced yet lightweight design allows for smoother and higher energy output.

Thirty turbine rotor blade manufacturers are currently active in the global wind supply chain, of which 16 are independent rotor blade producers and 14 are wind turbine OEMs. Based on their announced annual manufacturing capacity, collectively they can supply 157 GW per year of rotor blade capacity.

In terms of regional distribution, 73% (or 114 GW) of the identified rotor blade production capacity is located in APAC, 13% (or 20 GW) in Europe, 8.9% (or 14 GW) in LATAM, 4.9% (or 7.7 GW) in North America and 0.2% in Africa and the Middle East.

By country, 64% (or 101 GW) of the identified wind blade manufacturing capacity is located in China, of which 94% (95 GW) is owned by Chinese wind blade producers and 6% (6 GW) by European manufacturers. India is the world's largest wind blade manufacturing hub after

Wind blade demand and supply benchmark, 2023–2030 (MW)



	Blade demand vs. supply analysis, 2023-2030 (MW)							
	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
North America	8533	10955	13335	17535	20500	22500	23500	25500
Latin America	5900	5400	5200	5100	5000	5000	5000	6350
Europe	19648	20616	25427	30598	34108	39725	44465	51400
Africa & ME	1000	3200	3300	4800	5000	5500	5500	6000
India	3400	3900	5100	5020	4500	5000	5500	6000
China	65000	72000	74000	75000	75000	80000	80000	80000
Other APAC	5369	7459	8684	10075	10656	12030	12835	13995
Total	108850	123530	135046	148128	154764	169755	176800	189245

Source: GWEC Market Intelligence, September 2023

● Sufficient ● Potential bottleneck

China, with a market share of more than 8%, followed by Denmark (6.4%), Brazil (5.1%), the United States (4.3%), Mexico (3.8%), Turkey (2.7%), Poland (1.9%), France (1.3%) and Canada (0.6%). In addition, some blade manufacturing capacity exists in Morocco and Iran.

Demand and supply analysis

According to GWEC Market Intelligence's Q2 Global Wind Market Outlook, global wind turbine blade demand will grow from 109 GW in 2023 to 155GW in 2027. Worldwide, with 157 GW per year of wind turbine blade manufacturing capacity currently available, we expect no bottlenecks in the global wind blade supply chain between 2023 and 2027. Without further investment, however, a deficit is likely to occur from 2028.

The global supply chain for wind turbine blades is more diversified than that for wind gearboxes and generators, with China accounting for 64% of the global market. Although blade production facilities are available in all regions where wind turbines are expected to be built this decade, bottlenecks are likely to occur in some regions.

China and India are the world's two largest wind turbine blade manufacturing centres, and both markets have sufficient production capacity to cover the predicted demand for the rest of the decade.

Europe's current annual wind blade production capacity is 20.4 GW, which is sufficient to satisfy the predicted market growth in the near term (2023–2024). The ability of European blade producers to meet growth from 2025 will depend on whether they can continue to use their capacity in APAC and LATAM without any supply chain disruptions.

Wind blade production capacity is currently available in North America, LATAM, APAC excluding China and India, and Africa & Middle East. Only LATAM has enough blade production capacity available to accommodate the projected growth, however.

For North America, Africa & Middle East and APAC excluding China and India, today's blade production capacity can only meet 90%, 30% and 11% of their current demand, respectively. To fill the gap during the forecast period, the three regions will need imports from China, India and LATAM. Any trade policy restrictions and supply disruptions are likely to create supply chain bottlenecks in those regions.

Power converter

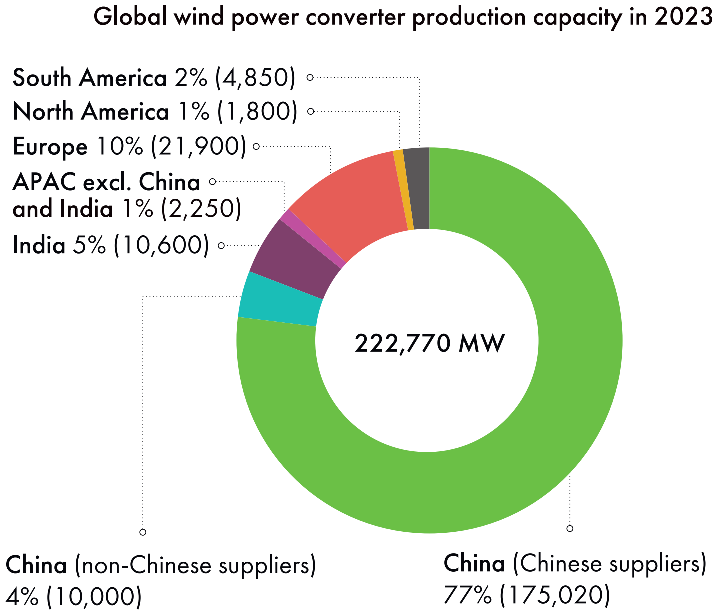
The power converter, which is used as an interface to the grid, is a key component of variable speed wind turbines. It converts the variable generator frequency and voltage of the turbine into a constant frequency and voltage (AC to DC or DC to AC), so that the electrical power generated by the wind turbine can be fed into the grid through the transformer. It accounts for approximately 4-5% of the cost of a conventional turbine.

Globally, 18 wind turbine power converter manufacturers are currently active, of which 14 are independent producers and four are wind turbine OEMs. According to our latest survey, they can produce 226 GW per year of power converter capacity, of which only 14 GW comes from wind turbine OEMs' in-house production.

In terms of regional distribution, 87% (or 198 GW) of the identified power converter production capacity is located in Asia Pacific, 10% (or 22 GW) in Europe, 2% (or 5 GW) in South America, 1% (or 2 GW) in North America. At present, no wind turbine power converter production capacity is identified in Africa & Middle East.

By country, 82% (or 185 GW) of the identified power converter manufacturing capacity is located in China, of which 95% (175 GW) is owned by Chinese power converter producers and 5% (10 GW) by

Power converter demand and supply benchmark, 2023–2030 (MW)



	Power converter demand vs. supply analysis, 2023-2030 (MW)							
	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
North America	8533	10955	13335	17535	20500	22500	23500	25500
Latin America	5900	5400	5200	5100	5000	5000	5000	6350
Europe	19648	20616	25427	30598	34108	39725	44465	51400
Africa & ME	1000	3200	3300	4800	5000	5500	5500	6000
INDIA	3400	3900	5100	5020	4500	5000	5500	6000
China	65000	72000	74000	75000	75000	80000	80000	80000
Other APAC	5369	7459	8684	10075	10656	12030	12835	13995
Total	108850	123530	135046	148128	154764	169755	176800	189245

Source: GWEC Market Intelligence, CWEA, Brinckmann, September 2023

● Sufficient ● Potential bottleneck

European manufacturers based in China. India is the world's second-largest power converter manufacturing base, with more than 10 GW of annual production capacity (or 5% global market share), followed by Denmark (9.5 GW or 4%), Germany (5.5 GW or 2%), Spain (5.5GW or 2%), Brazil (4.9 GW or 2%) and the US (1.8 GW or 1%).

Demand and supply analysis

GWEC Market Intelligence's Q2 Global Wind Market Outlook predicts that the global power converter market will grow from 109 GW in 2023 to 189 GW in 2030. Globally, more than 220 GW of annual power converter manufacturing capacity is available at present. In principle, no bottlenecks are expected for power converters for the rest of the decade.

Although existing power converter production capacity is able to accommodate global growth even beyond 2030, the situation is different at the regional level. Bottlenecks are likely to occur if the global supply chain flow is interrupted by trade policy restrictions and local content requirements.

China is the world's largest wind turbine power converter manufacturing centre with a current production capacity of nearly three times the current local demand. In India, annual power converter production capacity is close to 11 GW, which is also three times higher than its current demand. Therefore, we believe the two markets have enough capacity to cover their demand in 2023–2030.

Current power converter production capacity in Europe is 22 GW, which is sufficient to cope with the predicted market growth in 2023–2024. If European OEMs can mobilise their power converter capacity located in China and India, capacity will be enough to cope with growth in Europe up to 2027. However, a deficit is expected in Europe from 2028 unless further investment is made or European OEMs outsource power converters to China-based third-party suppliers.

Although power converter production capacity is available in North America, LATAM and APAC excluding China and India, it is insufficient to meet the predicted market growth in each region during the forecast period.

To fill the gap, there are two options: one is to invest more – an unrealistic prospect under current supply chain challenges including high inflation, high interest rates and low margins; another is for all regions to import power converters from China and India. Any trade policy restrictions and supply disruptions are likely to create supply chain constraints in those regions.

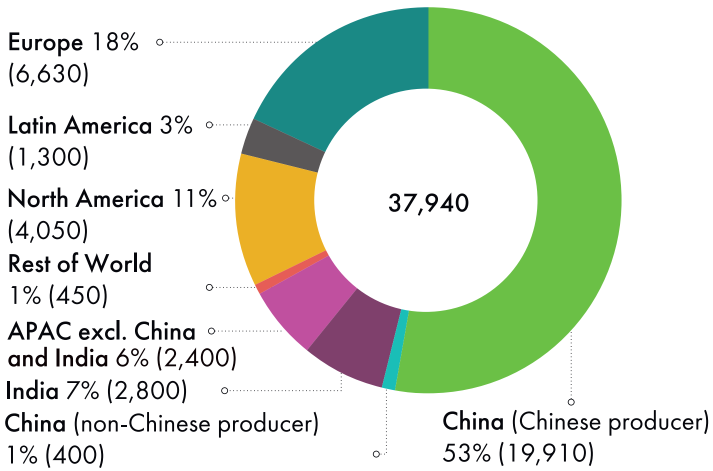
Towers

As the base of a wind turbine, the tower is an independent component that accounts for approximately 20% of the turbine cost, making it one of the most expensive components. Because its technical requirements are comparatively low, the tower is normally the first component that turbine vendors try to source locally. Towers, can be made of three materials: steel, concrete and wood. They do not need to be assembled together with other turbine components until installation.

Greater diversification in the supply chain

Worldwide, there are more than 50 wind tower suppliers. Together, they can produce nearly 38,000 towers per year – 90% (34,000 towers) for onshore wind and the rest (nearly 4,000 towers) for offshore wind.

Total global onshore and offshore wind tower production capacity in 2023 (units/year)



Source: CWEA, Brinckmann, September 2023

According to GWEC Market Intelligence's latest survey, China can produce around 20,000 units of wind towers per year, accounting for 54% of the global market. Although China is the global leader, the global supply chain for towers is more diversified than for other key components.

In terms of annual output, Europe is the second largest wind tower production base, with a global market share of 18%, followed by North America, India, the APAC region excluding China and India, LATAM and Africa & ME.

Tower demand and supply analysis

To produce a demand and supply benchmark for towers, GWEC Market Intelligence converted its Q2 2023 Global Wind Market Outlook for towers from MWs into a number of units. For offshore wind, the conversion is based on the project pipeline we have identified for each market. In many cases, developers announce the turbine models for their offshore wind projects several years ahead of construction. For onshore wind, the conversion is based on the average turbine size estimated for the key markets and each region.

Challenges in the supply chain for onshore wind towers

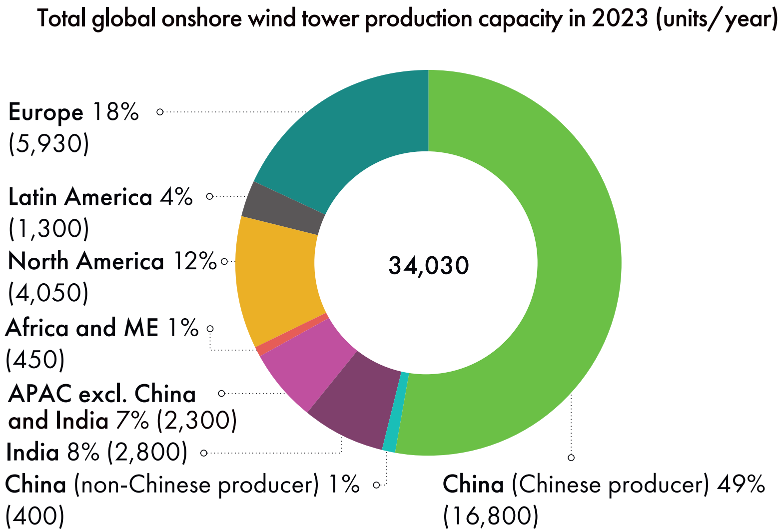
Globally, more than 34,000 units of onshore wind towers are available today, and another 4,450 units are expected by 2026 according to the plans disclosed by tower producers.

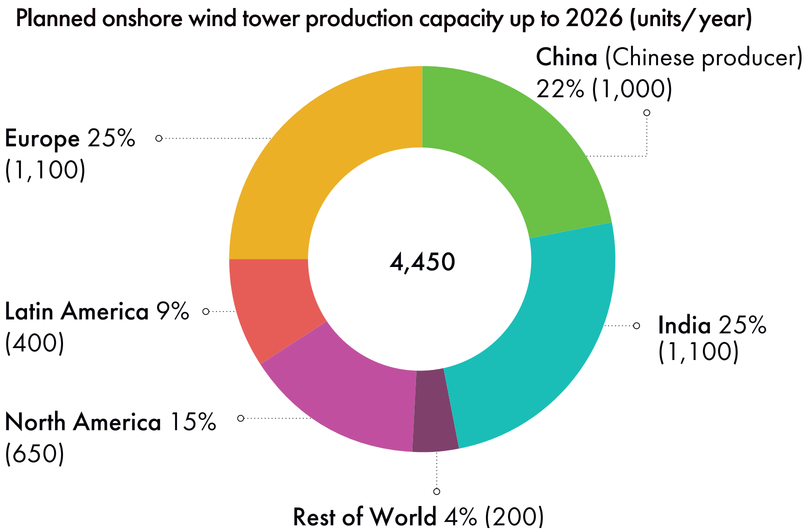
The onshore wind tower demand and supply benchmark shows that the wind industry appears to have enough onshore wind towers to meet the projected global demand up to 2030 in all regions except Africa and the Middle East.

The current production capacity for onshore wind towers in Africa & ME is 450 units per year, which is enough to cope with the growth in 2023. Although 200 towers are expected to be added in this region by 2026, we expect a bottleneck when growth in this region resumes from 2024.

Given that there is a surplus of onshore wind towers outside this region and no trade restrictions in place for imported wind components, we believe the gap can be easily covered.

Demand and supply side benchmark, onshore wind towers, 2023–2030





	Demand and supply side benchmark, onshore wind towers, 2023–2030 (units)							
	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
North America	2286	2222	2444	2800	3200	3273	3167	3500
Latin America	1311	1080	1040	927	909	833	833	769
Europe	3222	3540	3780	4200	4236	4273	4000	3846
Africa & ME	250	711	733	960	1000	1000	917	923
India	1360	1418	1700	1538	1286	1200	1250	1111
China	11400	10909	10000	9231	8571	8667	8125	7647
Other APAC	800	1180	1160	1345	1345	1250	1300	1231
Total	20629	21061	20858	21002	20548	20495	19592	19027

Source: GWEC Market Intelligence, CWEA, Brinckmann, Sepetember 2023

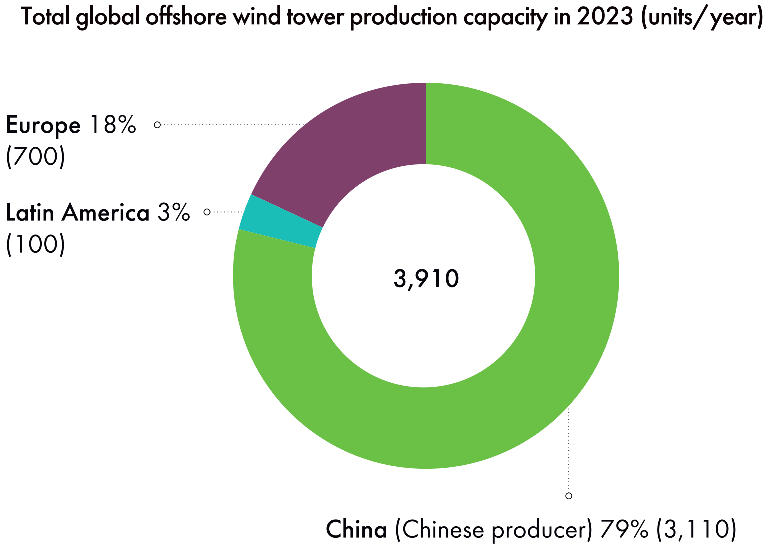
● Sufficient ● Potential bottleneck

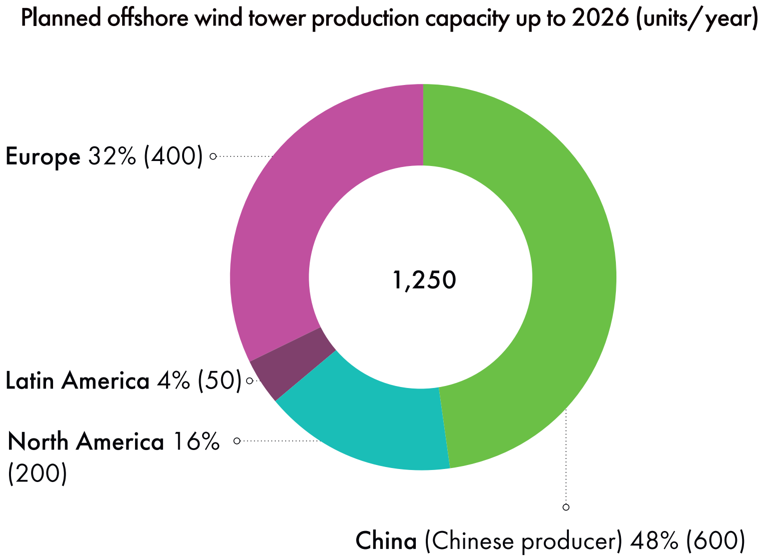
Challenges in the supply chain for offshore wind towers

The global supply chain for offshore wind towers looks more challenging than that for onshore wind. Bottlenecks are likely to appear in all regions aside from China.

In Europe, annual production capacity for offshore wind towers is currently about 700 units, which is enough to accommodate demand in 2023–2025. However, offshore wind tower demand is expected to surpass current annual production output from 2026. While the potential bottlenecks predicted for 2026 and 2027 can be addressed if the announced production plans for this region – an extra 400 units/year –materialise on time, a deficit is still expected from 2028, when offshore wind tower demand is expected to exceed 1,100 units.

Demand and supply side benchmark, offshore wind towers, 2023–2030





	Offshore wind tower demand vs. supply analysis, 2023-2030 (units)							
	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
Europe	520	259	559	760	761	1147	1436	1821
China	889	1,263	1436	1364	1250	1154	1071	1000
India	0	0	0	2	0	34	34	68
APAC ex. China & India	241	231	263	240	285	334	363	422
North America	42	74	194	294	339	308	306	302
LATAM	0	0	0	0	0	0	0	108
Africa & ME	0	0	0	0	0	0	0	0
Total	1692	1827	2452	2660	2635	2977	3210	3721

Source: GWEC Market Intelligence, CWEA, Brinckmann, September 2023

● Sufficient ● Potential bottleneck

In the APAC region excluding China and India, 100 offshore wind tower units are currently available, which can only meet less than half of the demand predicted for this region.

Currently, no offshore wind tower production capacity is available in North America, LATAM and India. Bottlenecks are expected if the current flow of the global supply chain is interrupted by restrictive trade policy and no new investment is made locally.

It is worth highlighting that building a new offshore wind tower facility requires a coastal location with significant laydown areas (>150,000m²) and takes at least three years, depending on the permitting process for the production site.

Castings

Castings play a key role in assembling and operating a wind turbine. As the wind turns them, the rotor blades transfer severe fatigue loads to the casted components and then to the wind tower. Through the rotor hub to the drivetrain and the nacelle bed frame, a wind turbine demands several castings, including rotor hub, main frame, gearbox housing, main shafts and bearings housing.

Spheroidal Graphite Cast Iron EN-GJS-400-18-LT, also known as ductile iron, is the preferred casting material in the megawatt-dominated wind turbine industry. Other material grades from GJS-500 and up to GJS-700 are also in use, but all have the same basic properties as ductile iron.

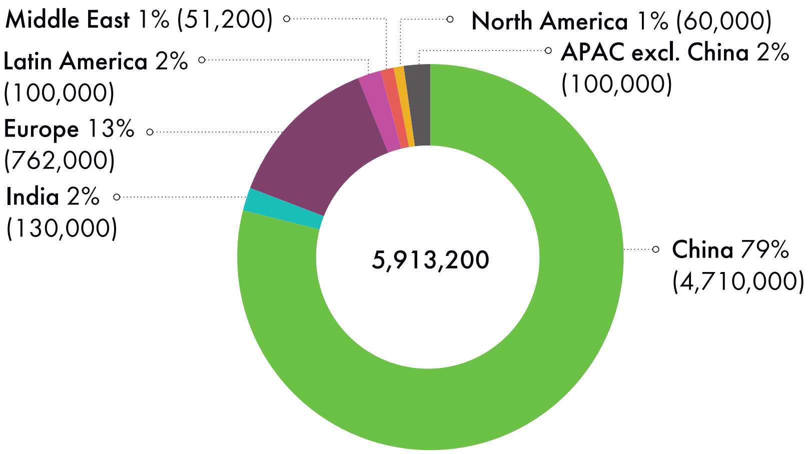
Because of its higher carbon and silicon content, ductile iron has greater fluidity and less shrinkage compared with other materials and, therefore, offers superior fatigue properties. Moreover, ductile iron has higher yield strength, is abrasive and corrosion resistant, as well as better at shock absorption.

As a traditional industry with non-automated technology and low annual production volumes scattered across several foundries in Europe, China and India, the casting industry would benefit from heavy CAPEX investments for the future. This is limited by today's focus on LCOE and price, however.

Traditionally, foundries have acted as tier 2 or tier 3 suppliers, letting the machining supply base be the OEM interface. Several large wind turbine OEMs typically owned their own in-house foundries and machine shops in the past, but this is now limited to a few OEMs such as Dongfang and Suzlon. Currently the

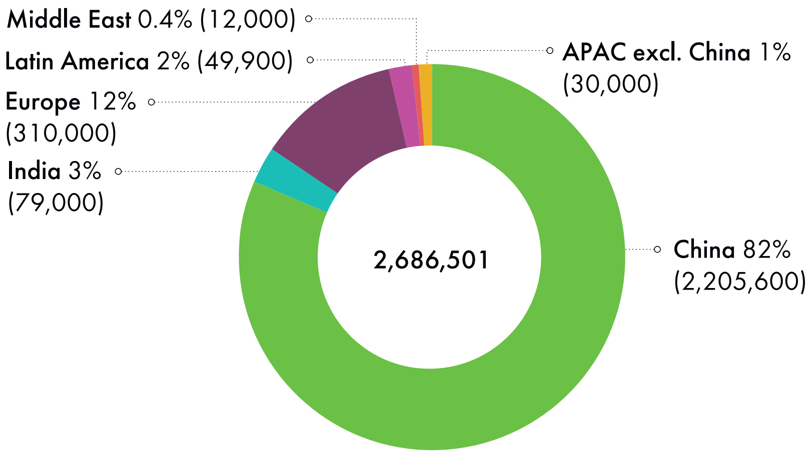
Total global casting capacity vs. total global casting capacity allocated to the wind industry in 2023

Total global castings capacity in 2023 (tonnes/year)



Source: GWEC Market Intelligence, company inputs, September 2023

Total global wind castings capacity in 2023 (tonnes/year)



Source: GWEC Market Intelligence, company inputs, September 2023 inflow is handled through known independent suppliers globally.

China dominates the global wind castings supply chain

Based on a survey completed in Q3 2023, foundries capable of producing casted items weighing more than two tonnes have a global annual production capacity of nearly six million tonnes of ductile iron castings.

Worldwide, around 60 castings suppliers are currently serving the wind industry. Annual wind castings production capacity is 2.7 million tonnes. Asia Pacific has the world's largest wind castings manufacturing base in terms of annual output and total number of suppliers – as well as the lowest cost. Since casted components are 'built-to-print' products with lower barriers for market entry, the rapid growth of the Chinese wind market from 2006 has motivated many local Chinese suppliers to invest in this sector.

China has more than 40 foundries in operation today. With an annual wind production capacity of 2.2 million tonnes, it accounts for 82% of the global market, making it the world's dominant supplier for wind castings.

Europe is the world's second largest wind castings production base, with foundries primarily located in Germany, Spain, Denmark, France and Sweden. India is next, with a global market share of nearly 3%, followed by LATAM, mainly Brazil, and APAC excluding China and India – mainly in the Chinese Taiwan area.

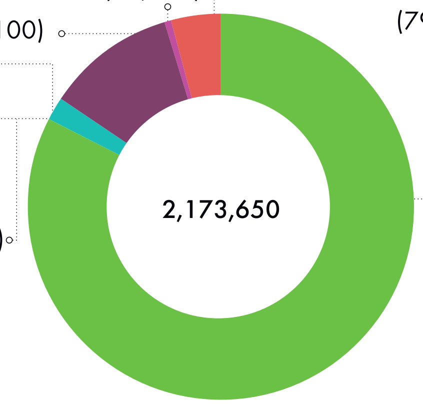
Some casting production capacity is present in North America, but the region only has a small number of foundries and none dedicated to the wind industry.

Castings demand and supply analysis

To work out the total global demand for castings, we first need to estimate the weight of casted components

Demand and supply side benchmark, onshore wind castings, 2023–2030

Total global onshore wind castings capacity in 2023 (tonnes/year)



	Onshore wind castings demand vs. supply analysis, 2023-2030 (tonnes)								
	2022	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
North America	116,730	97,275	121,594	133,753	170,231	194,550	218,869	231,028	255,347
Latin America	62,013	71,740	65,661	63,229	62,013	60,797	60,797	60,797	60,797
Europe	203,061	176,311	215,221	229,812	255,347	283,313	285,745	291,825	303,984
Africa & Middle East	8,512	12,159	38,910	40,126	58,365	60,797	66,876	66,876	72,956
India	23,103	41,342	47,422	62,013	60,797	54,717	54,717	60,797	60,797
China	396,395	693,084	729,562	729,562	729,562	729,562	790,359	790,359	790,359
Other APAC	30,398	43,774	71,740	70,524	89,979	89,979	91,195	94,843	97,275
Total	840,212	1,135,684	1,290,108	1,329,018	1,426,293	1,473,715	1,568,558	1,596,524	1,641,514

Source: GWEC Market Intelligence, September 2023

● Sufficient ● Potential bottleneck

used in wind turbines. Mainstream onshore and offshore wind products offered by three of the world's largest suppliers have been selected as samples. According to analysis by castings supply chain experts, the average weight of castings is 12.2 t/MW for onshore wind turbines and 17.7 t/MW for offshore wind turbines. Based on GWEC Market Intelligence's Q2 2023 Global Wind Market Outlook, global castings demand for onshore and offshore wind castings in 2023-2030 is calculated.

Challenges in the supply chain for onshore wind castings

Globally, more than 2.1 million tonnes of onshore wind castings are available in 2023. The wind industry appears to have sufficient capacity to meet the projected global demand for onshore wind castings up to 2030.

However, the picture is different if separate demand and supply benchmarks are applied at the regional level. We expect onshore wind castings capacity to be sufficient to accommodate the growth in China and India. The capacity available for onshore wind in Europe is sufficient to cover the demand up to 2025, but shortages are likely to occur from 2026 if no extra castings capacity is allocated to onshore wind.

In addition, supply chain constraints are likely to occur in North America, LATAM, other APAC and Africa & the Middle East due to either insufficient supply or no capacity allocated to wind in those regions.

As China has significant excess capacity in onshore wind casting, we believe that bottlenecks outside of China can be solved if the current free flow of the global wind supply chain is retained.

Challenges in the supply chain for offshore wind castings

As northern Europe is the birthplace of offshore wind, in the early days most casting suppliers for this sector came from Germany and the Nordic countries. Driven by a desire to reduce LCOE and the takeoff of the offshore wind market in China, the wind castings supply chain has also shifted from Europe to China.

Globally, offshore wind only accounts for less than 15% of annual wind power installations. In parallel, only 19% of the identified capacity for wind castings in 2023 is for offshore wind.

Compared with onshore wind, the castings supply chain for offshore wind looks more challenging. Worldwide, half a million tonnes of castings are available for offshore wind at present. This is only enough to cope with the global market growth up to 2025.

As the minimum lead time to build a large foundry capable of covering the offshore wind industry is two years – and often longer depending on the permitting process – additional capacity for offshore wind castings needs to start being built next year to avoid future bottlenecks.

On the regional level, there may be supply chain bottlenecks in every region of the world except China. In the short term (2023–2024), demand for castings from offshore wind in the APAC region excluding China and India is expected to be met by a large local foundry, but new capacity from this foundry has to be allocated to offshore wind from 2025 to cover the gap.

In Europe, following offshore wind growth, casting demand has recently surpassed supply. At present, there is no identified casting capacity available for offshore wind in North America, LATAM and India.

As turbines with power ratings greater than 10 MW have become the norm for offshore wind, the investment needed for a new foundry to produce large castings for offshore wind is around $100 million. Since the global wind supply chain is suffering from challenges such as high inflation and increased interest rates, it is unlikely that investments of this scale will be made by non-Chinese foundries in either Europe or other regions in the short term.

The growing demand for larger castings in turn narrows the supply base that is capable of manufacturing them. Volatility in the wind market, relatively small annual volumes and profit pressures on OEMs are reducing long-term investments and the prospects for future supply of large castings for the whole industry.

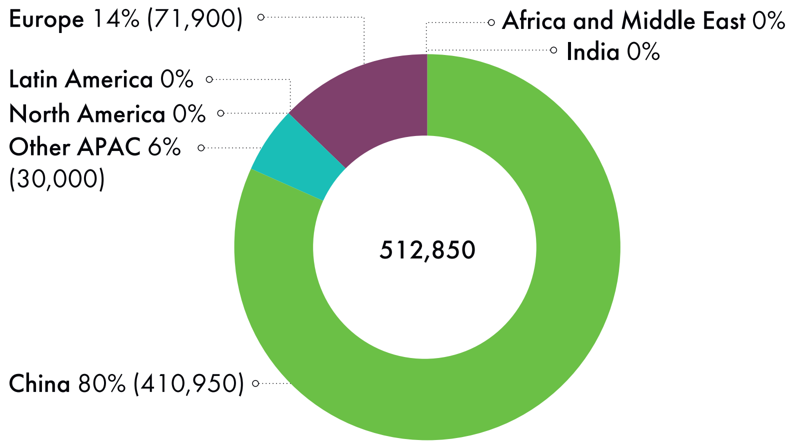
Environmental concerns may also prevent foundries from investing in new and large facilities. Melting metal is an energy-intensive process that generates significant amounts of CO_2 emissions. Strict environmental permitting requirements in regions such as Europe and North America are likely to pose a major challenge for foundry expansion.

It is essential that we have in place trade policies that ensure the free flow of the global wind supply chain in order to achieve the correct balance and avoid interruptions.

China is currently the only market with a surplus for offshore wind castings, but its spare capacity is not enough to fill the gap predicted for the global offshore wind market outside of China from 2026. New and timely investment is needed to avoid major bottlenecks in global offshore wind deployment.

Demand and supply side benchmark, offshore wind castings, 2023–2030

Total global offshore wind castings capacity in 2023 (tonnes/year)



	Offshore wind tower demand vs. supply analysis, 2023-2030 (tonnes)								
	2022	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
North America	-	9,438	16,911	41,348	62,598	79,686	79,686	79,686	79,686
Latin America	-	-	-	-	-	-	-	-	23,906
Europe	43,562	91,161	51,637	115,581	169,962	191,389	287,314	362,396	467,493
Africa & Middle East	-	-	-	-	-	-	-	-	-
India	-	-	-	-	354	-	8,854	8,854	17,708
China	89,461	141,665	212,497	247,913	265,621	265,621	265,621	265,621	265,621
Other APAC	22,294	31,326	27,607	51,070	47,369	57,658	80,218	89,160	106,160
Total	155,318	273,590	308,652	455,912	545,905	594,354	721,693	805,718	960,575

Source: GWEC Market Intelligence, September 2023

● Sufficient ● Potential bottleneck

KEY MATERIALS

Rare earth materials

Meeting the increasingly ambitious wind energy targets arising from a growing desire to reduce reliance on traditional energy sources – both in terms of geographical and material dependence – presents a challenge from a supply chain perspective. This is particularly true for rare earths, with top policymakers increasingly eager to de-risk the supply chain away from China.

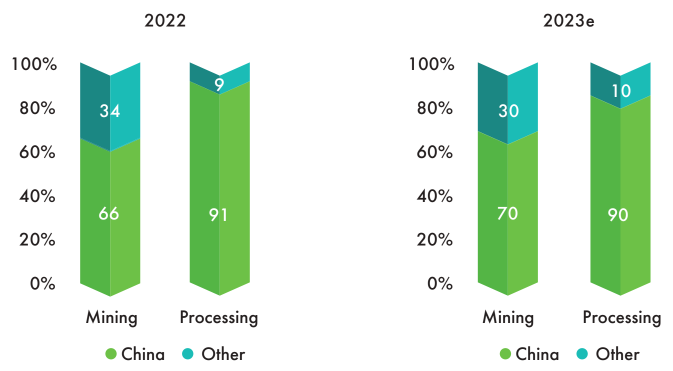
Wind energy OEMs have been struggling to obtain the large amounts of Rare Earth Permanent Magnets (REPMs) they need. This is despite supply growing at record speed and demand softening thanks to 'hybrid' wind energy technologies increasingly replacing standard direct drive (DD) turbines over the past five years. Hybrid systems (medium-speed drivetrains) use just one-tenth of the REPMs needed in a DD drivetrain. But even with reduced REPM demand, sourcing materials from non-China sources remains a challenge.

In major markets such as Europe, the US and Australia, demand for REPMs in wind energy is substantially larger than local supply. The vast majority of non-China REPM sources – both existing and incoming – operate on the fourth quartile of the REPM production cost curve, meaning that their economic incentives are lower than those for Chinese producers.

Chinese REPM producers are supported by low energy costs and energy subsidies from local governments seeking to attract more industrial production, as well as VAT rebates on purchased feedstock. Feedstock procurement often represents more than 90% of the total REPM production cost. Thanks to government support for an already low-cost REPM manufacturing hub, Chinese producers in Zhejiang and Baotou dominate REPM price dynamics through the large amounts they are able to produce.

E-mobility is a major driver of REPM demand, which is estimated to have grown 22.5% CAGR from 2018 to 2023 for this end use. Benchmark estimates that REPM for wind energy consumption will account for no more than 7% of total REPM demand in 2023, growing at the average rate of other demand applications to retain the same market share by 2026.

Estimated share of rare earth materials mined and processed by China and the rest of the world in 2022 and 2023



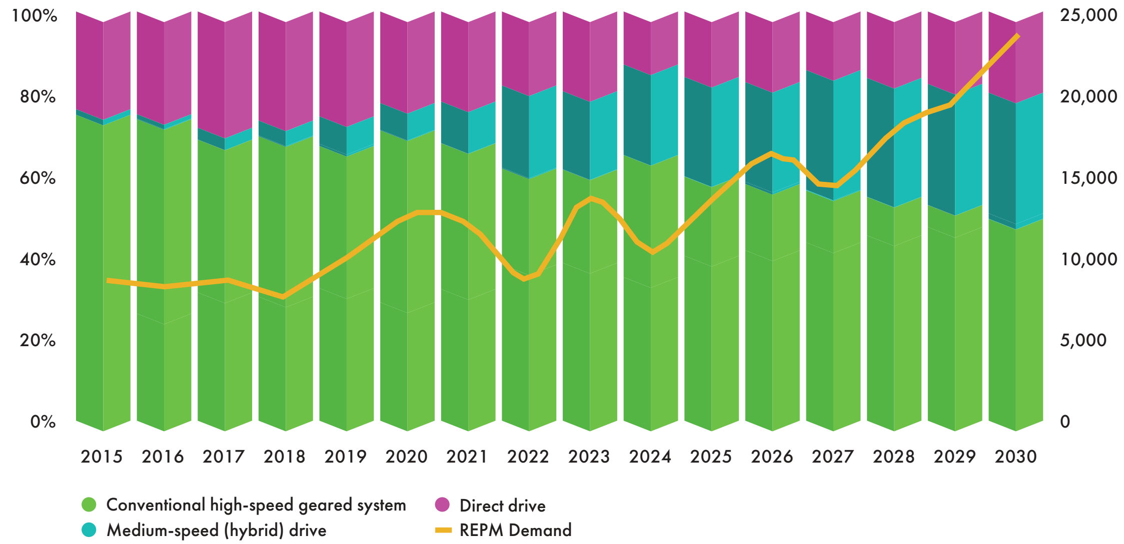
Source: Benchmark

The demand outlook for REPMs in Europe differs significantly from that in other regions. Our data shows European REPM demand in the wind energy sector is growing rapidly, largely driven by offshore installations. Over the 2023–2030 period, annualised REPM demand in Europe is forecast to reach 23% CAGR for offshore installations, and 14% CAGR for onshore, with Europe likely to account for around 55% of global REPM demand in the wind energy sector.

Over the same period, there is a tentative expectation that rare earth mining in Europe could deliver first volumes by 2027, albeit from only a handful of reliable producers and with modest capacity figures. European wind manufacturers will therefore have to rely on a global supply chain to satisfy their REPM needs.

The opposite is true of China. Although Chinese producers dominate rare earth mining and

GWEC wind turbine technology forecast (%) and equivalent REPM consumption (tonnes)



Note: This chart displays direct REPM use (magnent volumes) in DD and medium-speed drivetrains per annum. it is not normalised to final raw materials demand.
Source: Benchmark, GWEC

processing – and REPM manufacturing – REPM demand for wind energy is expected to drop substantially as a result of the cost-driven shift from direct drive to medium-speed and high-speed drive. From 2023 to 2030, Chinese wind energy REPM demand may fall by 14% CAGR for onshore installations and grow by only 4% for offshore installations. By 2030, China is forecast to account for only 19% of wind energy REPM demand, against 64% in 2023.

Given average REPM grade and PrNd, Dy and Tb content assumptions, the global non-China wind energy sector will require a cumulative 30,000 tonnes of rare earth materials by 2030. In 2023, mining operations outside of China (in Australia and the US) are set to account for no more than 13,000 tonnes of relevant rare earth oxide materials.

Although alternative sources of rare earth materials exist, it is difficult to reduce single-source dependence across the entire supply chain. As far as mining is concerned, China currently accounts for more than 70% of total PrNd mining in 2023 and 51% for Dy. And the picture is much less diverse further downstream.

If the global rare earth market is to build regional supply chains able to meet wind energy demand – not to mention other, larger, end uses – for REPMs, the economics of processing need to be favourable. This includes a consideration not only of cost structures, but also of the ability to source the required feedstock at scale.

Mining

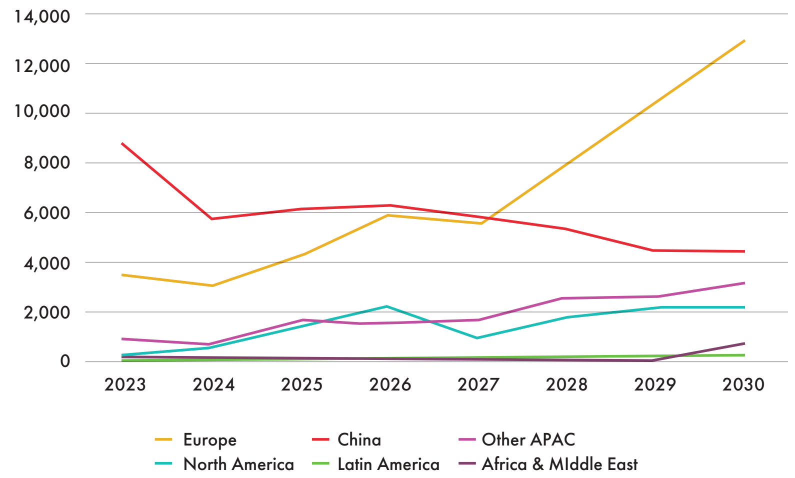
Mining, already the most diversified part of the industry, is likely to achieve greater supply-side plurality as the need for new raw materials continues to expand.

Benchmark expects mining capacity growth outside of China in a multitude of jurisdictions spanning Africa, South America, South and Southeast Asia, and Oceania. A share of growth is expected to come from brownfield expansion at existing operations, such as in Mt. Weld, Australia, where output capacity is expected to double to 12,000 tonnes of PrNd per year by 2026.

Benchmark counts at least 12 projects of note expecting first output before 2026 for a capacity of 23,000 tonnes of PrNd across ten countries. Naturally, not all of this will be realised within this timeframe. Rare earth mines are complicated and require large capital expenditure, which relies on investors with a sizeable risk appetite.

Benchmark expects that non-China PrNd mining in Australia, the US and

Regional REPM demand for wind energy, 2023–2030 (tonnes)



Source: Benchmark, GWEC

elsewhere – not including Myanmar due to Chinese ownership and direct flows into Yunnan after mining – will only account for 27% in 2023 and 36% by 2028. For dysprosium, mining estimates drop to 8% and 29%, respectively, due to the lower number of heavy rare earth-centric orebodies in advanced stages of development outside of China and Myanmar.

Processing

Most of the material mined in North America, Australia or elsewhere passes through China at some stage in the process before REPM consumption. Indeed, there is no established rare earth processing market outside of China that is able to meet regional demand.

The outlook is not entirely pessimistic, given that processing capacity is far more elastic than mining capacity and can scale up faster, and that concrete steps are being taken to ensure a global processing market may arise by 2026. Processing capacity may see substantial growth in Europe, Australia and the US.

By the end of 2023, as the only existing North American rare earth miner – MP Materials – scales up its own separation capacity, both major sources of non-China mined supply will be processing their own feedstock. This ensures a capacity of roughly 12,000 tonnes of PrNd Oxide produced in Malaysia (from Mt. Weld) and in the US (from Mountain Pass).

Several mine developers are intending to build processing capacity able to use feedstock produced at their sites. Some notable examples are Mkango and Grupa Azoty's Pulawy facility in Poland and Pensana's Saltend Chemicals Park facility in the UK.

Combined with existing light rare earth separation capacity in Estonia from Neo Performance, Europe may see additional independent capacity growth in France (Solvay's La Rochelle) and Norway (REEtec). This would grow Europe's rare earth processing market to three independent facilities, plus a further two facilities integrated with mining operations abroad.

Australia's Iluka Resources' received an AUD 1.25 billion non-recourse loan from Export Finance Australia as part of a wider AUD 2 billion critical minerals facility set up by the government. The Eneabba facility is intended to consume not only feedstock from its monazite stockpile but also from external third parties.

In the US, the government has played a crucial role in funding the buildout of domestic processing capacity. Aside from $35 million in support for MP Materials' expansion, the Department of Defense recently increased its $120 million contribution to Lynas' planned heavy rare earths-inclusive processing facility in the US to $258 million. Various announcements and plans by USA Rare Earths, Ucore and several other firms indicate the potential for further growth in US processing capacity.

> Processing capacity is far more elastic than mining capacity and can scale up faster.

It is important to note, however, that offtake agreements tend to allocate certain levels of processed material for designated customers, meaning that the numbers presented are demonstrative of the size of the non-China processed market, and not the size of materials that are available for spot sales.

A further complication arises from the fact that many announced processing facilities aim to only separate light rare earth oxides, likely leaving the remaining dysprosium and terbium to be processed in China. Although REPMs used in wind energy require lower levels of Dy and Tb than e-mobility, these are still crucial parts of the magnet composition, else it would demagnetise when the generators reach high temperatures.

> Rapidly growing areas of demand will have to rely on Chinese REPM capacity for the short and medium term.

Magnet making

REPM production is concentrated in China. At-scale REPM production capacity exists in Germany and Japan, but the vast majority is produced in Zhejiang and Inner Mongolia.

Magnet makers in Germany have said it is difficult for them to scale up due to the significant economic advantages enjoyed by Chinese magnet makers through a lower cost base and government support in the form of subsidies and VAT rebates. This means that major players such as JL Mag, Zhongke Sanhuan, Ningbo Yunsheng, Baotou Tianhe and Ningbo Heli are well placed to achieve an increasingly dominant position.

The US is the largest market outside of China for potential REPM production. Recent announcements include REPM production by MP Materials at a new facility in Texas and a binding agreement between Germany's largest REPM producer – Vacuumschmelze – and General Motors to build a facility in the US. Although the volumes associated with these announcements are likely allocated to e-mobility, other facilities such as those planned by Noveon Magnetics may indicate the emergence of a market for REPM production that would be meaningful for the wind industry.

End of Life (EoL) recycling presents another opportunity for growing magnet production in the US and particularly in Europe, where government policy favours circular economics.

Some pilot facilities have proven the practical viability of using hydrogen decrepitation to recycle EoL REPMs, but economic viability is harder to prove. Extracting REPMs from end uses is often difficult because of product design, while easily accessible REPMs, such as those in hard drives, represent relatively small amounts.

It is unlikely that EoL recycling will form a source of REPMs sizeable enough to supply the wind energy sector before 2026.

Conclusion

The ambition for regional supply chains to meet REPM demand for wind energy is tempered by the many challenges the rare earth industry faces across multiple stages of its supply chain. Given the small and disjointed nature of rare earth mining and processing – and of REPM manufacturing – outside of China, rapidly growing areas of demand will have to rely on Chinese REPM capacity for the short and medium term.

This is particularly true for Europe, which is expected to be the largest driver or REPM demand from wind energy installations and has little-to-no scaled REPM capacity that can source rare earths from outside of China.

Although rare earth mining and processing growth is expected in Australia, the US, Sub-Saharan Africa and Europe, it is unclear whether these facilities will serve local markets or form part of a wider global rare earth supply chain.

The outlook for sourcing REPMs from local supply chains is therefore uncertain. A true solution to single-source supply chain dependence requires the economics of mining, processing and REPM production to be favourable, which may need continued and extended government support in the US, Australia and Europe.

Even if those events materialised, OEMs may need to accept that, for rare earths, a true 'local' supply chain might only develop in the US before 2028, leaving European and other wind turbine manufacturers outside of China to rely on a global – or Chinese – rare earths supply chain to meet growing REPM demand.

Even with favourable market conditions, continuous demand growth suggests the need to be pragmatic in the short and medium term at least.

With inputs from Benchmark Mineral Intelligence

Carbon fibre

More carbon fibre needed to meet wind turbine blade demand

As wind turbines continue to scale in size to boost energy production, the two key factors of stiffness and weight have become even more critical for blade design.

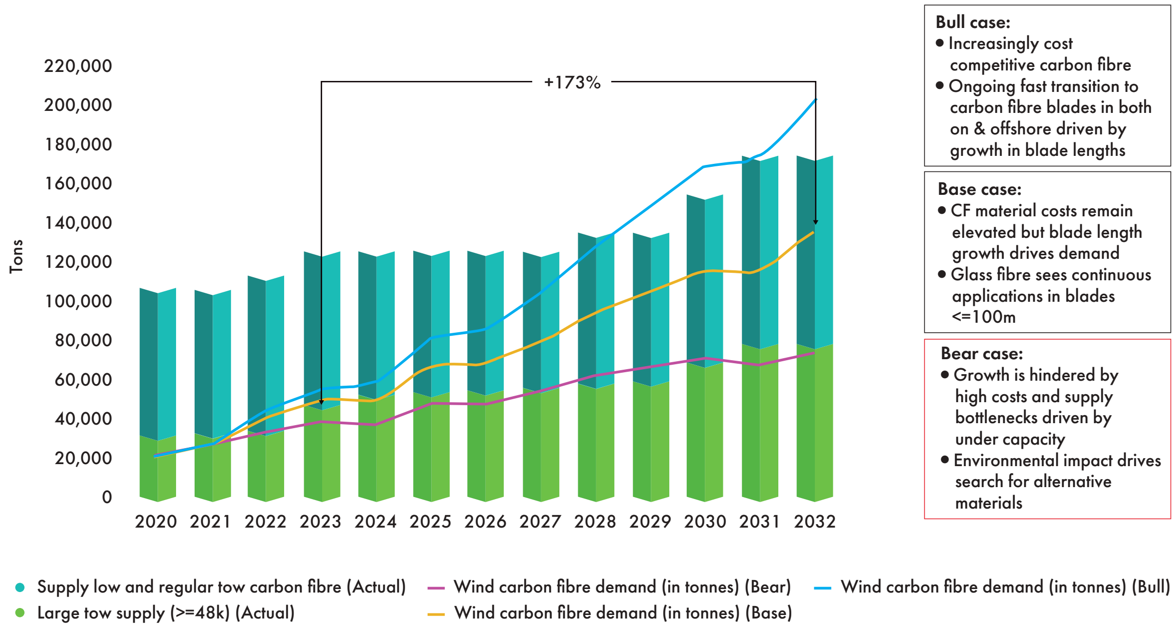
Most utility-scale wind blades are made of glass fibre composites that have a relatively stiff, lightweight design with a high fatigue life. To increase the stiffness, turbine OEMs and large blade manufacturers have started incorporating carbon fibre reinforcement into their larger blades starting in the 2000s.

Carbon fibre has almost five times the axial stiffness per kilogram of weight compared with fibreglass, which enables longer blades without increased rotor loads.

However, carbon fibre is expensive. For this reason, glass fibre remained the preferred choice for wind turbine blades in 2022, with carbon fibre being used only in about one-third of blades. Due to cost pressures, Chinese OEMs in particular have continued to use fibreglass for rotors of up to 200m in diameter.

Following an estimated peak of around 21,000 sets in 2024, carbon fibre demand for onshore wind turbine blades is expected to stabilise at or just below the 20,000 mark over the rest of this decade. Geographical market share is expected to remain stable in 2026–2030, with China representing half of the demand, followed by Europe (20%) and the Americas (20%). Asia Pacific (excluding China) and Africa & the Middle East shared the remainder.

Global supply* and demand of carbon fibre in tonnes



Note: *Reflects the operating capacity, and not theoretical nameplate capacity

Source: Brinkmann, Composites World, Composites United

As wind turbines continue to scale in size to boost energy production, the two key factors of stiffness and weight have become even more critical for blade design.

As the power rating of turbines and the length of blades grow, demand for carbon fibre is expected to escalate. Globally, by 2027 it is estimated that more than 70% of blades will be using carbon fibre.

Carbon fibre demand for offshore wind blades is estimated to nearly double over the decade, with EMEA outstripping China by 2029 and Asia except China also growing fast. By 2030, around 3,700 blade sets are expected to be required.

The wind industry represents a significant portion of the global demand for carbon fibre

Wind turbine blades are behind a significant portion of the global demand for large-tow carbon fibre. The wind turbine market represented more than one-third (36%) of the global demand for industrial-type carbon fibre in 2022, rising from ~27% in 2020. Further increases are expected as Brinckmann estimates carbon fibre demand for wind power to increase by more than 170% between 2023 and 2032.

> Wind turbine blades are behind a significant portion of the global demand for large-tow carbon fibre.

There is currently no dedicated production of carbon fibre for the wind market due to the high costs associated with it and the manufacturers' preference for maintaining production that targets a wide range of users. As a result, the competition between the wind market and other industries in securing carbon fibre is a growing challenge.

China set up in 2022 its first facility capable of producing large-tow carbon fibre, but rolling out such facilities is both expensive and lengthy, as they require about two years to construct and commission. This reduces the ability to quickly react to strong demand growth with capacity expansions.

As the wind industry competes with other end users for carbon fibre supplies, it is estimated that supply shortages of large-tow carbon fibre for wind applications will intensify from 2025/26 and become acute from 2028.

It is expected that glass fibre blades will remain popular, especially in onshore applications, both for cost reasons and because blade suppliers will struggle to source carbon fibre over the coming years.

With input from Brinckmann.

Steel

Fast-growing wind demand for steel may call for sustainability compromises
There is no shortage of steel in the world. Yet, for the rapidly growing wind energy sector, it is possible that bottlenecks and supply constraints will materialise in the coming years unless the sector is flexible on some of its ideal sourcing requirements.

The sector's demand for steel could double by the end of the decade.

The wind energy sector is a key source of demand growth for steel plate. Looking at ten-year CAGR rates forecast by CRU for 2018–2027, wind is by far the fastest-growing end use worldwide.

Based on GWEC Market Intelligence's 2030 global wind market outlook, CRU believes that the sector's demand for steel could double by the end of the decade.

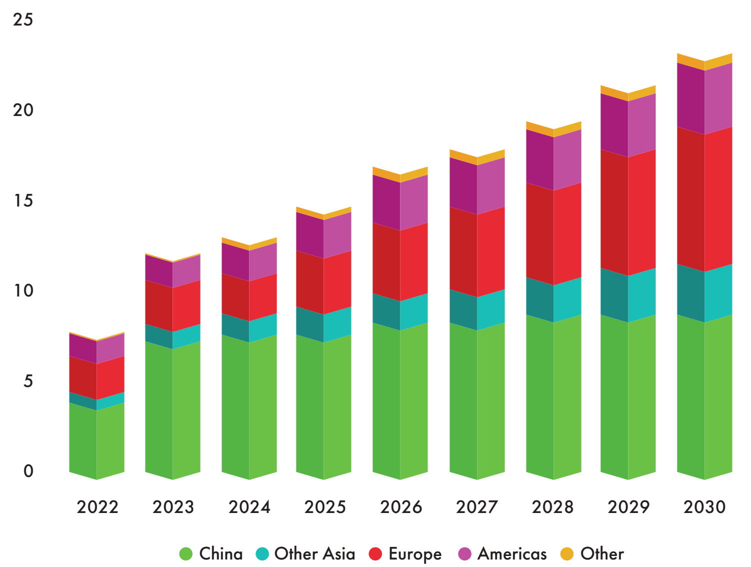
The absolute scale of wind demand for plate is dwarfed by other end uses, especially construction. When putting wind into the wider context of total demand, the sector looks small and only accounts for 8% of total world plate demand.

On the face of it, there seems to be plenty of steel plate in the world that could potentially serve the wind energy industry. Why then would there be any concern over supply chain bottlenecks and shortages?

Steel is a critical raw material for the wind industry
Part of the concern from the wind energy side arises because of the critical importance of steel to the sector. For onshore wind, steel is about one-quarter of the total materials required per MW, though as an individual item it is the second largest behind concrete. But for offshore wind, steel represents 90% all of the materials consumed per MW.

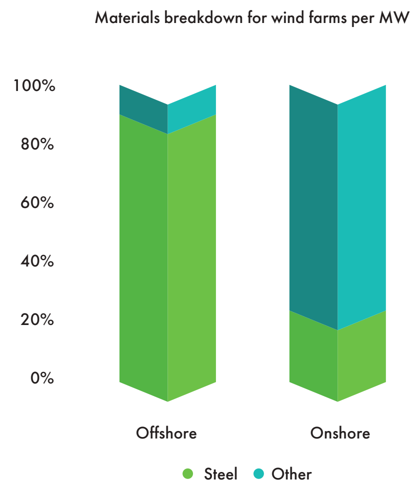
It's not just about total steel plate
The challenge for the wind energy supply chain comes not because steel is scarce – it is not – but because of the way that the industry

Modelled* steel plate consumption in the wind energy sector 2023-2030, Mt



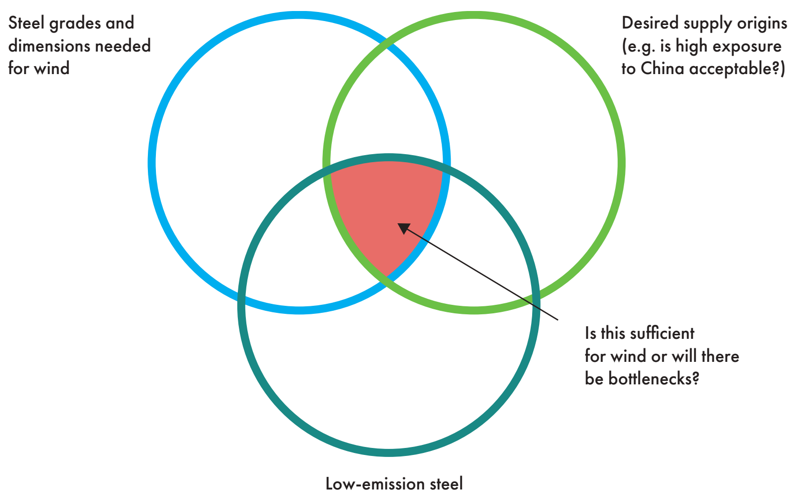
Source: CRU, GWEC. *Estimated steel needs of wind energy capacity forecast to be installed per year

Steel is a vital input to the wind energy sector



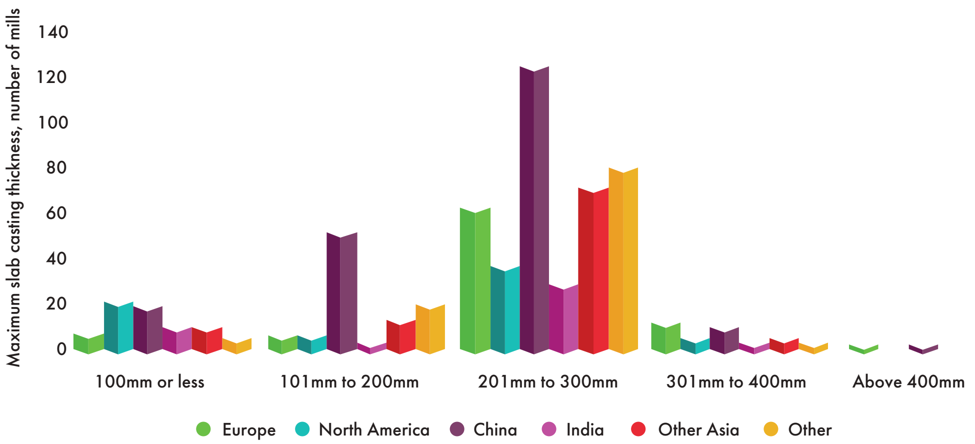
Source: GWEC Market Intelligence

The steel required in wind is the result of overlaps of several sub-areas



Source: CRU

Few mills worldwide can cast very thick slabs suitable for the heaviest wind needs



Source: CRU, PlantFacts

ideally requires several sub-areas of steel to all intersect.

The adjacent Venn diagram illustrates this in qualitative terms.

Common steel grades are sufficient for wind but dimensions can be niche

Much steel in wind goes into monopile foundations; for this purpose, the most common grade used is S355 (European standard; equivalent to A572 in the USA). This is not quite a basic commercial quality grade but it is not far off it, and most if not all plate mills would be able to make this.

Where wind becomes a more demanding customer is on product dimensions. In extreme cases, plates of up to 150mm thick may be required. Most plate in general demand is 10–60mm thick and so, even without extending all the way to 150mm, the requirements for wind tend towards the thicker end of mill product ranges.

Achieving optimal physical properties of plate requires a certain degree of thickness reduction from the slab – ideally at least a three-fold reduction. Therefore, to make a 100mm plate you need to start from at least a 300mm slab. Not many mills can go thicker than this, meaning the pool of suppliers able to meet all of the wind industry's product needs is small.

The origin of materials has risen up the agenda

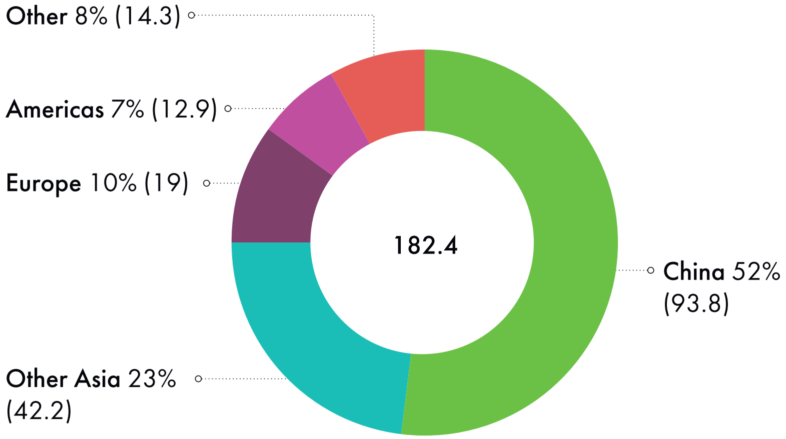
More attention is being paid in recent years to the origin of materials used in the industry. The supply chain disruptions caused by the Covid-19 pandemic have triggered questions on whether 'just in case' should be preferred over 'just in time', and on the advantages of nearshoring versus offshoring.

> More attention is being paid in recent years to the origin of materials used in the industry.

A deterioration in some geopolitical relationships is driving similar considerations. Following Russia's invasion of Ukraine, Russia has been removed from many supply chains, which has some important implications for steel as Russia is a large, low-cost supplier. Additionally, Ukraine's export capabilities – in 2021, the country accounted for nearly half

Most plate capacity is located in Asia, especially China

Reversing mill capacity, Mt/y, 2023



Source: CRU

of the EU's plate imports according to statistics from Fastmarkets – have reduced significantly.

But China is the true elephant in the room in this area. China produces more than 50% of the world's reversing mill plate and is the world's biggest exporter. Many of China's plate mills are relatively modern, capable of producing high-quality, wide and thick products.

The US is leading efforts to diversify or 'de-risk' away from China. Local content requirements for steel to be used in towers and foundations in the US under IRA Domestic Content Bonus Guidance are expected to further accelerate the process.

Several western countries and regions have put in place a set of formal trade defence measures, including high tariffs on Chinese plate. For its part, China has shown that it is prepared to act to restrict its exports of gallium and germanium.

Sourcing decisions made in such an environment are complex. It is possible that what looks like a wide range of potential suppliers is reduced, in practice, to a small number of acceptable origins.

Renewables are a key demand source of low-emission steel

Wind is part of any pathway to decarbonisation. As such, the sector has a strong interest in using low-emission steel and has been a leader in driving its development. Leading offshore wind project developer and operator Ørsted has stated that over half its Scope 3 emissions from constructing an offshore wind farm come from steel; emissions it has committed to reducing to net zero by 2040.

Some OEMs have launched low-emission turbines that use low-emission steel. A good example is the Greener Tower, a wind turbine tower made of more sustainable steel, launched by SGRE in April 2023.

But most steel in the world, including plate used in wind, is still produced via unabated blast furnaces. Data from CRU's Steel Cost Model shows that the weighted average Scope 1 emissions from the world's plate mills is 2.2 tCO2/t. Low-emission mills that use electricity or green hydrogen are capable of producing plate with a Scope 1 CO2 footprint of below 0.4 tCO2/t. But today there are not very many of those.

Some OEMs have launched low-emission turbines that use low-emission steel.

The steel industry is working hard on its decarbonisation. Results at scale are likely to take years because it is an expensive, technologically uncertain process that also depends upon the concurrent decarbonisation of other connected industries like electricity generation or hydrogen production. As the wind energy industry is growing rapidly, it may not be possible for all developers to access low-emission steel for several years to come.

With input from CRU

OFFSHORE BALANCE OF PLANT

Foundations

Different types of foundations are in use for offshore wind, as it is accepted that there is no one-type-fits-all solution. The design and structure of foundations, and the choice of materials used to construct them, are heavily dependent on the circumstances of each project, mainly seabed conditions, water depth and wind turbine size.

At present, two main concepts dominate the industry: steel structures (including monopiles and jackets) and concrete structures (gravity-based foundations).

Steel monopile foundations still dominate the market with nearly 70% global market share for projects already in operation as of the end of 2022. However, jackets are being used increasingly in deeper waters together with innovative XXL monopile designs. Jacket foundations have gained some market share over the years and accounted for 17% of the global market installations by the end of last year.

Gravity-based foundations are preferred for projects with a rocky seabed and where piling or suction solutions are not possible due to noise restrictions.

As projects continue to expand into deeper waters and to more remote locations, floating foundations have begun to emerge.

Fixed-bottom foundations

APAC dominating the fixed-bottom foundation supply chain

More than 30 manufacturers are currently producing fixed-bottom foundations for the wind industry, with annual production capacity of 3,880 units in 2023. Asia Pacific is the world's largest manufacturing base with 81% of the global market, followed by Europe (16%), North America (2%) and the Middle East (1%).

Europe used to be the world's largest foundation production base with suppliers primarily from Germany, the Netherlands, Denmark and Belgium. With offshore wind taking off in APAC, suppliers have emerged in the Far East, particularly China and most recently South Korea, Chinese Taiwan and Vietnam.

To accommodate the growth of the global offshore wind market, suppliers continue to expand their production capacity for fixed-bottom foundations. According to our survey, more than 2,200 units are planned to be added worldwide by 2026, of which 53% from China, 33% from Europe, 10% from APAC excluding China and 3% from North America.

Challenges in the supply chain for fixed-bottom foundations

In 2022, 1,301 units of fixed-bottom foundations were installed worldwide. Demand is expected to grow from 1,679 units in 2023 to 3,430 units in 2030, according to GWEC Market Intelligence's latest projection. Given current production capacity of 3,880 units per year and plans for another 2,200 units by 2026, it seems that the offshore wind sector has enough capacity to cover the growth for the rest of this decade. However, challenges remain if regional-level benchmarks are applied.

With annual production capacity of fixed-bottom foundations close to 3,000 units, China has enough capacity to support its domestic offshore wind market growth. In fact, our offshore wind growth projection for this market shows a significant surplus in China.

In Europe, the existing capacity is capable of supporting demand in 2023–2025. Whether deficits will occur after 2025 depends on whether the planned production capacity materialises. Assuming all the planned capacity – totalling 745 units – can be delivered by 2026, supply chain constraints are expected to surface by the end of the decade.

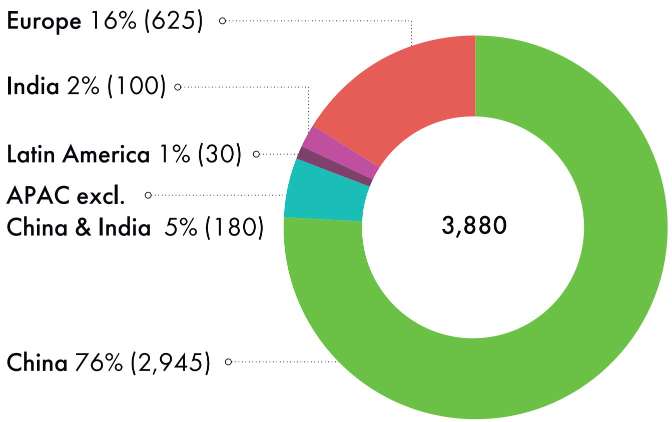
When we look at the demand and supply situation per foundation type in Europe, current production capacity for either monopiles or jackets can only support demand up to 2025. Even if planned capacity for monopile and jacket foundations comes online on time, deficits are expected by the end of the decade.

No bottleneck is expected for the US in 2023–2024 as the country's first offshore wind foundation facility, EEW American Offshore Structures (AOS), came into operation early this summer at the Port of Paulsboro marine terminal in New Jersey.

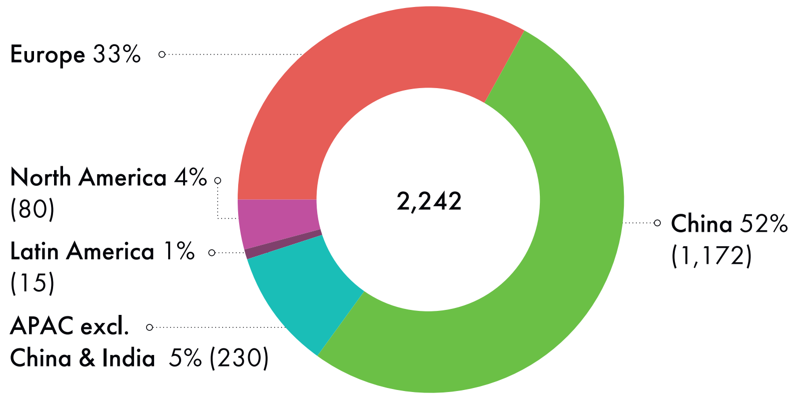
The US local supply chain is expected to increase its annual production for fixed-bottom foundations from 100 units in 2023 to 180 units by 2025, when a facility planned by US Wind is expected to enter service. This is not enough to

Demand and supply benchmark for fixed-bottom foundations, 2023–2030

Fixed bottom foundation production capacity in 2023 (units/year)



Planned fixed bottom foundation production capacity up to 2026 (units/year)



	Fixed bottom offshore foundations (units)								
	2022	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
Europe	347	509	252	551	734	732	1097	1306	1639
China	683	887	1263	1411	1324	1210	1154	1071	1000
India	0	0	0	0	2	0	34	34	68
APAC ex China & India	271	241	223	263	229	253	277	288	345
NORTH AMERICA	0	42	73	193	294	339	308	294	270
LATAM	0	0	0	0	0	0	0	0	108
Africa&ME	0	0	0	0	0	0	0	0	0
Total	1301	1679	1811	2418	2583	2534	2870	2994	3430

Source: GWEC Market Intelligence, CWEA, Brinckmann, September 2023

● Sufficient ● Potential bottleneck

cope with the predicted demand in 2025–2030, however.

At present, no jacket foundation production is available in the US. This will represent an issue in terms of local sourcing if developers decide to use jacket foundations for their projects.

APAC excluding China and India does have foundation facilities in operation, but current annual production capacity is only for jacket foundations and suction buckets. This means that projects designed with monopile foundations have to source them from elsewhere.

Although an annual output of 120 monopile foundations is planned in the region by 2026, it is still not enough to cover the predicted demand in 2027–2030, assuming half of the projects will use monopile foundations.

Current production capacity for jacket foundations in this region is 130 units per year. Another 60 units per year are expected to be added by 2026. Assuming half of the predicted installation in this region will use jacket foundations, demand throughout this decade will be easily covered.

In India and Latin America, no offshore wind foundation facilities exist at present. Since the demand for fixed-bottom foundations in both markets is relatively low, bottlenecks can be addressed either through imports or new investment, with an average lead time of two years to get a facility built.

Floating foundations

China replaced Europe as the world's largest floating foundation production base

Compared with fixed-bottom offshore wind, the size of the floating wind market is really small. At the end of 2022, only 206 MW of floating offshore wind capacity was installed worldwide.

However, following more than a decade of testing, floating wind has passed the demonstration stage and entered the pre-commercial phase. GWEC Market Intelligence believes that floating wind will achieve commercialisation towards the end

of this decade, with annual demand for floating foundations surpassing 200 units per year.

Europe is the world's largest market in floating offshore wind installations, which explains why leading floating wind foundation suppliers including Aker Solutions and Navantia come from this region.

Having installed its first floating turbine in 2021, China entered the floating wind sector relatively late compared with European countries. However, the domestic floating foundation supply chain has grown rapidly in the past three years.

Although the number of foundation suppliers and floating technology companies active in China is still lower than in Europe, their annual production capacity is much higher than that of European companies.

Based on our recent survey, four suppliers – CSSC CWHI, Wison, JUTAL and CNOOC Offshore Oil Engineering – can produce 142 units per year, marking China the world's largest floating foundation manufacturing centre, followed by Europe (56 units), APAC excluding China (19 units) and the Middle East (4 units).

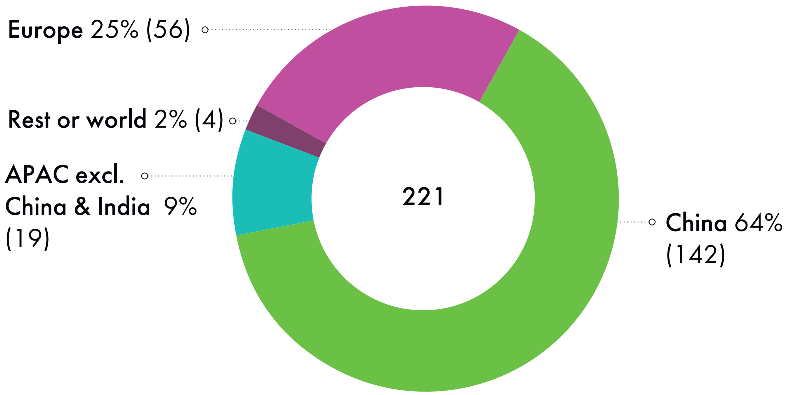
Challenges in the supply chain for floating foundations

Current global manufacturing capacity for floating foundations is 221 units per year. No bottleneck is expected until 2030 if we retain a free flow of the global wind supply chain. However, a deficit is likely to occur in all regions except China if restrictive trade policies and local content requirements come to play.

Because the floating foundation supply chain is immature, standardisation for existing floating foundation designs is low and the cost is still very high compared with fixed-bottom foundations. Global collaboration is the key to addressing supply chain constraints and bringing down the cost of LCOE for floating wind at the same time.

Demand and supply benchmark for floating foundations, 2023–2030

Floating foundation production capacity in 2023 (units/year)



	Floating offshore foundations (units)								
	2022	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
Europe	7	11	7	8	26	29	50	130	182
China	1	2	0	25	40	40	0	0	0
India	0	0	0	0	0	0	0	0	0
APAC ex China	0	0	8	0	11	32	57	75	77
North America	0	0	1	1	0	0	0	12	32
LATAM	0	0	0	0	0	0	0	0	0
Africa & ME	0	0	0	0	0	0	0	0	0
Total	8	13	16	34	77	101	107	217	291

Source: GWEC Market Intelligence, CWEA, Lumen Energy & Environment, September 2023

● Sufficient ● Potential bottleneck

Cables

High voltage cable production: a critical constraint for offshore wind

Cable demand for offshore wind consists of two main types: array cables, which connect individual turbines together, and export cables, which connect offshore substations to an onshore grid location. Demand for cables, measured in core-km, is expected to grow by an average of 18% year-on-year from 2023 to 2030. In value terms, demand is expected to rise by 15% year-on-year over the same period as the industry shifts to larger and more valuable cable types.

There are two key trends in the demand for offshore cables. One is the shift from 33kV to 66kV for array cables to accommodate the growing transmission requirements of larger turbines that generate more power. The other key trend is the shift to direct-current (DC) technologies as opposed to alternating-current (AC) cables to reduce electrical losses during transmission over long distances, as wind farms are increasingly being built further from shore.

High-voltage direct current (HVDC) technology also enables the interconnection of offshore wind farms across different countries, promoting crossborder energy sharing, which is a key component of new energy security plans such as the EU's REPowerEU initiative.

Decarbonisation and energy security drive rapid demand growth

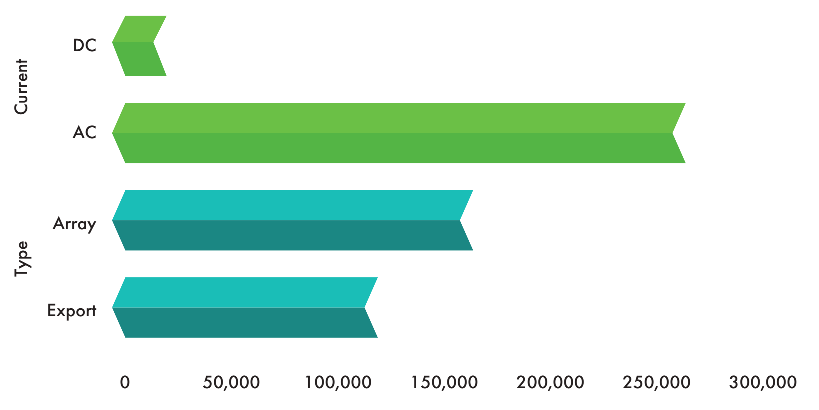
The rapid growth of offshore wind technologies has ignited a surge in demand for high-voltage cables that connect wind farms to the power grid. This could become a bottleneck in the rollout of offshore wind as demand for new capacity rises quickly while cable supply and demand centres grow geographically distinct.

China

Offshore wind cable consumption in China amounted to nearly 16,000 core-km in 2021, which represented 76% of total global offshore wind cable consumption. However, submarine cable consumption contracted significantly in 2022 due to fewer offshore wind projects being installed after the subsidies ended, falling to 7,000 core-km.

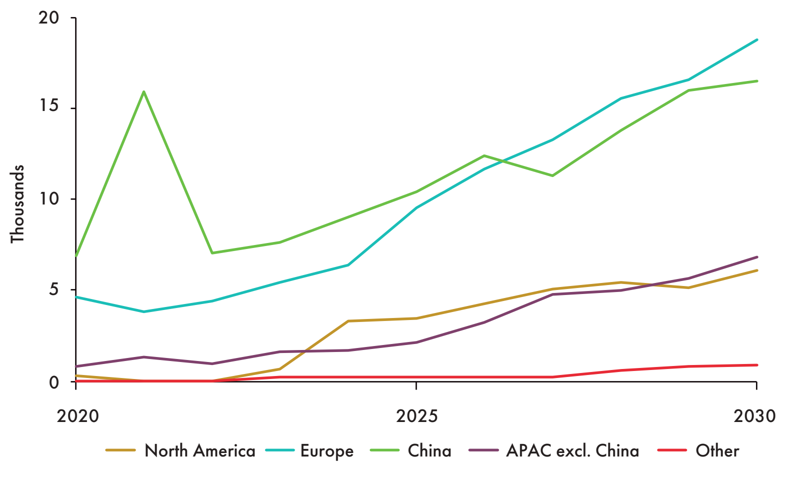
In 2023, China is expected to account for 35% of offshore wind

Demand for cables in offshore wind applications, 2023-2030 (core-km)



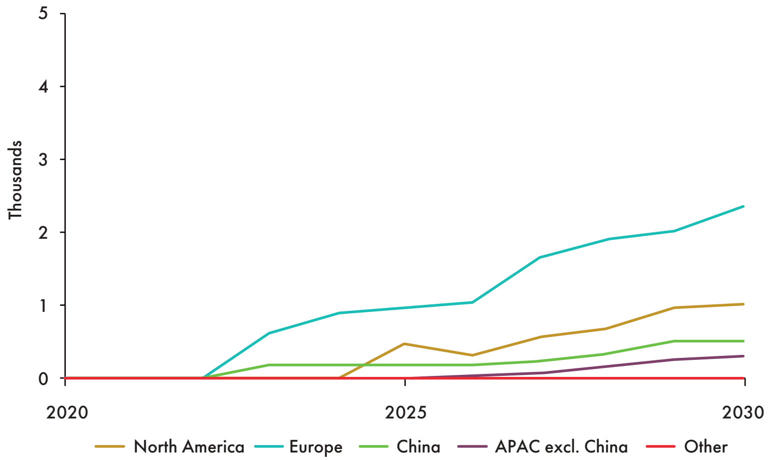
Source: CRU, September 2023

MV and HV cable demand for offshore wind applications (core-km)



Source: CRU, September 2023

EHV cable demand for offshore wind applications (core -km)



Source: CRU, September 2023

cable demand. From 2023 to the end of this decade, cable demand for offshore wind applications in China is forecast to grow 13% per year. This estimate could turn out to be conservative as China has a track record of exceeding its installation targets.

Europe

In 2023, Europe is predicted to account for 27% of global offshore wind cable demand. Growth is expected to average 21% per year to the end of the decade. Within Europe, the UK represents one-third of cable demand for offshore wind projects, with the Nordics and Baltics representing a further third.

> Currently there is only one operational offshore wind cable production plant in the US.

Decarbonisation goals and energy security needs have pushed Europe to ramp up its long-term renewable energy pipeline, with renewables expected to represent 32% of the EU's energy mix by 2030, under existing legislation. This goal is likely to be met ahead of schedule, which has instigated discussions about increasing the target.

APAC excluding China

The Asia-Pacific region excluding China is expected to account for 3.5% of offshore wind cable demand in 2023. Demand for cables in this region is projected to grow 18% per year to the end of the decade. The Chinese Taiwan area and Vietnam are the two largest offshore wind markets. Offshore wind is a key component of Taiwan's green economy vision: CRU expects 26 GW of offshore wind projects to come online between 2023 and 2029, with 84% of these being fixed-bottom and the rest floating.

At COP26, Vietnam made a strong commitment to achieve net zero by 2025 and recently increased its offshore wind target for 2030 to 6 GW. Most of the current projects in Vietnam are nearshore intertidal, within a couple of kilometres from shore. For this reason, most subsea cable demand will consist of 35 kV array cables, with most of it supplied by Chinese cable producers.

North America

In 2023, North America represents 4% of global cable demand for offshore wind applications, though this is anticipated to rise to 13% by 2030. Most offshore wind targets in North America are from the United States. Although offshore wind generates only around 0.1% of US electricity at present, roughly 35 GW of capacity is planned for the US East Coast, enough to meet 3% of the country's demand in 2022.

Currently there is only one operational offshore wind cable production plant in the US, located in South Carolina. This facility, operated by Nexans, is estimated to produce roughly 10% of the current demand for domestic subsea cables. Cable manufacturers are opening plants in the US to capitalise on the booming demand for offshore wind cables later this decade, supported by large federal spending under the Inflation Reduction Act and the Infrastructure Investment and Jobs Act.

Fast-growing demand spurs race to produce submarine cables

In 2022, only about 0.5% of global energy cable production facilities were capable of producing submarine cables. These highly specialised manufacturers in Europe are fully booked with multiple-year cable order backlogs. Additionally, the complex, resource-intensive installation process requires specialist equipment such as cable-laying vessels and highly skilled personnel. These supply bottlenecks have led to project delays and rising project costs, most notably in Europe.

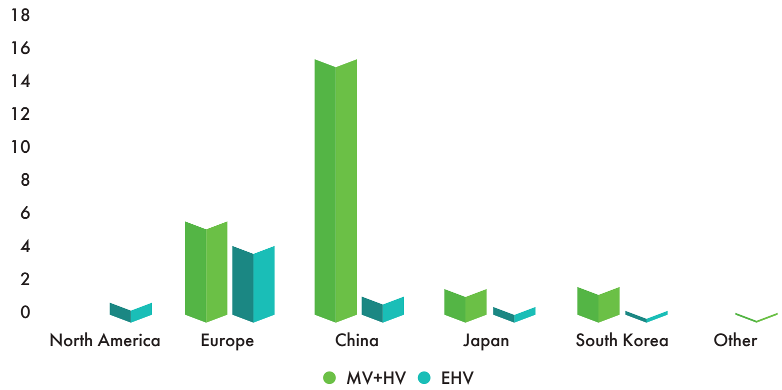
CRU estimates that global submarine cable production capacity in 2023 is approximately 30,900 core-km, split between 24,200 core-km for medium-voltage (MV, mainly 33–35 kV) array cables and high-voltage (HV, 37.5–245 kV) export cables, and 6,700 core-km for extra high-voltage cables (EHV, above 245 kV).

Global demand – including for offshore wind, interconnection and oil & gas applications – is forecast at approximately 18,000 core-km for MV and HV submarine cables and 6,400 core-km for EHV cables.

In theory, there is enough capacity to support global submarine cable demand this year. However, a Chinese firm with excess capacity may struggle to win an offshore wind project in Europe. Excluding China, we expect global shortages of 1,400 core-km for MV and HV submarine cables and 500 core-km for EHV cables in 2023.

Technically, a land cable production line making HV or EHV cables can switch to producing submarine cables. However, this involves changes in the manufacturing process and may not be feasible due to cable manufacturing facilities in Europe enjoying a strong pipeline of underground cable projects for electricity transmission and distribution.

MV+HV and EHV subsea cable manufacturing capacity, '000 core-km/y, 2023



Source: CRU, September 2023

Nevertheless, several submarine cable plants and expansions have been announced in the past two years, as cable manufacturers eye the opportunities presented by rapid growth in the sector.

In China, companies including Baosheng YOFC, Futong Sumitomo JV, Far East, Qingdao Hanhe and Qifan have entered submarine cable production with new plants over the past couple of years. Incumbent players like Hengtong, ZTT and Orient Cable are building new facilities in other Chinese provinces in preparation for local offshore wind projects.

> Several submarine cable plants and expansions have been announced in the past two years.

CRU understands that a total of 20 submarine cable manufacturing plants are currently under construction in China, more than the rest of the world combined. This

could lead to overcapacity in China in the next few years. On the other hand, China could represent a solution for supply shortages elsewhere in the world.

Europe has a 31% share of global subsea cable production capacity, which is likely to increase as four new subsea cable manufacturing plants for array and/or export cables are already under construction or planned.

In the UK, JDR Cables is building a new subsea unit at Blyth, northeast England, and newcomer XLCC is in the process of solidifying plans for two units, one at Hunterston, Scotland and another at Port Talbot, Wales. JDR is expanding existing facilities at Hartlepool, England.

Elsewhere in Europe, TKH will build a new subsea plant near Velsen-Ijmuiden, Netherlands. Expansion of existing facilities is also taking place by Prysmian at Arco Felice, Italy and Pikkala, Finland; Nexans at Halden, Norway; NKT at Karlskrona, Sweden and Cologne, Germany; Hellenic Cables at Soussaki, Corinth, Greece and TKH at Lochem, Netherlands, just to name a few.

Northeast Asia has a 13% share of subsea cable production capacity with new plants being built in South Korea by LS Cable at its existing site in Donghae, Gangwon-do, and Taihan at Dangjin Port Godae Pier. With a groundbreaking ceremony held this September, NKT and Walsin Lihwa – based in the Chinese Taiwan area – also plan to launch a subsea cable factory in Taiwan by 2027.

In North America, there is currently only one operational subsea cable production facility, though there are plans for new facilities to supply the burgeoning demand from newly announced offshore wind projects. Prysmian's construction of an HV subsea cable plant at Brayton Point, Massachusetts is connected to its awards totalling $900m for Vineyard Wind's 804 MW Park City OWF and the 1.2 GW Commonwealth Wind OWF, to be commissioned by 2026 and 2027, respectively.

Hellenic Cables plans to build an array cable plant at Tradepoint Atlantic in Baltimore County, Maryland, following its award for the 846 MW Skipjack Wind 2 OWF, to be commissioned in 2026. Two more US companies, Rise Light & Power and Delaware River Partners (DRP), are "prepared to invest millions" for an array and export cables plant in Greenwich Township, NJ, as part of the Outerbridge Renewable Connector project.

Bridging the demand and supply gap through collaboration

To meet ambitious offshore wind installation goals and accelerate the energy transition, a higher level of global collaboration is imperative. Offshore wind cable manufacture and installation often require an intricate interplay of suppliers, developers, governments and investors from several countries. Collaborative efforts can lead to knowledge sharing, cost optimisation and technology advancement. These can be jeopardised by geopolitical concerns affecting commercial choices.

Critical regions for offshore wind deployment such as the US and Europe exemplify the need for greater levels of global exchange. Targeted offshore wind installations are currently outpacing the realities of the highly technical and costly startup of new high-voltage cable production. The achievement of decarbonisation goals hinges on greater global connectivity of the high-voltage and extra high-voltage cable supply chain.

With input from CRU

OFFSHORE WIND ENABLERS

Offshore Wind Turbine Installation Vessels (WTIVs)

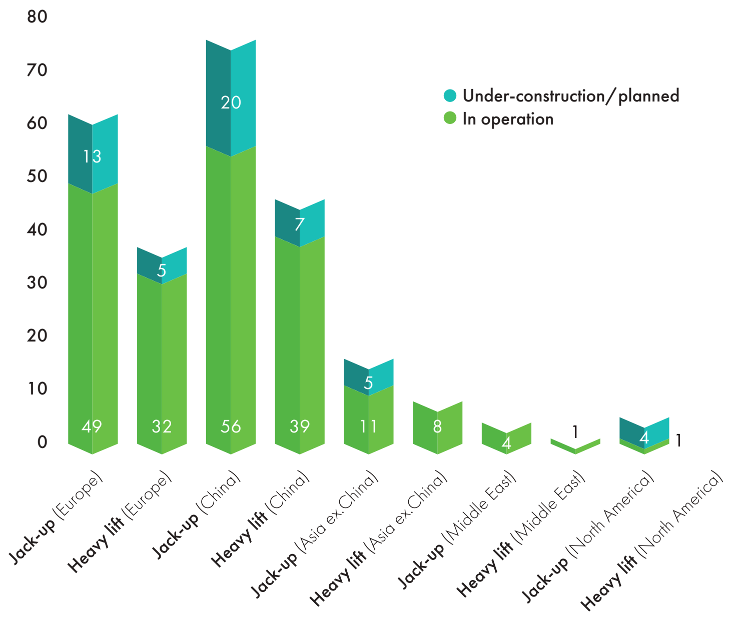
Offshore wind installation vessels play a significant role in the timely completion of offshore wind projects. Vessels for the installation of wind turbines and foundations fall in two categories: jack-up vessels – including self-propelled vessels and barges without propulsion – and heavy lift vessels. In the majority of cases, jack-up vessels are used for wind turbine installation while heavy lift vessels focus on foundation installation.

According to GWEC Market Intelligence's Global Offshore Wind Turbine Installation Vessels (WTIVs) database, updated in September 2023, China and Europe operate the majority of jack-up and heavy-lift vessels used for offshore wind turbine installation, followed by Asia excluding China, the Middle East and North America.

As offshore turbine power ratings continue to grow, two major factors have impacted the availability of WTIVs: the weight of nacelle, tower and foundation; and turbine hub height.

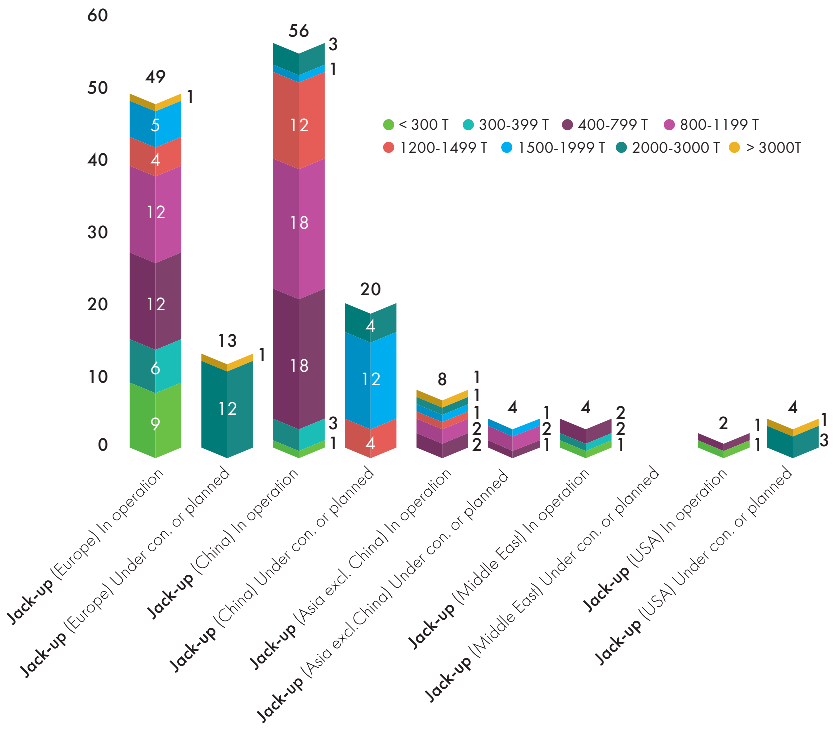
The weight of nacelles for 10-15 MW

Overview of offshore wind turbine installation vessels in 2023



Source: GWEC Market Intelligence Global Offshore Wind Turbine Installation Vessel Database, September 2023

Overview of offshore wind turbine installation vessels by lift capacity in 2023



Source: GWEC Market Intelligence Global Offshore Wind Turbine Installation Vessel Database, September 2023 wind turbines ranges between 500 tonnes and 800 tonnes, but the weight of a pre-assembled tower for a 14 MW turbine can be greater than 2,000 tonnes and for an XXL foundation more than 1,000 tonnes.

The hub height of a MHI Vestas 9.5–10 MW turbine is in the 110–115m range; for an SGRE 8 MW turbine it is 109–120m, for an SGRE 10–11 MW it is 125–128m, for an SGRE 14 MW it is greater than 150m, and for the GE Haliade X 12-14MW turbine it is more than 150m.

Due to the specialised technical requirements in the lift capacity of the main crane – as well as the hook heights – the availability of vessels capable of installing the new generation of offshore wind turbines in the 12-18 MW size range is significantly reduced.

According to the offshore wind vessel availability report, which was prepared by H-BLIX for Wind Europe and PWEA in 2022, the average WTIV wind turbine installation efficiency is 0.5 GW/v/year in 2021 and is likely to increase to 1.31 GW/v/year in 2030.

GWEC Market Intelligence has used the lower end of WITV installation efficiency as a reference to convert the numbers of jack-up WTIVs into annual installation capacity in GWs, as buffer room is needed for project coordination and the main crane upgrade for some existing WTIVs.

Considering the required main crane lift capacity and the hook heights to install offshore turbines with power ratings larger than 10 MW, we assumed that WTIVs with main crane lift capacity below 1,200 tonnes are no longer fit for purpose. Additionally, we assumed that all the WTIVs under construction today will be delivered by 2026. Based on this methodology, we calculated the annual WTIVs installation capacity we present in the table below.

WTIV Wind Turbine Installation Efficiency	2021	2030
Average number of projects/v/y	1.3	1.1
Average installation capacity (GW/v/y)	0.50	1.31
Real average insatllation time - dyas/turbine (including loading and transit & all other project effects	3.7	3.1
Average number of turbines/v/y	61	80
Average days in operation/v/y	229	251

Source: H-BLX

Challenges in the supply chain for WTIVs

Based on current supply chain conditions and market dynamics, we expect no bottlenecks in meeting the global demand for offshore WTIVs up to 2026.

> We expect no bottlenecks in meeting the global demand for offshore WTIVs up to 2026.

Following an offshore wind installation rush in China driven by the feed-in-tariff cut-off in 2021, new installations slowed down in 2022 and we do not expect to see 2021-level installations (15 GW) again until 2026.

We believe that current Chinese WTIV supply chain availability is well-positioned to accommodate the projected domestic offshore wind growth in the near term. At the same time, we believe that Chinese EPC contractors will continue to use Chinese WTIVs to support nearshore wind turbine installation in Vietnam.

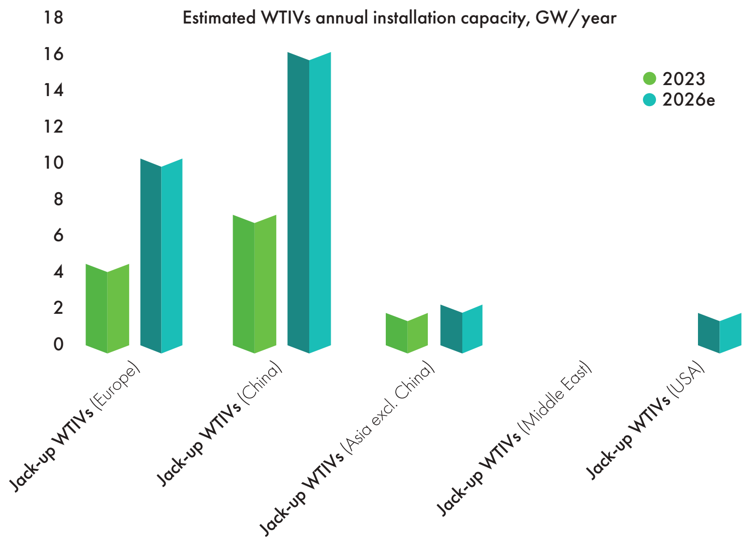
In Europe, the current WTIV supply chain can cope with demand, given that annual offshore wind installations are relatively flat and unlikely to reach the 10 GW level until 2026. This also explains why European vessel operators are able to release their jack-up and heavy lift vessels over the next two years to support demand from emerging markets in Asia – mainly the Taiwan area and Japan – and the US.

Looking at the 2027–2030 supply chain situation, GWEC Market Intelligence does not expect WTIV supply chain constraints in China. We saw in 2021 how quickly the country can mobilise vessels across the world and build vessels to support astonishing annual growth.

Although the average turbine size in China has reached 7.4 MW and turbines with power ratings greater than 10 MW will soon become the prevailing product, we believe the local industry can handle the challenge. In June 2023, Chinese developer CTG installed in Fujian the world's largest offshore wind turbine, Goldwind's GW252-16 MW, with its newly built WTIV 'Bai He Tan'.

As of June 2023, 27 offshore WTIVs are under construction in Chinese shipyards, of which 20 are tailor-made jack-up vessels and seven are purpose-built heavy lift vessels. In addition, local shipyards such as COSCO, CIMC Raffles and CMHI won the majority of WTIV orders placed in the past three years by large European vessel operators, namely Cadeler, Jan De Nul, Seaway 7 ASA, Van Oord and Havfram.

Regional demand and supply side benchmark, offshore, 2023–2030



To accommodate the growing demand for vessels that are capable of handling large offshore wind turbines with power ratings greater than 12 MW and hub heights of more than 150m, European vessel operators started upgrading existing WTIVs and placing orders for next-generation WTIVs in the past couple of years. However, based on our latest market growth projection, we foresee a likely shortage in Europe towards the end of this decade, unless investment in new WTIVs is made before 2026/2027 – assuming a lead time of three years for delivering a new WTIV.

This expected bottleneck also means that offshore wind markets in APAC that are heavily reliant on European vessels need to find a solution for the future. Large offshore WTIVs are very expensive and require a skilled workforce and specific knowhow. This means that regional cooperation for vessels in APAC is vital to ensure offshore wind deployment is not delayed, especially in new markets such as India, the Philippines, Australia and New Zealand.

In the US, where only one tailor-made Jones Act compliant WTIV is currently under construction, but with an eight-month delay, announced plans for another three WTIVs will have to be executed in the next two years if the Biden Administration's target of 30 GW of offshore wind by 2030 is to be met.

	Offshore units (floating)								
	2022	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
North America	0	533	955	2335	3535	4500	4500	4500	4500
Latin America	0	0	0	0	0	0	0	0	1350
Europe	2460	5148	2916	6527	9598	10808	16225	20465	26400
Africa & ME	0	0	0	0	0	0	0	0	0
India	0	0	0	0	20	0	500	500	1000
China	5052	8000	12000	14000	15000	15000	15000	15000	15000
Other APAC	1259	1769	1559	2884	2675	3256	4530	5035	5995
Total	8771	15450	17430	25746	30828	33564	40755	45500	54245

Source: GWEC Market Intelligence Global Offshore Wind Turbine Installation Vessel Database, September 2023

● Sufficient ● Potential bottleneck

Ports

Ports are important infrastructure for offshore wind development, providing the support from site survey to component manufacturing, construction, operation and decommissioning.

Because ports are used for different purposes, the offshore wind industry names them differently to reflect their functions: marine survey ports, manufacturing ports, marshalling ports (staging ports), and operations & maintenance ports.

As offshore wind turbines and project sizes have been getting bigger, handling extra-large nacelles and components has become increasingly difficult for port facilities, especially during the construction stage.

Specialised equipment and a dedicated laydown area and quayside are required to lift and store those big components before loading them on to wind turbine installation vessels (WTIVs). The availability of large marshalling ports to support offshore wind growth has turned out to be an issue in some markets. For this reason, we have chosen to focus on marshalling ports in this report.

Geographic overview of marshalling ports

Worldwide, there are more than 30 large marshalling ports with a track record in offshore wind project installation. This excludes ports that were used for turbine assembly in the past and have not been very active in recent years. Of these, 14 are located in Europe, 16 in the APAC region and one in the US.

Collectively, these ports can support 25 GW of offshore wind power installation capacity per year. More than ten large marshalling ports, some purpose-built for offshore wind, have been built along the Chinese east coast to cope with the offshore wind installation rush in China. With more than 16 GW of annual operational port capacity available to support offshore wind installations, China has replaced Europe as the market leader.

Expansion plans for a total 2.4 GW/year have been announced by some of the existing marshalling ports with an offshore wind track record. Additionally, more than 50 ports worldwide have announced plans to support offshore wind development. If all the announced plans materialise, another 45 GW of annual operational port capacity would be available for offshore wind.

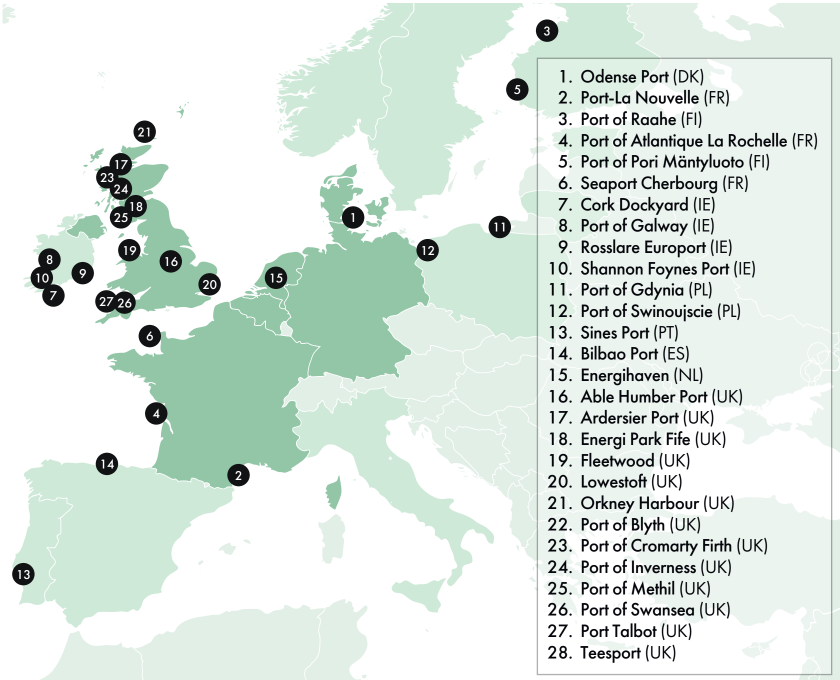
Operational marshalling ports with a track record in offshore wind – Europe

Source: CWEA, Brinckmann, September 2023

Growing pains for existing ports infrastructure

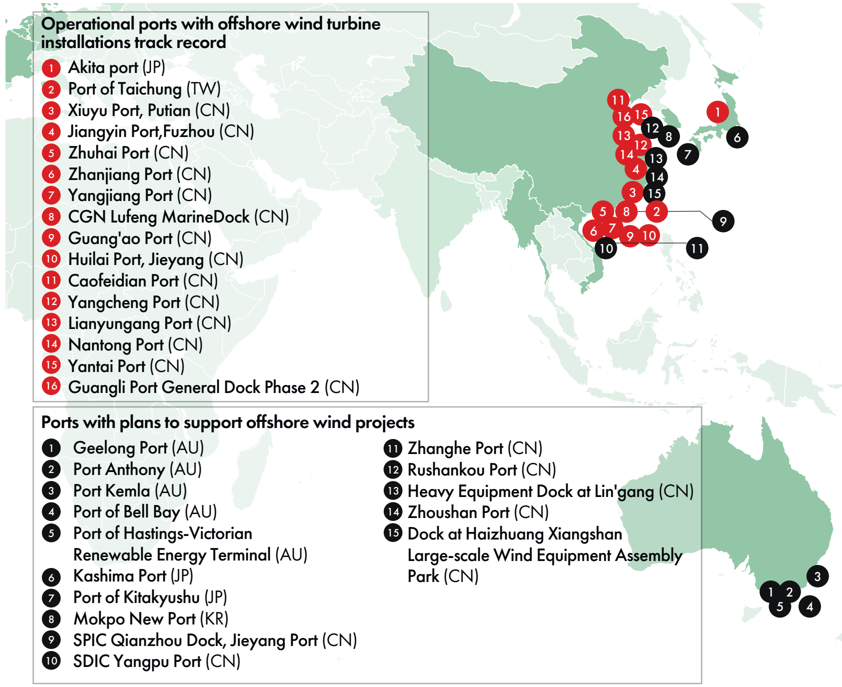
Based on the existing operational port capacity available for the

Ports with plans to support offshore wind project construction – Europe



Source: CWEA, Brinckmann, September 2023

Ports with a track record in offshore wind and plans for offshore wind – APAC



Source: CWEA, Brinckmann, September 2023

offshore wind industry today, we believe that China will have enough port infrastructure to accommodate domestic market growth.

In Europe, while the current operational port capacity is well-positioned to cover demand in the near term (2023–2025), more port capacity will be needed from 2026 in order to avoid bottlenecks.

In the APAC region excluding China, simultaneous construction of utility-scale offshore wind projects is expected for the first time in 2023 in Japan, South Korea and Chinese Taiwan. This is likely to stretch the existing port facilities beyond their ability to cover demand during the forecast period, unless new port capacity is built and released to support the offshore wind growth.

Only one purpose-built offshore wind port is available in the US at present, located on the east coast. It is imperative to bring new port capacity online to fill the gap.

How to address the challenges associated with port infrastructure

As extra port capacity is required in all regions except China, it is clear that significant investment will be needed to underpin the rollout of offshore wind. According to our survey, more than 50 offshore wind port projects are currently in the pipeline across the world. In theory, those new ports could be sufficient to support the growth up to 2030. However, $18 billion of investment will be required to bring those announced projects online – assuming a cost of $400 million to build a

Ports with a track record in offshore wind and plans for offshore wind – North America

Source: CWEA, Brinckmann, September 2023

marshalling port with an annual operational capacity of 1 GW.

Given the size of investment required, the current macroeconomic difficulties and the three-year lead time to build one purpose-built offshore wind marshalling port, political commitment is required to ensure delivery.

In addition to new investment, regional cooperation in port infrastructure is also important to support market growth. This is especially true in the early stages of development, when each market has yet to achieve a significant scale of deployment.

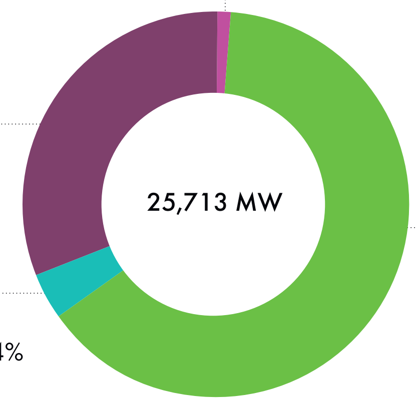
Before offshore wind ports were established in Germany, the

Netherlands and the UK, the Danish offshore wind port of Esbjerg played a vital role in supporting regional offshore wind expansion. According to Port of Esbjerg, it has so far supported more than 23 GW of offshore wind capacity across 59 projects – although Denmark itself has only installed 2.3 GW of offshore wind by the end of 2022.

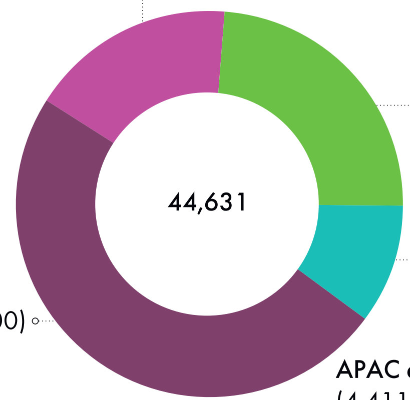
Regional cooperation is also crucial when the market has achieved maturity. In response to the Esbjerg Declaration, major European ports have come together to look at how they can collaborate to deliver the additional offshore wind capacity required. The ports of Esbjerg (Denmark), Oostende (Belgium), Groningen Seaports/Eemshaven (Netherlands), Niedersachsen Port/Cuxhaven (Germany), Nantes-Saint Nazaire (France) and Humber (UK) are working together to see how they can support each other to grow offshore wind activity. Countries from the APAC and other regions could certainly learn from markets connected with the North Sea in Europe.

Demand and supply side benchmark for ports, 2023–2030

Estimated operational port capacity available in 2023 (MW/year)



Planned port capacity to support offshore wind (MW/year)



	2022	2023e	2024e	2025e	2026e	2027e	2028e	2029e	2030e
North America	0	533	955	2335	3535	4500	4500	4500	4500
Latin America	0	0	0	0	0	0	0	0	1350
Europe	2460	5148	2916	6527	9598	10808	16225	20465	26400
China	5052	8000	12000	14000	15000	15000	15000	15000	15000
Other APAC	1259	1769	1559	2884	2695	3256	5030	5535	6995
Total	8771	15450	17430	25746	30828	33564	40755	45500	54245

Source: GWEC Market Intelligence, CWEA, Brinckmann, September 2023

● Sufficient ● Potential bottleneck

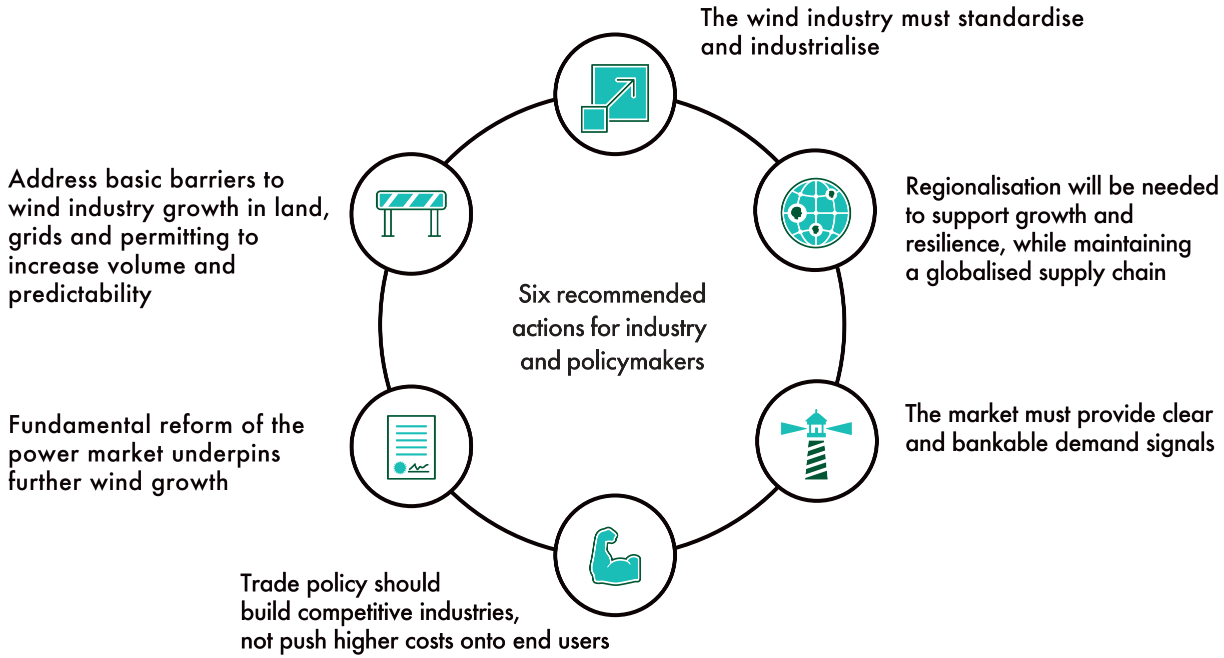
CHAPTER 3: RECOMMENDATIONS TO SECURE THE WIND SUPPLY CHAIN

There is a critical, global need for shifting from the current fossil fuel-based generation to renewable power, and for ensuring that large volumes of renewable energy are available to meet increased power demand and electrification levels. For this purpose, wind energy is a particularly strong solution due to its cost-competitiveness, technical maturity and ability to deploy offshore where land is not a limiting factor.

Looking towards 2030, just 7 years from now, global wind deployment must be scaled to at least 2.75 TW in order to deliver the much-needed energy transition for a net zero future.[1] The wind industry has just this year passed the 1 TW mark after 40 years of history.[2]

The wind industry has been able to scale quickly over the past few decades, driven by ever-growing demand for more efficient technology at the lowest possible cost. This has put the industry into a low-margin situation that makes it difficult to reinvest in future scale, despite wind and renewables now being widely recognised as central for national energy security and resilience.

Six recommended actions for the global wind energy supply chain



While the industry now benefits from more mature technology, lower LCOE, greater public support and mature, global delivery capacity, it will have to almost double its current supply chain production capacity by 2030 to keep our planet on the road to net zero. Achieving this will require a larger wind supply chain guided by strong and clear demand signals, but also one that is able to withstand the uncertainties of the future macro environment.

In order to ensure a sufficiently large and stable demand for a net zero future, delivered at a highly competitive cost, industry and policymakers must actively collaborate to act now. Six key recommendations for action are outlined below:

Recommendation 1: Address basic barriers to wind industry growth in land, grids and permitting to increase volume and predictability

Many of today's challenges to wind scaling are due to policy and regulatory barriers that lead to heightened uncertainty for project investment. These include overly complex permitting procedures, grid

1. IEA, Net Zero Roadmap: A global pathway to keep the 1.5 °C goal in reach - 2023 Update, 2023.
2. GWEC, Global Wind Report, 2023.

bottlenecks and impractical pricing signals at auction. These policy and financing environments are not fit for purpose if we are on a 1.5°C pathway where wind generates one-fifth of the world's electricity by 2030 and one-third by 2050.[3]

Addressing these barriers will require prioritised long-terms plans with the needed investment into infrastructure, support and compensation.

Recommendation 2: The wind industry must standardise and industrialise

The wind sector must industrialise with designs becoming standardised, global and modular, based on a massified and highly specialised global industry producing necessary components. The industry is already capable of supporting different wind turbine base models, optimised for market needs, but going forward these models should be designed in a more modular and scalable manner. This will allow the industry to return to the profit zone, making further investment attractive.

To enable this, turbine platform growth must slow down to the extent needed to avoid serial damage in the field, allowing OEMs to capitalise on their R&D investments and the supply chain to use its equipment for more than a few years and achieve economies of scale.

Recommendation 3: Regionalisation will be needed to support growth and resilience, while maintaining a globalised supply chain

As markets move towards more regional diversified supply chains, industry players (local or foreign) should work with local authorities to build resilient manufacturing hubs with consideration for what is needed in terms of investment, infrastructure or regulatory requirement relief in order to provide competitive, regional structures for key refining and manufacturing activities.

Governments should adopt a balanced approach between fostering regional supply chain security and enabling continued global interlinkages of the wind energy supply chain in order to ensure availability, flexibility and competitiveness. Regions will need to pursue supply diversification strategies, reshore/onshore some segments and grow their own capacities. But this should not manifest in measures that outright block current trade flows and interrupt or delay deployment. International suppliers from any country should be encouraged to expand in markets outside of their home region to ensure that global learning benefits can transfer across borders. This is particularly important for North-South learning transfers and to ensure a just transition.

Attention to diversification should in particular be paid to gearboxes, generators and power converters, for which global resilience is currently low and concentration risk in China is high. Regionalising the mining and refining of critical rare earth elements is a greater challenge; it will likely take considerable time before sufficient production capacities are permitted and built.

Countries and regions should pursue multilateral cooperation and interconnection to enable open flows of critical materials, components, services and knowledge that can support a secure and resilient supply chain. These can take the form of bilateral or multilateral trading partnerships (so-called green corridors) within a region or globally.

3. IRENA, World Energy Transitions Outlook: 1.5°C Pathway, 2023.

Recommendation 4: The market must provide clear and bankable demand signals to reach net zero

Credible build-out trajectories in the shape of market targets will be crucial to unleashing supply chain investment. These must be stable, bankable and much stronger than they are today. By stating clear targets and roadmaps over a long horizon stretching beyond 2030, policymakers will be able to grow wind power demand as needed through communicated targets for electrification, decarbonisation, sector coupling and storage, involving the broader industry in building renewables ecosystems.

Recommendation 5: Trade policy should aim to build competitive industries, not push higher costs onto end-users

Collaboration and trade must be protected to foster healthy future wind pipelines. Cost reduction depends on supply chain capacity utilisation, and is only possible if resources can be shared across regions with competitive cost positions and limited trade barriers.

Markets will benefit from public investment in workforce skills and infrastructure, while prescriptive and undue regulation against cross-border trade will significantly reduce industry growth and increase cost. This would ultimately be paid for by households, commercial and industrial consumers, cities and other consumers of electricity. This is especially the case for offshore wind, where demand remains more volatile and infrastructure such as installation vessels and ports can be shared.

The global wind industry is committed to a rules-based trading system and level playing field worldwide. Unfair market practices that result in legitimate injury to market actors may warrant investigation, which can result in the imposition of trade defence measures. It is essential to consider such measures with caution, given the globally interconnected nature of the wind supply chain and the risk of retaliatory measures.

Rather than pursuing defensive mechanisms likely to enhance trade barriers, governments should focus on supporting strategic segments of the domestic industry to create an attractive market environment that ensures adequate pricing and returns, makes competitive finance available and removes bureaucratic barriers. This will create a sustainable foundation of growth for the private sector to rapidly ramp up its investment in supply chain and skills.

The IRA is a good example of an incentive-based approach to counteract inflation and provide financial support for supply chain investments, while the EU's Wind Power Package offers a multidimensional demand-side approach to speeding up project deployment and improving overall investment conditions for wind manufacturing and development.

Recommendation 6: Fundamental reform of the power market underpins further wind growth

Current merit order power markets are designed for fuel-based, or 'OPEX-loaded' dispatchable generation – not for renewable generation. Investment-heavy projects such as wind need strong offtake and long-term price certainty, requiring an updated power market design.

In order to provide the certainty needed to attract investment, we need a power market reform that better addresses the needs of renewable generation. These include long-term operating margins based on solutions with a higher system value, for example through a better production profile, rather than awards based on strong competition for the lowest price per MWh.

The broader societal benefits of wind energy could also be considered to further stimulate innovation and domestic value creation. If we want to increase the value placed on the resilience of local supply chains and the benefits/quality of wind projects, strong pre-qualification criteria and the alignment of supply chain actors with international protocols and frameworks can be among the measures used. These measures should avoid creating market distortions or undermining clarity and objectivity in the procurement process.

A better future for wind is a better future for the world

We can only walk this path towards a better future if people are willing and able to invest in it, and if there is sufficient demand-side ambition, policy and investment signals. Given recent market developments, there are many compelling reasons for a stronger demand-side pull:

- The cost competitiveness of grid-connected wind and PV power versus fossil generation is so great that renewable power now costs less than the marginal cost of fuel in some markets. Continued fossil fuel price volatility and market uncertainty means the relative value of wind power continues to strengthen, even as the immediate cost environment for wind has sharpened. There is a positive business case for every hour of fossil generation that can be replaced.

- The growth of PV creates tailwinds for wind, since a balanced generation profile should mix every 1 MWh from solar PV with 2 MWh of wind power.[4] Wind and solar generate power at different times of day, and have different seasonal outputs and capacity factors, so a complementary balanced mix of both resources is necessary to deliver a generation profile that can meet demand-side needs.

- Energy flow resilience has become a higher priority for governments and individuals as the world has become more uncertain. Renewable power provides this resilience and greater independence from imported fossil fuels – in a world where most countries are net importers of fossil energy.

- Mini-grid costs have come down so far that a new value proposition is becoming economically feasible. Hybrid plants with wind and PV can bring power to the estimated 745 million people that lack access to electricity today.[5] While the first micro- and off-grid solutions were very expensive, they now cost less than using diesel generators or building new transmission systems.

Wind power is a source of massive capital investment across the world. It can create multiplier effects in sustainable employment opportunities, industrial growth and development of local supply chains. This can in particular enable the transition of value chains and labour markets in fossil fuel-dependent markets.

As one of the most innovative, scalable and cost-effective renewable energy sources, the global wind industry is prepared to continue making large and long-term investments in technology, supply chain and people. To do this, governments and industry must work together to create stable policy environments, adequate price signals and a strong global supply chain for wind energy.

The net zero pathway is not an easy one, but it is worth all the effort, both from a quality of life and economic perspective. Every dollar invested in climate mitigation will save the world many dollars in adaptation costs. When it comes to the critically important question of climate, the math is simple.

4. BCG analysis and client work
5. Access to electricity improves slightly in 2023, but still far from the pace needed to meet SDG7, according to the IEA.

APPENDIX

Definitions and Terminology

Definition of regions
GWEC uses the following definitions for regions of the world:

Europe: Geographic Europe including Norway, Russia, Switzerland, Turkey and Ukraine

North America: United States and Canada

Latin America: South, Central America and Mexico

Asia Pacific: East Asia, Central Asia, South Asia, Southeast Asia and Oceania

Africa and Middle East: North Africa, Sub-Saharan Africa, Middle East excluding countries in Central Asia

Terminology

AC	Alternating Current
BAU	Business-as-Usual
C&I	Commercial And Industrial
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CfD	Contract for Difference
CO2/	
CO2e	Carbon Dioxide/ Equivalent
COP	Conference of the Parties
DC	Direct Current
DD	Direct Drive
Dy	Dysprosium
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EoL	End of Lift
EPC	Engineering Procurement Construction
ESG	Environmental, Social, and Corporate Governance
EU	European Union
EV	Electric Vehicle
EHV	Extra Hight Voltage
FID	Final Investment Decision
FiT	Feed-In Tariff
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GW	Gigawatt
HSSE	Health, Safety, Security, And Environment
HVDC	High-Voltage Direct Current
IEA	International Energy Agency
IFC	International Finance Corporation
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producers
IRA	The US Inflation Reduction Act
IRENA	International Renewable Energy Agency
ITC	Investment Tax Credit
kt	Kilo Tonnes
kWh	Kilowatt Hour
LCCs	Low Cost Countries
LCOE	Levelised Cost of Energy
LCRs	Local Content Requirements
MOU	Memorandum of Understanding
MS	Medium Speed
Mt	Metric Tonnes
MV	Medium Voltage
MW	Megawatt
MWh	Megawatt Hour
NDCs	Nationally Determined Contributions
NEA	China's National Energy Administration
NPC	Non-Price Criteria
NSEC	North Seas Energy Cooperation
O&M	Operation And Maintenance
OEMs	Original Equipment Manufacturers
OPEX	Operational Expenditure
P&L	Profit and Loss Statement
PPA	Power Purchase Agreement
PrNd	Praseodymium
PV	Photovoltaic
PTC	Production Tax Credit
REPMs	Rare Earth Permanent Magnets
R&D	Research And Development
RECs	Renewable Energy Certificates
REE	Rare Earth Element
ROI	Return on Investment
RPS	Renewables Portfolio Standards
Tb	Terbium
TW	Terawatt
TWh	Terawatt Hour
VAT	Value Added Tax
VRE	Variable Renewable Energy
WTGs	Wind Turbine Generators
WTIVs	Wind Turbine Installation Vessels

About GWEC

Global Wind Energy Council (GWEC) is the industry association representing the global wind industry sector. GWEC articulates the vision for wind energy to major world bodies, including the International Energy Agency, the International Renewable Energy Agency, the UNFCCC and other bodies, as well as governments which are responsible for strategies, targets and implementation thereof in electricity generation and supply. GWEC works together with the leading representative industry associations as well as the global wind energy industry to build a platform which communicates a common vision to all leading global decision-makers, policymakers and key opinion leaders. https://gwec.net/

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