Wind power

Investing into deeper seas

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KEARNEY | Energy Transition Institute

Compiled by the Kearney Energy Transition Institute

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About the FactBook: Wind power

This FactBook provides an overview of the wind power sector, highlighting its status, future trajectory, key technological challenges, and economic trends. Wind energy has grown into a mainstream renewable source, with rapid expansion fueled by technological advancements and increasing competitiveness. While onshore wind is now a well-established and cost-effective technology, offshore wind—especially floating systems—represents the next frontier, with significant potential but ongoing cost and infrastructure hurdles. As wind power scales up, continued innovation in grid integration, along with supply chain resilience, will be crucial to unlocking its full potential in the global energy mix.

About the Kearney Energy Transition Institute

The Kearney Energy Transition Institute is a nonprofit organization that provides leading insights on global trends in energy transition, technologies, and strategic implications for private-sector businesses and public-sector institutions. The Institute is dedicated to combining objective technological insights with economic perspectives to define the consequences and opportunities for decision-makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

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1. Wind power concepts and technologies

Wind power concepts and technologies

Global wind power potential

– Wind potential differs across regions, due to the global distribution of wind power density as well as seasonal and weather variabilities.

Wind to electricity conversion

– Turbines harness wind energy using rotor blades and an electricity generator to convert the **kinetic energy of moving air into electrical energy**.

– Converting wind energy to useful electricity through wind power systems results in power losses of **around 55 percent.**

Wind power technologies

– Wind turbines can be classified by **axis direction, location, foundation type, and turbine (drivetrain and generator) type.**

– Most of the wind projects operational so far have been **onshore (land based)** with recent advances in **offshore** wind deployment.

– Onshore wind turbine foundation types depend on **soil structure** while appropriate turbine foundations for offshore wind are determined according to **water depth and seabed composition**.

– **Turbines have grown larger and taller** to maximize energy capture over a range of wind speeds while lowering cost per unit of capacity.

– **Permanent magnet generators**, developed for their higher efficiency, are now sometimes used to replace traditional induction generators.

– **Onshore wind is a mature technology** while **offshore wind** deployment is expected to ramp up in the coming years, with fixed-based and floating projects.

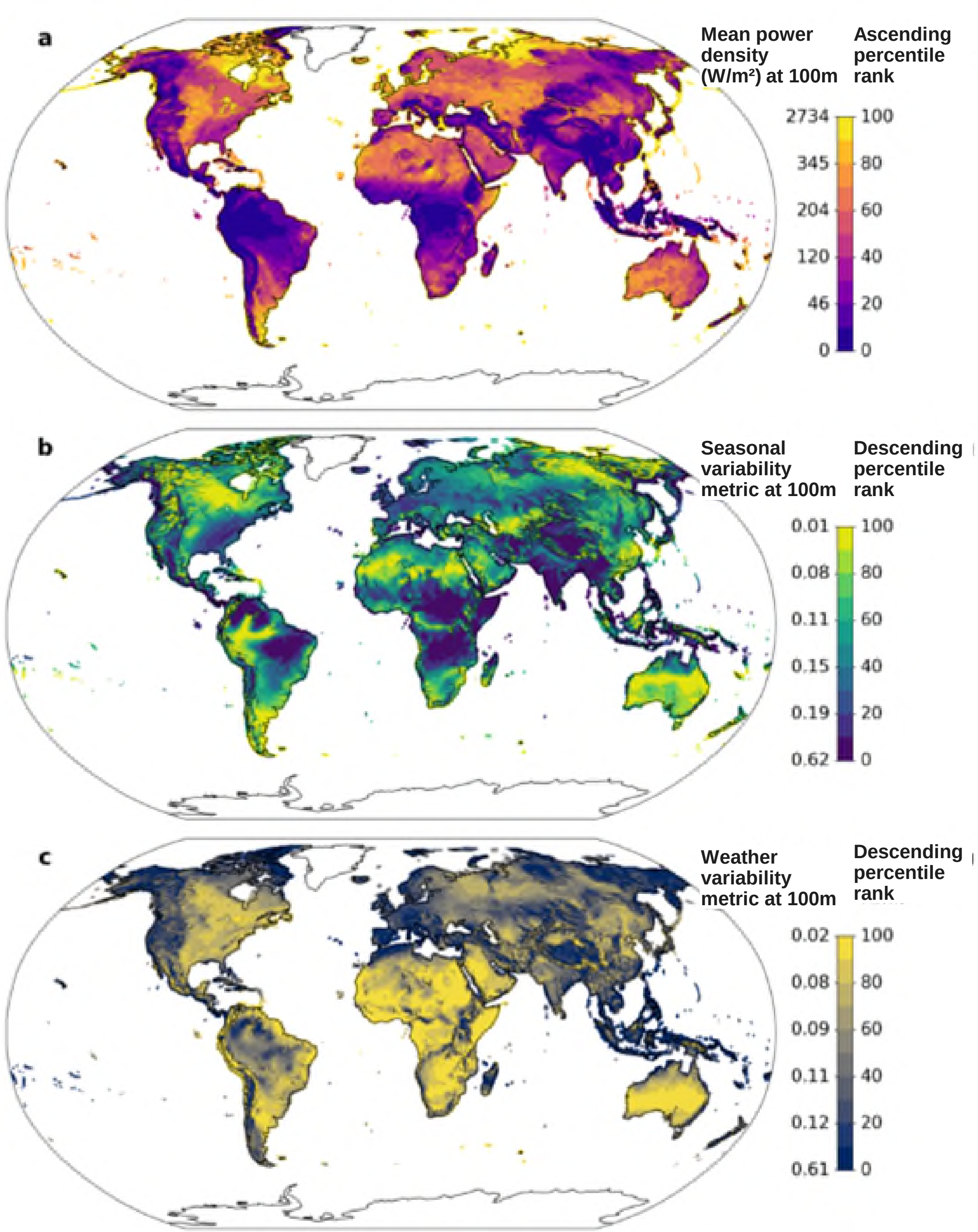
Transmission infrastructure

– A robust power transmission system is needed to transport electrical energy from wind assets. The cable network for offshore-to-onshore wind power consists of **sub-stations, array cables** and **export cables.**

Wind potential has great variability across regions, due to the global distribution of wind power density and the seasonal and weather variabilities

Mean power density is related to the cube of the wind speed, considers the elevation of the site, and can provide additional information about the strength of the wind not found in the mean wind speed alone.

Note: global distribution for land and coastal areas, excluding Greenland and Antartica
Sources: Antonini, E. et al., 2024, Identification of reliable locations for wind power generation through a global analysis of wind droughts; Kearney Energy Transition Institute analysis



Mean power density

American Midwest, Northeastern Canada, Australia, the Sahara, Argentina, parts of Central Asia and Southern Africa, Northern Russia, and Central and Northwestern Europe have relatively high-power densities.

Seasonal variability metric

Climatological mean seasonal cycle of the wind power density. Of the above-mentioned regions, some are characterized by high amounts of seasonal variability, such as Europe.

Weather variability metric

Departures from the climatological mean seasonal cycle of the wind power density. Mean weather variability appears more uniform across land and coastal areas, with low variability in parts of Africa and Australia.

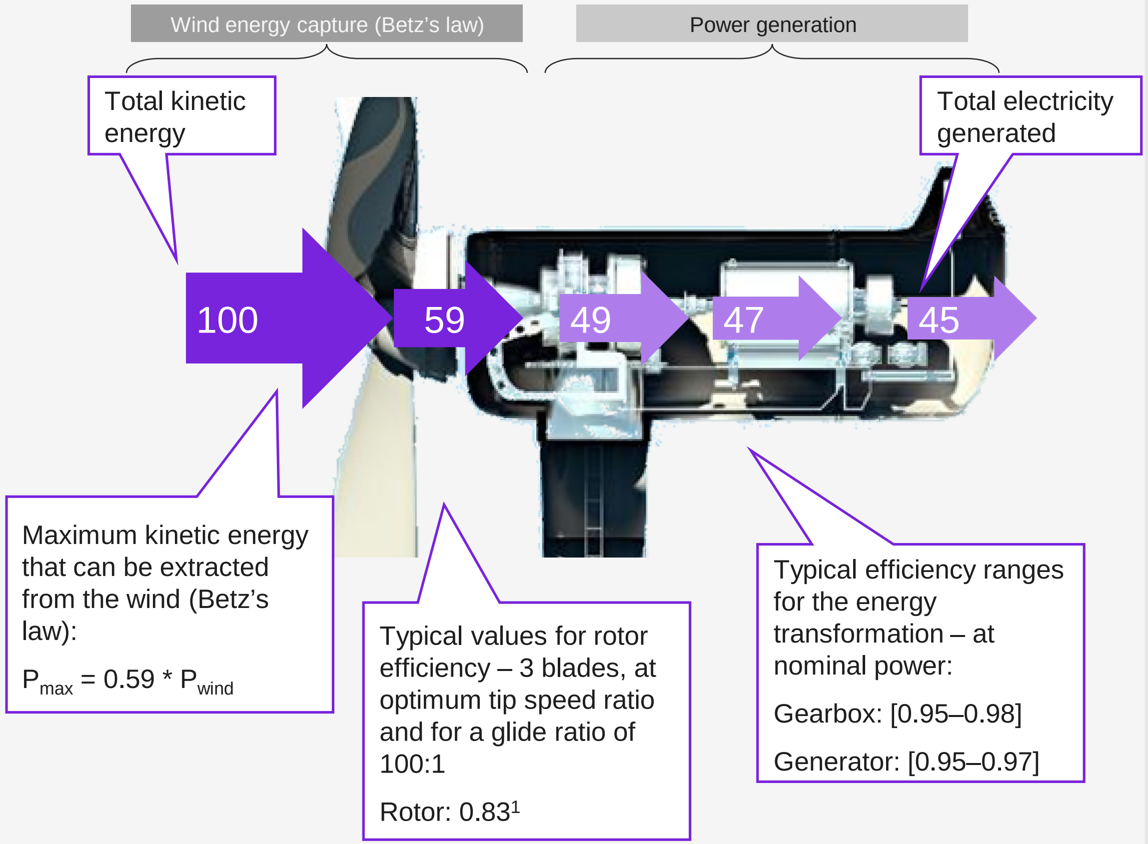
Converting wind energy to useful electricity through wind power systems results in power losses of around 55%

Mechanical efficiency is a meaningful design factor of wind turbine gearboxes since it defines the rate of electricity conversion. Research efforts continue to enhance turbine efficiency by optimizing gear ratios and designs/ configurations based on wind conditions.

1.2 Wind to electricity conversion

Theoretical power conversion losses for wind power

Base 100 on rated power



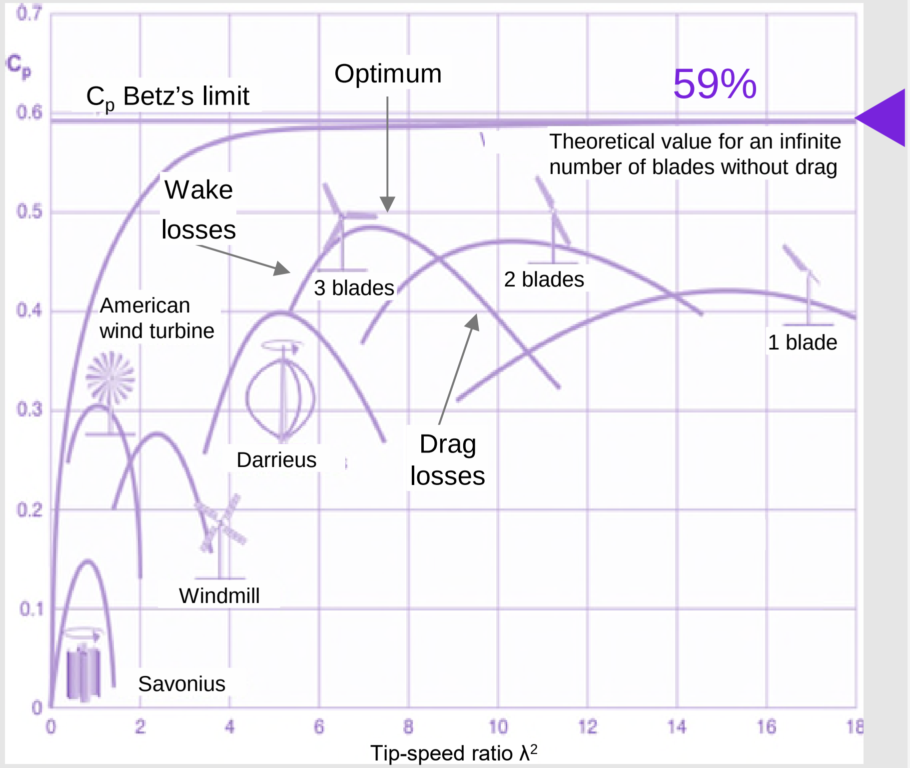
[1] The glide ratio corresponds to lift coefficient over drag coefficient.
[2] Transmission and distribution losses depend on distance and technologies, but also vary greatly by country. The global average transmission and distribution loss is 8%, but it ranges from 2% in Qatar to 46% in the Republic of Congo.
[3] Energy efficiency is particularly important from an economic perspective since it affects the levelized cost of electricity of wind power.
Sources: Gundtoft, 2009, Wind Turbines; Kearney Energy Transition Institute, 2015, Introduction to smart grids

Losses and efficiency

- **The rotation of the blades**, which drag the shaft, transmitting mechanical energy through a gearbox, leads to additional losses of about 20%.
- **The generator**, which converts mechanical energy into electrical energy, engenders losses of around 4%. Therefore, a wind turbine with a typical three-bladed power system and an optimal tip-speed ratio can theoretically convert around 45% of wind energy into electricity.
- **Conversion efficiencies from installed systems are lower than theoretical efficiencies obtained in laboratories.** In real-world conditions, inferior performance results from manufacturing defects, bad electrical connections, maintenance, and malfunctions. Also, the electricity produced needs to be transmitted to end users via transmission and distribution lines, further increasing losses.[2]
- **Energy efficiency is an important parameter.[3] However, its impact is somewhat lower than for fossil fuels**, since wind energy is available for free and does not directly engender greenhouse gas emissions.

According to Betz's law, a maximum of about 59% of the energy in wind can theoretically be extracted from it

Power extraction of wind turbines
Power coefficient C_p



Drag loss: Drag is created when air resistance acts against the blades, lowering their efficiency and ability to generate energy. Reduced drag allows wind turbines to produce more power at lower wind speeds, increasing their productivity and efficiency.

Wake loss: As the wind passes through the upstream turbines in a wind farm, due to the energy extraction by the first-row turbines and churning effect of the rotating blades, the flow will get weakened and disturbed, which is termed the wake effect.

- Physical law, called **Betz's Law**, states that no turbine can capture more than **16/27 (59.3 percent)** of available kinetic energy of the wind, **regardless of the design of the wind turbine in open flow**. This implies that power coefficient **Cp** will never exceed Betz's limit.[1]
- In general, all **horizontal-axis wind turbines** (**HAWT**) are more efficient than **vertical-axis wind turbines** (**VAWT**) (Darrieus or Savonius rotors).
- However, despite the fact that **extracting maximum available power** from kinetic energy of wind is the main goal, these two vertical designs have significant issues with **aerodynamical forces** and **balance** which make them difficult to commercialize.
- On the other hand, **three-blade** design provides the most **reliability** and **stable power output**. Any design with greater number of blades is simply inefficient due to large air resistance caused by too many blades, assuming current blade design. However, as industry evolves toward larger rotors, there seems to be some room still left for experimental design.

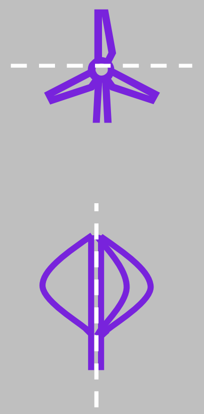
[1] Fraction of the wind power that can be effectively harnessed by the turbine
[2] Tip-speed ratio is the ratio between the tangential speed of the tip of a blade and the actual speed of the wind.
Sources: Energie+, Rendement des éoliennes, accessed January 2025; Gundtoft, 2009, Wind Turbines; Kearney Energy Transition Institute analysis

Wind turbines can be classified by location, foundation type, and turbine type

Non-exhaustive

A Axis

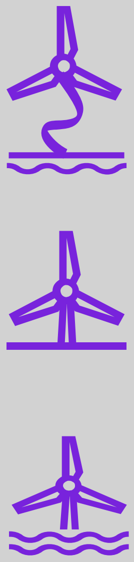
Position of the wind turbine



- Horizontal
- Vertical

B Location

Setting of the wind turbine



- Airborne (onshore or offshore)
- Onshore
- Offshore

C Foundation

Structure to support the turbine

Airborne
- Floating[1]

Onshore
- Gravity base
- Stone columns
- Piles
- Hybrid foundations
- Rigid inclusions
- Composite foundations

Offshore – fixed bottom
- Gravity base
- Tripod
- Monopile
- Jacket
- Suction bucket

Offshore – floating
- Barge
- TLP[2]
- Semi-submersible
- SPAR[3]

D Turbine

Conversion from kinetic energy to electricity

Drivetrain
- Gearbox
- Direct drive

Generator
- Permanent magnets synchronous
- Doubly fed induction
- Squirrel cage induction
- Electrically excited synchronous
- Wound-rotor induction

[1] Not covered in this factbook; [2] Tension leg platform; [3] Single point anchorage (SPAR) buoys

Sources: Nehad A. R. et al., 2022, Wind turbine drivetrains: state-of-the-art technologies and future development trends; Kearney Energy Transition Institute analysis

While wind turbines can theoretically have different axis configurations, vertical axis turbines are not commercially available today

A Axis
B Location
C Foundation
D Turbine

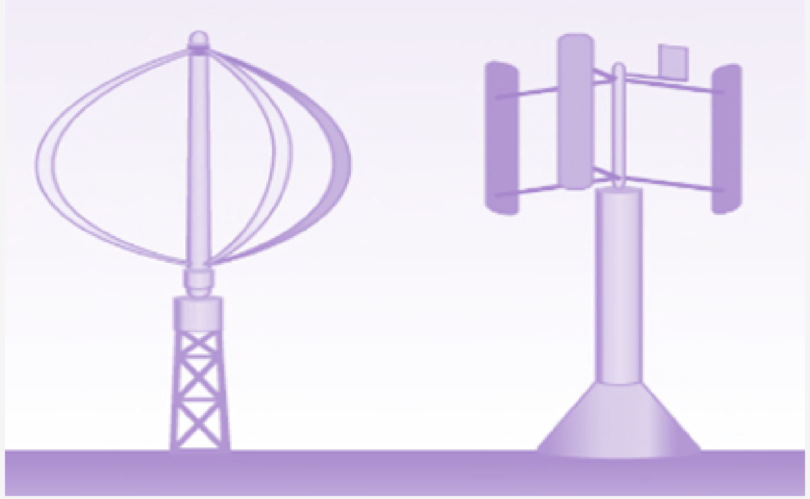
1.3 Wind power technologies

Horizontal axis

- **The horizontal wind turbine** is a turbine in which the axis of the rotor's rotation is parallel to the wind stream and the ground. They are of two types: upwind and downwind.
- The upwind turbine is a type of turbine in which the rotor faces the wind while in downwind turbines the rotor is on the downwind (lee) side. A vast majority of wind turbines have upward design. Its basic advantage is that it avoids the wind shade behind the tower.

Advantages	Disadvantages
– Blades are to the side of the turbine's center of gravity, helping stability. – Tall towers help access winds in a variety of sites	– Turbines face difficulties operating near the ground. – Tall towers and long blades are hard to transport and need special installation procedures.

Vertical axis



- **The vertical axis wind turbine is an old technology, and some of the earliest wind turbines were based on vertical axis designs.** The rotor rotates vertically around its axis instead of horizontally. Vertical turbines use lift, drag, or a mixture of the two.

Advantages	Disadvantages
– Easier and safer to build. – Can be mounted close to the ground – Can handle turbulence better than the horizontal axis	– Lower maximum efficiency (~30%), it is usually operated just for private use.

Sources: IPCC, 2011, Wind Energy in IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation; Kearney Energy Transition Institute analysis

Wind turbines can be installed in three different settings

A Axis

B Location

C Foundation

D Turbine

Airborne

An airborne wind turbine is a wind turbine with a rotor supported **in the air** without a tower, thus benefiting from the higher velocity and persistence of wind at high altitudes.

Airborne wind turbines have never been commercially deployed.

Advantages	Disadvantages
– Reduced material usage compared to conventional wind turbines – Can access higher altitudes – More mobile in operations	– Safely suspending and maintaining turbines under high winds and storms – Transferring the energy back to earth – Interference with aviation

Onshore

Onshore wind power refers to **land-based turbines**. They are typically located in sparsely-populated areas.

Onshore wind turbines have been extensively deployed.

Advantages	Disadvantages
– Less expensive than offshore – Quicker installation – Low impact on surroundings	– Higher variability in the operation – Physical blockages from buildings and landscape – Visual and noise factors

Offshore

Offshore wind refers to **turbines located in water bodies**, mainly sea.

The commercial deployment of these turbines is relatively recent.

Advantages	Disadvantages
– Greater electricity production due to higher wind speeds – More regular operation as wind speed and direction vary less – Less visual and sound impacts	– Higher costs due to complex infrastructure – Difficult conditions (waves and winds) – Requires more maintenance than onshore

Sources: Kearney Energy Transition Institute analysis based on desk research

Onshore wind turbine foundation types depend on soil structure and wind-turbine-intrinsic and operating characteristics

A Axis
B Location
C Foundation
D Turbine

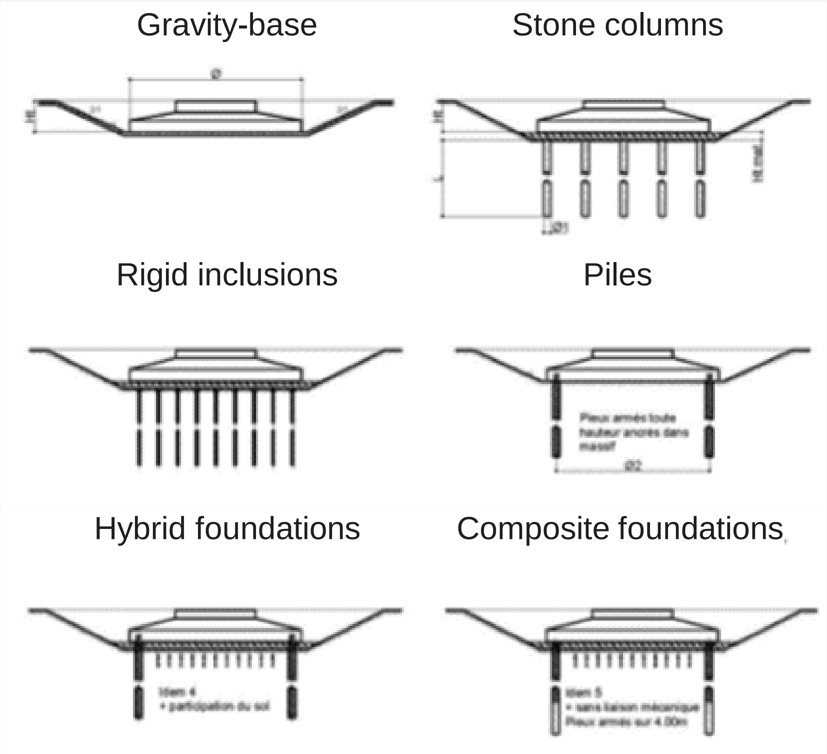
Spread foundations

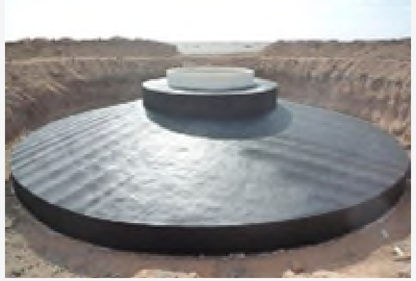
- **Shallow foundations** are dispersed on or just below the ground. The base area of the shallow foundation is sufficiently large to prevent topple of the wind turbine tower. It is easy to build, requires minimal excavation, and can be filled in quickly.
- **Gravity foundations** are positioned below the surface of the ground by digging the soil after construction. The excavated area is then either filled with the same soil or a different type of soil, depending on the project.

Pile foundations

- **Pile foundations** are used depending on the geological structures; the bed rock may occasionally be found at a relatively shallow depth. For greater wind turbine tower sustainability in such circumstances, the piles can be driven or positioned at such bedrock formation levels.
- **Pile-raft foundations are** the combination of spread foundations, and a number of piles is known as a "pile-raft foundation." Loads can be distributed equally over the top layer of soil by using a spread foundation.

Schematic diagram of different foundation types





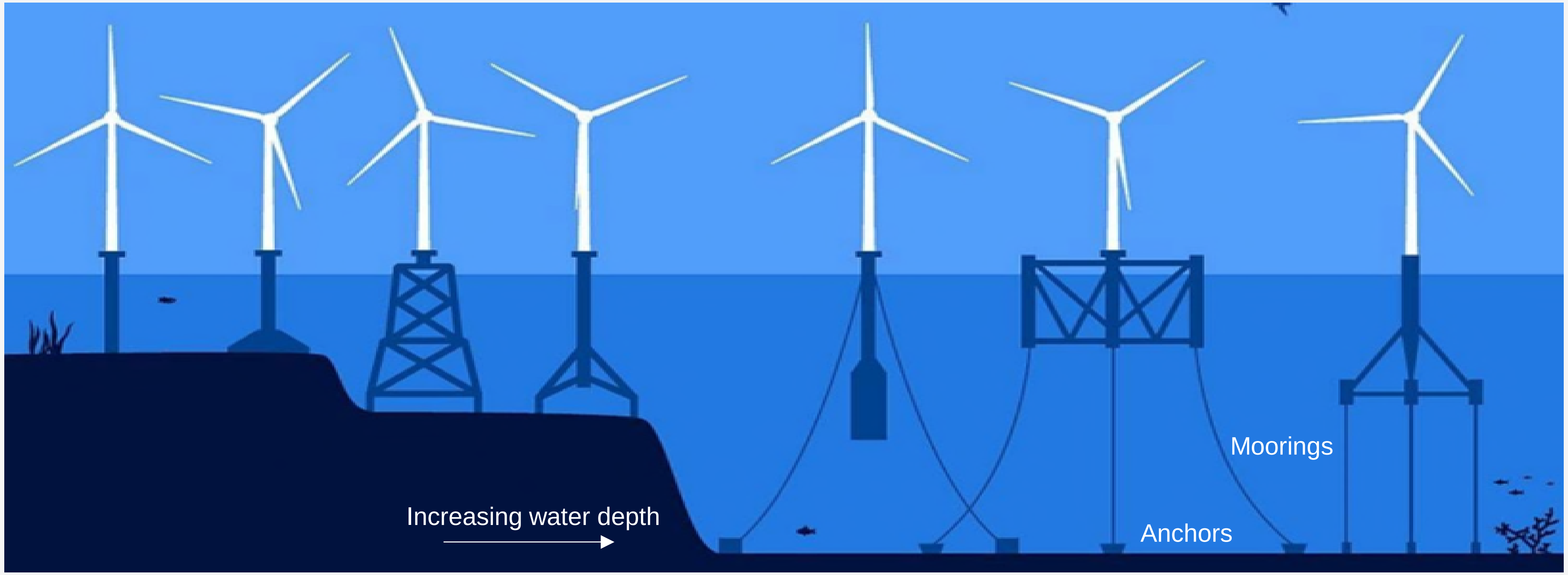
Sources: Kearney Energy Transition Institute analysis based on desk research.

1.3 Wind power technologies

Offshore wind turbine foundation types

Indicative; non-exhaustive

Offshore wind foundation types



Fixed-bottom foundations (usually <60 m depth)

There are **different types of fixed-bottom offshore wind turbine foundations** on which the turbine can be installed, depending on the **depth and substrate**.

Fixed-bottom offshore wind technology is substantially more mature than floating. In many regions of the world offshore wind still comes in at a high-cost relative to other energy sources.

Challenges remain, however, to further **integrate** the fixed-bottom offshore wind sector into maritime activities and setting up an industrial sector and dedicated port areas to manage the construction of a farm.

Floating foundations (usually >60 m depth)

The floating foundation—or floating sub-structure or floating platform—is the dynamic construct on which a floating offshore wind turbine is installed. The turbines themselves are the same as those used for fixed-bottom configurations.

Stabilization is achieved through one of three methods:
- **Gravity-stabilized:** increasing the distance between the center of gravity and the center of buoyancy
- **Waterplane-stabilized:** increasing the up-and-down movement of different angles of air across water, i.e. pitch moment
- **Moor-stabilized:** using mooring lines and anchors to keep the structure stable

Sources: Kearney Energy Transition Institute analysis

Kearney XX/ID

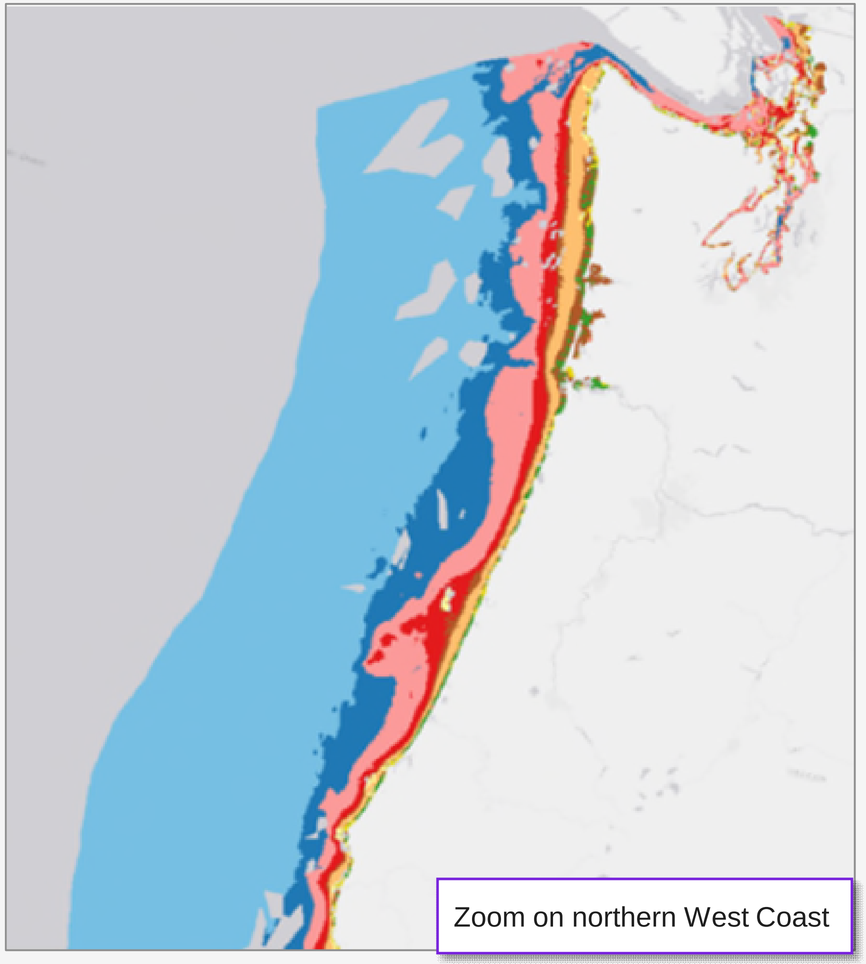
Appropriate turbine foundations are determined according to water depth and seabed composition

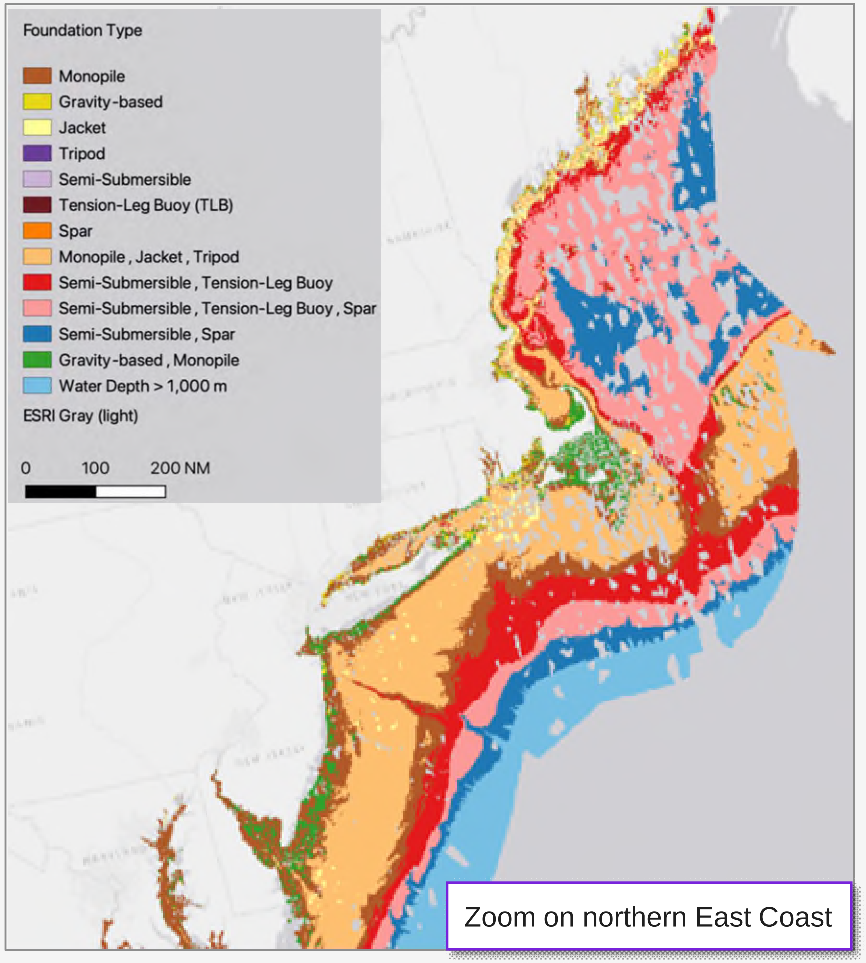
Indicative; example

- A Axis
- B Location
- C Foundation
- D Turbine

In general, the difference in bathymetry results in different substructure technology requirements.

US coast zones by turbine foundation type





West Coast: Relatively close to shore, in some cases less than 10 km from the coast, it is difficult to find water depths shallower than 1,000 m.

East Coast: The lease areas are close to shore, ranging from approximately 15–100 km off the coast, and in mostly shallow water. This implies monopile and gravity-based substructures will likely be predominant in these areas.

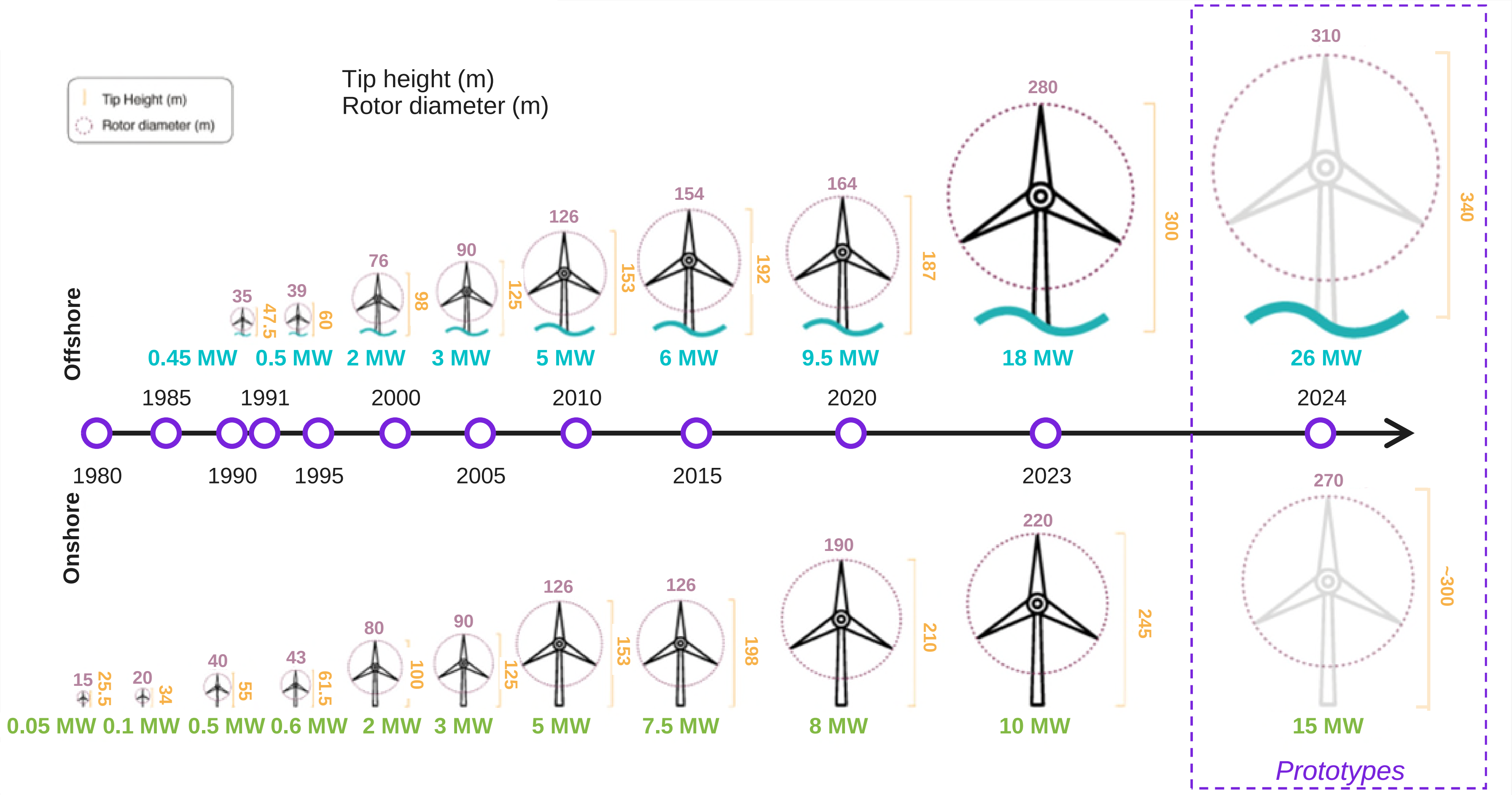
Note: NM corresponds to nautical mile (1852m)
Sources: Krauland, A. et al., 2023, United States offshore wind energy atlas; Kearney Energy Transition Institute analysis

Turbines have grown larger and taller to maximize energy capture over a range of wind speeds while lowering cost per unit of capacity

A Axis
B Location
C Foundation
D Turbine

Evolution of the onshore and offshore turbines

Maximum length of rotor blade + hub height and rating (MW)



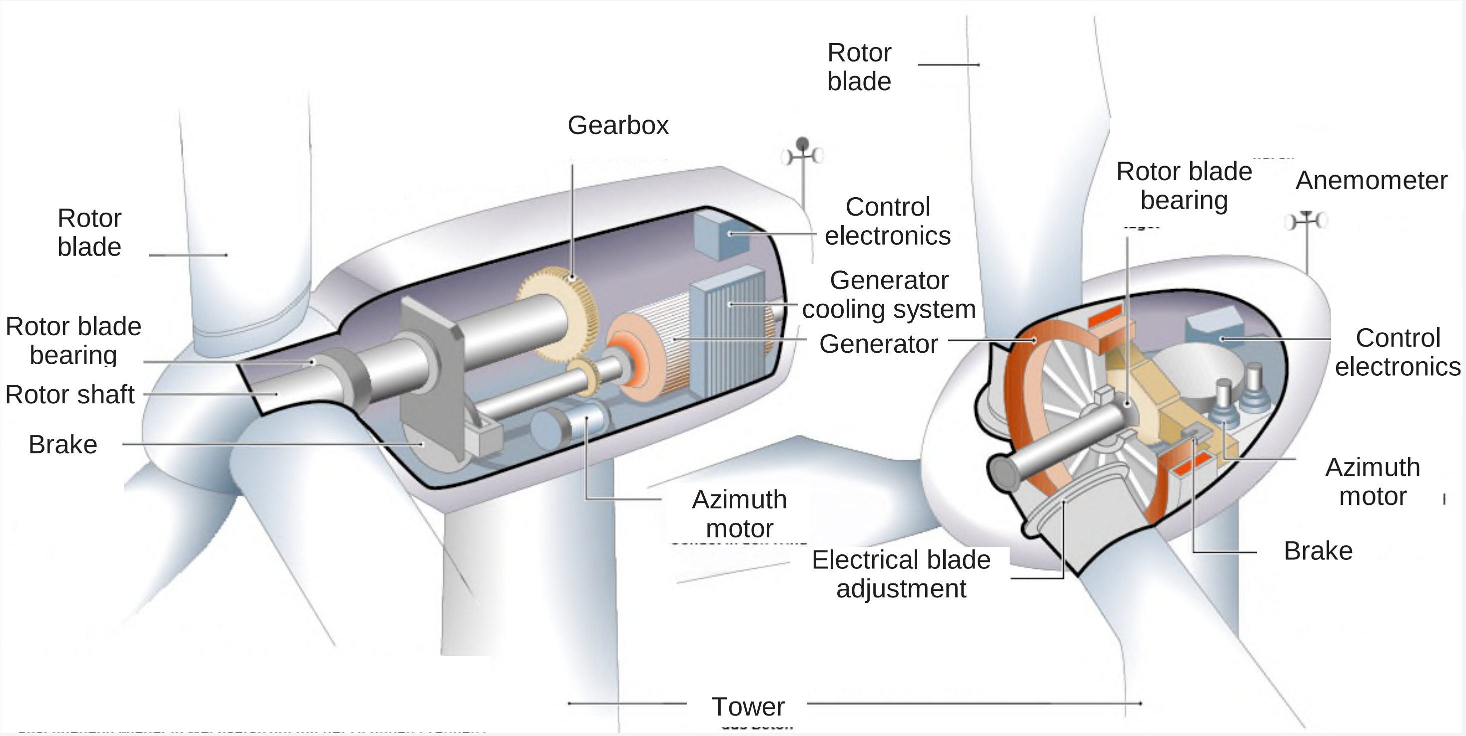
- **There is an important trade-off for wind-power developers between investment costs and capacity factor.** Higher turbines may incur higher upfront capital costs, but this may be offset by a higher capacity factor and lower generation costs.
- **Improved blade efficiency should help to capture more energy at lower wind speeds.**

Sources: GWEC, 2024, Global wind report; desk research; Kearney Energy Transition Institute analysis

A typical wind turbine is composed of three blades attached to a hub, containing a generator and a control system mounted on a tower

A Axis
B Location
C Foundation
D Turbine

Key components of a wind turbine



Most turbines have an upwind rotor with a yaw motor to turn the rotor and preserve alignment with wind direction. **Blades are attached to the hub, from which power is transferred through a gearbox or a direct drive to a generator.**

There are several designs for the layout of the rotor support, gearbox (when applicable), and generator, depending on manufacturer. Some designs avoid the use of a gearbox by using direct-drive instead.

The gearbox, generator, and control systems are contained within a housing unit called a nacelle. Electricity is transmitted down the tower from the generator to a transformer at the base of the tower.

Support structures are commonly tubular steel (and increasingly in conjunction concrete) towers tapering in some way (for example, in metal wall thickness and in diameter). Tower height is site specific and dependent on blade size.

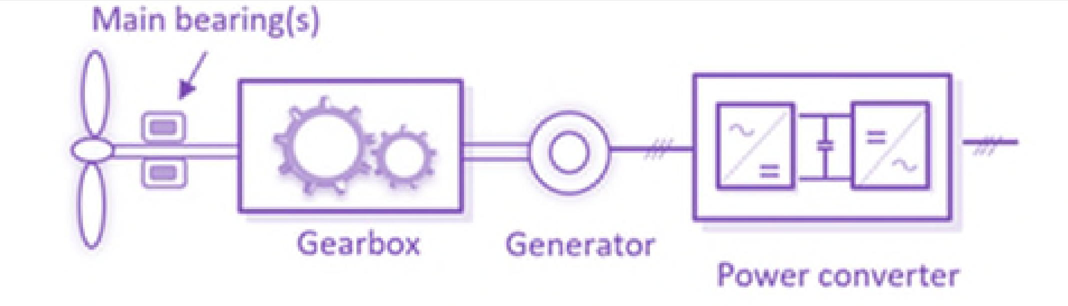
Sources: IPCC, 2011, Wind Energy in IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation; Kearney Energy Transition Institute analysis

Wind turbines produce electricity by transferring the kinetic energy to the generator

Drivetrain design is dictated by cost implications related to turbine reliability, operation and maintenance costs, but also the availability of rare earths.

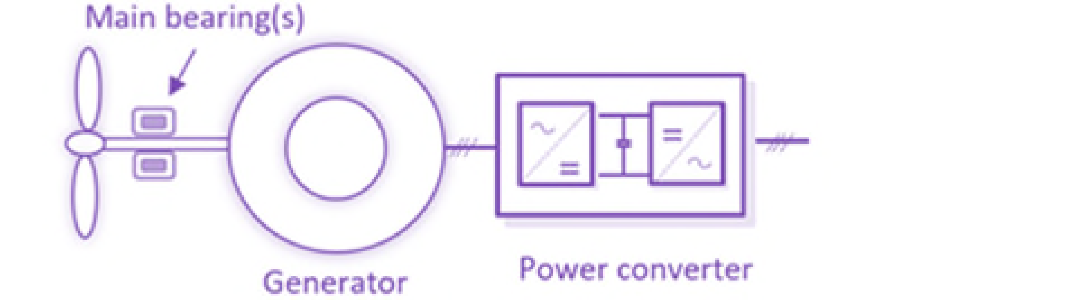
Drivetrain design principles for gearbox and direct drive

***Gearbox** increases rotational speed from rotor before feeding the generator, to reach a highest rotational speed.*



Advantages	Disadvantages
– Cheaper compared to direct drive – Allows the use of smaller generator	– Subject to failures due to high loads and stress from turbulences and high winds – Heaviest and highest maintenance element in a turbine

***Direct drive** allows the direct connection between the rotor and the generator and using the slow rotational speed from rotor.*



Advantages	Disadvantages
– Improves turbine reliability – Higher efficiency for higher power rating – Reduced mechanical noise – Less maintenance and repair costs	– Limited torque delivery – Higher cost

Sources: Nejad A. R. et al., 2022, Wind turbine drivetrains: state-of-the-art technologies and future development trends; Kearney Energy Transition Institute analysis

Induction generators are the most used type of generator in wind turbines, representing more than 96% of market share

Illustrative; non-exhaustive

A Axis
B Location
C Foundation
D Turbine

To achieve higher efficiencies, some new wind turbines are incorporating permanent magnets.[1]

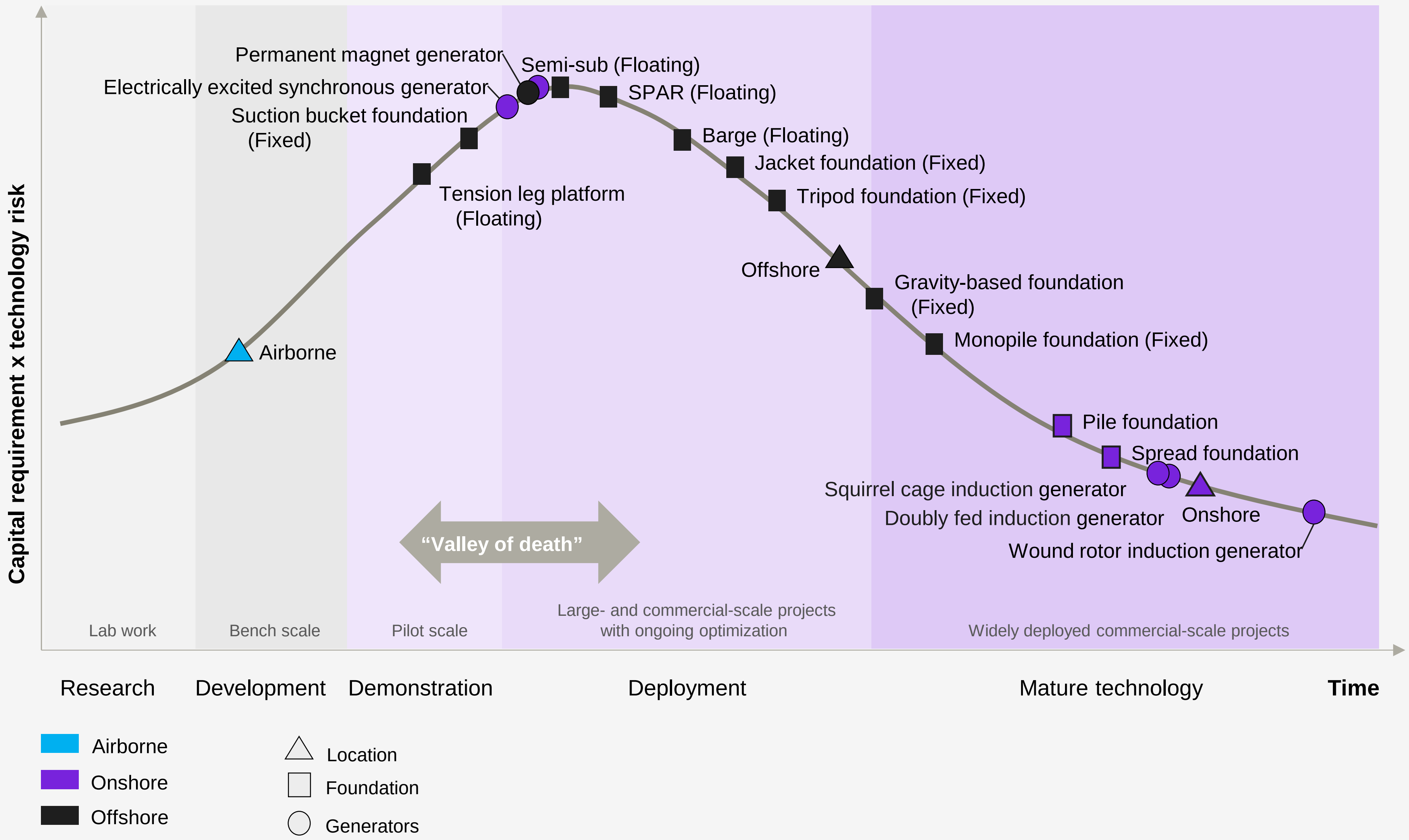
	Market share	Range (MW)	Drivetrain	Speed system	Advantages	Disadvantages
Doubly fed induction generator (DFIG)	49%	3–7	Gearbox	Variable	– Lower efficiency (due to Joule effect) – Less expensive – Simple design	– Increased maintenance and repair when generators have brushes and slip rings
Squirrel cage induction generator (SCIG)	48%	0.25–1.5	Gearbox	Fixed	– Simple and reliable design – Lower cost	– Requires a power rotor control
Permanent magnets synchronous generator (PMSG)	~3%	1–21	Gearbox or direct drive	Variable	– Higher efficiency – Less prone to failures – Less noise associated to the gear – Higher cost	– Rare earths used in permanent magnets
Electrically excited synchronous generator (EESG)	<1%	0.5–7.5	Gearbox or direct drive	Variable	– Less noise associated to the gear	– Heavier and larger than PMSG
Wound rotor induction generator (WRIG)	<1%	0.5–1.8	Gearbox	Fixed	– Simple and reliable design – Lower cost	– Increased maintenance and repair – Consumption of reactive power from the grid – Limited power quality control

[1] The latest developments have included permanent magnet generators, e.g., MingYang 24 MW, Siemens Gamesa 21 MW, and CRRC 20 MW.
Sources: Bensalah M.A. et al., 2018, Large wind turbine generators: State-of-the-art review; Chen H. et al., 2021, Modern electric machines and drives for wind power generation: A review of opportunities and challenges; Nejad A. R. et al., 2022, Wind turbine drivetrains: state-of-the-art technologies and future development trends; JRC, 2016, Wind Energy Status Report 2016; Kearney Energy Transition Institute analysis

Onshore wind is a mature technology while floating offshore wind deployment is expected to ramp up in the coming years

Non-exhaustive

Wind technology maturity curve



Sources: Kearney Energy Transition Institute analysis

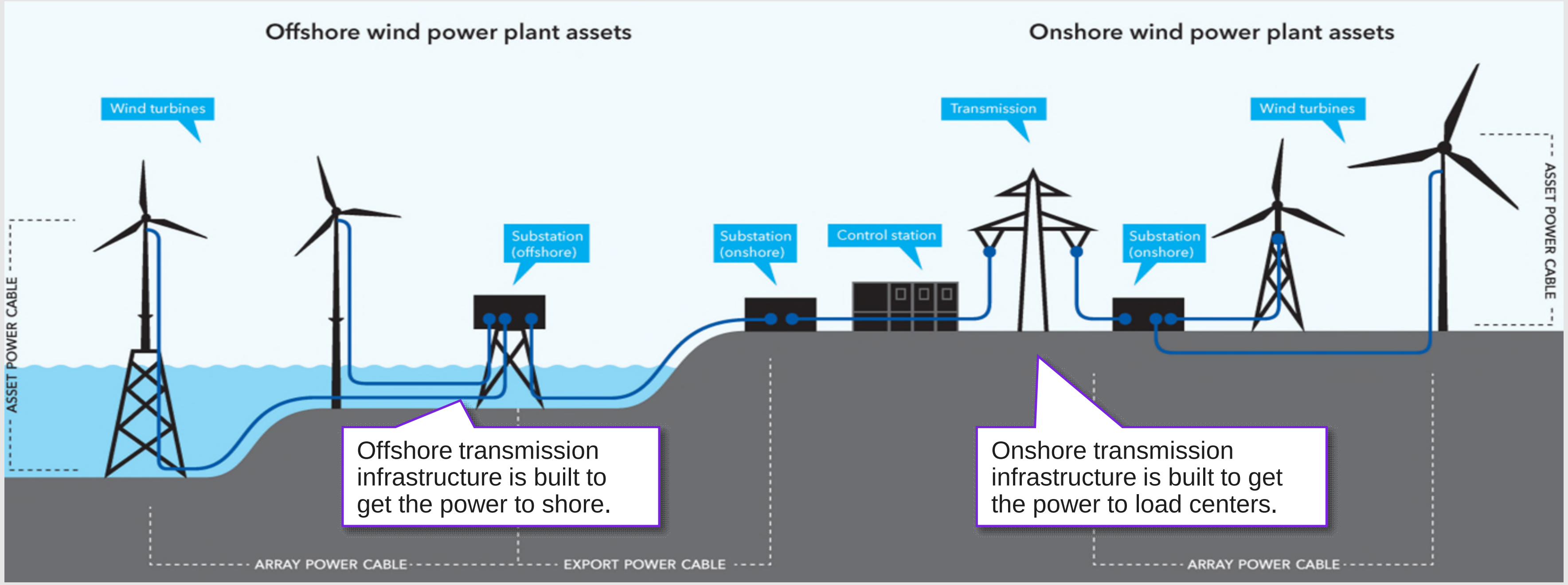
1.4 Maturity curve

A robust power transmission system is needed to transport electrical energy from wind assets

The cables used in floating offshore projects are **dynamic,** i.e., designed to follow and withstand the motion of the floating sub-structure caused by wind, waves, and current and are developed to be exposed to saltwater.

1.5 Transmission infrastructure

Wind power transmission concept



Cabling

The cable network sequence for offshore-to-onshore power transmission consists of:

- **Array cables:** They are used to transfer the power generated from the wind turbine to an offshore sub-station.
- **Export cables:** They are used to then transfer the power from the offshore sub-station to an onshore sub-station.

For onshore wind farms, only **array cables** are present.

Sub-station

- **Offshore sub-station:** Converts electricity to higher voltages suitable for long-distance transmission to onshore substations. It is usually fabricated offshore and installed directly on a jacket/monopile foundation.

- **Onshore sub-station:** It transforms power to reach grid voltage and can also be used to convert power from DC to AC if power was transported in DC. It can also host switchgears to provide protection from fault conditions.

Sources: IRENA, 2024, Floating offshore wind outlook; Kearney Energy Transition Institute analysis

2. Market status and projections

Market status and projections

History of wind power

– **Wind has been used for millennia** for propulsion, water pumping, and grain grinding. **Electricity generation** began in the **late 19th century**, with the first commercial onshore wind farm a century later, followed by offshore a decade after.

Wind power potential

– Wind power technical potential falls in the mid-range, relative to other renewable sources. **About 3.5% of this technical potential** is needed to reach **net zero emissions** by 2050.

Wind generation in power mix

– In 2023, wind power capacity generated about 2,300 TWh, which corresponds to **8% of global electricity production**.

Wind power capacity

– Wind power reached **1 TW of installed capacity in 2023**, mostly driven by Asia and Europe. **China dominated by far, with 442 GW**. **Europe accounts for less than 30%** of global capacity; Germany with 70 GW is the largest market followed by Spain with 31 GW. **North America has 172 GW** of wind power capacity, with the United States accounting for 86% of it.

– When looking at the split between onshore and offshore, **onshore wind power capacity** represents about **93% of total installed capacity** and **global offshore capacity** represents the remaining **7%**. **China is leading each segment with 405 GW and 37 GW** respectively.

Wind power projects pipeline

– From the pipeline of 130 GW **under construction, onshore represents 77% (100 GW)** of the total pipeline while offshore accounts for the rest. At **permitting stage there is 183 GW of onshore** projects, **while offshore projects account for about 303 GW**. However, signs of growing interest for floating technology are visible with 244 GW of projects in the pipeline at different stages (under permitting and announced).

Capacity factor

– The global weighted **average capacity factor of onshore wind** increased from 27% to **36%** between 2010 and **2023**, driven primarily by technological advancements. For newly commissioned **offshore wind** farms, the capacity factor has increased from 38% to **41%** in the same period.

Wind power projections

– By **2050**, wind energy is expected to **deliver between 21 and 29% of global electricity**, second to solar PV at 37-42%.

2.0 Chapter summary

Humankind has leveraged wind energy for millennia, but only commercialized the renewable source for power generation in recent decades

5,000 BC Wind used to propel boats along River Nile.

200 BC Wind-powered water pumps used in China; windmills used to grind grain in Middle East.

1850s Daniel Halladay **patents first commercial windmill** and creates US Wind Engine and Pump Company for production and sale.

1880s James Blythe builds **first turbine for electricity generation** in Glasgow; Charles Brush installs first US turbine.

1980 First commercial onshore farm, Crotched Mountain, in New Hampshire by US Windpower (0.6 MW. 20 turbines).

1991 First offshore farm, Vindeby, in Denmark by DONG Energy (4.95 MW, 11 turbines)[1]

2001 EU sets target to double share of renewable energy in energy mix by 2010, propelling wind development.

2007 First full-scale floating turbine, Hywind Demo, in Norway by Equinor.

2012 Alta Wind Energy Centre built in California by Terra-Gen Power; named largest onshore farm globally (1,320 MW, 440 turbines).

2014 Wind achieves cost parity with fossil fuels in several European countries.

2015 Gansu Wind Farm in China named **largest onshore farm (8,000 MW with planned expansion to 20,000 MW).**

2017 First floating farm, Hywind Scotland, by Equinor (30 MW, five turbines).

2019 Global wind capacity reached 651 GW; significant contributions from China, Europe, and US.

2020 Hywind Tampen built in Norway by Equinor named **largest floating farm (88 MW).**

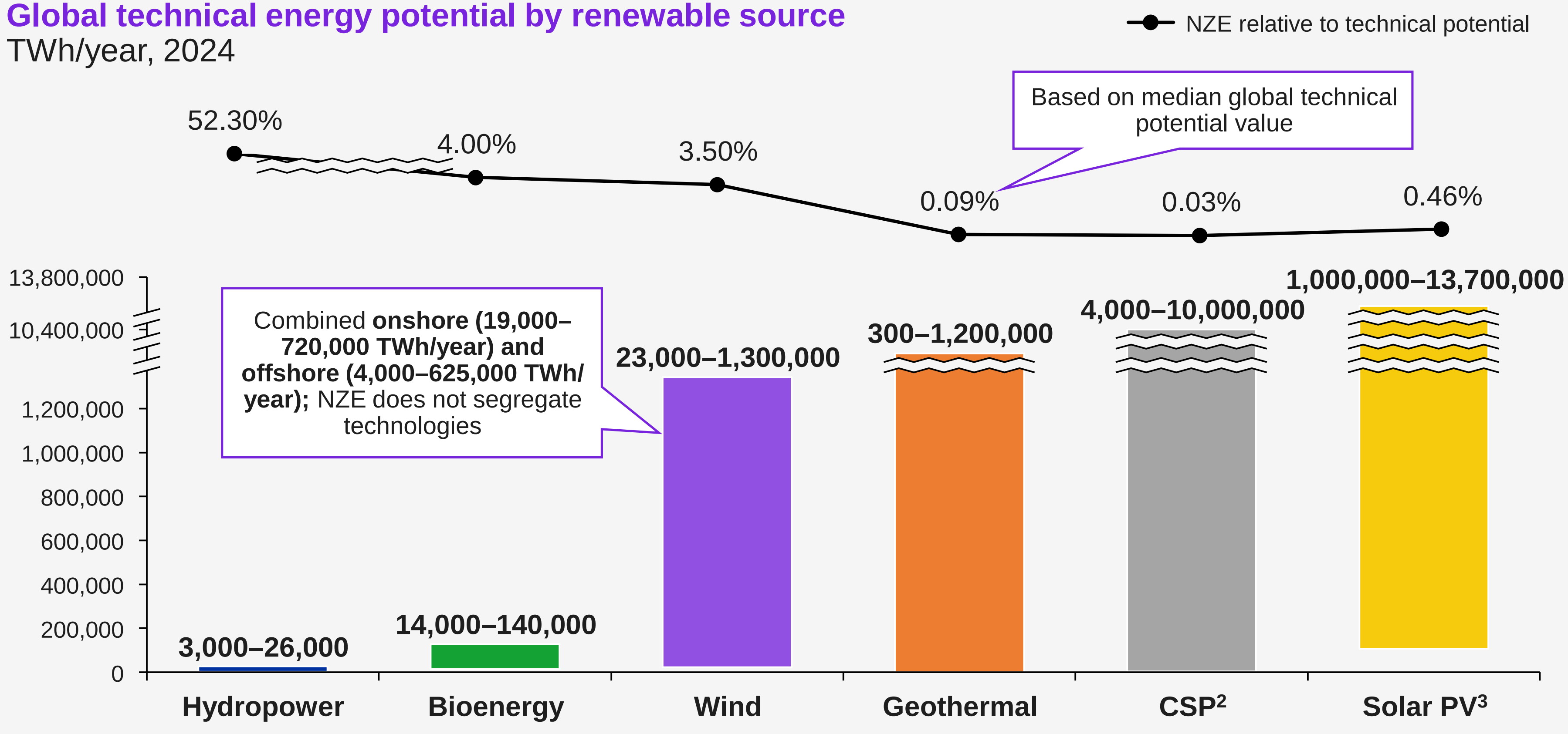
2022 Hornsea 2 built in England by Ørsted named **largest offshore farm (1,386 MW).**

[1] Now Ørsted

Sources: Equinor, 2024, Hywind Tampen; European Commission, 2024, Renewable energy targets; Gipe, P., 2023, Austrian was First with Wind-Electric Turbine Not Byth or de Goyon; IRENA, 2024, FLOATING OFFSHORE WIND OUTLOOK; National Grid, 2024, The history of wind energy; Ørsted, 2024, Making green energy affordable; Ørsted, 2024, Hornsea 2 Offshore Wind Farm; QFWE, 2024, GLOBAL FLOATING WIND MARKET & FORECAST REPORT; Tarantino, J., 2023, The largest and most spectacular wind farms in the world; The Guardian, 2008, Timeline: The history of wind power; Wind Energy Technologies Office, 2024, History of U.S. Wind Energy; Kearney Energy Transition Institute analysis

Wind energy offers mid-range potential relative to other renewable sources, but falls at the upper end of utilization in the NZE scenario[1]

Global technical energy potential by renewable source
TWh/year, 2024



	Hydropower	Bioenergy	Wind	Geothermal	CSP[2]	Solar PV[3]
Median potential	14,765	76,390	683,235	795,155	5,202,085	6,888,000
NZE 2050	7,720	3,055	23,940	739	1,330	34,070

2.2 Wind power potential

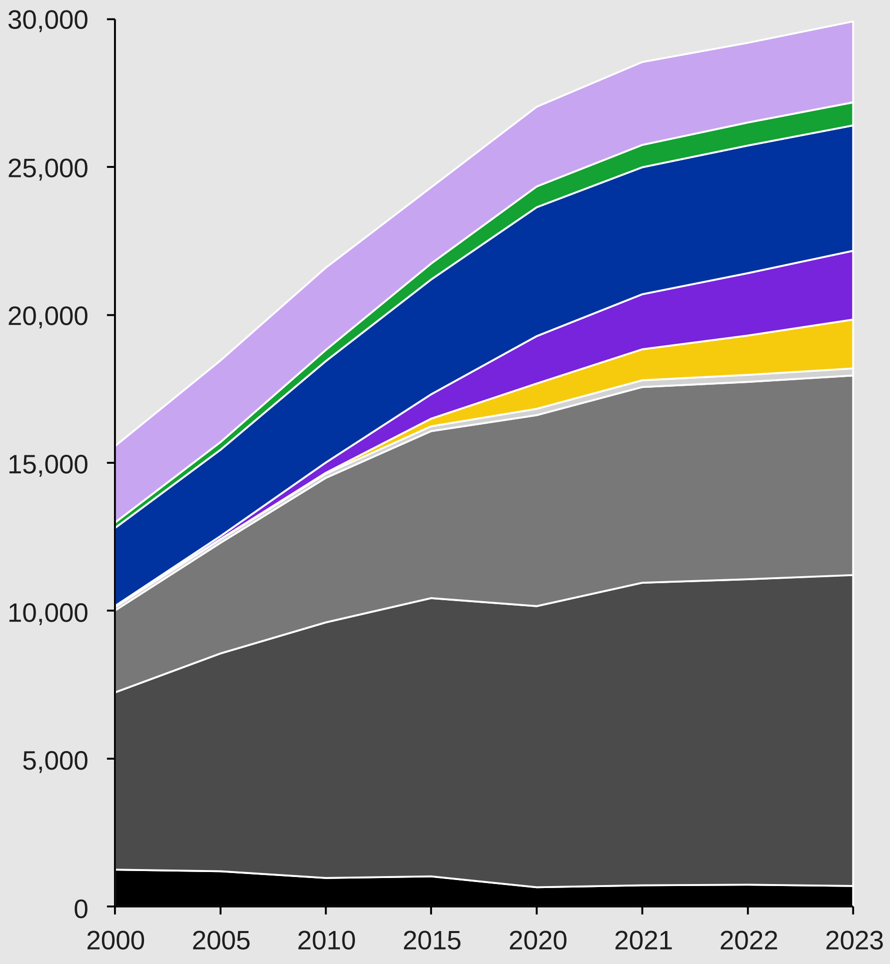
[1] Net Zero Emissions by 2050
[2] Concentrated solar power
[3] Combined utility (101–13,600 PWh/year) and rooftop (6–101 PWh/year).
Sources: de la Beaumelle, N. A. et. al, 2023, The Global Technical, Economic, and Feasible Potential of Renewable Electricity; IEA, 2024, World Energy Outlook 2024; Kearney Energy Transition Institute analysis

Wind energy generated about 2,300 TWh in 2023, accounting for nearly 8% of global electricity generation

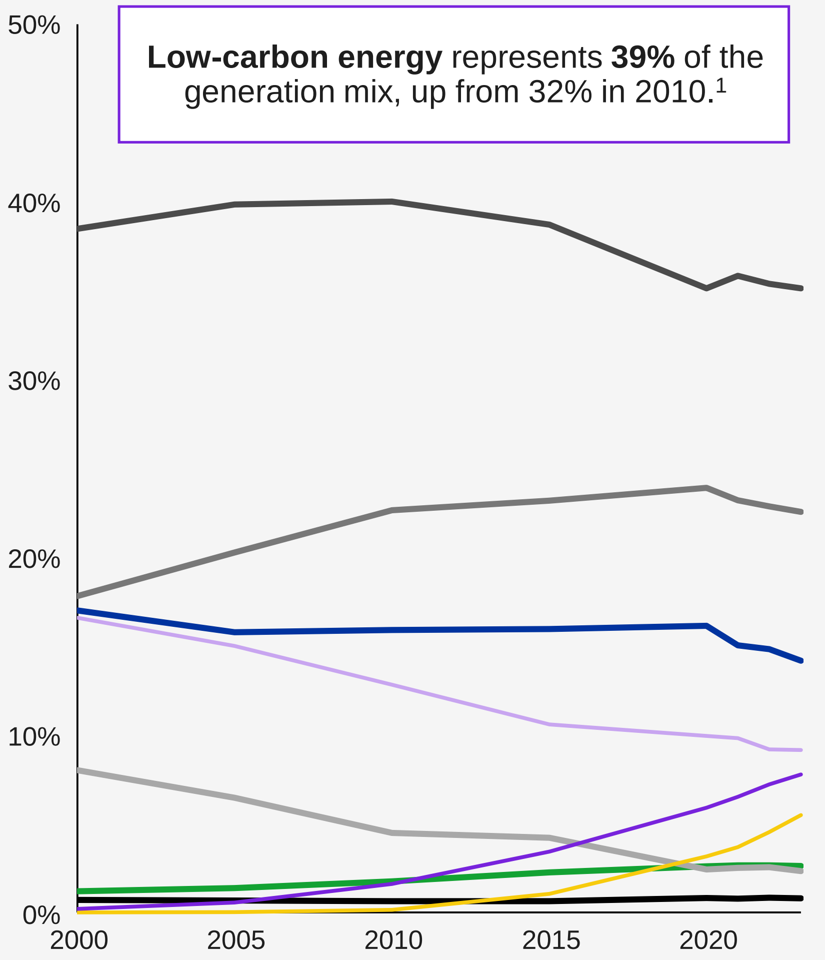
Wind power supplies about 8% of global electricity, an increase of more than 6 percentage points since 2010.

2.3 Wind generation in the power mix

Global electricity generation
TWh, 2000–2023



Energy sources percentage in generation mix, %



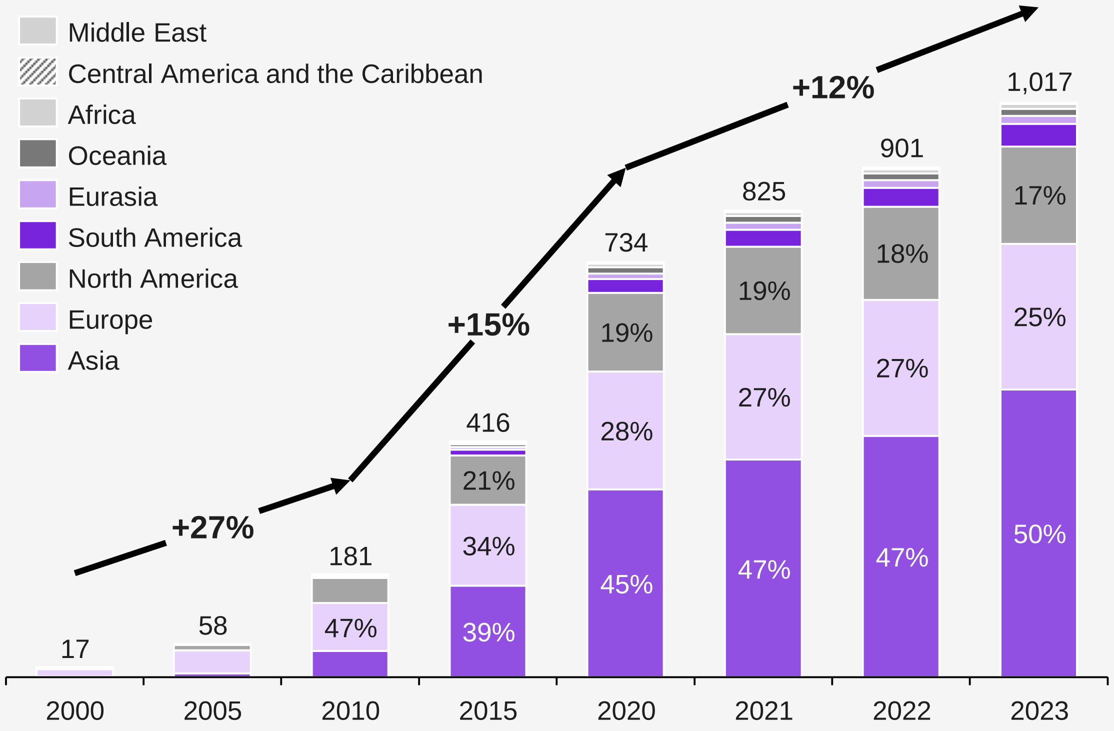
Nuclear | Biomass and geothermal | Hydro | Wind | Solar | Other fossil fuels | Gas | Coal | Oil

[1] Low-carbon energy includes nuclear, hydro, renewables.
Sources: Energy Institute, 2024, Statistical Review of World Energy; IRENA, 2024, Renewable capacity statistics; Kearney Energy Transition Institute analysis

Global installed wind capacity surpassed 1 TW in 2023 while wind share in the global electricity mix accounts for 8%

Global installed wind capacity by region

GW, 2000–2023

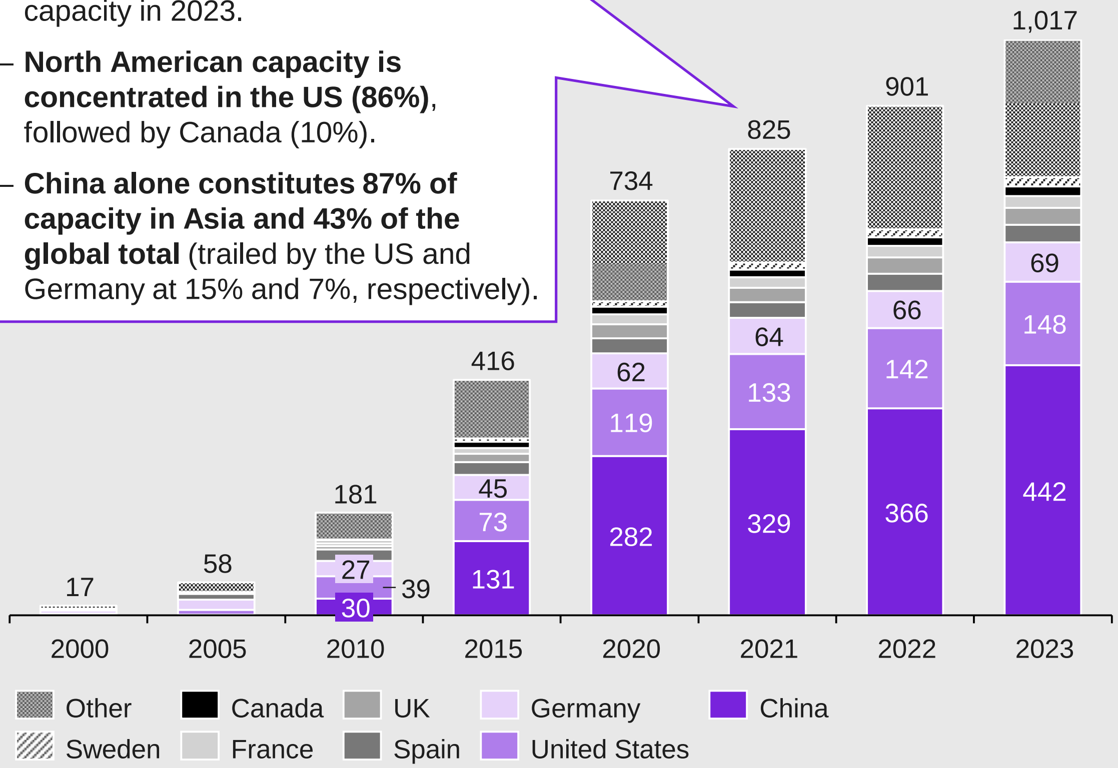


2.4 Wind power capacity

Installed wind capacity by country

GW, 2000–2023

- **European capacity is dispersed**; nine countries accounted for 81% of capacity in 2023.
- **North American capacity is concentrated in the US (86%)**, followed by Canada (10%).
- **China alone constitutes 87% of capacity in Asia and 43% of the global total** (trailed by the US and Germany at 15% and 7%, respectively).

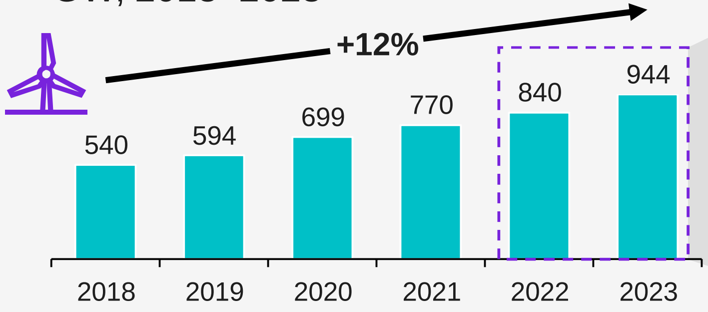


Sources: IRENA, 2024, Renewable capacity statistics; Kearney Energy Transition Institute analysis

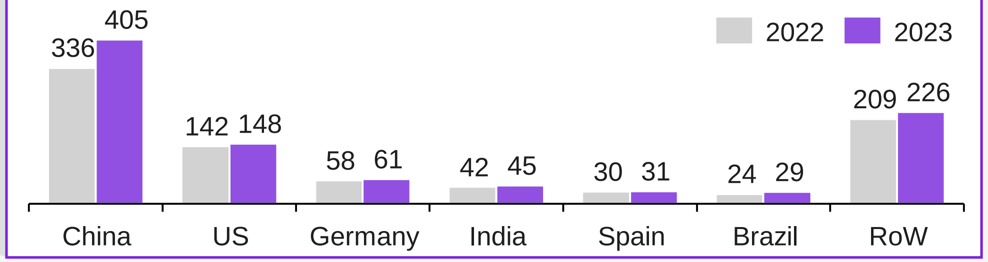
Wind global capacity has been driven by massive onshore capacity additions, mostly concentrated in China and the United States

Non-exhaustive; illustrative

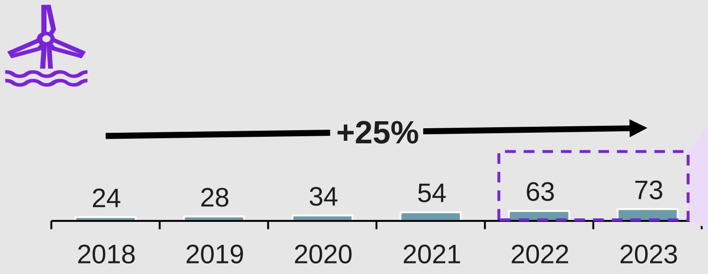
Global onshore capacity evolution
GW, 2018–2023



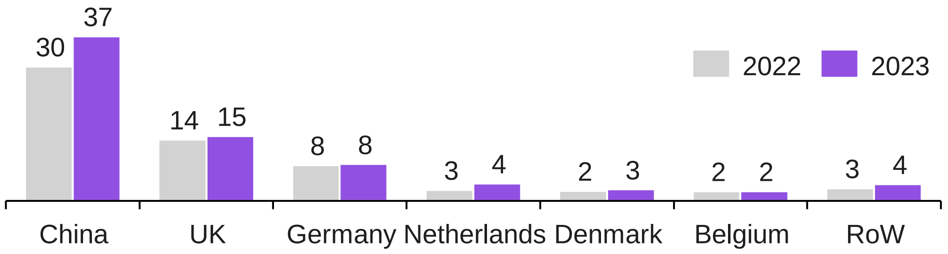
Wind onshore installed capacity by country
GW, 2022 and 2023



Global offshore capacity evolution
GW, 2018–2023



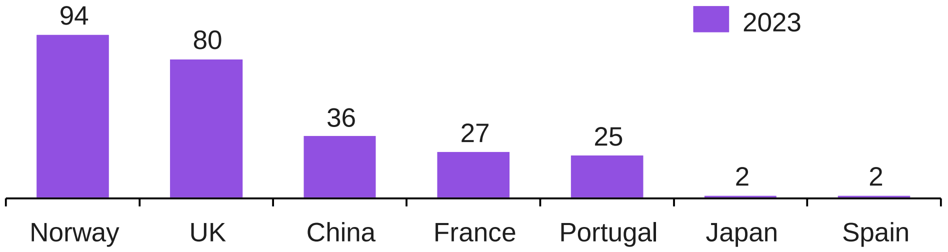
Wind offshore installed capacity by country
GW, 2022 and 2023



Global floating offshore capacity
MW, 2023

Floating offshore is still nascent and has around **270 MW** of **operating capacity** as of 2023.

Floating offshore installed capacity by country
MW, 2023



Sources: IRENA, Power capacity and generation from IRENASTAT, accessed December 2024; IRENA, 2024, Floating offshore wind outlook; Power Technology, Power plant profile: Goto floating wind farm, Japan, 2024; CRCC installs "World's largest' floating offshore wind turbine in China," 2025; Kearney Energy Transition Institute analysis

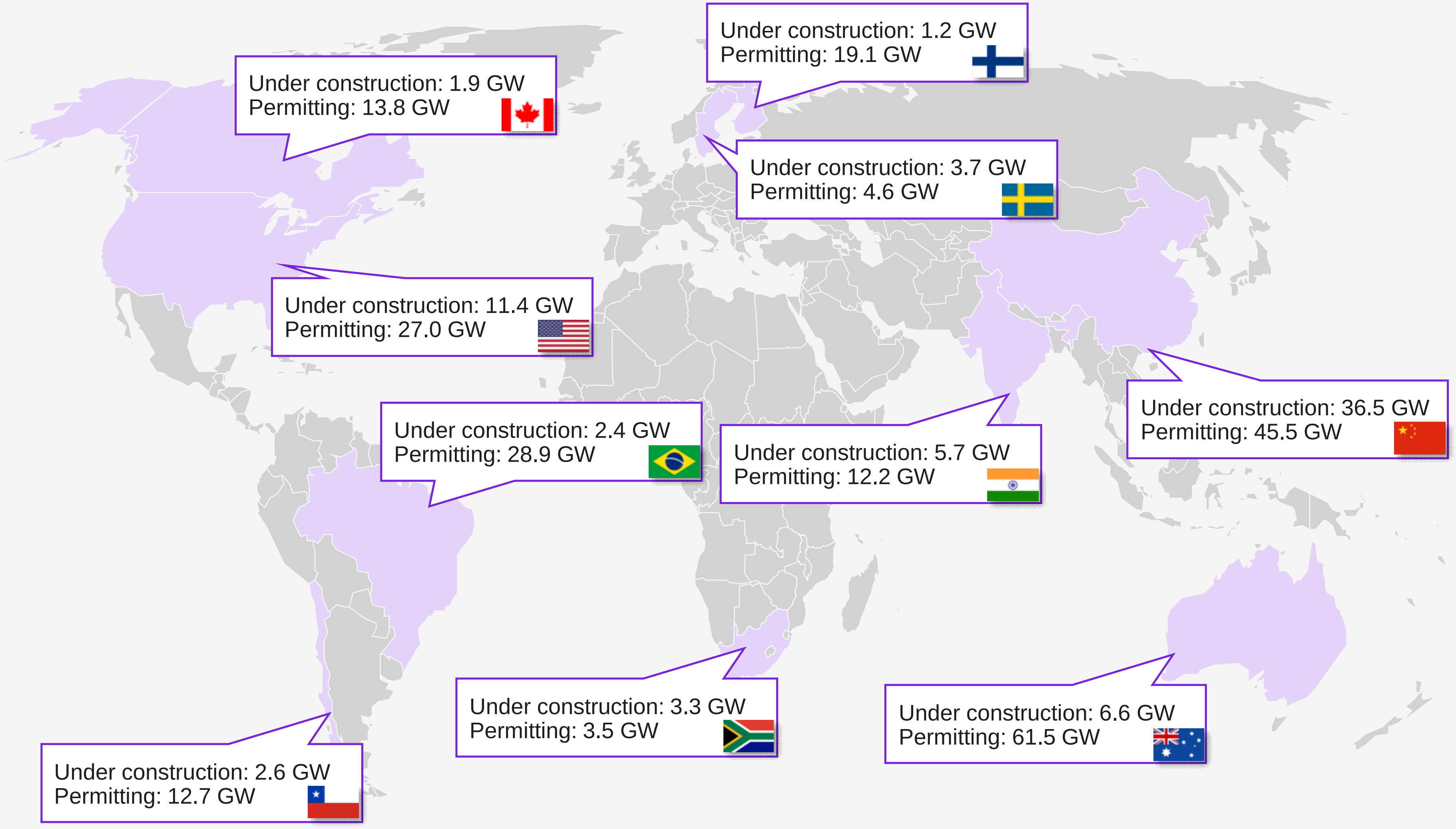
2.4 Wind power capacity

Almost 100 GW of onshore wind capacity is currently under construction, and about 412 GW is in the permitting stage

In the rest of the world, an additional **22.9 GW** are currently **under construction** and more than **183 GW are undergoing permitting processes**.

2.5 Wind power projects pipeline

Top 10 countries with largest onshore pipeline
GW, as of December 2024, 2025–2039

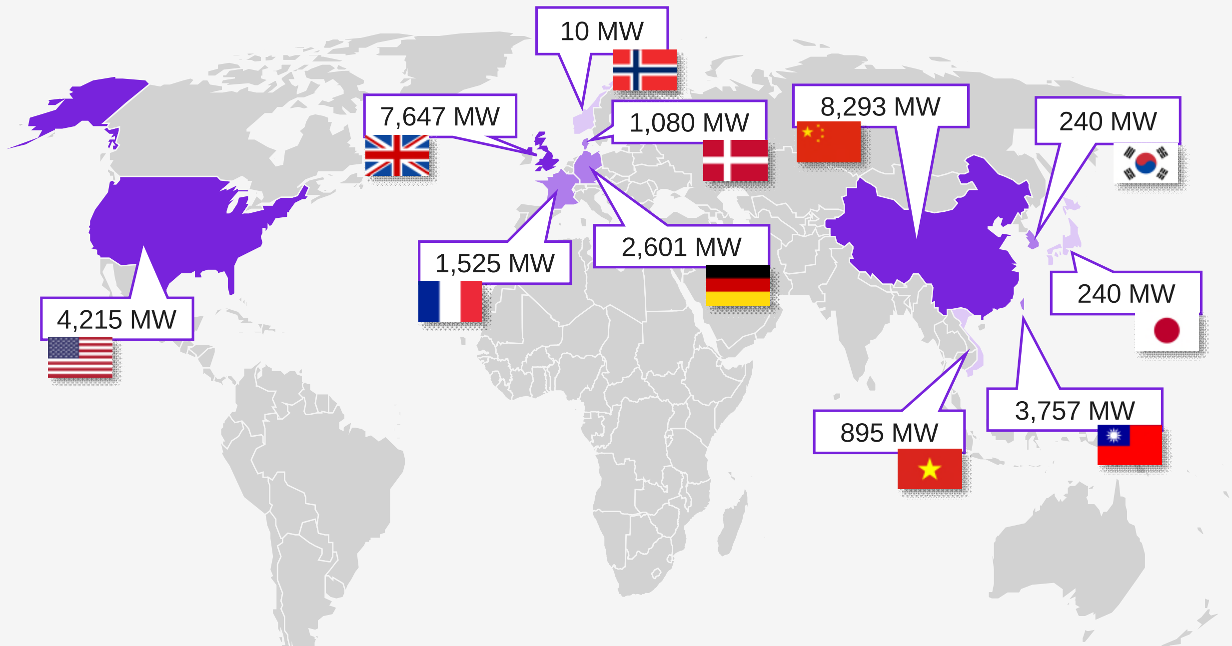


Note: The permitting pipeline includes projects in broad stages of permitting development, including permitted projects.
Sources: GlobalData, 2024, List of upcoming wind power plants; Finish Renewable energy association, Wind power projects in Finland, 2025; Kearney Energy Transition Institute analysis

Offshore pipeline has been increasing in recent years, but the 30 GW currently under construction are limited to a dozen countries

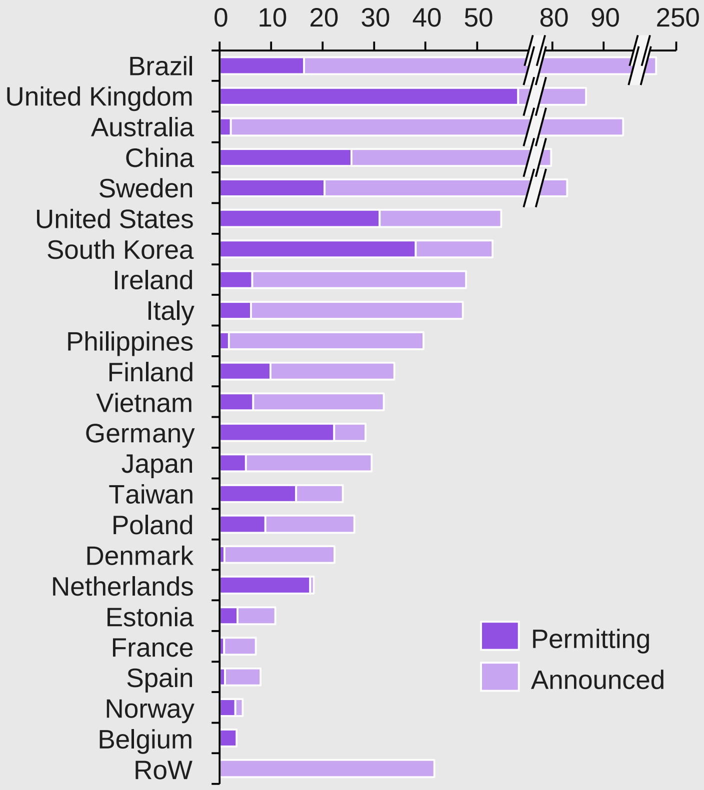
Non-exhaustive

Offshore wind projects under construction
As of December 2024



Since last year, several projects have been halted or even cancelled in the United States and Europe. Recent policy changes are putting the offshore pipeline at risk.

Offshore wind project pipeline
GW, as of December 2024, 2025–2039



Floating offshore wind

The **global pipeline for floating** capacities is about **244 GW** as of November 2023, including countries with operating installations and others, such as Italy, Japan, Republic of Korea, and the United States, that are actively developing offshore projects.

Of this pipeline:

- **175 GW** consist of projects in **early stages of development.**
- **68 GW** include projects in **planning and/or with lease agreements.**
- **576 MW** are in **pre-construction phase.**
- **46 MW** are currently **under construction**.

Sources: IRENA, 2024, Floating offshore wind outlook; GlobalData, 2024, List of upcoming wind power plants; Kearney Energy Transition Institute analysis

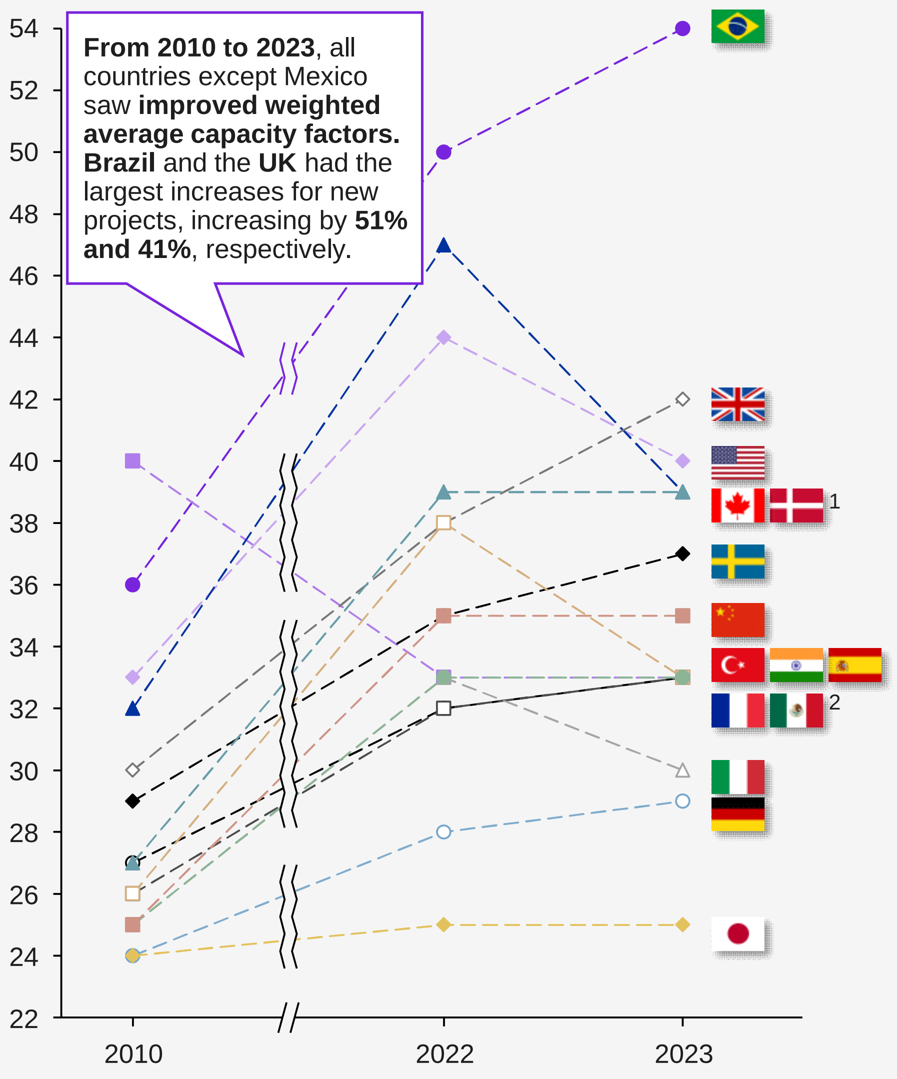
From 2010 to 2023, global onshore and offshore wind capacity factors rose by 25% and 8%, respectively, driven by technological advancements

In 2023, new onshore wind projects saw slight capacity factor declines in some regions due to expansion into lower-wind areas. This change was driven by the shift toward projects closer to population centers to reduce transmission constraints and the saturation of high-wind areas.

2.6 Capacity factor

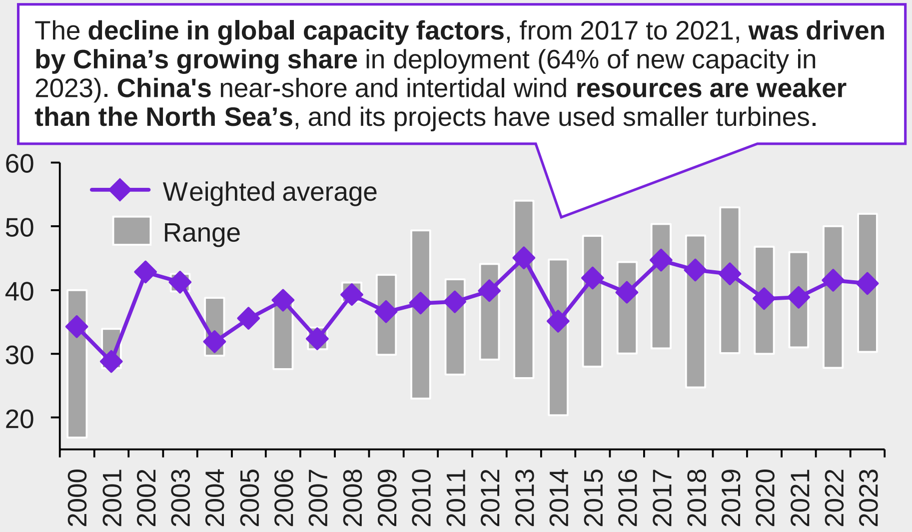
Average capacity factor for new onshore wind from selected countries

%, 2010–2023



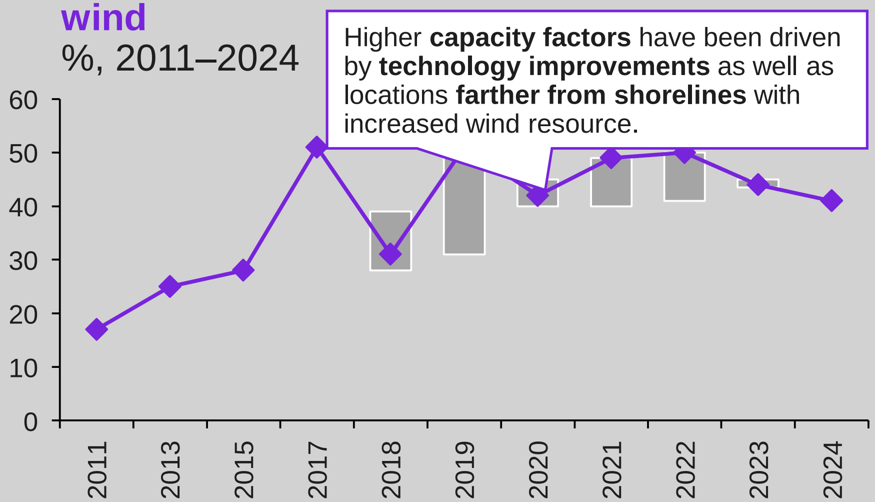
Global capacity factors for offshore wind

%, 2000–2023



Global capacity factors for floating offshore wind

%, 2011–2024



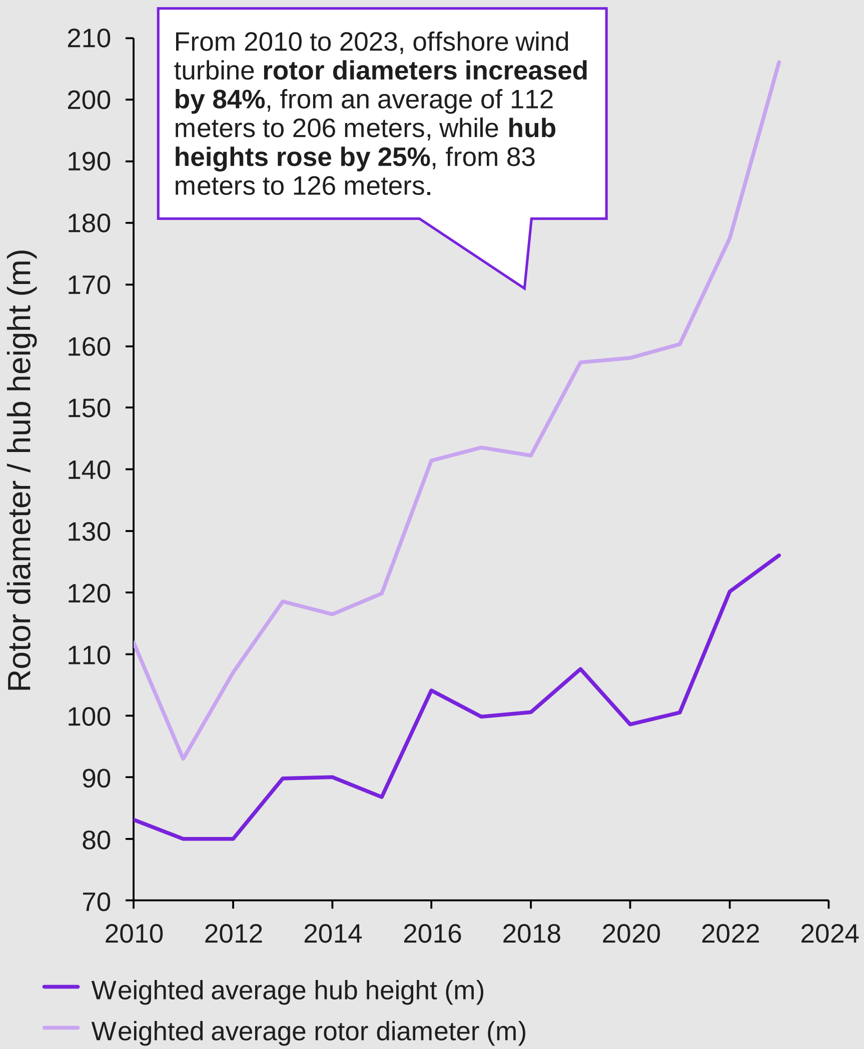
1 Denmark has data available only for projects commissioned in 2020; 2 Mexico has data available only for projects commissioned in 2022.
Sources: IRENA, 2024, Renewable Power Generation Costs in 2023; IRENA, 2024, Floating offshore wind outlook; Kearney Energy Transition Institute analysis

From 2010 to 2023, advancements in offshore wind technology drove capacity factor gains despite the variability of wind resources

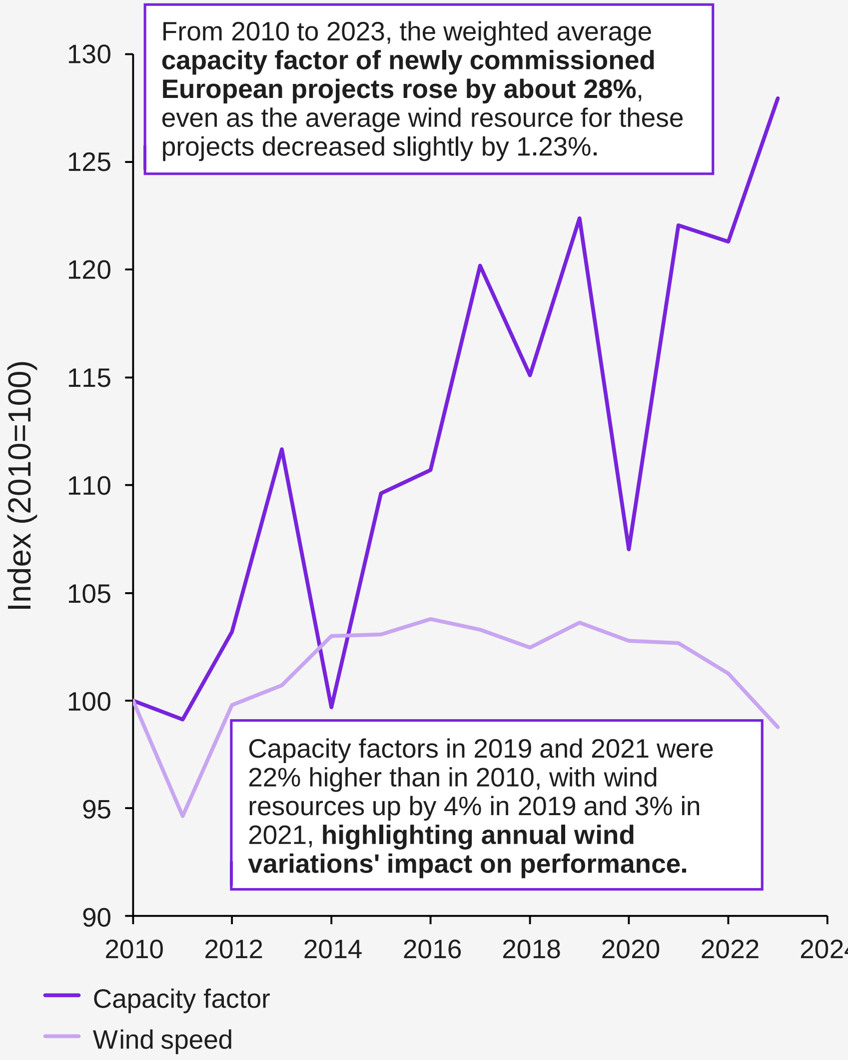
Rotor diameters have grown faster than hub heights, resulting in a decrease in specific power (W/m²). This trend, especially evident in Europe, has positively influenced capacity factors, as lower specific power levels can improve capacity factors in suitable conditions.

2.6 Capacity factor

Global weighted average offshore wind rotor diameter and hub height
m, 2010–2023



Capacity factor and wind speed trends by project in Europe
2010–2023



Sources: IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

Wind energy is expected to deliver 21–29% of global electricity by 2050, second to solar PV at 37–42%

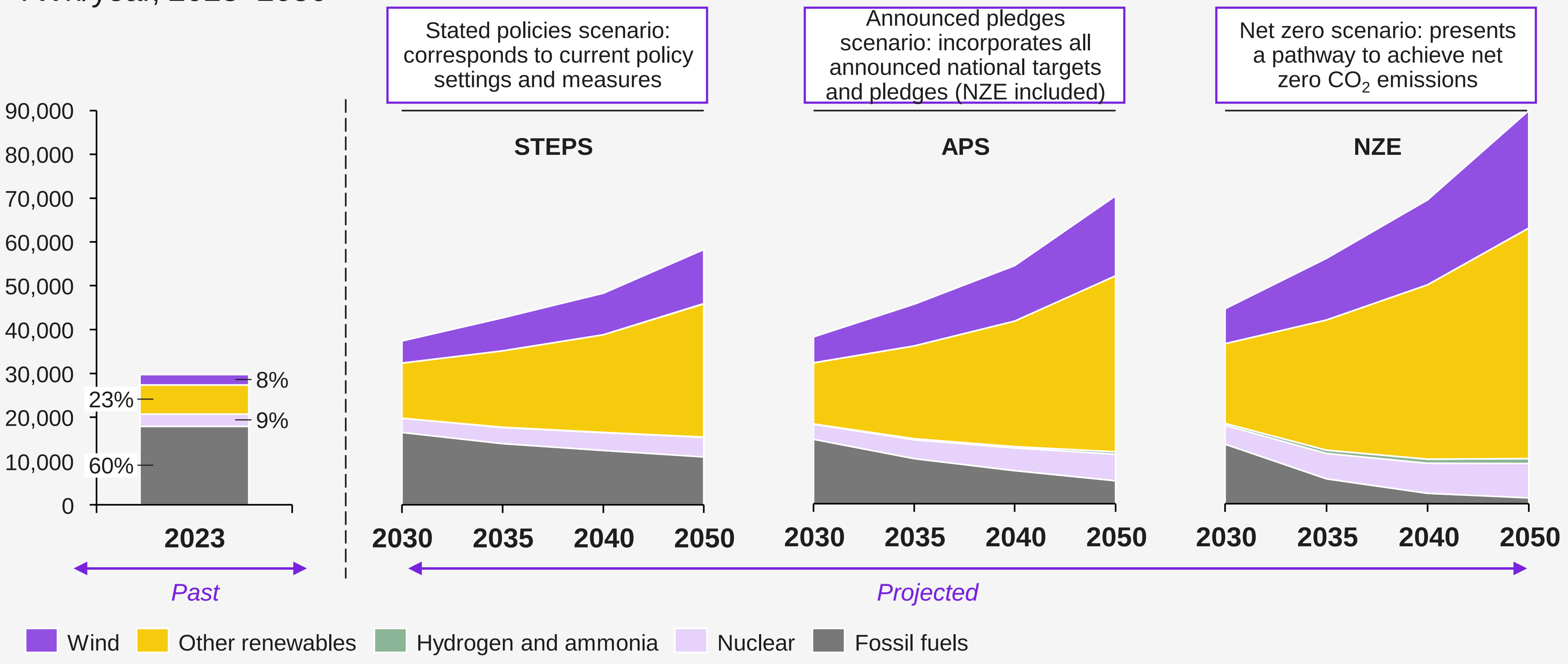
Higher utilization of wind energy in future scenarios is driven by the **technology's relative maturity, ease of scalability, and favorable policy incentives.**

[1] Fossil fuels include coal, oil, natural gas, natural gas with CCUS, and coal with CCUS
[2] Renewables include solar PV, wind, hydropower, bioenergy, geothermal, CSP, and marine.
Sources: IEA, 2024, World Energy Outlook 2024; Kearney Energy Transition Institute analysis

2.7 Wind power projections

Global electricity generation by source and scenario

TWh/year, 2023–2050



Key insights

- **Fossil fuels dominate electricity generation in 2023** at 60% of the total mix, driven by coal (36%) and natural gas (22%).[1]
- **Renewables trailed behind fossil fuels in 2023** at 30% of the total mix, namely hydropower (14%), wind (7.9%), and solar PV (5.4%).[2]
- **Electrification of end-use sectors, such as buildings and transport, will increase demand electricity supply** from ~30 TWh in 2023 to ~58–80 TWh in 2050 (96 to 169% increase).
- **Wind energy supply will increase by 429 to 925%** from 2023–2050 to address increasing demand as well as displace fossil fuels.

3. Key players of the wind power value chain

Key players of the wind power value chain

Wind stakeholders

– **The wind energy sector** features a **complex value chain requiring significant geographic diversification to meet regional demands.**

Wind turbine manufacturers

– **China leads global wind turbine manufacturing, contributing to 68% of onshore and 65% of offshore capacity additions in 2023 among top players. Chinese manufacturers** dominate their domestic market and are expanding internationally, **with exports rising more than 60% in 2023**, with countries like Uzbekistan, Egypt, and South Africa among top buyers. Western OEMs remain strong in Europe and the Americas but struggle in Asian markets.

Offshore-focused specialized value chain

– The **offshore** wind value chain **relies heavily on turbine installation vessels and port infrastructures.**
– **Installation vessels are** slowly **adapting to larger and heavier turbines.** Jack-up vessels with crane capacities under 1,200 tons are unsuitable for installing offshore turbines above10 MW.
– **Marshaling ports** play a vital role in the offshore wind value chain by serving as **central hubs for staging, pre-assembly, and installation of wind farm components**. With more than 30 large marshaling ports worldwide supporting 25 GW of offshore wind installations annually and more than 50 additional ports planned, their expansion could add 45 GW of annual capacity, significantly boosting global offshore wind deployment.

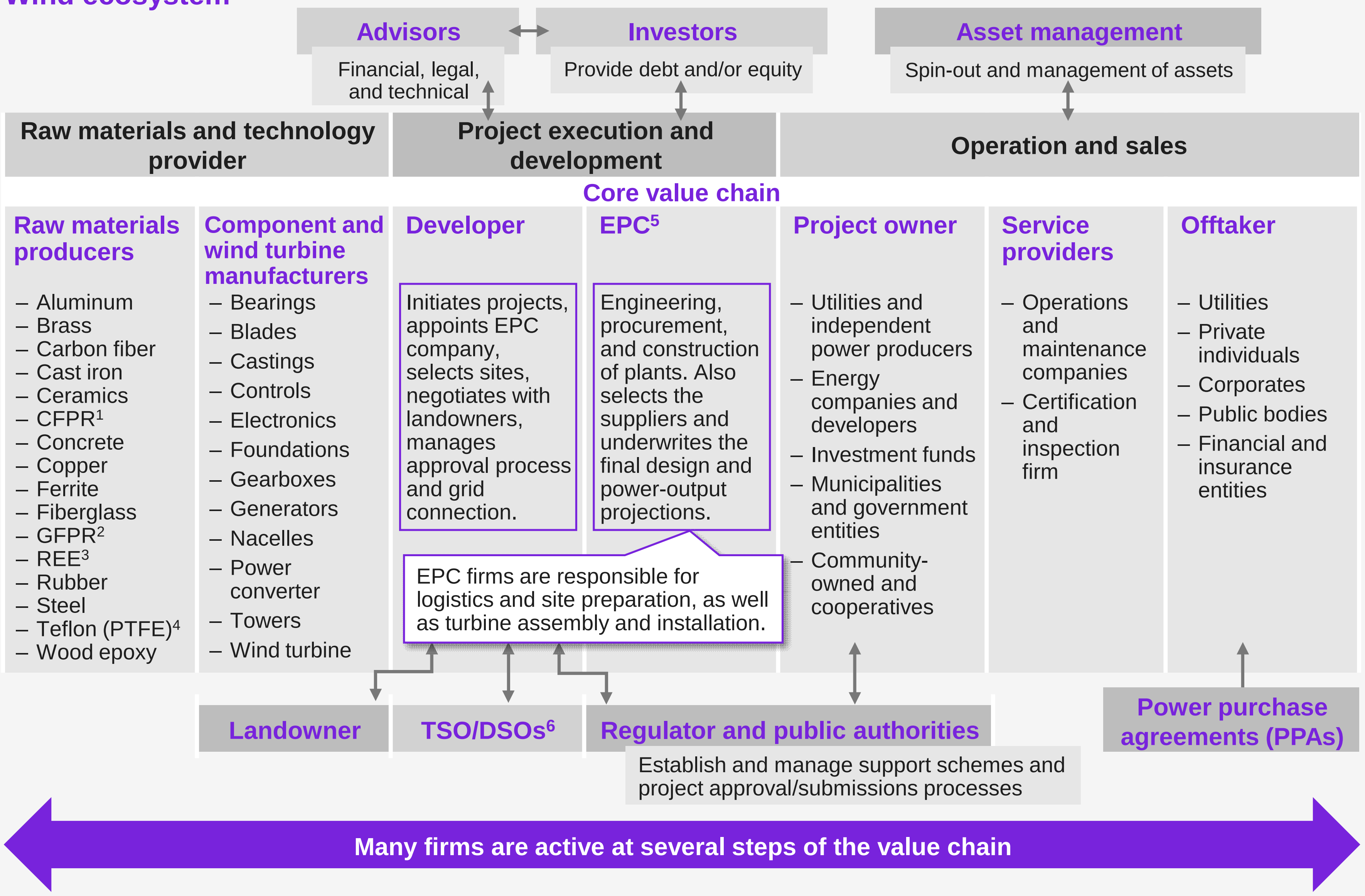
Wind asset owners and operators

– **Chinese companies dominate global wind ownership**, with two-thirds of the top 15 asset owners, holding a combined **333 GW capacity—more than 30% of global capacity**. Their average portfolio per owner is **33 GW**, nearly three times larger than the **non-Chinese** owners' average.
– By the end of 2023, **China and Europe accounted for more than 95% of global offshore wind capacity**, but ownership remained regionally concentrated—Chinese firms led the **Asia Pacific market**, while European companies controlled **European offshore wind assets.**

The wind energy value chain includes a diverse stakeholder network, and geographic diversification is key to meet regional demands and enhance supply chain resilience

Illustrative

Wind ecosystem



[1] Carbon-filament reinforced plastics; [2] Glass fiber reinforced plastics; [3] Rare earth elements; [4] Polytetrafluoroethylene
[5] Engineering, procurement and construction; [6] Transmission system operator and distribution system operator
Source: Kearney Energy Transition Institute analysis based on desktop research

The wind energy value chain is characterized by a large and diverse number of players and stakeholders, reflecting the complexity of the sector

Non-exhaustive

Component manufacturers

- ABB
- Anhui Yingliu Group
- CFHI
- CS Wind Corporation
- Danfoss
- Delta Electronics
- Emerson Electric
- Enercon GmbH
- Envision Energy
- Fuji Electric
- GE Renewable Energy
- Goldwind
- Hitachi Energy
- Mingyang Smart Energy
- Mitsubishi Heavy Industries
- NGC
- Nordex Group
- Schneider Electric
- Senvion S.A.
- SGRE
- Shanghai Taisheng Wind Power Equipment
- Siemens Energy
- Sinovel Wind Group
- Suzlon Energy Limited
- Titan Wind Energy
- Trinity Structural Towers
- Valmont Industries
- Vestas Wind Systems A/S
- Weichai Holding Group
- Winergy
- ZF Wind Power

Wind turbine suppliers/OEMs

- Goldwind
- Envision
- Vestas
- Windey
- Mingyang
- SGRE
- GE Vernova
- SANY
- Nordex SE
- Dongfang
- Sewind
- CRRC
- CSSC Haizhuang
- Enercon
- United Power

EPC (foundations – vessels – cables)

- Aker Solutions
- Bladt Industries
- CNOOC Offshore Oil Engineering
- CSSC CWHI
- CS Wind
- EEW Group
- Jutal
- Iemants N.V.
- Lamprell
- Navantia-Windar
- Offshore Structures Ltd.
- Sif Group
- Smulders
- Steelwind Nordenham
- ST3 Offshore
- TAG Energy Solutions
- Tata Steel
- Técnicas Reunidas
- Wison Offshore & Marine
- Yantai CIMC Raffles Offshore
- Boskalis
- Cadeler
- CHMI
- COSCO Shipyard
- CSBC-DEME Wind Engineering Co
- Energy China
- Eneti
- Fred. Olsen Windcarrier
- Havfram
- Heerema
- Jan De Nul
- Power China
- Sapura Energy
- Seajacks
- Seaway 7 ASA
- Van Oord
- JDR Cable Systems
- LS Cable & System
- Nexans
- NKT Group
- NSW Technology
- PRYSMIAN Power link
- Walsin Lihwa

Owners and operators

- Berkshire Hathaway Energy
- CGN Power Group
- CR Power
- CTG
- Datang Corporation
- EDP Renovaveis
- Enel Green Power
- Energy Investment Corporation
- Guangdong Energy Group
- Huadian Group
- Huaneng Group
- Iberdrola Renewables
- NextEra Energy Resources
- Ørsted*
- Power China
- RWE Renewable
- State Power Investment Corporation
- Tianrun (Goldwind)
- Vattenfall

Service providers

- Airway Services
- Clobotics Wind Services
- Comantur, S.L.
- Dellner Hydratech
- Flex wind
- GE Power
- GEV Wind Power
- Global Wind Service
- IMFutuRe
- James Fisher Renewables
- Linjebygg AS
- Moventas
- RTS Wind AG
- Sapphire Renewables
- SGRE
- Vestas Wind Systems
- Vento Energy Support
- Vilo Wind
- WindCom
- Ynfiniti Energy Group

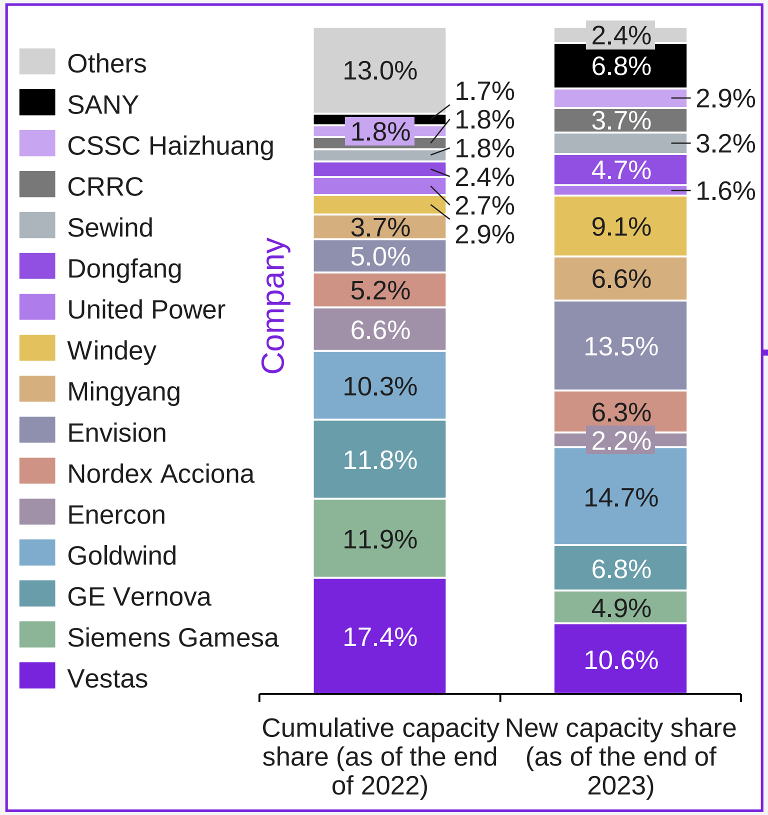
Recycling

- Arkema S.A.
- Avangrid, Inc.
- Carbon rivers
- Enva
- LM Wind Power
- Makeen Power
- Owens Corning
- Regen fiber
- SGRE
- SUEZ
- Veolia
- Vestas Wind Systems A/S
- WindLoop

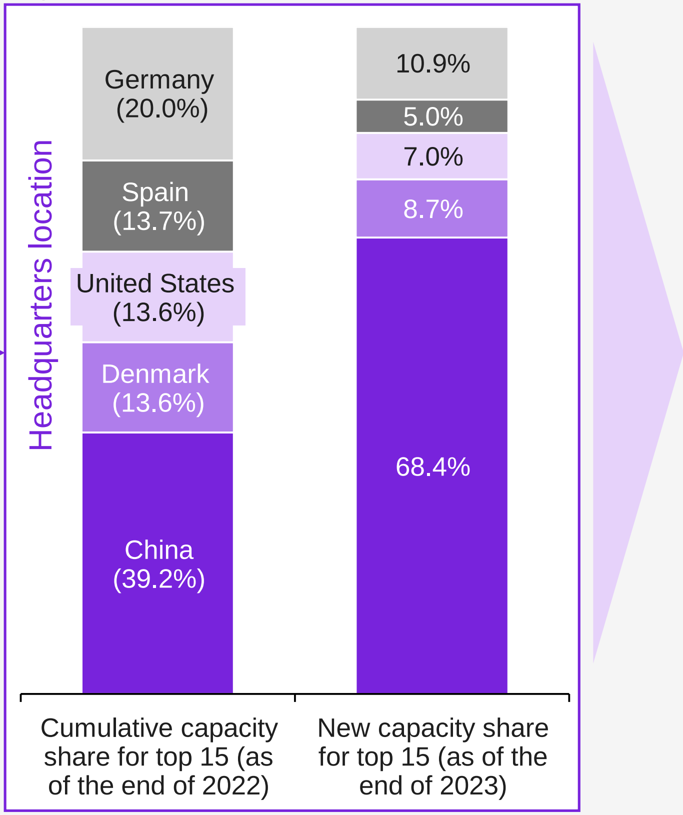
Source: Kearney Energy Transition Institute analysis based on desktop research

The global onshore wind turbine manufacturing market is shifting significantly, with Chinese companies accounting for 68% of global capacity additions among the top 15 players in 2023

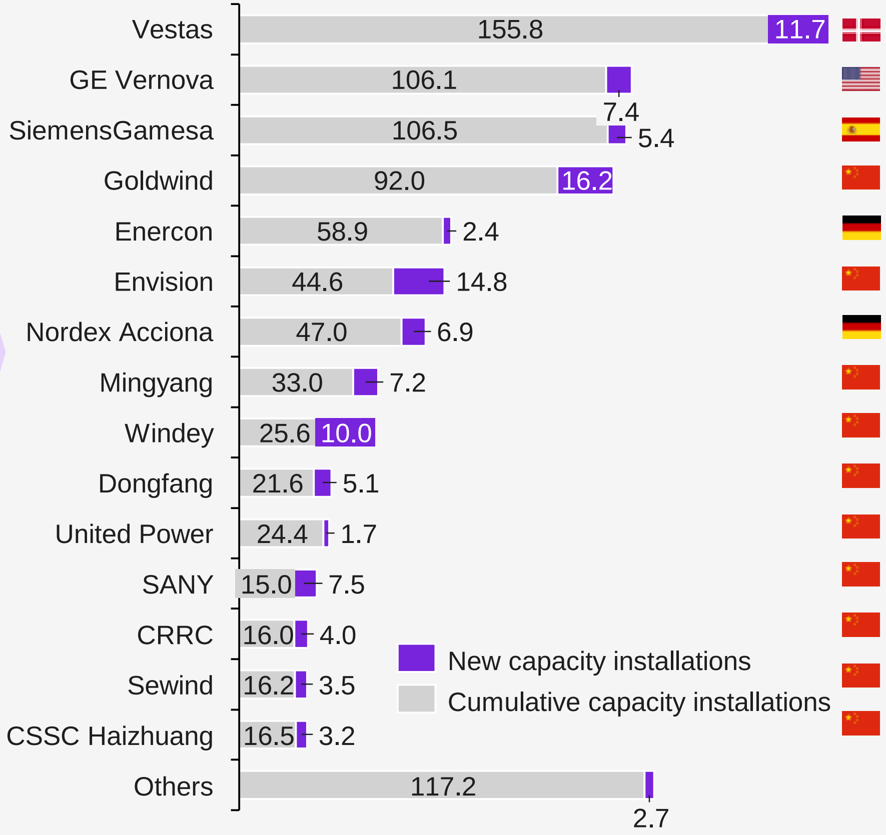
Onshore turbine market share in cumulative and new installations
%, 2023



Onshore turbine market share in cumulative and new installations by headquarters location
%, 2023



Cumulative and new installations by onshore turbine supplier
GW, 2023

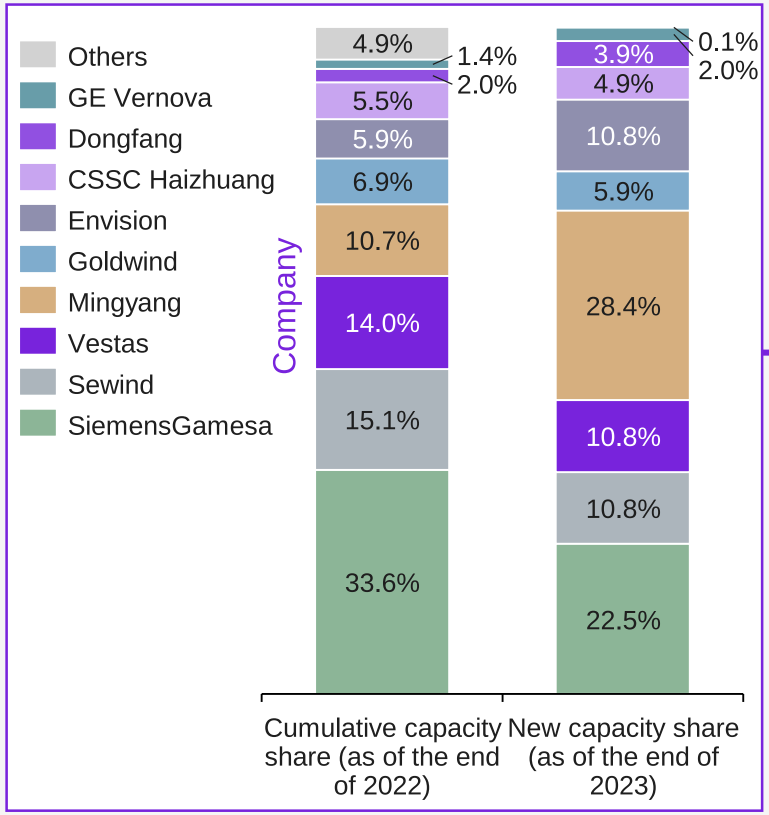


Sources: GWEC, 2024, Market Intelligence; Wood Mackenzie, 2024, China leads global wind turbine manufacturers' market share in 2023; Kearney Energy Transition Institute analysis

The global offshore wind turbine manufacturing market is shifting significantly, with Chinese companies accounting for 65% of global capacity additions among the top 10 players in 2023

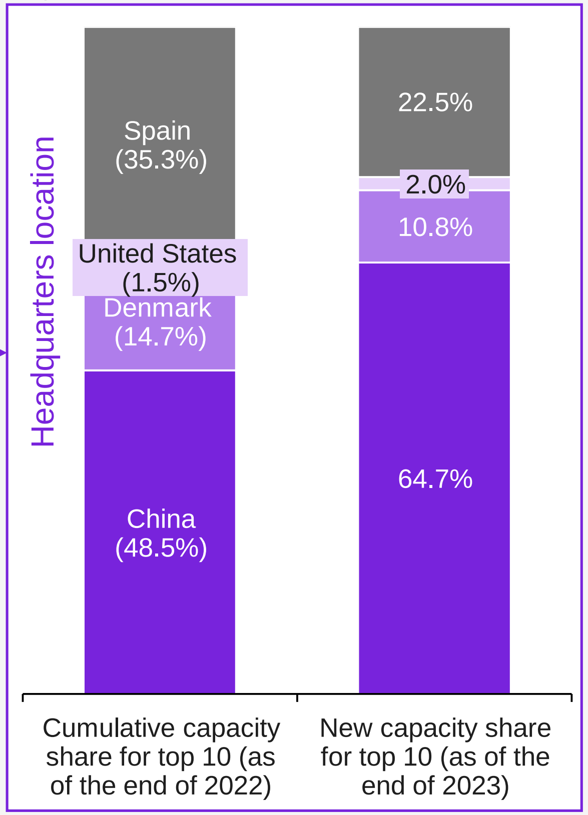
Offshore turbine market share in cumulative and new installations

%, 2023



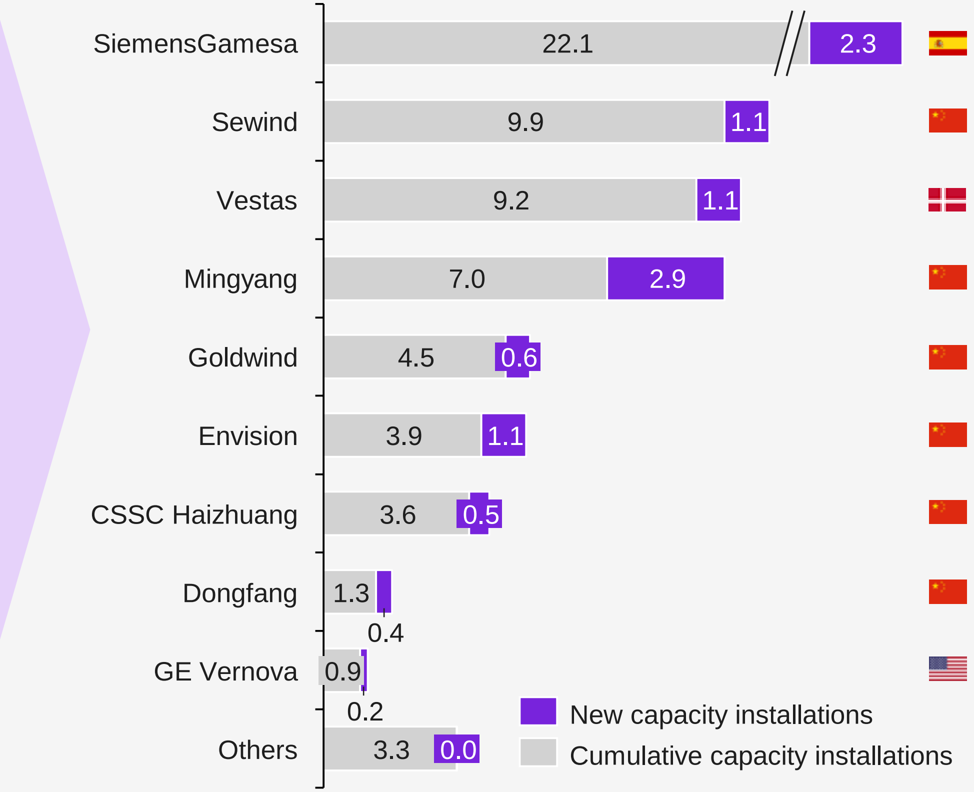
Offshore turbine market share in cumulative and new installations by headquarters location

%, 2023



Cumulative and new installations by offshore turbine supplier

GW, 2023



Sources: GWEC, 2024, Market Intelligence; Wood Mackenzie, 2024, China leads global wind turbine manufacturers' market share in 2023; Kearney Energy Transition Institute analysis

Chinese OEMs dominate their domestic market while gradually expanding internationally, whereas Western OEMs retain strength in Europe and the Americas but struggle to penetrate Asian markets

Top 5 wind turbine suppliers delivering to the top 10 largest global markets
GW, 2023

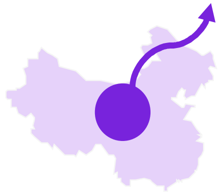
GW installed across the entire market

Market	1	2	3	4	5	% of 5 suppliers	New GW installed
China	Goldwind (20%)	Envision (19%)	Windey (13%)	Mingyang (13%)	SANY (9%)	74%	79.4
United States	GE Vernova (52%)	Vestas (33%)	Nordex Acciona (11%)	Siemens Gamesa (4%)	EWT (0.02%)	100%	5.9
Brazil	Vestas (39%)	Nordex Acciona (24%)	GE Vernova (19%)	Siemens Gamesa (13%)	WEG (5%)	100%	5.1
Germany	Vestas (40%)	Nordex Acciona (26%)	Enercon (24%)	Siemens Gamesa (5%)	GE Vernova (4%)	99%	3.9
India	GE Vernova (29%)	Suzlon (20%)	Envision (17%)	Siemens Gamesa (16%)	Senvion India (9%)	91%	3.7
Sweden	Siemens Gamesa (51%)	GE Vernova (35%)	Vestas (6%)	Nordex Acciona (5%)	Enercon (2%)	99%	2.7
Netherlands	Siemens Gamesa (73%)	Vestas (13%)	Nordex Acciona (12%)	Enercon (1%)		99%	1.8
France	Vestas (40%)	Siemens Gamesa (26%)	Nordex Acciona (22%)	Enercon (8%)	GE Vernova (3%)	99%	1.7
Finland	Nordex Acciona (45%)	Vestas (39%)	GE Vernova (10%)	Siemens Gamesa (5%)	Enercon (0.5%)	99.5%	1.7
United Kingdom	Vestas (58%)	Nordex Acciona (29%)	GE Vernova (5%)	Enercon (5%)	Siemens Gamesa (3%)	100%	1.7

Sources: GWEC, 2024, Market Intelligence; Kearney Energy Transition Institute analysis

3.2 Wind turbine manufacturers

Global Chinese wind turbine exports surged more than 60% between 2022 and 2023, with manufacturers shipping more than 3.6 GW

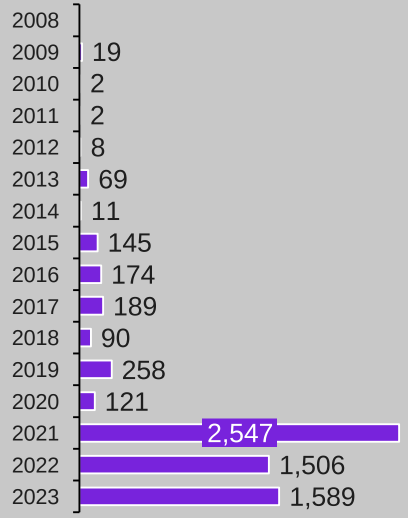


Turbines made in China were exported to 18 countries, with Uzbekistan (25%), Egypt (14.1%), South Africa (9.4%), Laos (8.8%), and Chile (7.9%) being the top five buyers in 2023, accounting for more than 65% of the total.

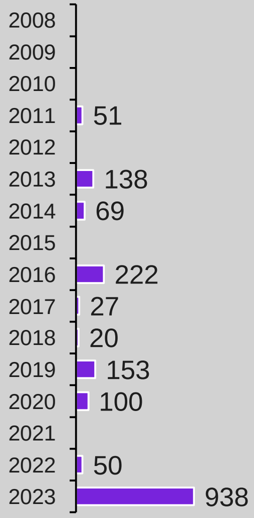
Sources: GWEC, 2024, Market Intelligence; Chinese Wind Energy Association, 2023; Caixin GLOBAL, 2024, Charts of the Day: China Wind Turbine Exports Surged 60% in 2023; Kearney Energy Transition Institute analysis

3.2 Wind turbine manufacturers

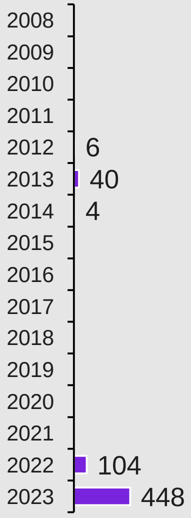
Asia
MW, 2008–2023



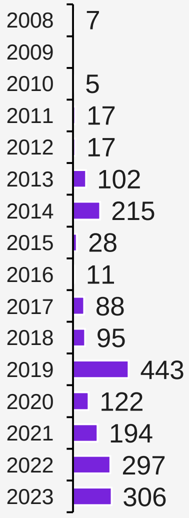
Africa
MW, 2008–2023



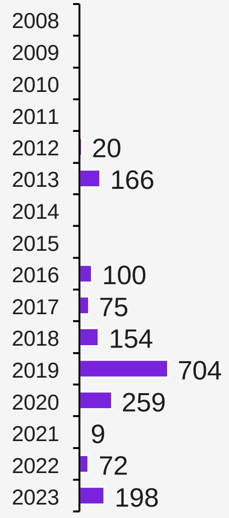
Middle East
MW, 2008–2023



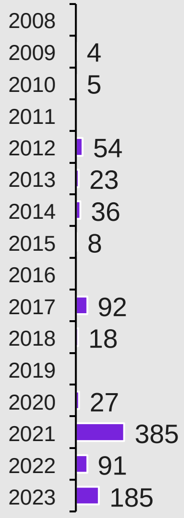
South America
MW, 2008–2023



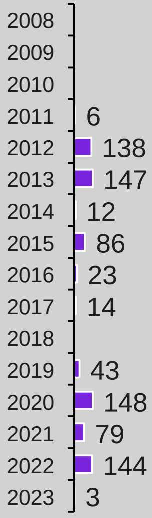
Pacific
MW, 2008–2023



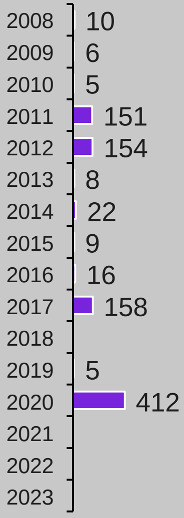
Other Europe
MW, 2008–2023



EU 27
MW, 2008–2023

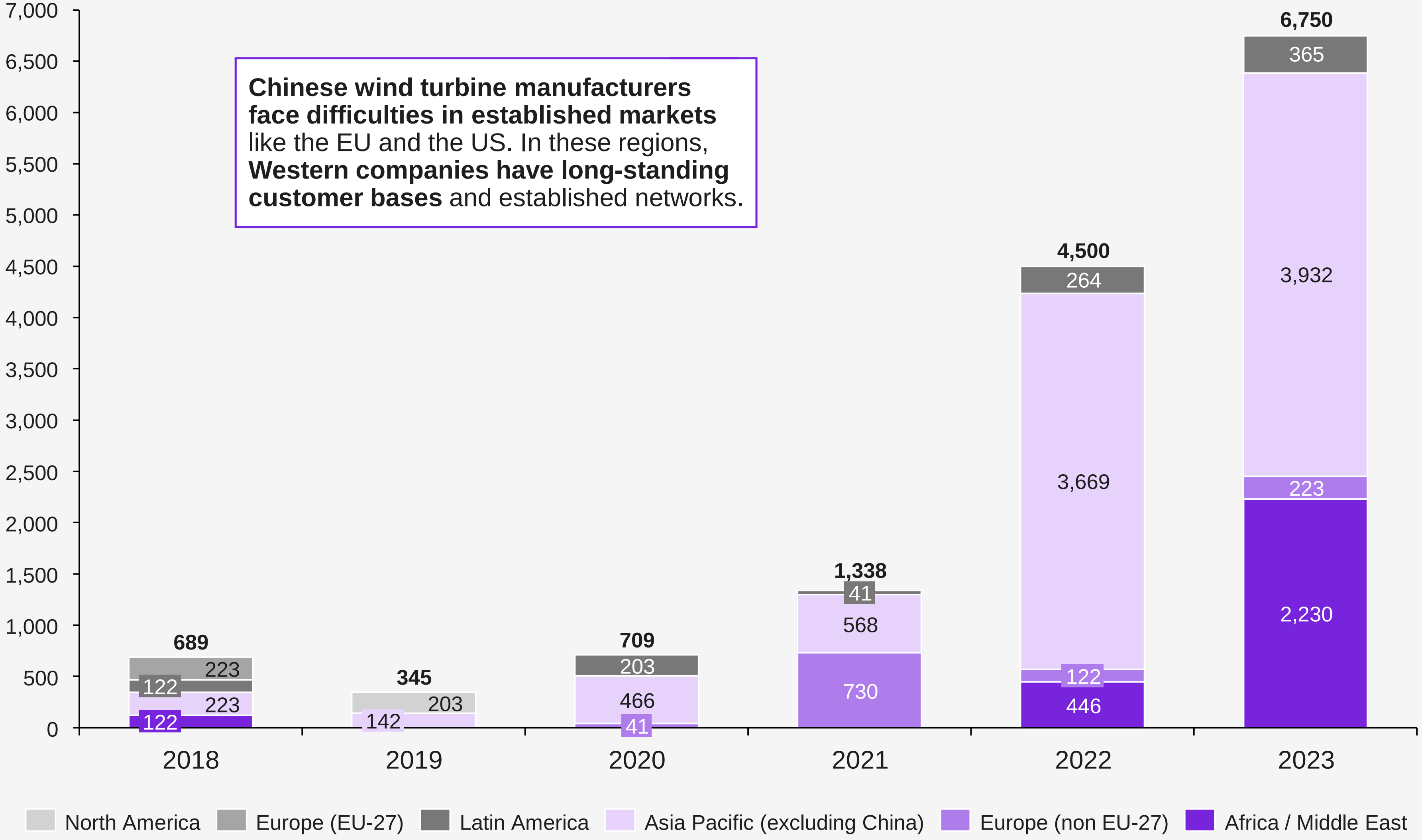


North America
MW, 2008–2023



In 2023, Chinese manufacturers secured nearly 7 GW of wind turbine orders from outside China[1]

Chinese wind-turbine makers growing overseas orders
MW, 2018–2023



[1] As of January 2024. Only includes announced firm project orders. Excludes non-firm orders such as preferred supplier contracts and conditional agreements.
Sources: S&P Global, 2024, Allure of low-cost Chinese wind turbines grows in overseas markets; EnergyWatch, 2024, Chinese turbines sell 20% below rivals' prices in export markets; Kearney Energy Transition Institute analysis.

Kearney XX/ID

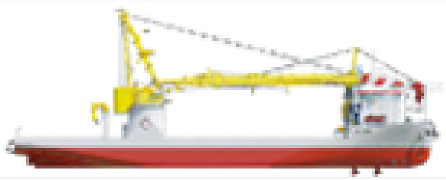
The offshore wind value chain relies heavily on installation vessels (WTIVs), classified into two primary types: heavy lift vessels and jack-up vessels

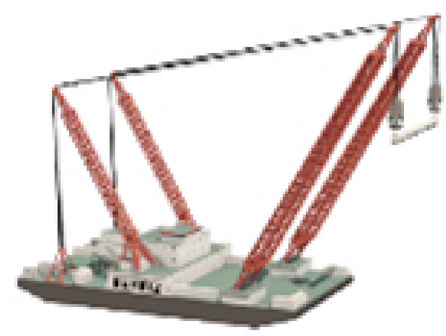
Illustrative

Heavy lift vessels

Heavy lift vessels are specialized offshore ships designed for **transporting and installing** mainly wind **turbine foundations**.

- They utilize **powerful cranes and dynamic positioning (DP) systems** for precise **lifting and placement** of monopiles, jackets, or floating **foundations** onto the seabed.
- Advanced **ballast systems** ensure **stability** during transit and installation, while **sea fastenings secure cargo** for safe transport.





Gulliver, Rambiz, and Les Alizés, heavy lift vessel models by Jan De Nul, have a lifting capacity of less than 5,000 tons.

Jack-up vessels

Jack-up vessels are specialized offshore platforms and are used to **transport mainly turbines.**

- **They transition from floating on their hull during transit** to an elevated operational mode for stability and safety.[1]
- **These vessels use retractable legs and a jacking system to lift the hull** above the waterline, ensuring a stable base for activities like wind turbine installation or maintenance.

Vole au vent and Voltaire, jack-up vessel models by Jan De Nul, have a lifting capacity of less than 3,200 tons.

[1] Hull refers to the main body or structure of the vessel that is designed to float on water. The hull is the part of the vessel that provides buoyancy, allowing it to move across water during transit.
Sources: Kearney Energy Transition Institute analysis based on desktop research

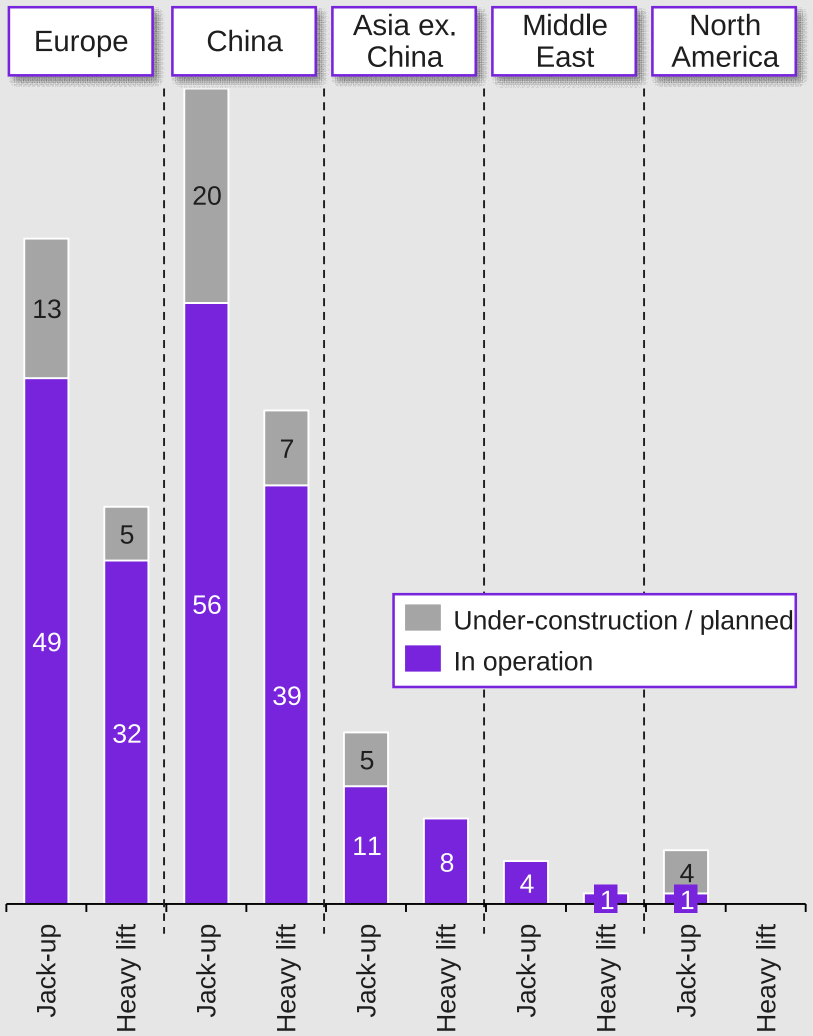
China and Europe dominate the global offshore vessel supply, with China accounting for 46% of jack-up vessels and 49% of heavy lift vessels globally

The increasing size of offshore turbines poses significant challenges for vessels. Higher nacelle, tower, and foundation weights, along with greater turbine hub heights, have rendered many WTIVs inadequate for installing larger turbines.

3.3 Offshore-focused specialized value chain

Overview of offshore wind turbine installation vessels

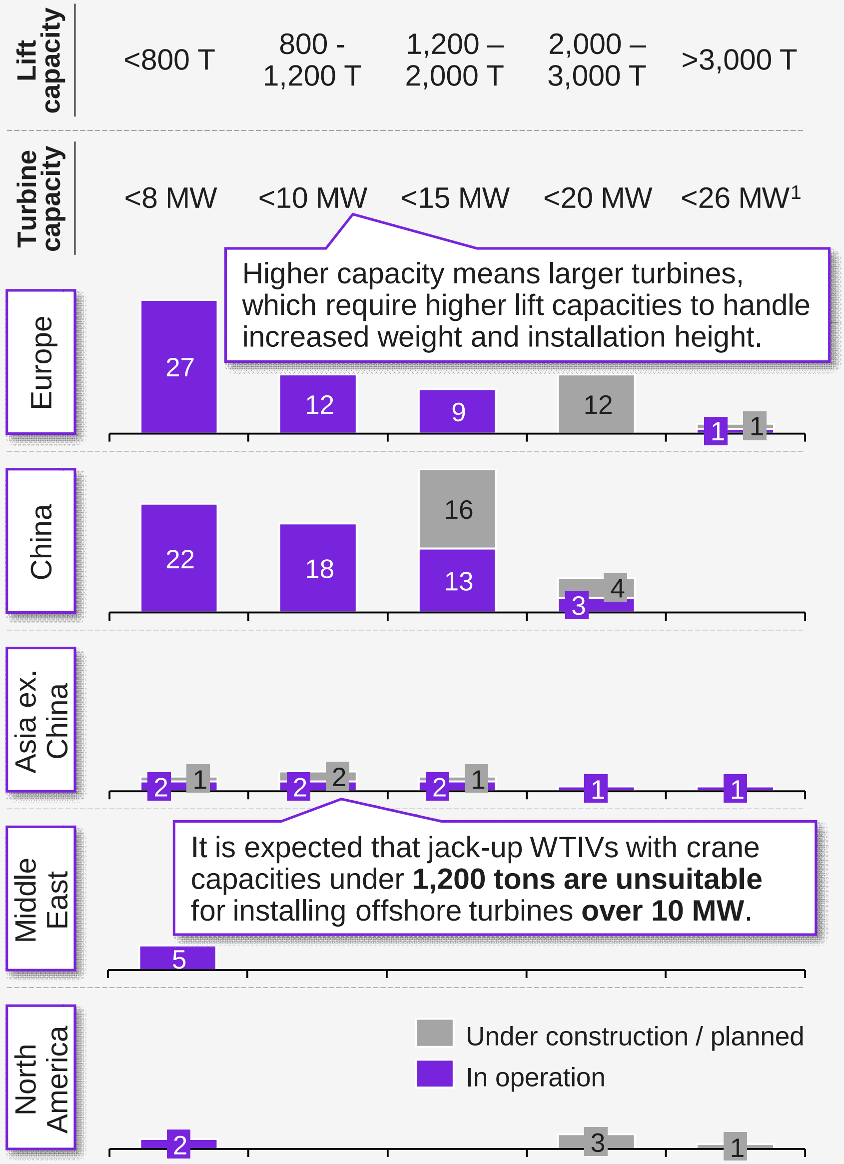
units, 2023



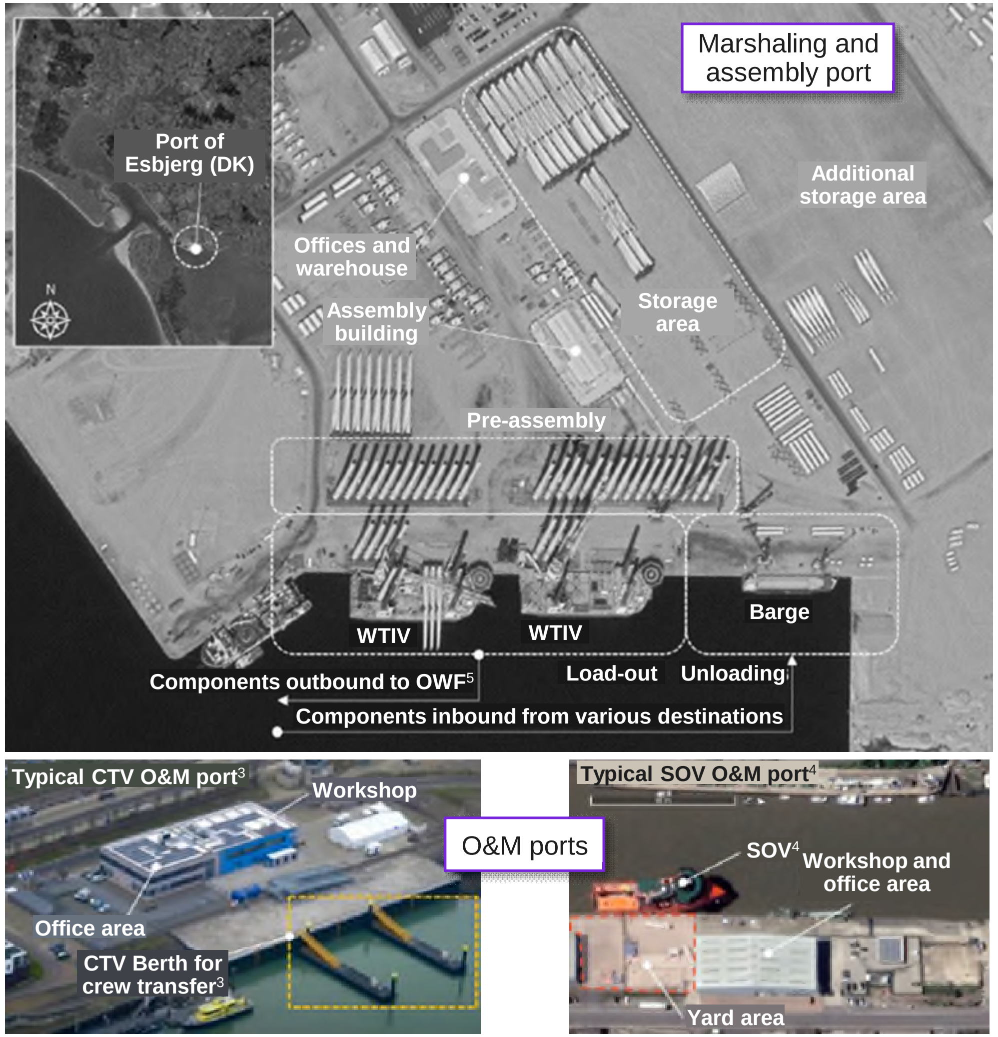
[1] 26 MW corresponds to the capacity of the largest offshore wind turbine.
Sources: GWEC, 2024, Global offshore wind report; GWEC, 2023, Global offshore wind turbine installation vessel database; H-BLIX, 2022, Offshore wind vessel availability until 2030: Baltic Sea and Polish perspective; Kearney Energy Transition Institute analysis based on desktop research

Overview of offshore wind turbine installation vessels (jack-ups) by lift capacity

units, 2023



Ports are important infrastructure for offshore wind development, providing various services



	Fabrication and manufacturing port	Marshaling and assembly port	Operations and maintenance (O&M) port
Role	**Production and initial processing of wind farm components** such as foundations, towers, and nacelles	**Central hub for staging, pre-assembly, and installation of wind farm components**, such as turbines, blades, and monopiles	**Supports ongoing O&M of offshore wind farms**. The proximity to wind farms is critical, typically within 100 km for CTVs and 200 km for SOVs, to minimize transit times.[3,4]
Facilities	– **Fabrication yards** near waterways – Adjacent workshops and **processing facilities** – **Storage** for finished goods	– **Storage** areas for heavy components – **High-load-bearing quaysides** to accommodate HLVs and WTIVs[1,2] – **Equipment** for **handling** and **assembling** wind farm components – Connectivity for **receiving and dispatching large-scale components** via sea transport	– Berthing for CTVs and SOVs – Spare parts storage and **maintenance facilities** – **Small-scale infrastructure** compared to **construction ports**, as it primarily handles smaller vessels and components

Example
3.3 Offshore-focused specialized value chain

[1] HLV is heavy lift vessels; [2] WTIV is wind turbine installation vessels; [3] CTV is crew transfer vessel; [4] SOV is service operations vessel.
[5] OWF is offshore wind farm.
Sources: Nordic Innovation, 2024, New Offshore Wind Ports in the Nordics: Opportunities for collaboration and strategic innovation; Danish Energy Agency, Royal Danish Embassy in Vietnam and Electricity and Renewable Energy Authority, 2024, Ports for Offshore Wind in Vietnam: Mapping Port Infrastructure for the Offshore Wind Industry and Job Creation in Vietnam; Kearney Energy Transition Institute analysis

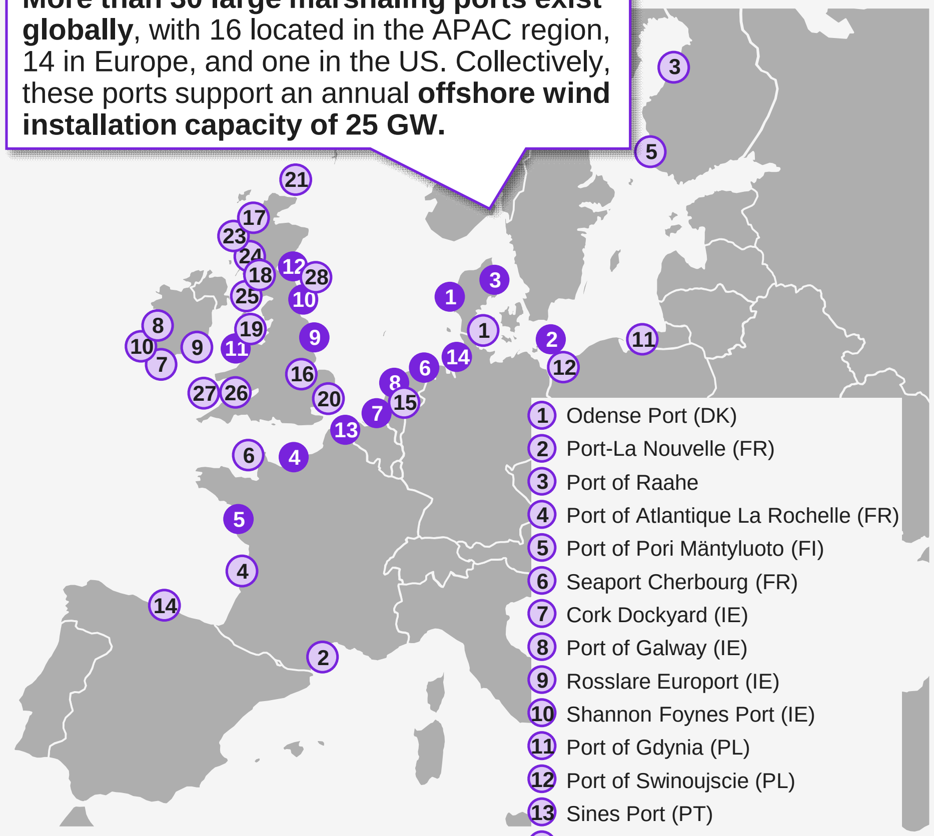
Marshaling ports with a track record in offshore wind and plans for offshore wind

More than 30 large marshaling ports exist globally, with 16 located in the APAC region, 14 in Europe, and one in the US. Collectively, these ports support an annual **offshore wind installation capacity of 25 GW.**

(1) Operational ports with offshore wind turbine installations track record

(1) Ports with plans to support offshore wind project construction

In the United States, there is one operational port with a track record of offshore wind turbine installations, while 13 ports have future plans to support offshore wind projects.

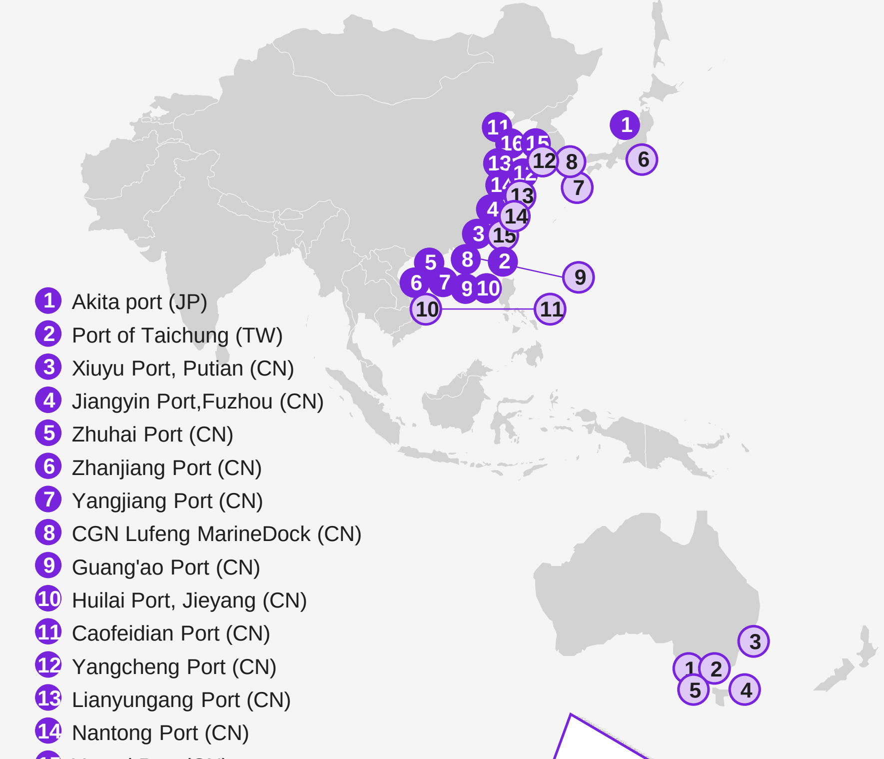


Operational ports (Europe):

1. Port of Esbjerg (DK)
2. Port of Rønne (DK)
3. Port of Grenaa (DK)
4. Port of Le Havre (FR)
5. Port of Nantes Saint-Nazaire (FR)
6. Seaport Emden (DE)
7. Port of Rotterdam-Maasvlakte 2 terminal (NL)
8. Eemshaven-Groningen Seaports (NL)
9. Green Port Hull (UK)
10. Able Seaton Port (UK)
11. Port of Mostyn (UK)
12. Port of Nigg (UK)
13. Port Oostend-REBO Terminal (BE)
14. Cuxhaven (DE)

Ports with plans (Europe):

1. Odense Port (DK)
2. Port-La Nouvelle (FR)
3. Port of Raahe
4. Port of Atlantique La Rochelle (FR)
5. Port of Pori Mäntyluoto (FI)
6. Seaport Cherbourg (FR)
7. Cork Dockyard (IE)
8. Port of Galway (IE)
9. Rosslare Europort (IE)
10. Shannon Foynes Port (IE)
11. Port of Gdynia (PL)
12. Port of Swinoujscie (PL)
13. Sines Port (PT)
14. Bilbao Port (ES)
15. Energihaven (NL)
16. Able Humber Port (UK)
17. Ardersier Port (UK)
18. Energi Park Fife (UK)
19. Fleetwood (UK)
20. Lowestoft (UK)
21. Orkney Harbour (UK)
22. Port of Blyth (UK)
23. Port of Cromarty Firth (UK)
24. Port of Inverness (UK)
25. Port of Methil (UK)
26. Port of Swansea (UK)
27. Port Talbot (UK)
28. Teesport (UK)



Operational ports (APAC):

1. Akita port (JP)
2. Port of Taichung (TW)
3. Xiuyu Port, Putian (CN)
4. Jiangyin Port,Fuzhou (CN)
5. Zhuhai Port (CN)
6. Zhanjiang Port (CN)
7. Yangjiang Port (CN)
8. CGN Lufeng MarineDock (CN)
9. Guang'ao Port (CN)
10. Huilai Port, Jieyang (CN)
11. Caofeidian Port (CN)
12. Yangcheng Port (CN)
13. Lianyungang Port (CN)
14. Nantong Port (CN)
15. Yantai Port (CN)
16. Guangli Port General Dock Phase 2 (CN)

Ports with plans (APAC):

1. Geelong Port (AU)
2. Port Anthony (AU)
3. Port Kemla (AU)
4. Port of Bell Bay (AU)
5. Port of Hastings-Victorian Renewable Energy Terminal (AU)
6. Kashima Port (JP)
7. Port of Kitakyushu (JP)
8. Mokpo New Port (KS)
9. SPIC Qianzhou Dock, Jieyang Port (CN)
10. SDIC Yangpu Port (CN)
11. Zhanghe Port (CN)
12. Rushankou Port (CN)
13. Heavy Equipment Dock at Lin'gang (CN)
14. Zhoushan Port (CN)
15. Dock at Haizhuang Xiangshan Large-scale Wind Equipment Assembly Park (CN)

More than **50 global ports have announced plans** to support offshore wind, **potentially adding 45 GW of annual operational capacity.**

Sources: Chinese Wind Energy Association and Brinckmann, 2023; Kearney Energy Transition Institute analysis

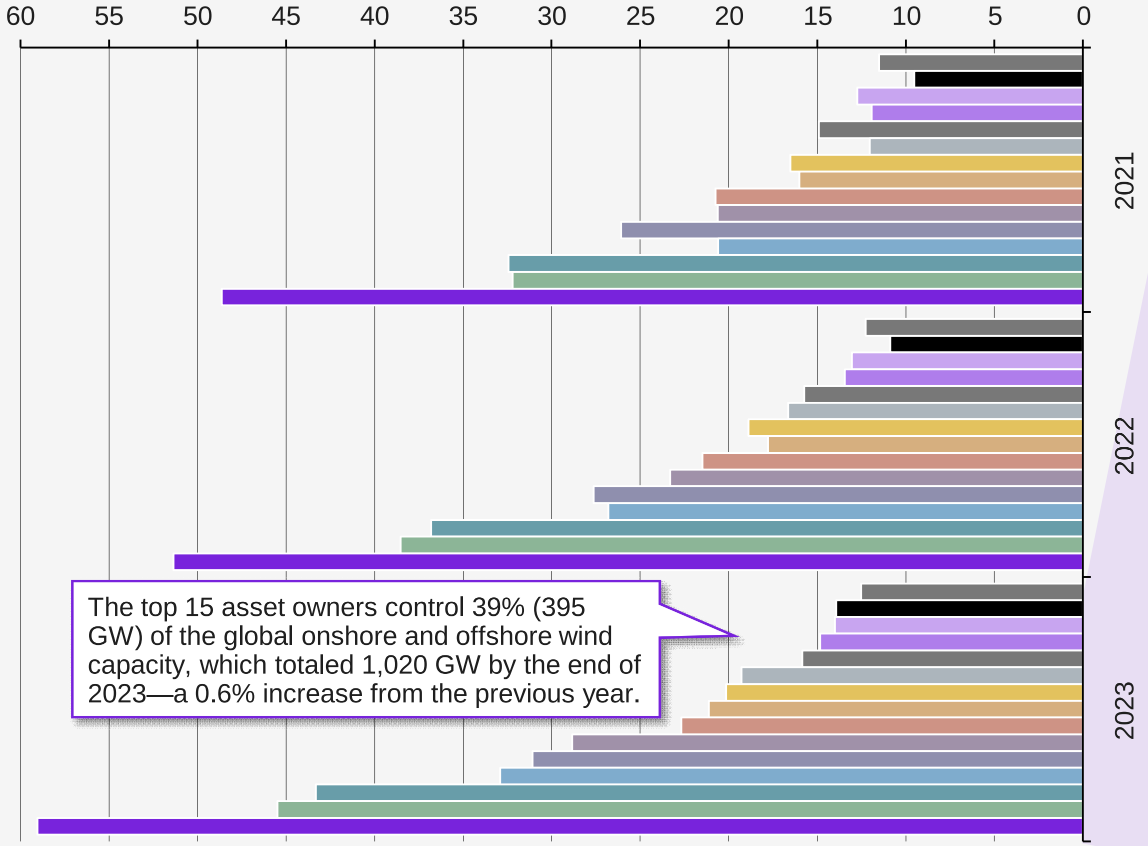
3.3 Offshore-focused specialized value chain

Kearney XX/ID

Ten of the top 15 global wind asset owners are Chinese, collectively holding 333 GW, with an average portfolio of 33 GW—nearly triple that of non-Chinese owners (12.4 GW)

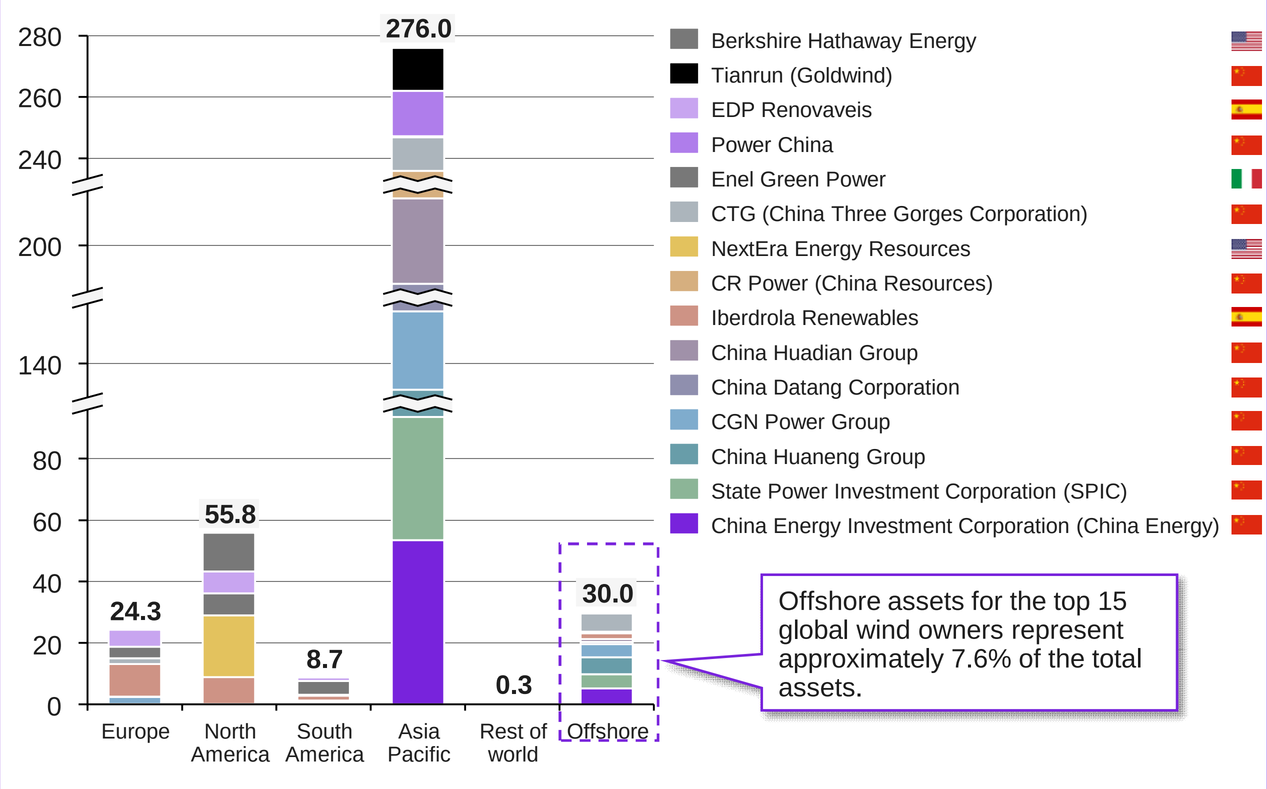
Global wind asset owners and operators

GW, 2023



The top 15 asset owners control 39% (395 GW) of the global onshore and offshore wind capacity, which totaled 1,020 GW by the end of 2023—a 0.6% increase from the previous year.

Despite holding 30% of global wind capacity, Chinese wind asset owners are not active in Europe or North America, focusing instead on their domestic and other Asian markets.



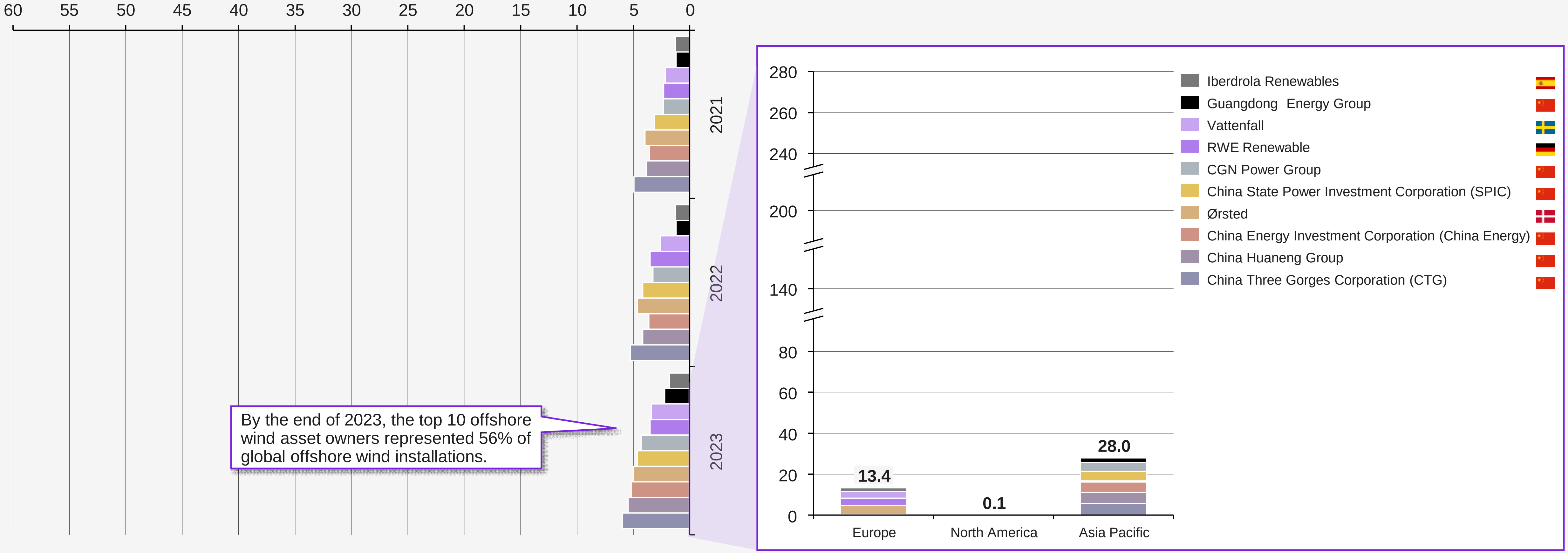
Offshore assets for the top 15 global wind owners represent approximately 7.6% of the total assets.

Sources: GWEC, 2024, Global Wind Asset Owners and Operators; Kearney Energy Transition Institute analysis

By the end of 2023, more than 95% of global offshore wind capacity was in China and Europe, but ownership remained regional, with Chinese firms dominating Asia Pacific while European owners controlled Europe

Global offshore wind asset owners and operators rankings

GW, 2023



Sources: GWEC, 2024, Global Wind Asset Owners and Operators; Kearney Energy Transition Institute analysis

4. Sector challenges

Sector challenges

Deep-dive to follow

Grids and transmission, permitting timelines, and social acceptance are the leading challenges for wind energy deployment in the short and long term.

Sources: GWEC, 2024, Global Wind Report 2024; IEA, 2024, Renewables 2023; REN21, 2024, Global Status Report Collection; US DOE, 2024, Pathways to Commercial Liftoff: Offshore Wind, accessed on December 2024; Kearney Energy Transition Institute analysis based on desktop research.

Competition with other power sources

- Pace of **coal generation phase** out
- **Natural gas price competitiveness** relative to wind power
- **Policy support for fossil fuels** vs. wind power
- Competition among non-dispatchable renewables, leading to lowering capture rates and putting pressure on business cases

Enabling technology development

- **Grid integration, balancing, and flexibility technology** development and adoption
- **Synergistic technology** development, such as electricity storage or green hydrogen
- **Circularity strategies** for reuse, repurposing, recyclability, and recovery of wind farm components

Financial market conditions

- Interest rate increases making financing more difficult
- Insufficient financing, particularly in developing countries

Grid and transmission infrastructure

- **Insufficient investment** made in grid reinforcement, buildout, modernization, and availability
- **Interconnection queues** dealing with backlogs in grid connection requests

See chapter 9

Permitting process

- **Difficulty in obtaining** necessary permits, licenses, and approvals
- **Required timeline** of permitting
- Response to **legal challenges** during permitting

Policy system design

- **Unclear and unsustained wind power targets** and support mechanisms
- **Auction and revenue stabilization mechanisms** that do not react to changing market conditions
- **Race to the bottom on auction prices** created by competition
- **Land and seabed allocation** policies

Society

See chapter 8

- **Social acceptance and support** by communities, including granting **land use rights** to projects
- **Public awareness** of energy transition and need for wind power

Supply chain bottlenecks

- Trade barriers and **supply chain disruptions** due to **geopolitical tensions**
- **Transportation constraints** and generation step-up **transformers lead times** (onshore wind)
- **Insufficient availability** of **ports** and installation **vessels** (offshore wind)

Technology standardization

- **Competition for continuous wind turbine size increase** preventing technology standardization

Workforce

- **Availability of a technical workforce** with necessary skills for the wind industry
- **Competition** with other industries for talent
- Development of a diverse workforce that reflects a **just energy transition**

Kearney XX/ID

In Europe, it can take up to nine years to get a grid connection permit for a new or a repowered wind farm

Grid and transmission infrastructure

Non-exhaustive

Key factors contributing to delays in grid connection for wind projects

Category	Description
Grid planning	**Lack of proactive planning for grid expansions and reinforcements:** Inefficient grid planning, slow decision-making for grid investments, and the slow deployment of consented projects.
	Lack of alignment between national wind and solar capacity targets and grid plans: In many European countries, grid plans are based on energy scenarios which trail 2030 national targets for wind and solar.
	Unbalanced generation mix connected to grid: Grid capacity could accommodate a more balanced mix of wind and solar. In some cases, such as in Greece, high solar production during sunny hours prevents more wind farms from being integrated.
Grid construction	**Lengthy grid equipment procurement processes:** System operators often go through public procurement processes for grid equipment, which can lead to delays in grid expansion.
	Supply chain/equipment bottlenecks: Wait time for a new power transformer has doubled from 50 weeks in 2021 to nearly two years in 2024. Costs have also climbed by 60 to 80 percent since 2020.
	Slow construction: In France, most grid connection delays are due to the slow construction of high-voltage substations in different regions; while in Croatia, delays stem from the need to construct a new 400 kV line.
	Public opposition: Transmission projects are often stalled by public opposition and court cases. For example, the 700 km long Suedlink HVDC project (to connect offshore wind in northern Germany with the south) was stalled for several years before commencing construction in 2023.
Grid access	**Inefficient grid permitting process:** In most countries, "the first come, first served" principle applies in most countries when grid connection requests are assessed, which leads to clogged grid access queues. Often, the grid permitting process is linked to other authorizations leading to delays.
	High number of immature and speculative bids: The waiting lists often include many speculative projects that will not be deployed but the system operator is obliged by law to assess them.
	Lack of incentives to apply uniform standards and accelerate assessments: System operators are often insufficiently incentivized to apply uniform EU standards in technical grid connection assessments leading to inefficient authorization processes contingent on project-specific factors.

Sources: Wind Europe, 2024, Grid access challenges for wind farms in Europe; Kearney Energy Transition Institute analysis

Wind projects account for more than 37% of projects awaiting grid connection, while solar PV makes up 66% and renewables 2% of the grid queues

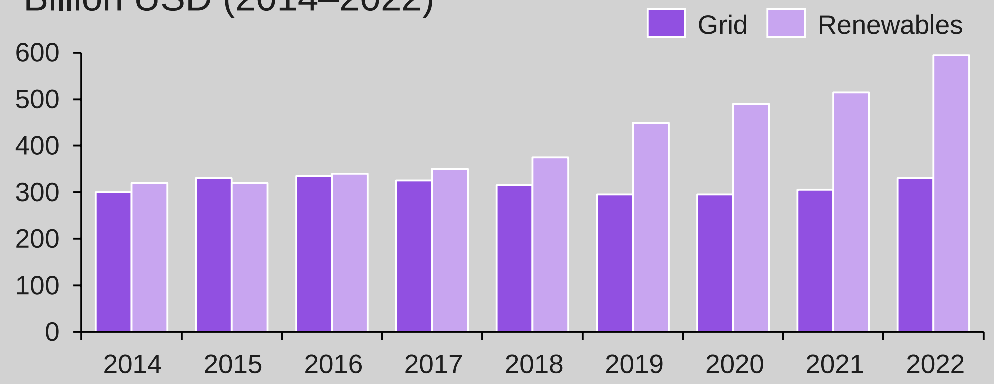
Grid and transmission infrastructure

– Despite the need of grid buildout, reinforcement, and modernization, annual **investment in grids has not changed** since 2014, while investment for renewables has almost doubled.

– Renewable projects are facing interconnection queues**.** Countries are introducing **measures and regulations to ease connection bottlenecks** and reduce the number of speculative projects.

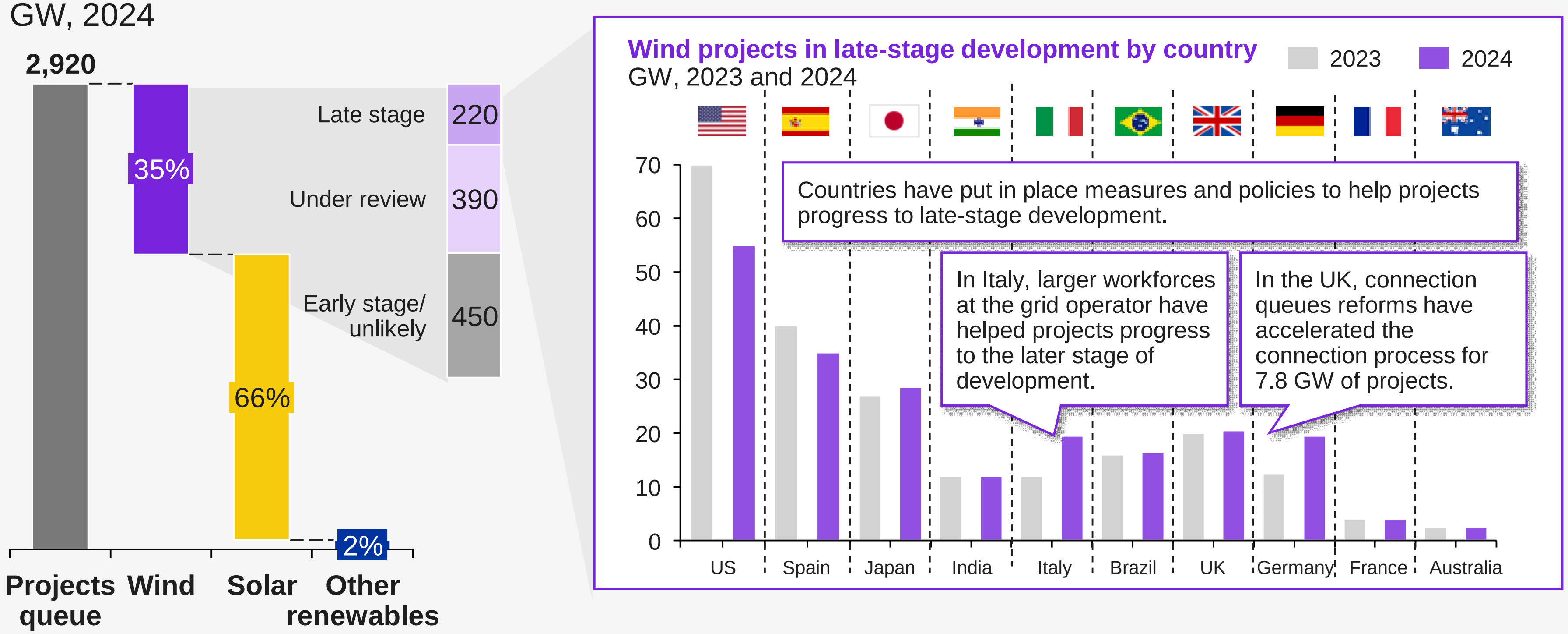
Global annual investment in grids and renewables

Billion USD (2014–2022)



Renewable projects in connection queues by project stage

GW, 2024



Sources: IEA, 2024, Renewables 2024 Analysis and forecast to 2030; IEA, 2023, World Energy Outlook 2023; Kearney Energy Transition Institute analysis

4.1 Grid and transmission infrastructure

Current offshore policies fail to address inflationary pressures and lack flexible price adjustments in PPAs, which affect auctions and project bankability

Policy system design

Governments have started including non-price criteria in offshore wind auctions to support industrial and decarbonization goals.

Negative or no bidding continues to burden offshore wind development

Examples of June and December 2024

- **TotalEnergies** will pay EUR 1.9 billion to develop the N-11.2 site, which has a capacity of approximately 1.5 GW, equating to **EUR 1.3 million per MW.**
- **EnBW** will invest EUR 1.1 billion to develop the 1 GW N-12.3 site, translating to **EUR 1.1 million per MW**.

- **UK-based SSE Renewables**, along with the Dutch state **pension funds APG and ABP**, will invest EUR 40 million to develop the 2 GW IJmuiden Ver Alpha site, equating to **EUR 20,000 per MW**.
- **Vattenfall and Copenhagen Infrastructure Partners** will pay EUR 800 million to develop the 2 GW IJmuiden Ver Beta site, translating to **EUR 400,000 per MW.**

- **Denmark's December 2024 3 GW offshore wind auction round ended without any bids** due to the lack of revenue stabilization mechanisms and uncapped negative bidding.

Sources: Guidehouse, 2023, Financial auctions for offshore wind; WindEurope, 2024, Negative bidding continues to burden offshore wind development; WindEurope, 2024, No offshore bids in Denmark – disappointing but sadly not surprising; WindEurope, 2022, WindEurope position on non-price criteria in auctions; Kearney Energy Transition Institute analysis

Offshore wind PPAs are under pressure

PPA price structures do not consider cost volatility

- Fixed-price PPAs assumed stable costs, but inflation and supply constraints drove them up over time.

Auction and contract designs encourage financially risky bidding

- Developers bid aggressively, expecting cost drops, while governments increased financial award forcing them into low offtake prices.

Contract termination penalties are too low to prevent exits

- Low PPA cancellation penalties make termination more attractive than absorbing losses, disrupting offshore wind expansion.

In 2023 and 2024, the Commonwealth, the Park City, and the New York Offshore wind projects saw their PPAs terminated in the US as a result of inflationary cost pressures and higher interest rates.

Non-price criteria for offshore wind auctions

Non-price criteria accelerate innovation, strengthen European supply chains, and enhance energy security while **ensuring:**

- High **environmental** (sustainability and biodiversity)**,**
- **Technical** (system integration and innovation)**,** and
- **Societal** (benefits to communities) **standards** in line with the EU Green Deal.

It remains to be determined whether these criteria complement existing policy instruments without duplicating them while also facilitating the auction process.

The wind energy sector might face various supply challenges in rare earth magnet elements, carbon fiber, steel, and copper

Permanent magnet generators require about six times more rare earth elements than their alternative technologies.

Supply chain bottlenecks

Directional

Offshore wind turbines need of specialized materials for their advanced technology, while onshore turbines require structural and high-performance materials to support their larger and heavier designs.

No exposure Significant exposure

4.3 Supply chain bottlenecks

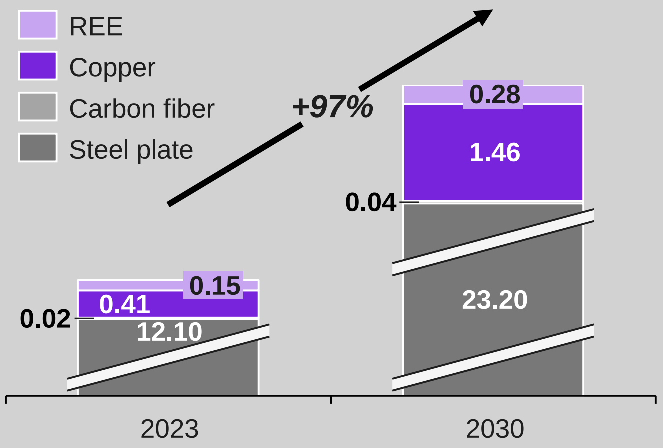
Material usage estimates for different wind turbine types

kt/GW, 2020

Material	DD-EESG[1]	DD-PMSG[2]	GB-PMSG[3]	GB-DFIG[4]
Concrete	369.0	243.0	413.0	355.0
Steel	132.0	119.5	107.0	113.0
Iron (cast)	20.1	20.1	20.8	18.0
Glass/carbon composites	8.1	8.1	8.4	7.7
Polymers	4.6	4.6	4.6	4.6
Copper	5.0	3.0	0.95	1.4
REE[5]	0.04	0.24	0.06	0.01
Other[6]	28.1	27.8	29.8	26.7

Steel plate, carbon fiber, copper, and magnet REE demand

Mt, 2023–2030



Raw materials supply chain bottleneck

Material	Supply chain criticality description	Exposure
Steel plate	**Steel demand could double by 2030,** challenging the wind energy supply chain due to the need for alignment of multiple steel sub-types and the adoption of low-emission production pathways.	◔
Carbon fiber	**Larger wind turbines require stiffer, lighter blades, increasing demand for carbon fiber.** High costs and manufacturers' preference for broader markets heighten competition with other industries.	◑
Copper	**Copper supply** is more **diversified** than other key energy transition minerals, but **the absence of large-scale projects** in development presents **challenges for its future supply.**	◕
REE[5]	The wind value chain faces high exposure to rare earth supply risks, **with heavy reliance on China** and growing demand **challenging efforts to secure a diversified** and sustainable **supply**.	●

[1] Direct-drive electrically excited synchronous generator; [2] Direct-drive permanent magnet synchronous generator; [3] Gearbox permanent magnet synchronous generator; [4] Gearbox doubly fed induction generator; [5] Rare earth elements; [6] Other materials used in the estimates for different wind turbine types are as follows: aluminum, boron, chromium, manganese, molybdenum, nickel, and zinc.

Sources: IEA, 2024, Critical Minerals Data Explorer; Carrara S. et al., 2020, Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system, EUR 30095 EN, Publication Office of the European Union; ATA CFT Guangzhou Co. Ltd., 2023, Global Carbon Fiber Composites Market Report; CRU, 2023; GWEC, 2023, Market Intelligence; Kearney Energy Transition Institute analysis.

Kearney XX/ID

China and India are the only markets with sufficient capacity to fully meet their demand for key components between 2023 to 2030

Supply chain bottlenecks

Directional

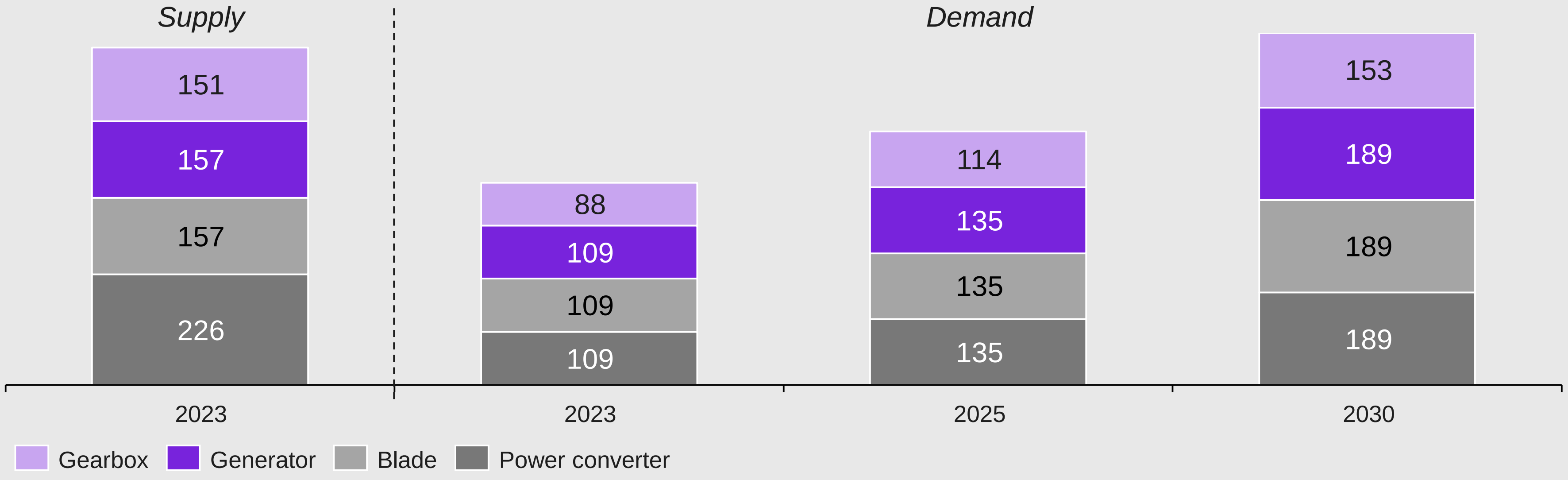
China (77%) and India (7%) accounted for 84% of global wind turbine components manufacturing capacity in 2023, making their exports crucial to prevent regional supply shortfalls and disruptions in wind energy deployment.

◯ No exposure ● Significant exposure

4.3 Supply chain bottlenecks

Wind gearbox, generator, blade, and power converter global demand and supply

GW, 2023



Nacelle components and blade supply chain bottleneck

Component	Supply chain criticality description	Exposure
Gearbox	While manufacturing capacity meets 2030 demand, **regional concentration and trade policies** may cause **bottlenecks where domestic manufacturing is lacking**; the capacity to diversify and manufacture these components can be implemented relatively swiftly.	◑
Generator	Global capacity is sufficient until 2028, but **regional concentration creates import dependency**, risking supply disruptions if trade restrictions or logistics **hinder access to Chinese and Indian generators**.	◕
Blade	Manufacturing capacity is sufficient until 2027, but beyond that, **trade restrictions or supply disruptions** could create **bottlenecks in regions lacking local manufacturing.**	◕
Power converter	Global capacity remains sufficient beyond 2030, but **regional imbalances create reliance on imports** from countries with local manufacturing capacity.	◔

Sources: GWEC, 2023, Market Intelligence; Kearney Energy Transition Institute analysis.

Supply chain bottlenecks arise in components due to regional imbalances, limited capacity, and the need for new investments to meet demand

Supply chain bottlenecks

Directional

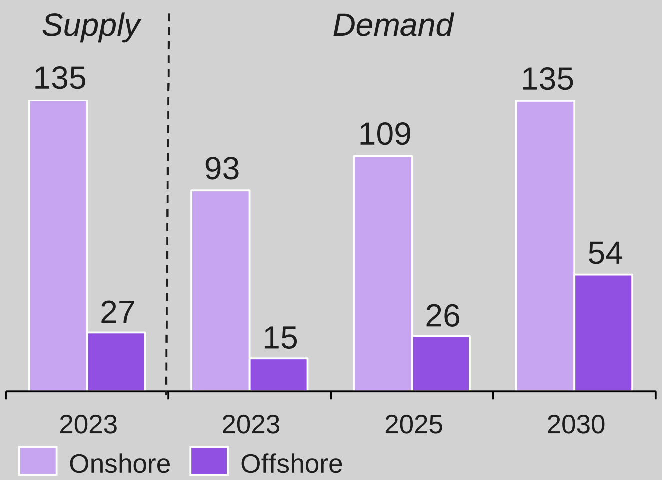
Onshore and offshore wind casting, tower, and foundation demand and supply

kt/year – units/year, 2023–2030

		Onshore		Offshore			
		Casting (kt/year)	Tower (units/year)	Casting (kt/year)	Tower (units/year)	Foundation (units/year) Floating	Foundation (units/year) Fixed bottom
Supply	**2023**	2174	34,030	513	3,910	221	3,880
Demand	**2023**	1136	20,629	274	1,692	13	1,679
Demand	**2025**	1329	20,857	456	2,452	34	2,418
Demand	**2030**	1642	19,027	961	3,721	291	3,430

Onshore and offshore turbine nacelle demand and supply

GW, 2023–2030



Components supply chain bottleneck

Component	Supply chain criticality description	Exposure
Casting	Onshore manufacturing capacity meets global demand until 2030; **however, offshore wind faces supply bottlenecks from 2026**, requiring new investments amid regional capacity constraints.	
Tower	The wind tower supply chain is more diversified than other components, **but offshore wind faces regional bottlenecks from 2026**, requiring new investments and an uninterrupted global supply chain.	
Foundation	**A deficit is likely to occur in all regions except China** if planned production capacity does not materialize and restrictive trade policies or local content requirements take effect.	
Nacelle	**China dominates nacelle production, meeting global demand until 2026**, but **offshore wind** faces regional bottlenecks, **requiring an uninterrupted global supply chain** to sustain growth.	

No exposure   Significant exposure

4.3 Supply chain bottlenecks

Sources: GWEC, 2023, Market Intelligence; GWEC, 2024, Global offshore wind report; Kearney Energy Transition Institute analysis

Transportation and generation step-up transformers lead times challenge the onshore wind supply chain

Supply chain bottlenecks

Transportation and site accessibility constraints

Port or manufacturing site

Component size challenges

Wind turbine components are increasing in size, requiring specialized transport equipment.

Infrastructure limitations

Many roads, bridges, and tunnels are not designed for oversized loads, requiring costly upgrades or alternative routing.

Regulatory and permitting bottlenecks

Transportation of oversized wind components requires **multiple state and local permits**, leading to delays.

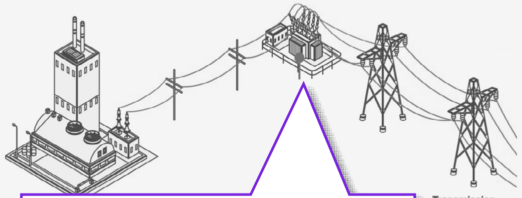
On-site delivery and installation issues

Remote locations of wind farms increase the **complexity of on-site delivery logistics.**

Project site

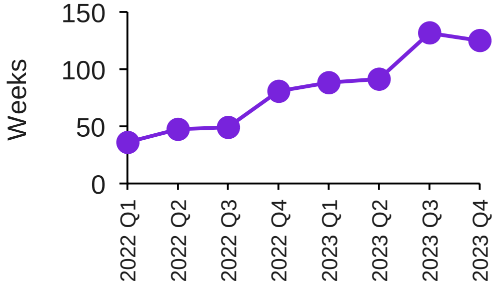
Increased supply chain pressure

Generation step-up (GSU) transformers lead time



A GSU transformer increases the voltage from the wind turbines to a medium or high-voltage level for efficient transmission to the power grid.

Lead time evolution
2022–2023, weeks



- Transformer lead times have increased **from 40 weeks in 2021 to 120 weeks in 2024**, driven by supply chain constraints and growing demand.
- Despite plans for capacity expansion, **many manufacturers are reluctant to invest due to long break-even periods.**
- **Transformer prices have risen 60–80% since 2020**, as pandemic-era production slowdowns have left manufacturers struggling to scale up.

Sources: US DOE, 2022, Wind Energy: Supply Chain Deep Dive Assessment; IRENA, 2017, Renewable energy benefits: leveraging local capacity for onshore wind; Wood Mackenzie, 2024, Supply shortages and an inflexible market give rise to high power transformer lead times; Kearney Energy Transition Institute analysis

Lead times, complexity, and geographic footprint increases the risks of disruption of the supply value chain

Supply chain bottlenecks

The supply chain is constrained by vessel capacity and size. Current estimates expect enough vessel capacity to reach capacity targets up to 2026 and new vessels are being built as the wind turbines get larger.

4.3 Supply chain bottlenecks

Supply chain challenges for offshore projects

- Need a **vast number of vessel days** to ensure the supply and construction of an offshore wind farm. The supply requires more vessel time than the construction phase, as elements are transported from their factories to their marshaling port.
- **Specific vessels** are needed for **transporting and installing** turbine components (heavy lift cargos) and cables (cable laying vessels).
- **Fabrication and marshaling ports** are required in different locations to ensure the supply and reception of the wind farm elements.

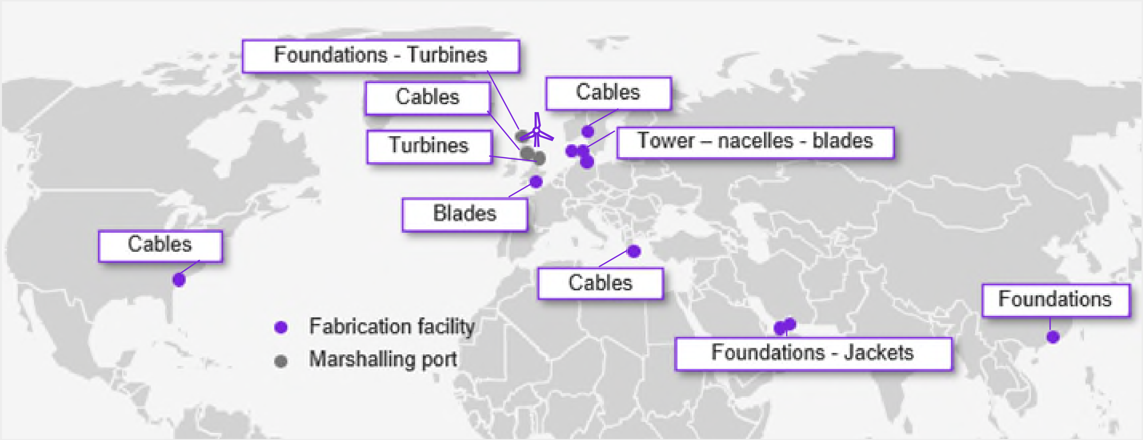
Sources: Spinergie, 2024, 5 supply chain lessons learned from analysis of a North Sea offshore wind farm; Kearney Energy Transition Institute analysis

Offshore wind farm: Seagreen

Location: The coast of Angus in Scotland
Developers: SSE and TotalEnergies
Capacity: 1,075 MW with 114 turbines
Foundations: Suction Bucket Jacket at 58.6 meters depth
Commissioning: fully commissioned in October 2023

- Supply required about four times more vessel time than construction. Jackets supply took more than 2,400 vessel days and 330 days for their installations; in contrast, turbines, locally supplied, took about 500 vessel days.
- Two heavy lift cargos were used in the European value chain, while three specific vessels were used for cable supply and installation.
- Ports across three continents, with marshaling ports in the UK and fabrication ports in UK, Norway, Denmark, Greece, US, UAE, and China

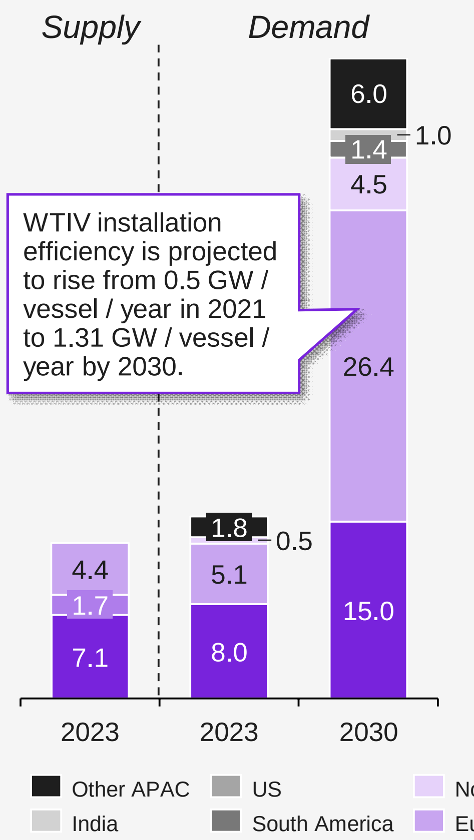
Supply chain for the Seagreen wind farm



Vessels for wind turbines need to adapt to larger turbines and their geographic availability is uneven, while marshaling ports require high investments to support future offshore installation

Wind turbine installation vessels (WTIV) demand and supply

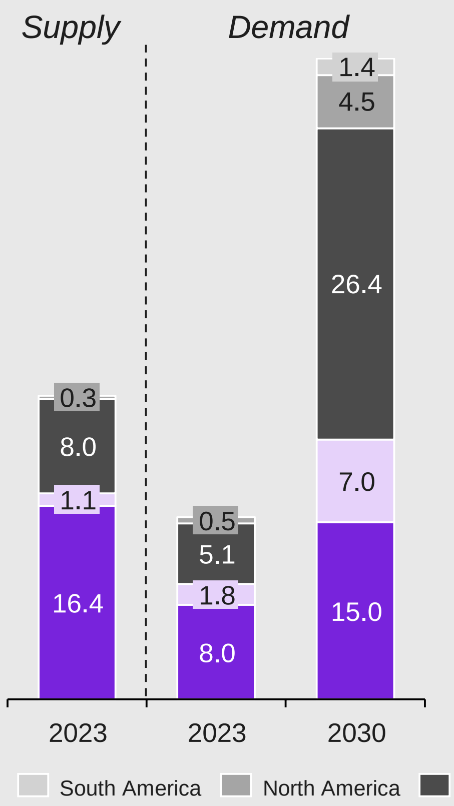
GW/year, 2023–2030



- **The Chinese WTIV supply chain is well-positioned for domestic growth and export projects.** Moreover, 27 WTIVs are under construction in Chinese shipyards.
- Flat offshore wind installations below 10 GW annually until 2026 allow European operators to deploy vessels to emerging markets in Asia and the US. **However, the rise in turbine size above 12 MW necessitates new WTIV investments.** A vessel shortage is anticipated in Europe by the late 2020s without significant investment by 2026/2027.
- Offshore wind markets in the **United States and the APAC region may face significant bottlenecks** due to their immature capacity for deploying their own WTIVs, making them highly dependent on Chinese and European vessels.

Operational port capacity demand and supply

GW/year, 2023–2030



- **More than 50 global ports** have announced plans to support offshore wind, potentially **adding 45 GW** of annual operational capacity to current installation capacity of 25 GW.
- However, an **estimated USD 18 billion investment will be required to bring these projects online**, based on a cost of USD 400 million to build a marshaling port with an annual operational capacity of 1 GW.
- **Europe requires additional port capacity by 2026 to meet offshore wind demand**. APAC (excluding China) risks overburdening existing ports without new facilities, while the US faces an urgent need for dedicated offshore wind ports to meet its targets..

Sources: GWEC, 2024, Global offshore wind report; GWEC, 2023, Global offshore wind turbine installation vessel database; WINDExchange U.S. DOE, and NREL, 2023, Gearing up for 2030: Building the offshore wind supply chain and workforce needed to deploy 30 GW and beyond; AECOM, 2022, Offshore Wind Marshalling Ports: Transforming marine ports and terminals for the offshore wind industry; Kearney Energy Transition Institute analysis

As wind deployment increases, the workforce shortage in the wind industry is mostly concentrated in skilled technicians

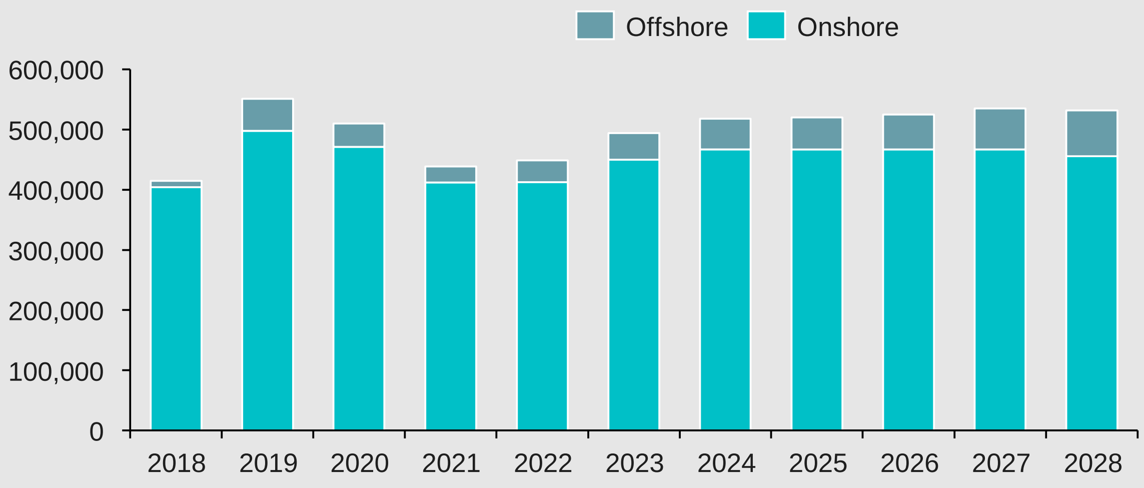
Workforce

Assuming the workforce demand in 2023 was fulfilled, meeting the 2028 forecast means approximately **40% of the total workforce will need to be recruited** between 2024 and 2028.

4.4 Workforce

Workforce demand for onshore and offshore segments

FTE, 2018–2028[1]



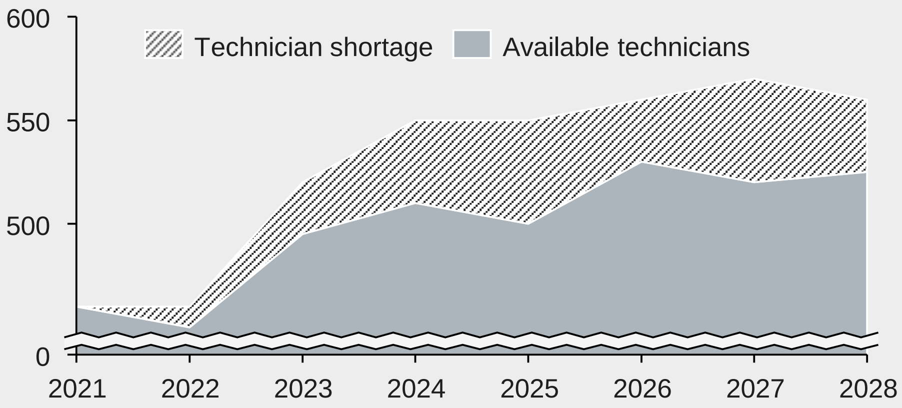
Globally, about 532,000 people will require training in constructions, installation, operation, and maintenance to meet wind energy growth by 2028.

Number of persons to be trained by 2028, for selected countries

China	205,291
United States	80,988
Germany	35,700
India	36,736
Brazil	12,370

Technician shortage for wind power

FTE, 2021–2028



- In a stated policies scenario, the labor gap is expected to represent approximately 6–8% of total wind workforce demand. This gap should increase if the net-zero emissions road map is achieved.
- The technician shortage is quantified between 6% and 8% and does not pose an immediate challenge to the sector.
- The increasing demand of technicians and the limited availability in the market has forced companies to recruit under-skilled technicians.
- The wind industry needs to focus its strategy in attracting and retaining talents.

[1] FTE corresponds to full-time equivalent.
Sources: GWEC and GWO, 2024, Global Wind Workforce Outlook 2024-2028; Kearney Energy Transition Institute analysis

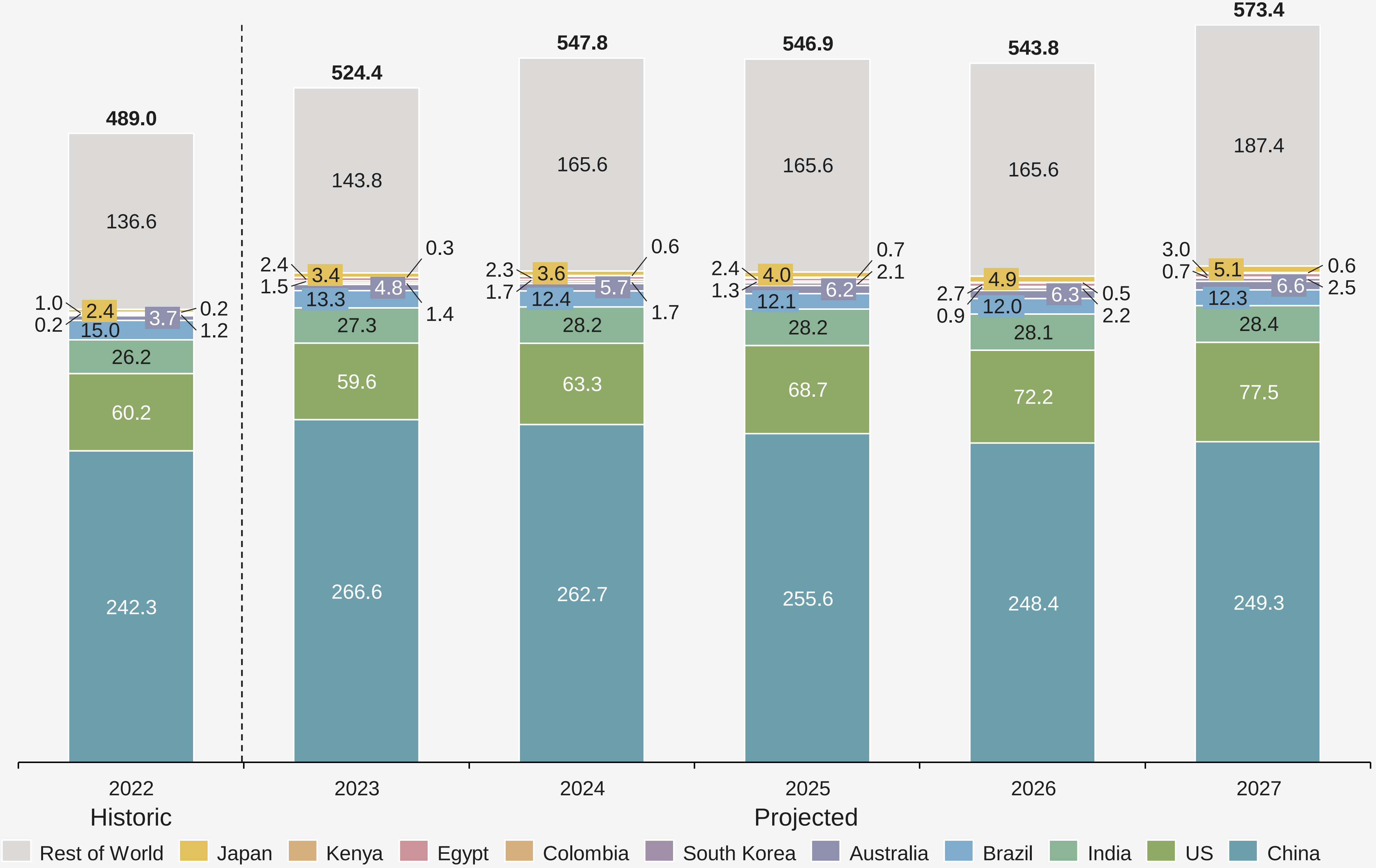
The training needs in these 10 countries represent about 67% of the total number of C&I and O&M technicians needed by 2027

Workforce

By 2027, 600,000 skilled workers will be needed to construct, install, operate, and maintain the global wind fleet.

4.4 Workforce

Trained C&I and O&M technicians needed in selected wind power countries[1,2]
thousands, 2022–2027



[1] C&I is construction and installation.
[2] O&M is operations and maintenance.
Sources: GWEC and GWO, 2023, Global Wind Workforce Outlook 2023-2027; Kearney Energy Transition Institute analysis

Kearney XX/ID

5. Economics of wind power

Economics of wind power

Levelized cost of electricity (LCOE)

– **The LCOE for wind energy has declined with technological advancements and increased capacity.**
– It is now one of the most competitive power generation technologies with **onshore wind's LCOE below fossil fuels for the past five years**.
– Brazil leads in the lowest onshore LCOE, followed by China and the UK, while Denmark, the UK, and the Netherlands dominate in offshore LCOE.

Total installed costs

– **Global onshore total installed costs fell 49% between 2010 and 2023, to USD 1,160/kW, driven by China's low costs.** After decreasing for more than a decade, in 2023 US costs rose due to supply chain and grid challenges.
– **Offshore costs have also registered significant (48%) reduction during the same time period but remain volatile, influenced by logistics, policies, and supply chain scale.** Costs have fallen due to shorter installation times thanks to larger turbines and specialized vessels, while floating wind costs dropped through standardization, scaling, and foundation advancements.

Wind turbine cost characteristics

– **Annual average prices have fallen between 41% and 64% from 2010 to 2023 (excluding China).**
– However, since 2020 the turbine price trend has diverged between Chinese and Western manufacturers. Western manufacturers are more exposed to supply chain pressures and high material prices, affecting their profitability.
– For offshore projects, the distance to the port and the foundation type affect the costs of O&M, decommissioning expenses, and vessel availability. Recent offshore projects are located further away from shore in relatively mature markets such as Europe.
– Between 2010 and 2023, **the average offshore wind project size increased by 106%,** from 136 MW to 280 MW, driving down costs.

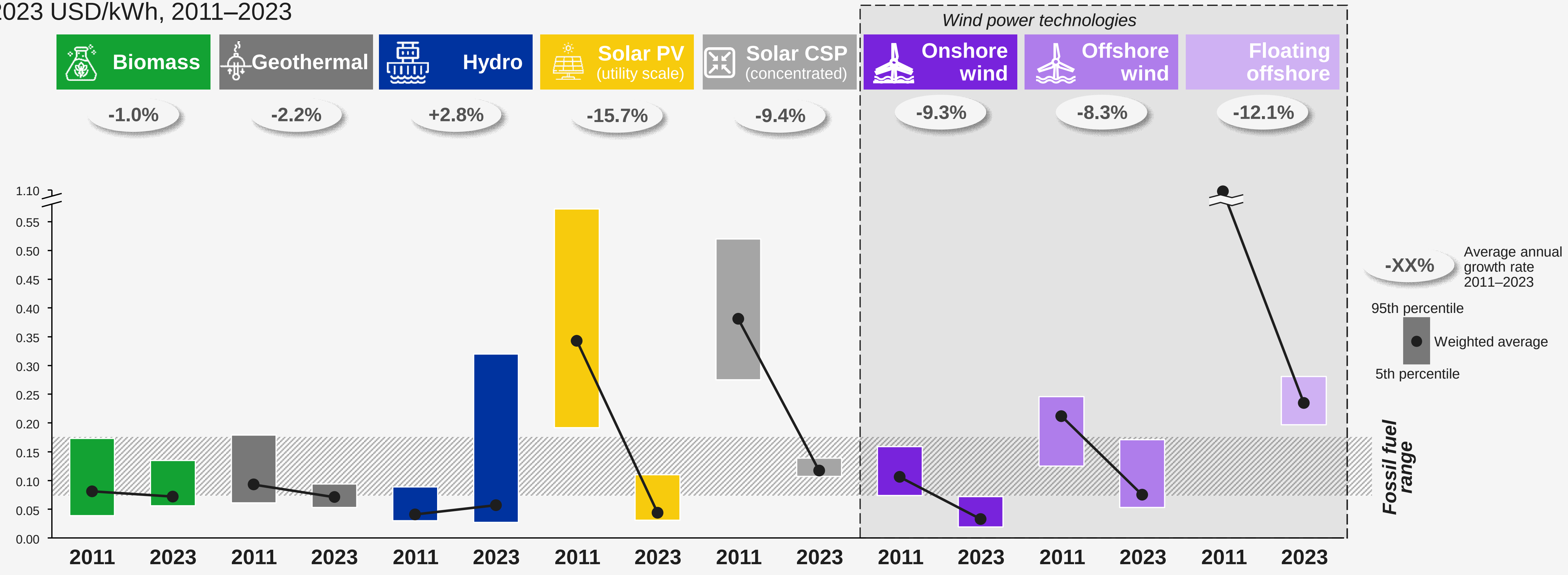
Future cost trends

– **Technological advancements and regulatory support** are expected to **drive significant cost** declines in the medium to long term, with possible reductions of LCOE of 58% and 63% in the US depending whether the project is onshore or offshore.

As the technology matures and capacity increases, the cost of wind will continue to decline and become one of the most competitive power generation technologies

Global LCOE by renewable energy source[1]

2023 USD/kWh, 2011–2023



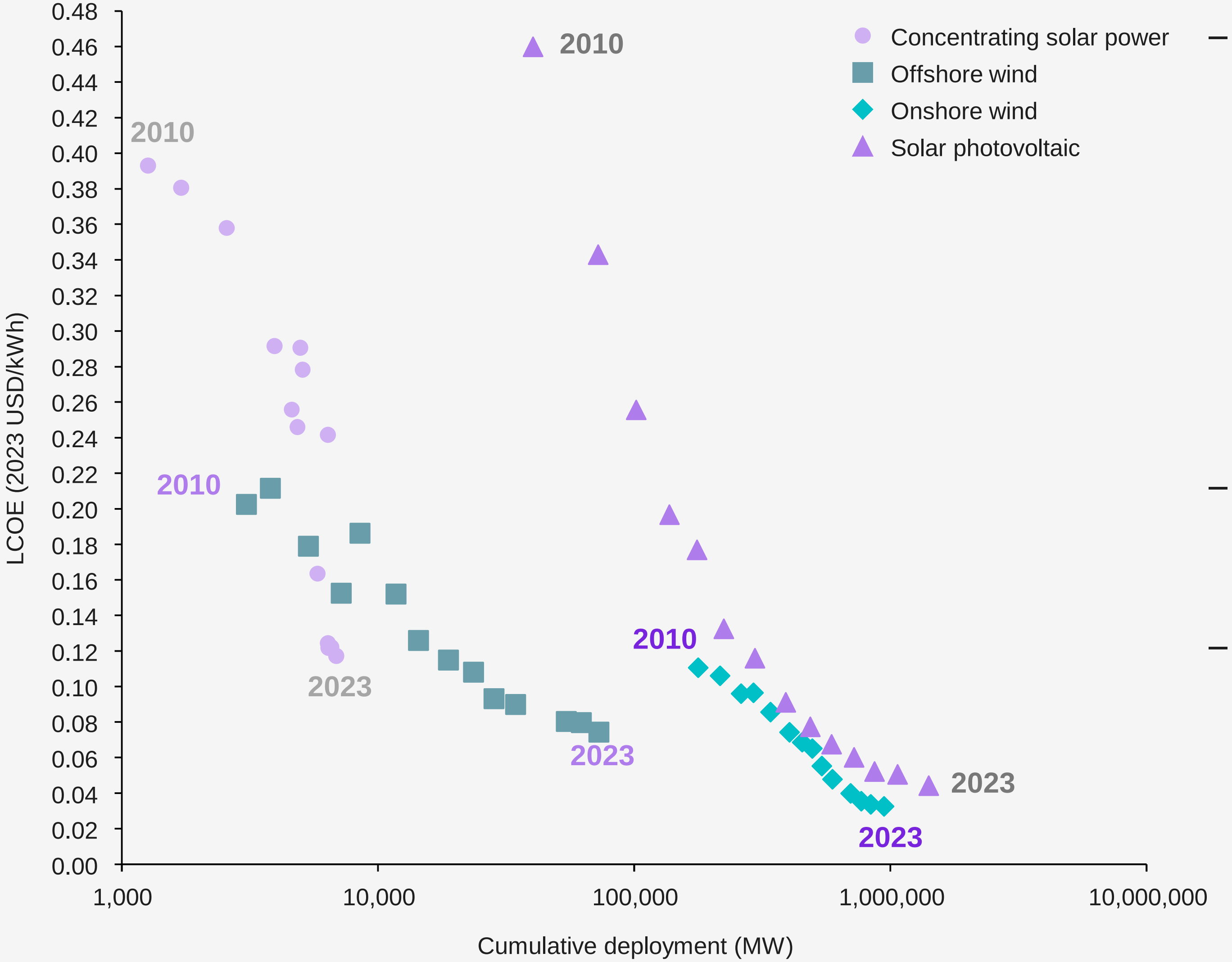
Note: In 2011, only a single floating offshore wind project was in operation.
[1] LCOE is levelized cost of electricity; outliers not considered in max/min but included in weighted averages.
Sources: IRENA, 2024, Floating Offshore Wind Outlook; IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

The cost declines have made wind and solar power technologies the economic backbone of the energy transition

A learning curve approach illustrates the relationship between cost reduction and technology performance improvement, highlighting how advances in technology and accumulated experience can drive down costs.

5.1 Levelized cost of electricity

Global weighted average LCOE learning curve trends for wind and solar technologies
2023 USD/kWh, 2010–2023



- **The LCOE learning rate for onshore wind from 2010 to 2023 reached 43.7%**, surpassing solar PV, due to better WACC characterization by market, significant cost reductions in China, and continued improvements in turbine technology.
- **The LCOE learning rate for offshore wind from 2010 to 2023 was 22%.**
- High learning rates for wind power and solar PV between 2010 and 2023 suggest that accelerated deployment will reduce the cost of the transition.

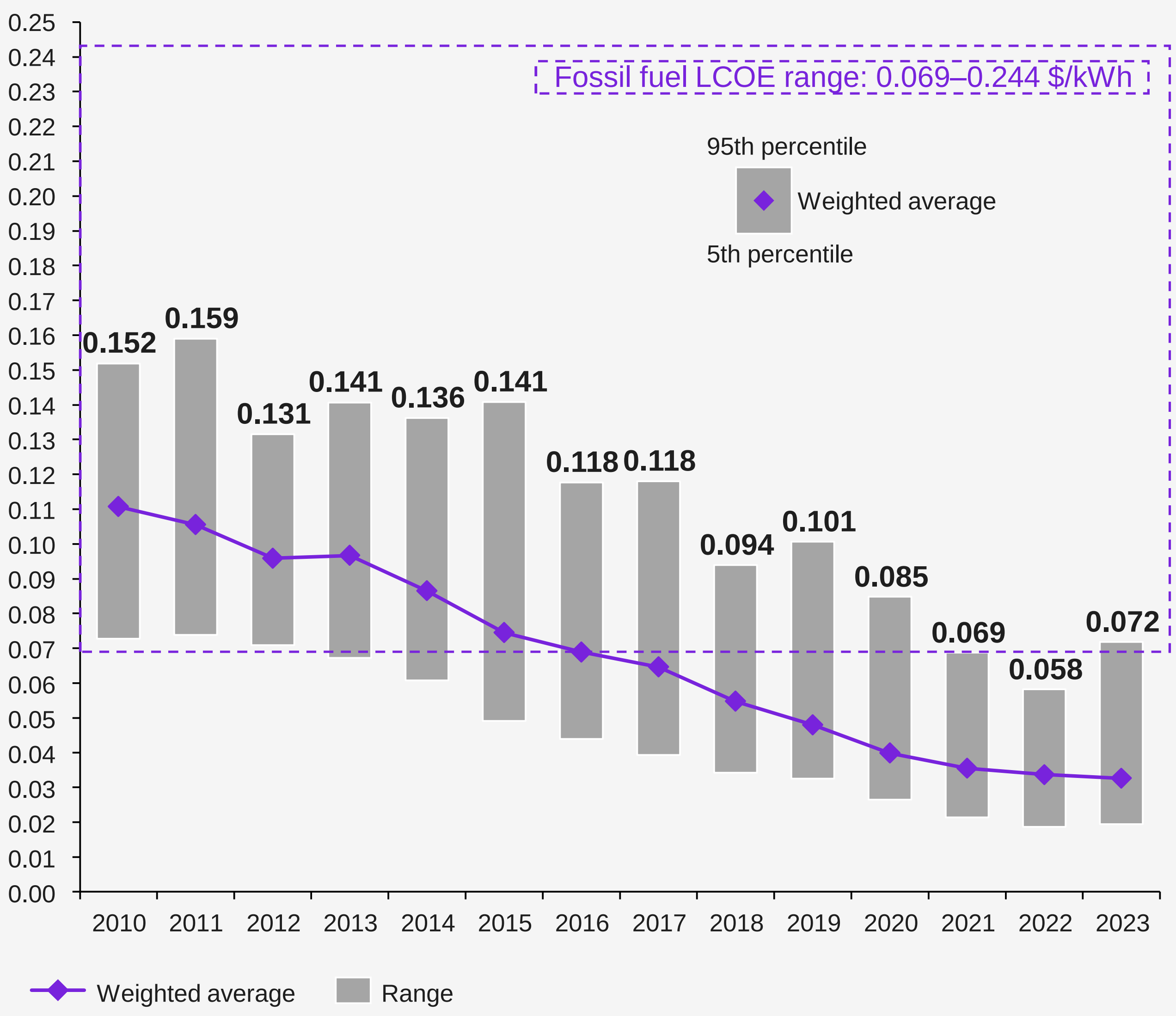
Sources: IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

Onshore wind's LCOE is on average below the entire range of fossil fuel LCOE for the past five years

China plays a significant role in these LCOE figures, accounting for approximately 43% of the global installed capacity in 2023.

5.1 Levelized cost of electricity

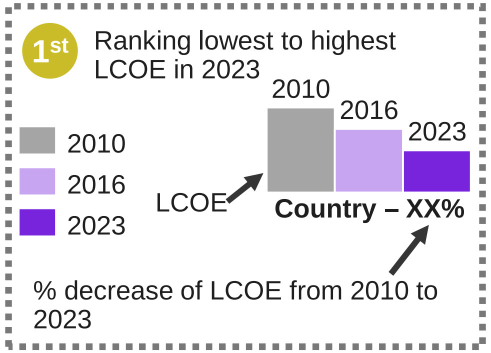
Global LCOE evolution for onshore wind
2023 USD/kWh, 2010–2023



- **Onshore wind's LCOE declined** on average **by 6.9%** every year before **2012**, and by **10.2% from 2013 to 2023**.
- **A 70.6% decrease was observed globally from 2010 to 2023**, with the largest LCOE reduction occurring in **Brazil**, amounting to **80%.**
- In 2023, with the exception of Japan and Türkiye, **all major markets had weighted average LCOEs below USD 0.050/kWh—significantly below** the weighted average of **fossil fuel**-fired power generation, which was **USD 0.100/kWh**.

Sources: IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

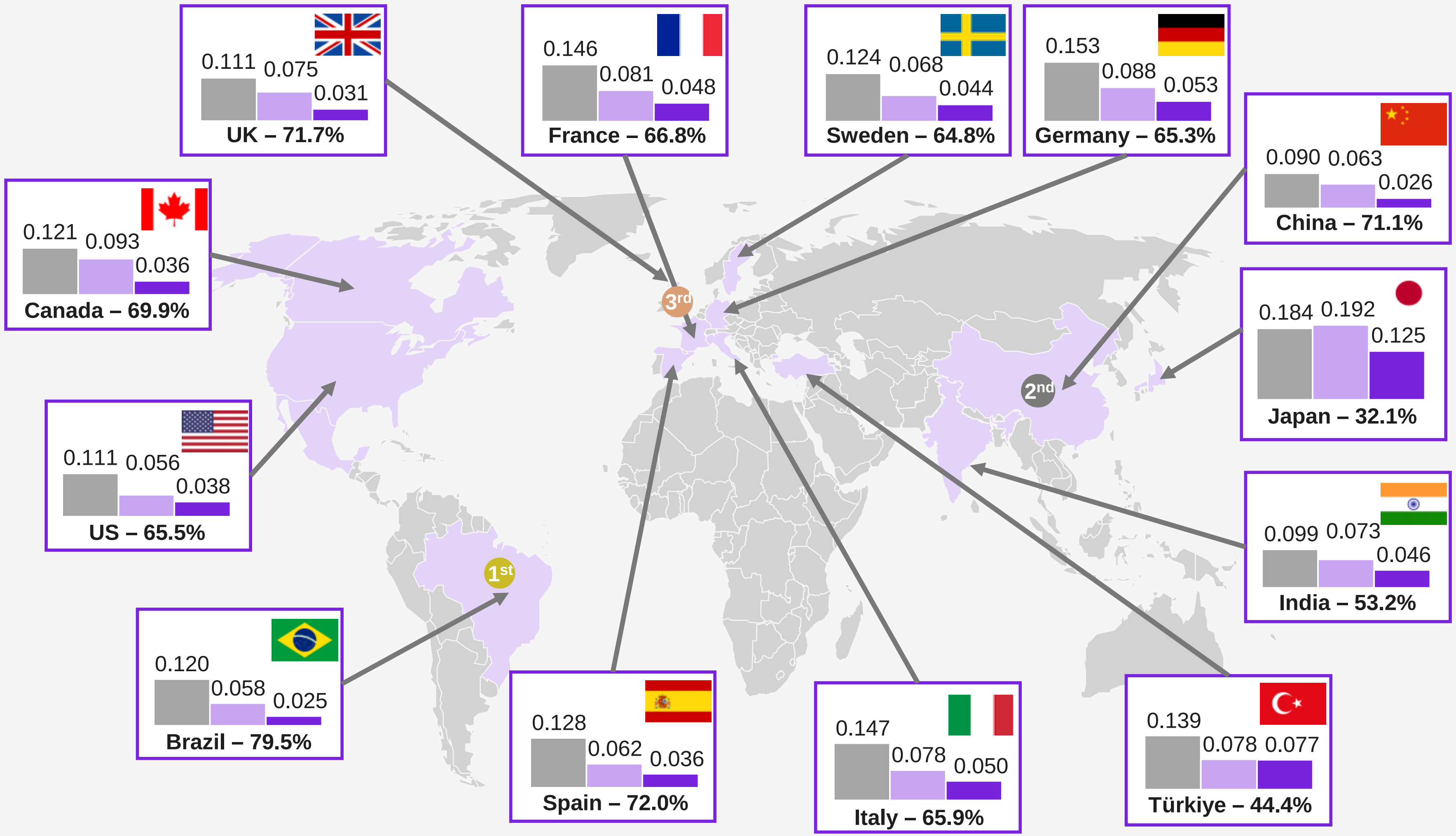
Onshore wind’s LCOE has rapidly decreased worldwide, with Brazil having reached the lowest LCOE, followed by China and the UK



5.1 Levelized cost of electricity

Onshore wind’s LCOE for selected countries

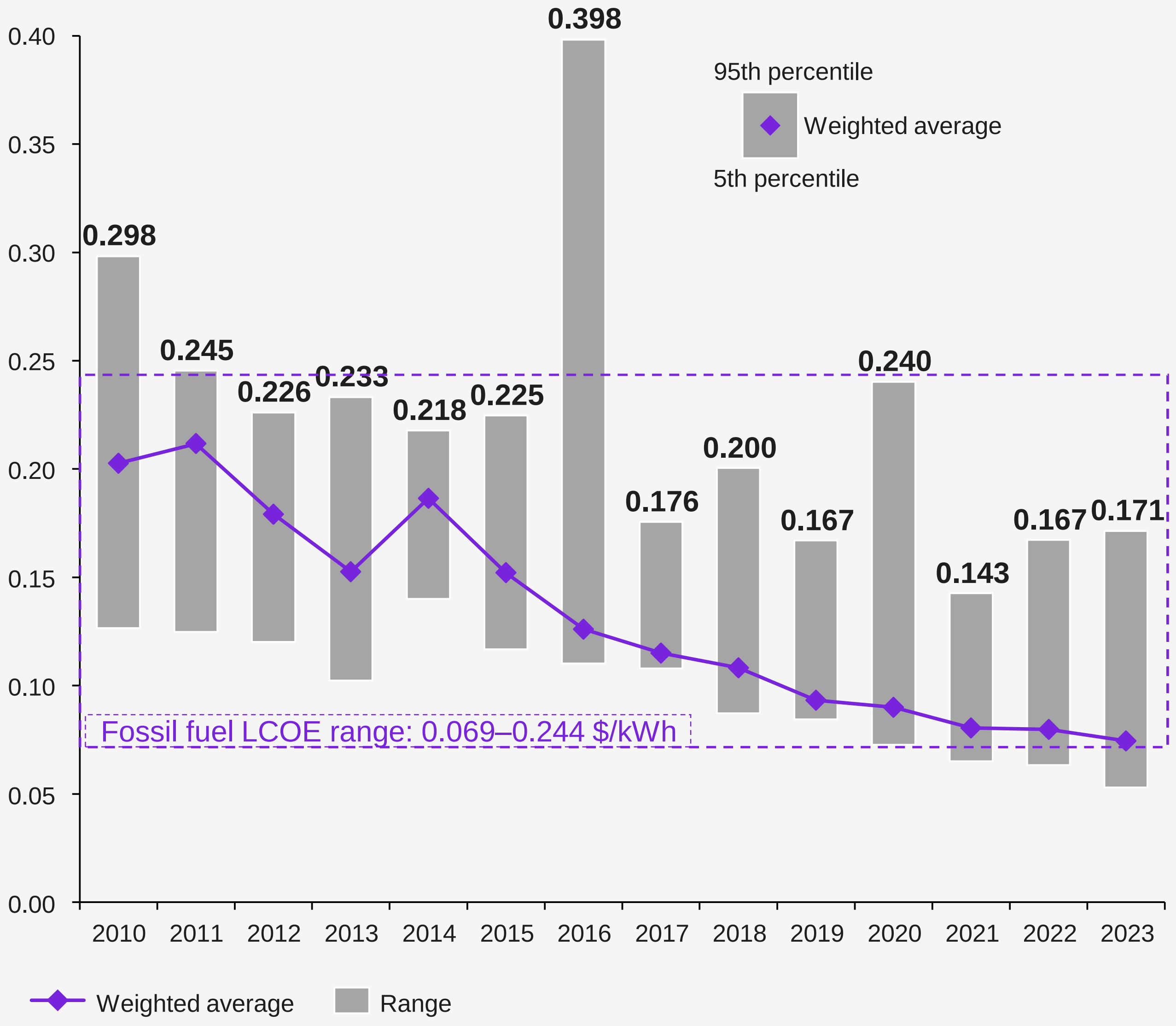
2023 USD/kWh, 2010–2023



Sources: IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

Offshore wind technology has matured rapidly since 2010, with LCOE steadily decreasing

Global LCOE evolution for offshore wind
2023 USD/kWh, 2010–2023

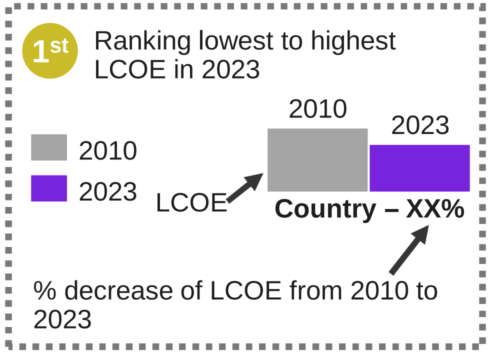


Sources: IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

- **Offshore wind's LCOE declined** on average **by 15.1%** every year **from 2011 to 2013**, and by **9.5% from 2014 to 2023**.
- **Between 2010 and 2023**, the global weighted average **LCOE of offshore wind fell 63%**, from USD 0.203/kWh to USD 0.075/kWh.
- In 2023, with the exception of Japan and Republic of Korea, **all major markets had weighted average LCOEs below USD 0.090/kWh—below** the global weighted average of **fossil fuel**-fired power generation, which was **USD 0.069–0.244/kWh**.

5.1 Levelized cost of electricity

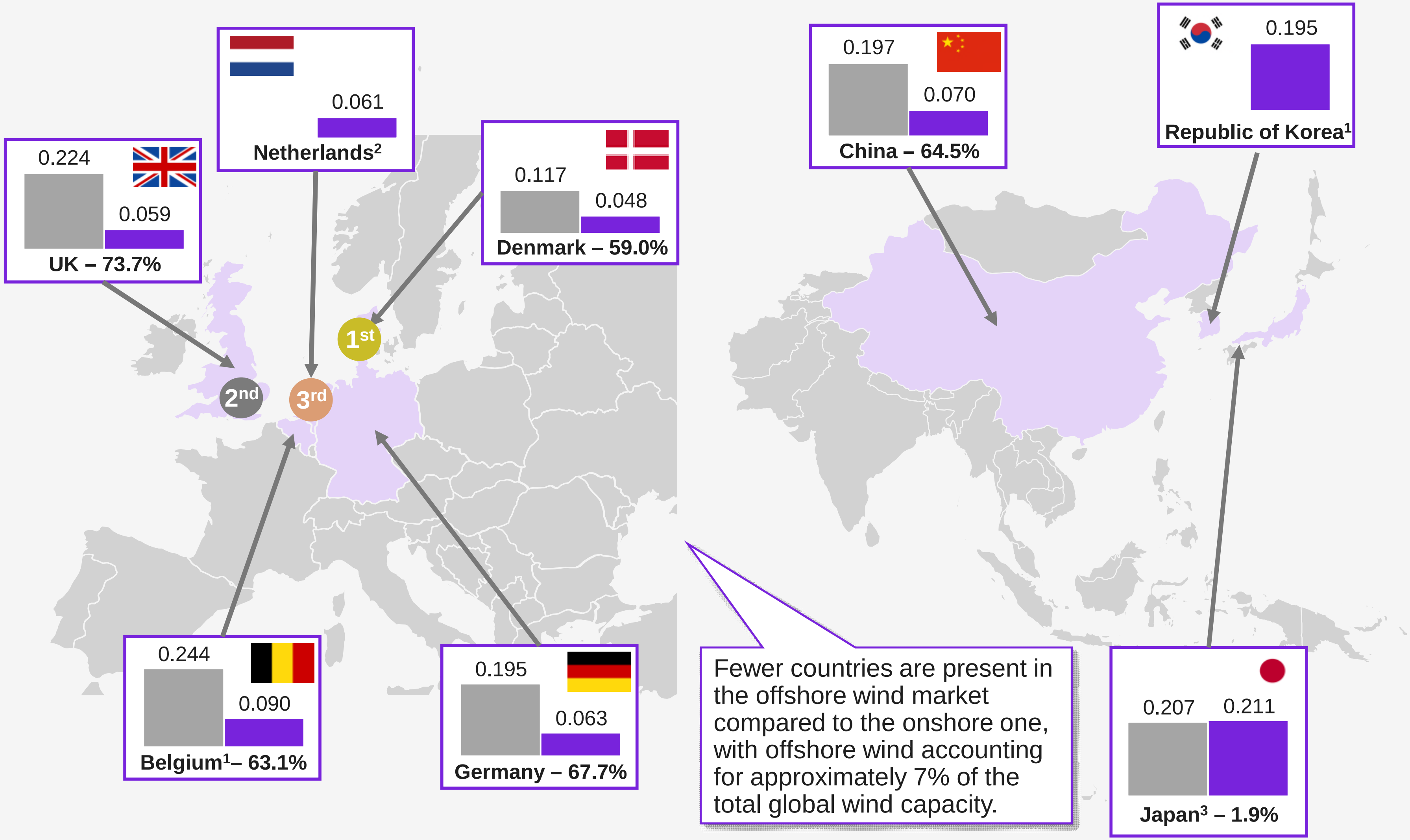
Offshore wind's LCOE has rapidly decreased worldwide, with Denmark having reached the lowest LCOE, followed by the UK and the Netherlands



5.1 Levelized cost of electricity

Offshore wind's LCOE for selected countries

2023 USD/kWh, 2010–2023



[1] Countries where data were only available for projects commissioned in 2020, not 2023.
[2] Countries where data were only available for projects commissioned in 2015, not 2010.
[3] The percentage for Japan represents the increase in LCOE.
Sources: IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

The LCOE definition regroups most factors affecting wind electricity generation cost

The LCOE allows for the combination of all direct costs associated with a power technology into a single metric. However, **LCOE does not include network integration or other indirect costs.**

- Onshore wind
- Offshore wind

5.1 Levelized cost of electricity

LCOE

Total installed costs

Value per kW, measuring how much it costs to produce kW of wind power capacity before the beginning of electricity generation

Turbine
- Rotor
- Nacelle
- Tower

Balance of system
- E&D[1]
- Project management
- Foundation
- Electrical infrastructure
- Assembly/installation
- Lease price
- Turbine transport
- Site access staging

Soft costs
- Contingency[2]
- Decommissioning bond
- Plant commissioning
- Wind turbine warranty
- Insurance during construction
- Construction finance

Capacity factor

Ratio between generated power and theoretical maximum output

All-in O&M[3]

Operating expenses from the moment the solar plant starts producing electricity

Other LCOE drivers

- WACC[4]
- Decommissioning[5]

Other costs associated to the electricity production phase of the power plant

Press Ctrl and click the image to navigate to the glossary details in the Appendix.

[1] E&D is engineering and development; [2] Cost category also includes insurance, permitting, bonding, and markup estimates [3] O&M is operations and maintenance; [4] WACC is weighted average cost of capital, which refers to the debt and equity needed to finance the initial investment; [5] Decommissioning cost should be included in the LCOE in jurisdictions where it is borne by the energy producer. It includes costs related to power plant dismantle and material recycling once it has ended its operation.
Sources: NREL, 2023, 2022 Cost of Wind Energy Review; Kearney Energy Transition Institute analysis

Wind is a highly capital-driven industry, with capex accounting for approximately 73% to 82% of the LCOE

Example

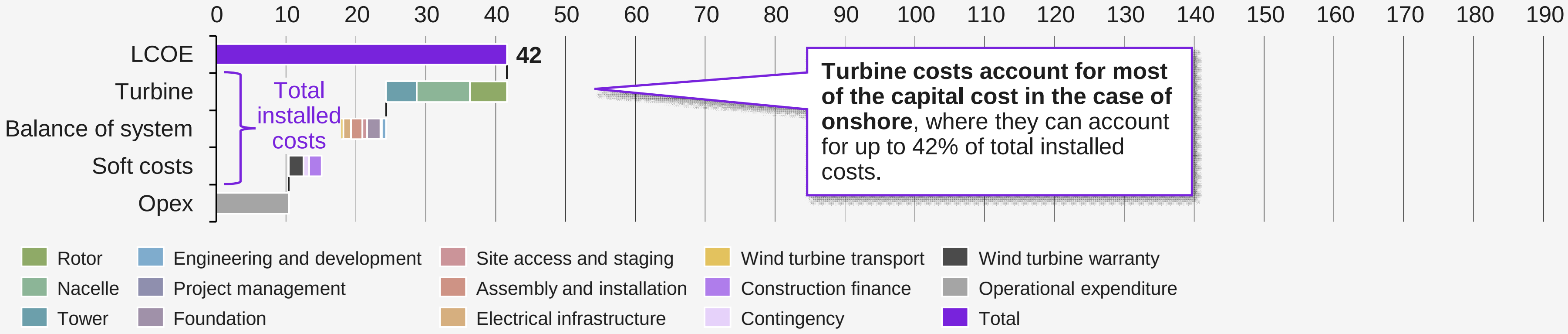
The cost of wind power predominantly consists of upfront investment. Operation and maintenance typically account for 18% to 26% of the electricity price.

Total installed costs

5.1 Levelized cost of electricity

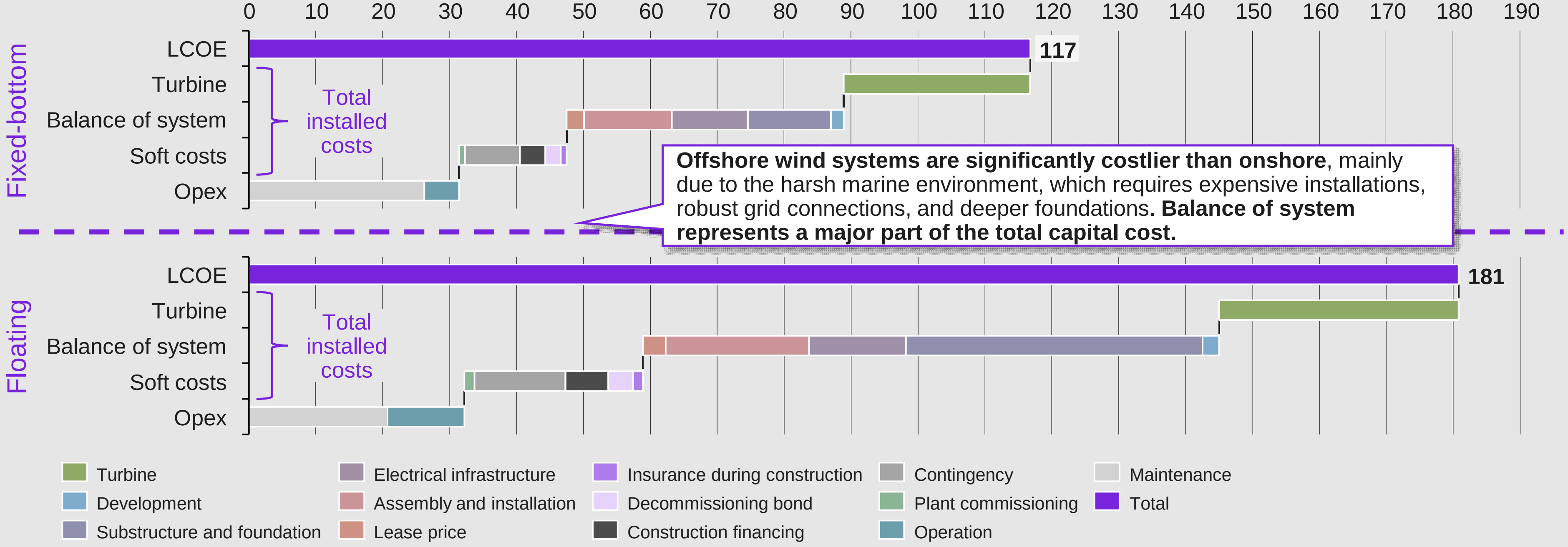
LCOE breakdown for onshore wind

USD/MWh, 2023



LCOE breakdown for fixed-bottom and floating offshore wind

USD/MWh, 2023



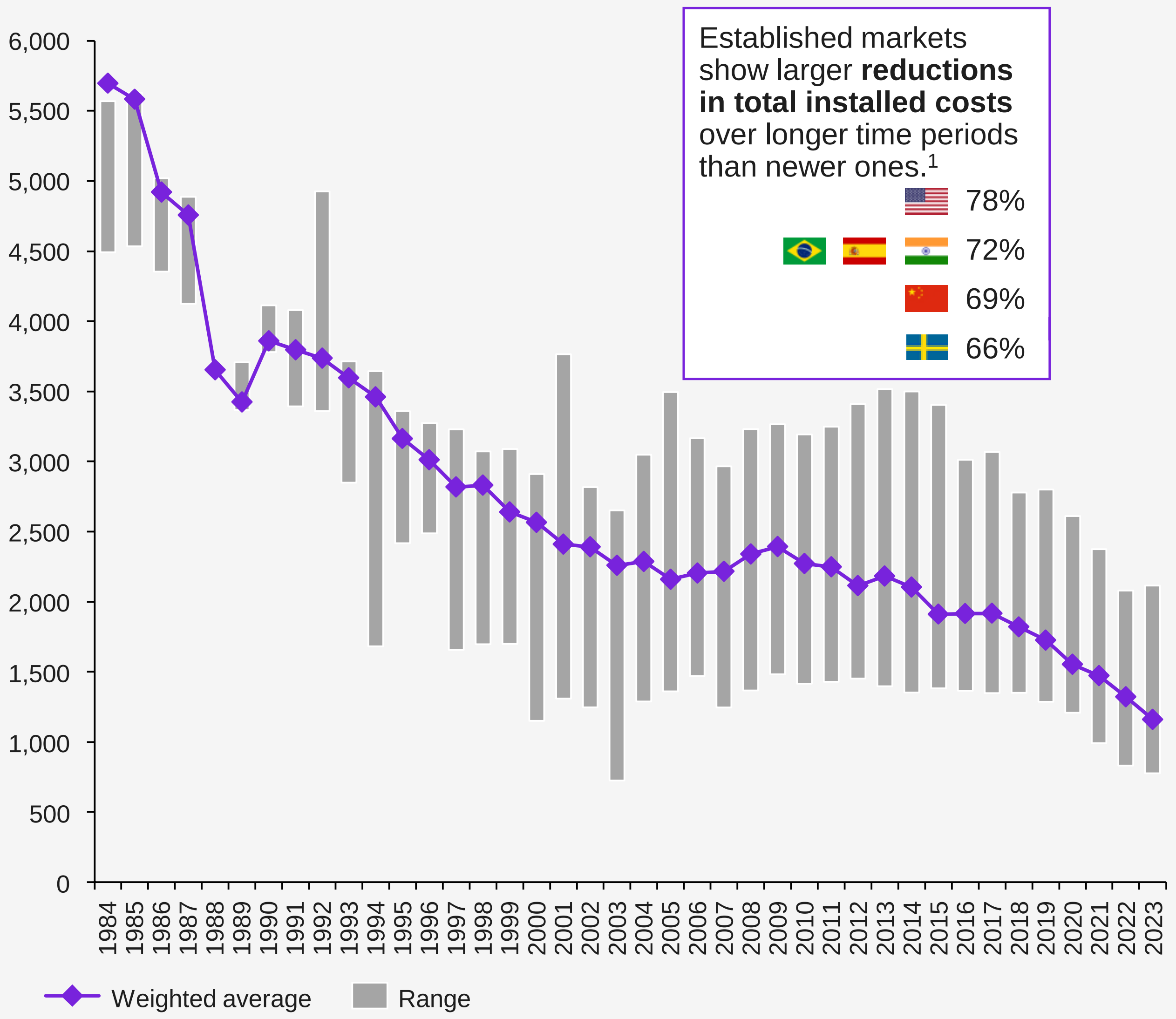
Sources: NREL, 2024, 2023 Cost of Wind Energy Review; Kearney Energy Transition Institute analysis

From 2010 to 2023, global total installed costs fell by 49%, driven by China's low costs. However, in 2023, the US saw a rise in costs after more than a decade of decline

Installed costs can vary significantly by country due to site-specific factors like logistics, local content policies, and land-use restrictions.

5.2 Total installed costs

Global weighted average total installed costs for onshore wind
2023 USD/kW, 1984–2023



- **Between 2010 and 2023**, the global weighted average **total installed cost** of onshore wind projects **fell by 49%**, **from USD 2,272/kW to USD 1,160/kW**, primarily due to advancements in turbine technology and reductions in balance-of-plant costs.
- **China** became the first country to achieve a **weighted average installed cost** below USD 1,000/kW, **reaching USD 986/kW in 2023.**
- **In 2023, US total installed costs rose by 19% from 2022** due to higher interest rates, supply chain constraints, and grid interconnection challenges, resulting in a slower year for installed capacity.

[1] Data for the United States covers the period from 1984 to 2023 (excluding 1992 to 1997), Brazil covers 2001 to 2023 (excluding 2004), Spain covers 1990 to 2023, India covers 1990 to 2023, China covers 1996 to 2023, and Sweden covers 1984 to 2023 (excluding 1985 to 1989 and 2000).
Sources: IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

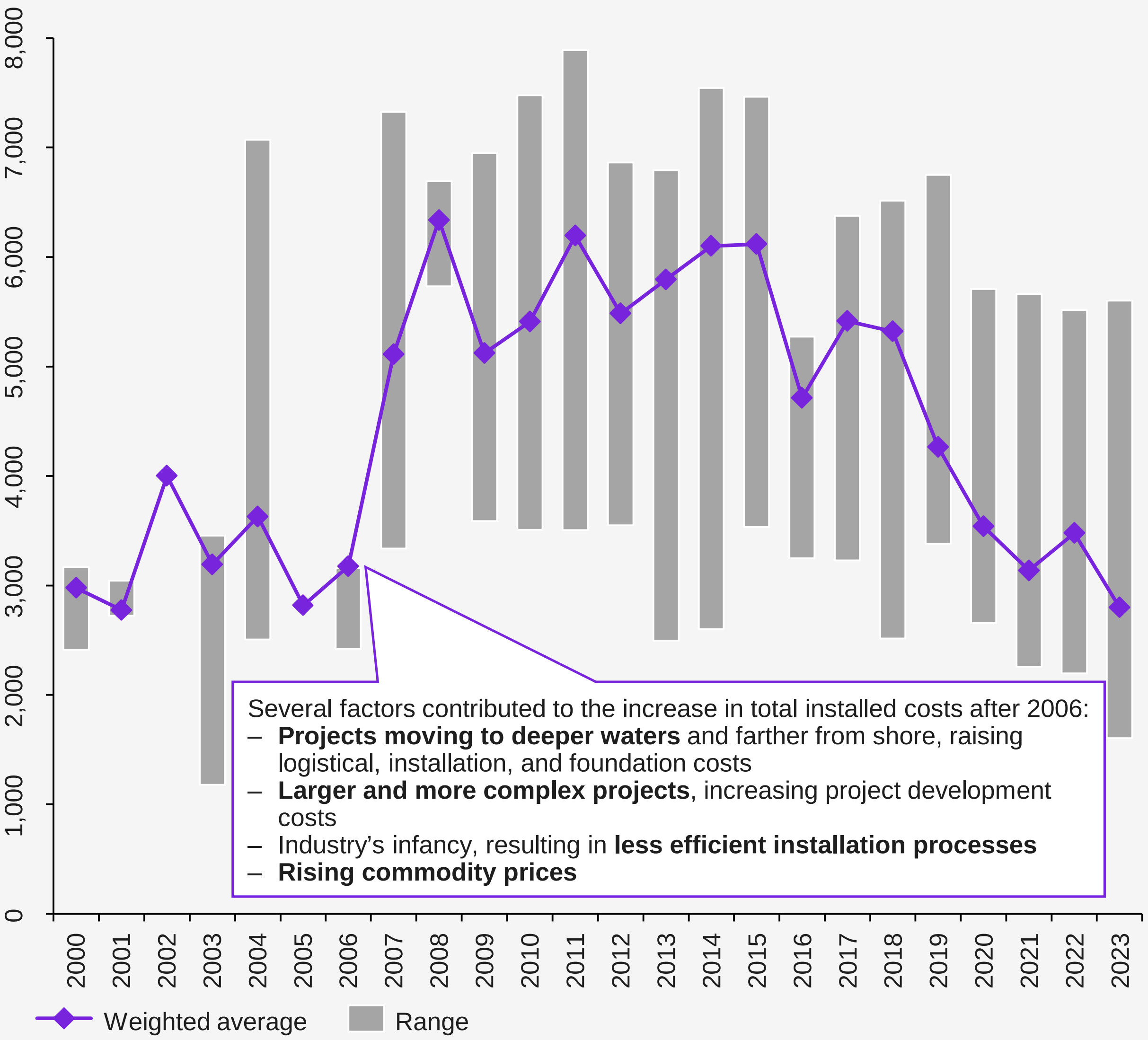
Total installed costs fell 48% from 2010 to 2023, though the offshore wind market remains volatile

The global weighted average total installed cost remains volatile due to the site-specific nature of offshore wind projects, the variations in market maturity, the scale of the local supply chain, and the entity responsible for the wind farm-to-shore transmission assets.

5.2 Total installed costs

Global weighted average total installed costs for offshore wind

2023 USD/kW, 2000–2023



Sources: IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

- **Between 2010 and 2023**, the global weighted average **total installed cost** of offshore wind **dropped by 48%, from USD 5,409/kW to USD 2,800/kW**, with a peak of USD 6,195/kW in 2011.
- **The cost-reduction trend since 2011 came from:**
  - lower commodity prices
  - lower risks from stable government policies and support schemes
  - improved turbine designs
  - standardization of design and industrialized manufacturing
  - improvements in logistics
  - economies of scale from clustered projects in Europe.

Specialized vessels and larger turbines have reduced installation times from more than two years to under 18 months, reducing total installed costs

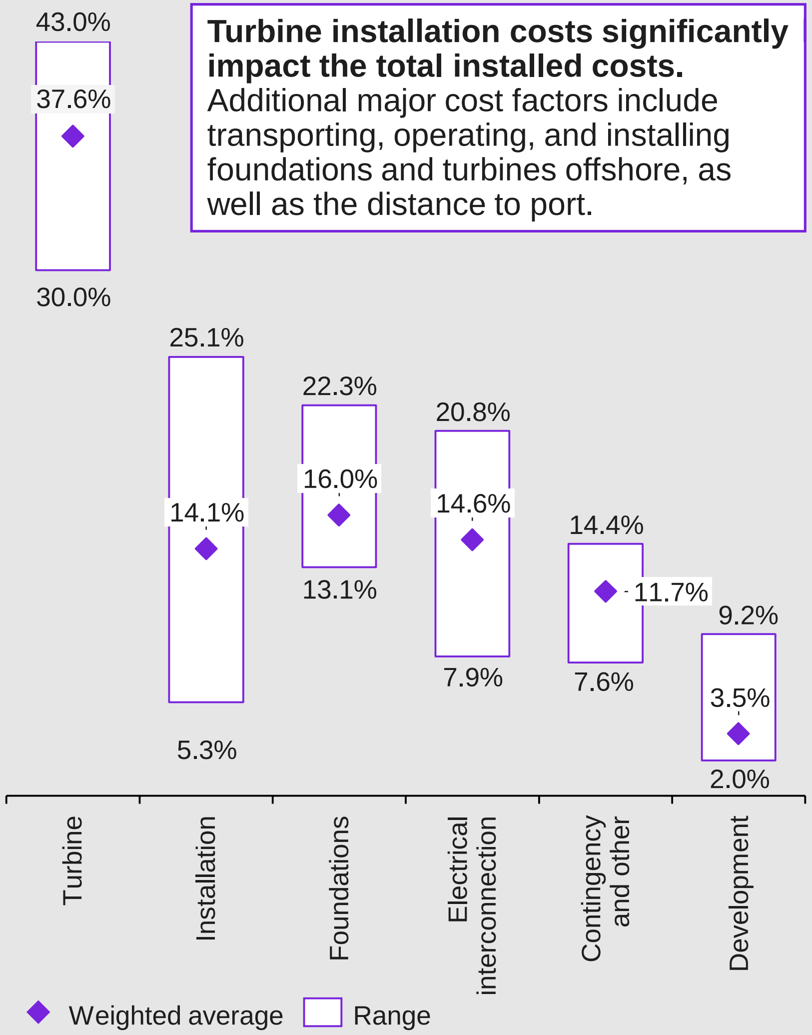
Projects have shifted from installing 100–200 MW annually (2010–2020) to more than 300 MW since 2021, allowing developers to achieve economies of scale that lower total installed costs.

5.2 Total installed costs

Offshore wind farm total installed cost breakdown

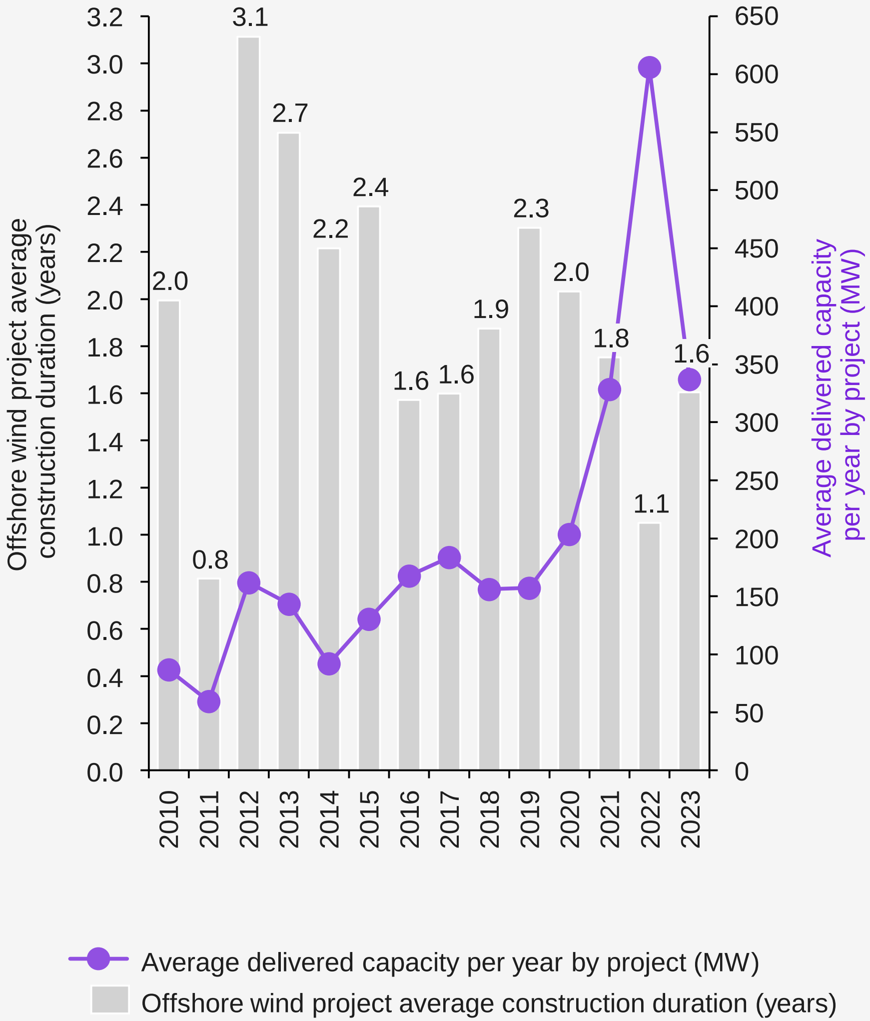
%, 2023

Turbine installation costs significantly impact the total installed costs. Additional major cost factors include transporting, operating, and installing foundations and turbines offshore, as well as the distance to port.



Installation time and MW installed per year by offshore wind projects in Europe and China

years – MW, 2010–2023[1]

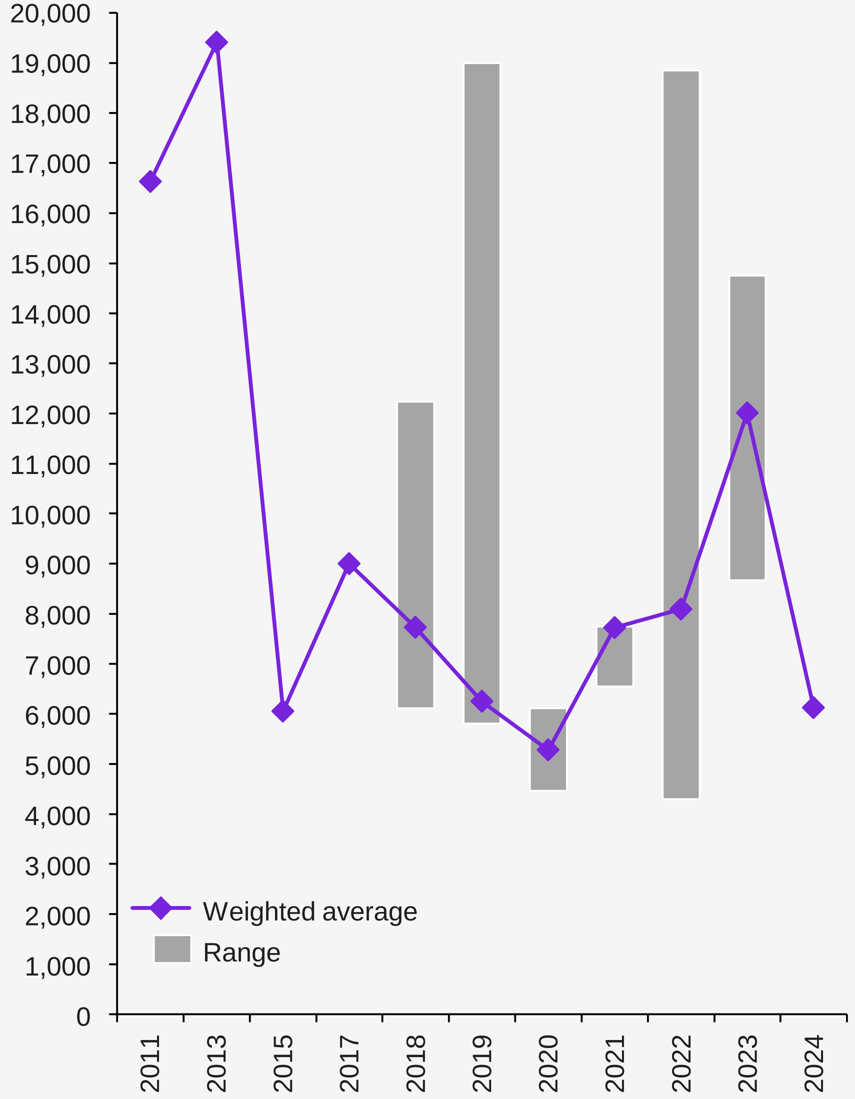


[1] Duration data represents the time from first foundation to last turbine.
Sources: IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

Total installed cost reductions in floating wind are driven by standardization, scaling up projects, and technological advancements in foundations

Global weighted average total installed costs for floating offshore wind

2023 USD/kW, 2011–2024



Sources: IRENA, 2024, Floating Offshore Wind Outlook; Kearney Energy Transition Institute analysis

– **Reducing the number of floating wind platform designs through standardization is seen as the top cost-cutting factor**, with 21% of survey respondents highlighting its role in achieving economies of scale and streamlining manufacturing.

– **Turbine costs are expected to decrease by 65% in the next 10 years, driven by the scaling up of wind farm projects** and a reduction in associated risks. **Current floating wind farms typically consist of 3–5 turbines. By 2030**, projects are projected to have **15–50 turbines**, significantly lowering the cost per MWh. **Beyond 2030, turbine costs for floating wind are expected to align with the cost trajectory of fixed-bottom wind turbines.**

– **Floating foundation costs are currently five times higher than fixed-bottom foundations** due to limited experience, supply chain immaturity, and the higher cost of components. **Over the next 10 years, cost reductions are expected to bring floating foundations down to two times the cost of fixed-bottom foundations**, aided by advancements in technology, scaling, standardization, and improved supply chains.

5.2 Total installed costs

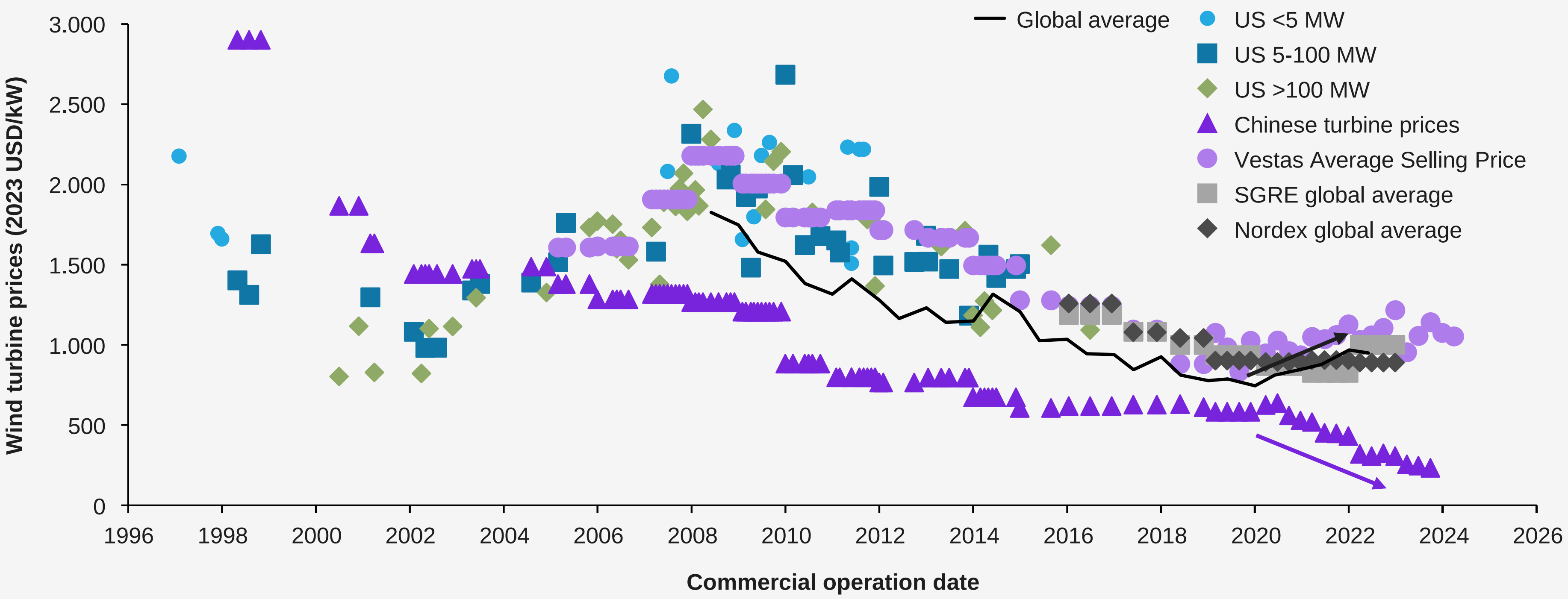
Since 2020, wind turbine prices have diverged significantly between Chinese and Western manufacturers, the latter being more exposed to supply chain issues and rising costs

Wind turbine prices have dropped significantly since 2008. However, due to supply chain pressures and elevated materials prices, global average turbine prices increased by 22% in 2022 compared to 2020.

5.3 Wind turbine cost characteristics

Wind turbine price indices and price trends

2023 USD/kW, 1997–2023



– **Most markets saw peak turbine prices between 2007 and 2010**, driven by high commodity costs (cement, copper, iron, and steel), supply chain bottlenecks, and strong government support for renewable energy. This period's high demand and tight supply allowed OEMs to charge higher margins. However, as the supply chain expanded and manufacturing capacity grew, these constraints eased, leading to a price peak. **From 2011 onward, annual average prices declined, dropping 41% to 64% from 2010 to 2023 (excluding China).**

– **In China, prices** declined from a peak of approximately USD 2,800/kW in 1998 to around **USD 233/kW** by the third quarter of **2023.** China’s pricing trends are distinct due to **intense competition, specific contract structures, and localized supply chain dynamics.**

– **In most markets**, excluding China, **2023 wind turbine prices ranged from USD 706/kW to USD 1,040/kW**, reflecting regional price disparities and the influences of demand and manufacturing locations.

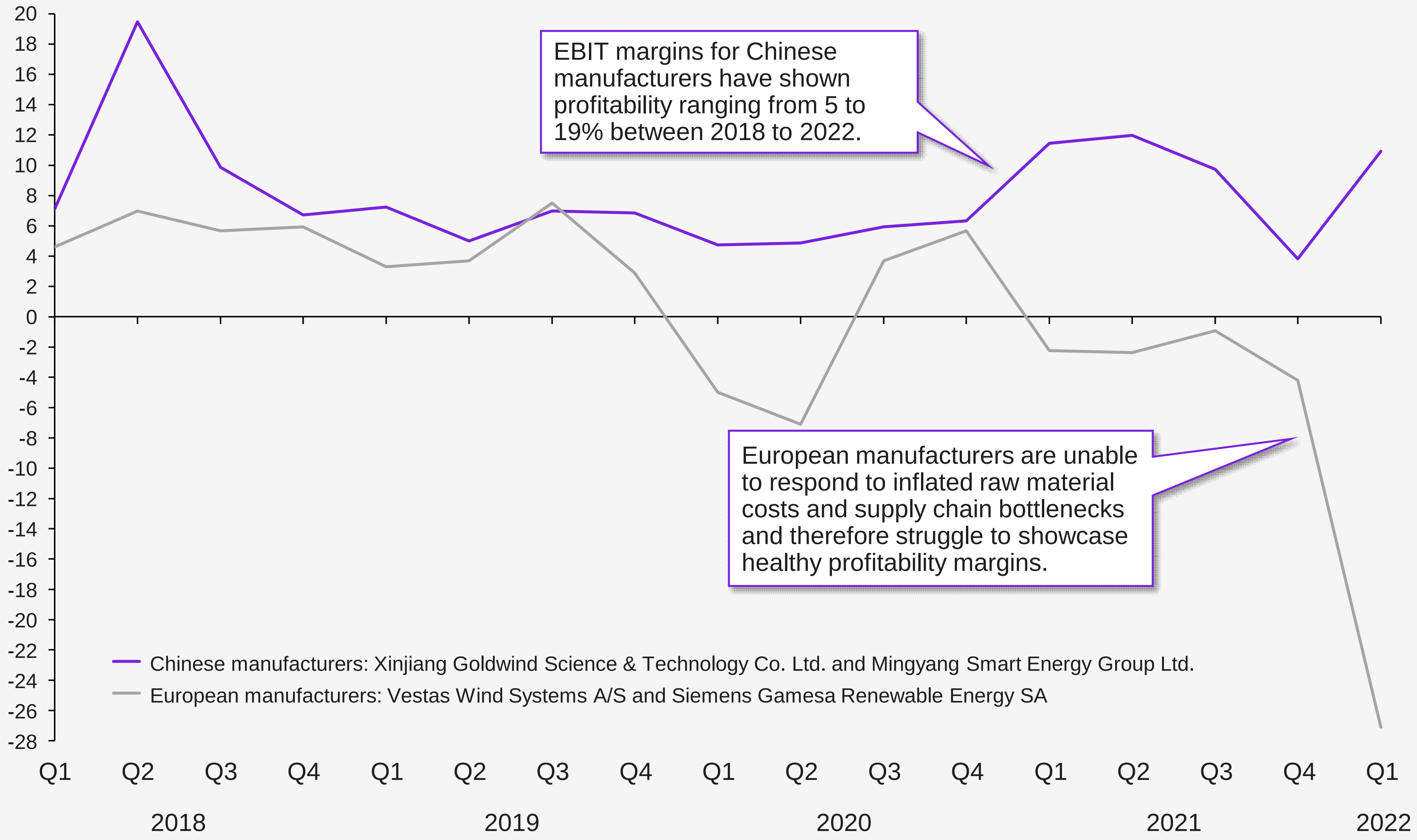
Sources: IRENA, 2024, Renewable Power Generation Costs in 2023; US DOE, 2023, Land-Based Wind Market Report: 2023 Edition; S&P Global, 2022, China’s increasingly cheap wind turbines could open new markets; Kearney Energy Transition Institute analysis

Chinese manufacturers primarily serve their expansive domestic market, which provides substantial demand and supports profitability

European wind turbine manufacturers began recovering positive EBIT margins in 2022, marking an improvement in profitability.

Divergence in profitability for wind turbine – European vs. Chinese manufacturers

EBIT margin %, 2018–2022



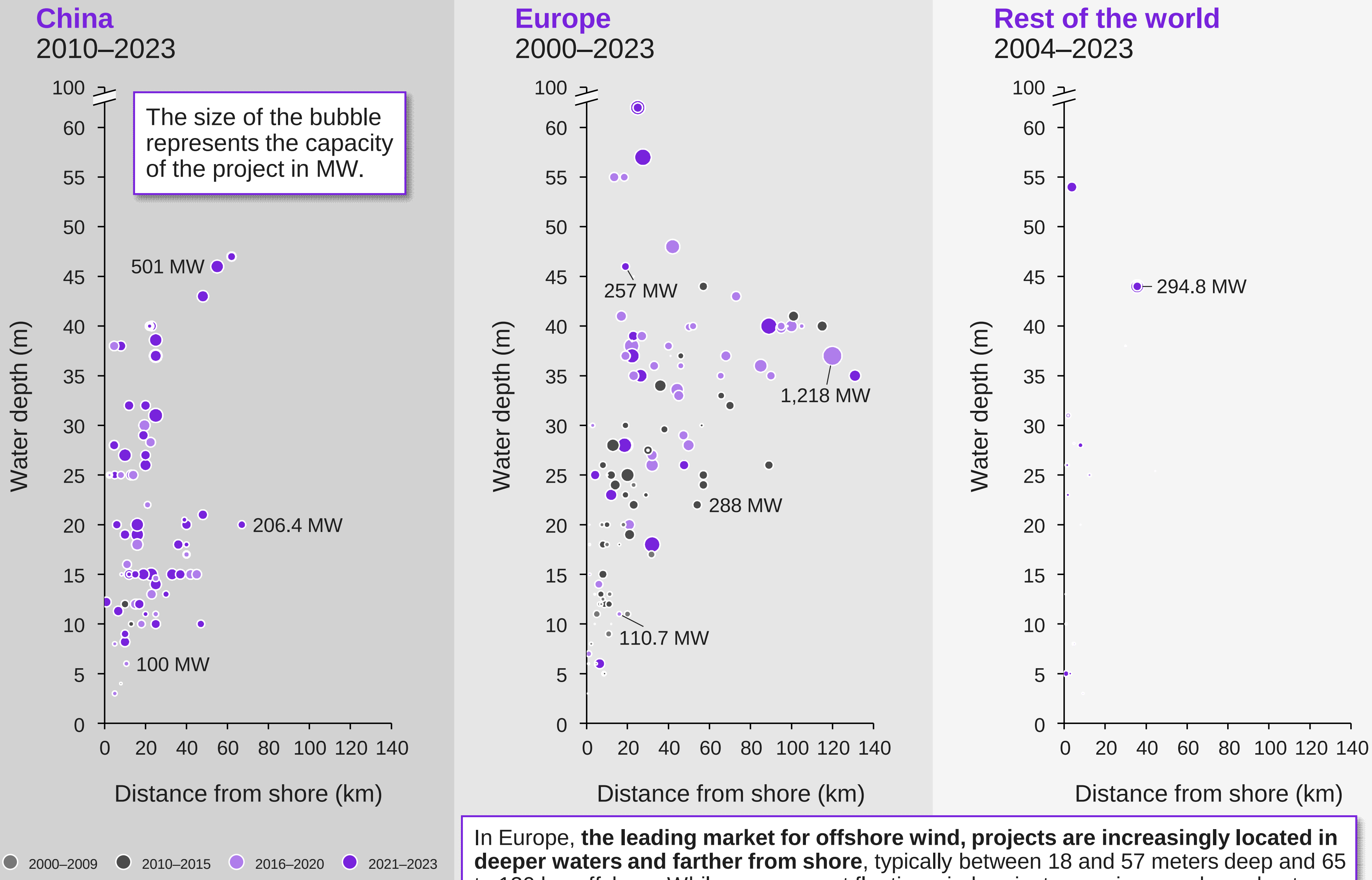
Sources: S&P Global, 2022, China's increasingly cheap wind turbines could open new markets; Kearney Energy Transition Institute analysis

5.3 Wind turbine cost characteristics

While China can still develop its capacity near shore, Europe needs to deploy wind further away from the shore

The distance from the shore influences the travel time between the port and the wind farm for the installation of foundations and turbines, while water depth determines the foundation's size and type. Both the distance to the port and the foundation type affect the costs of O&M, decommissioning expenses, and vessel availability.

5.3 Wind turbine cost characteristics



In Europe, **the leading market for offshore wind, projects are increasingly located in deeper waters and farther from shore**, typically between 18 and 57 meters deep and 65 to 130 km offshore. While many recent floating wind projects remain near shore due to early development stages, future projects are expected to move even farther out.

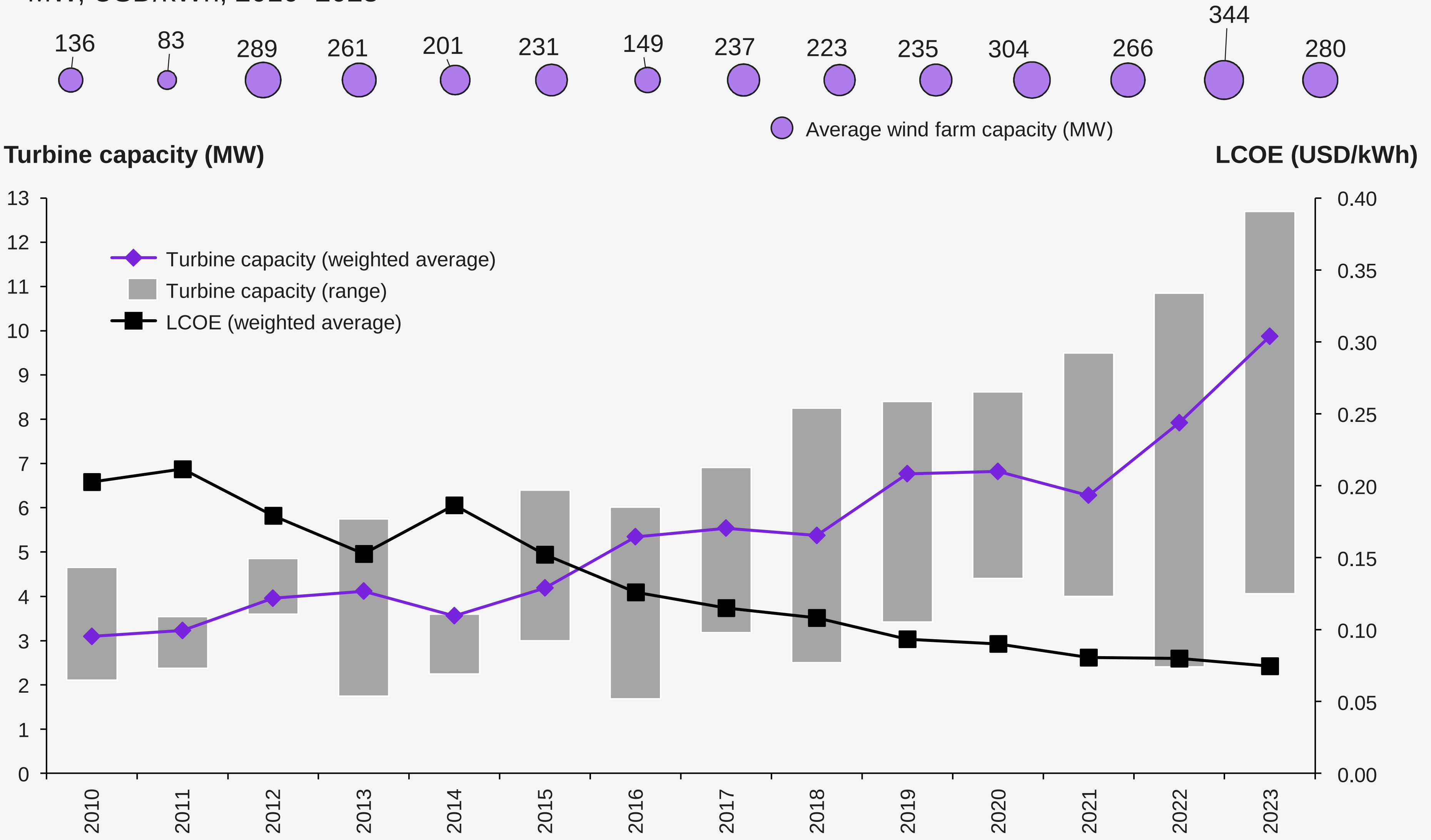
Sources: IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

Between 2010 and 2023, the average offshore wind project size increased by 106%, from 136 MW to 280 MW, driving down costs

In 2023, the average project size fell by 19% compared to 2022 due to the deployment of smaller projects in China and the UK. However, since 2020, multiple projects have surpassed 1 GW, with more large-scale projects anticipated, especially in the UK. Turbine capacities also rose from an average of 3 MW in 2010 to 10 MW in 2023.

5.3 Wind turbine cost characteristics

Project turbine size, global weighted average turbine size, global weighted LCOE, and wind farm capacity for offshore wind
MW, USD/kWh, 2010–2023



Sources: IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

Future LCOEs will be significantly impacted by technological advancements and regulatory support

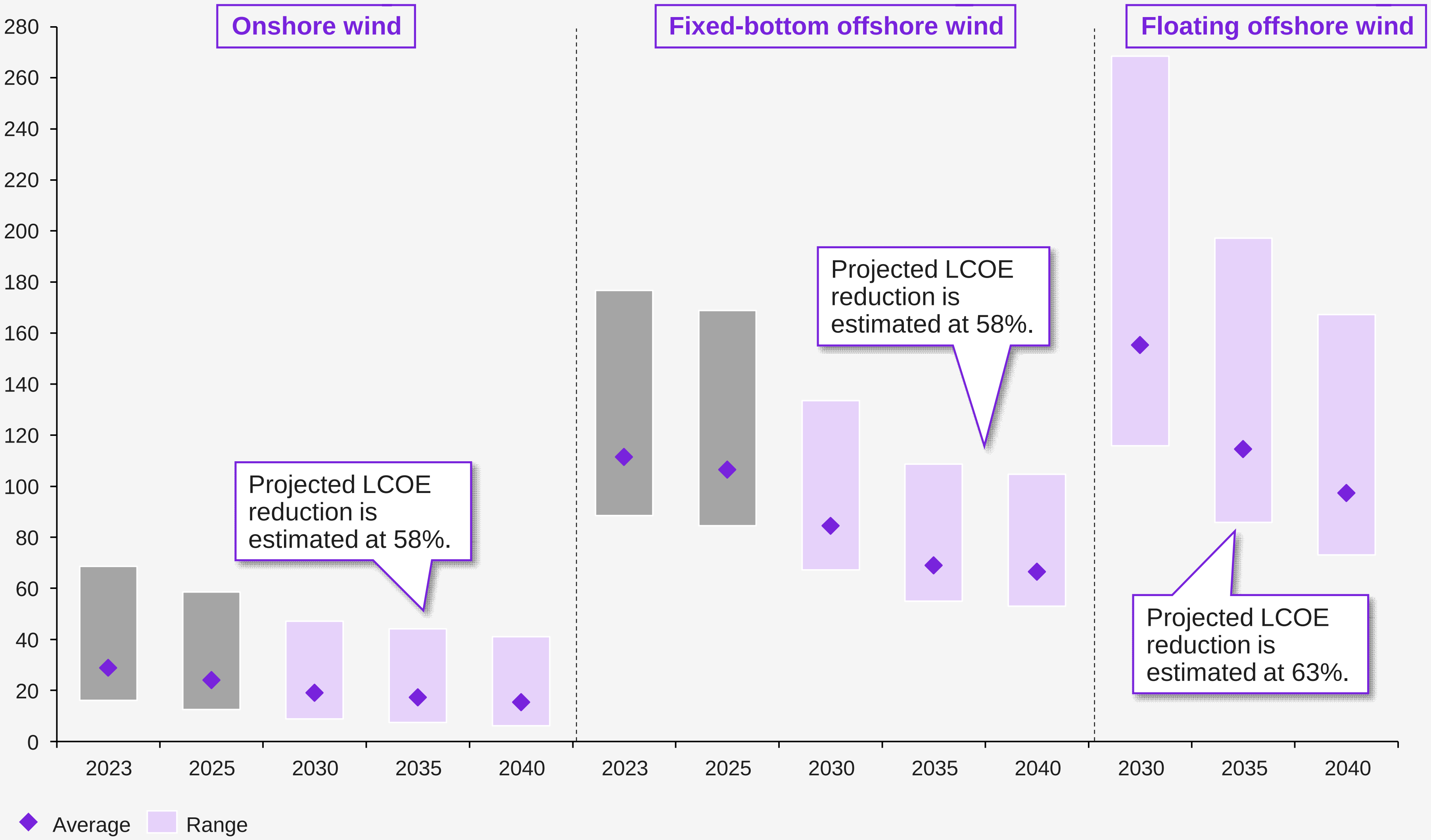
Example

Technological advancements will enable economies of scale, improve balance-of-plant efficiencies, and enhance energy extraction across various turbine configurations and wind regimes, while regulations will facilitate permitting and boost regional supply chains.

5.4 Projection of levelized cost of electricity

US LCOE projection for onshore, fixed-bottom offshore, and floating offshore wind

2022 USD/MWh, 2022–2040



Note: The values presented above are based on NREL's moderate scenario. According to this scenario, from 2022 to 2030, cost trajectories are determined using bottom-up scaling relationships and process-based BOS and turbine cost models for each technology in 2022 and 2030. From 2030 to 2050, cost trajectories are based on moderate historical learning rates. The range occurs because different wind classes are assigned to specific wind turbine technologies, thereby representing a more accurate LCOE curve. Each wind resource class corresponds to specific wind speeds.
Sources: NREL, 2024, 2024 Electricity Annual Technology Baseline; Kearney Energy Transition Institute analysis

6. Investment and business models

Investment and business models

Global wind power investment

- Investment in wind power capacity **represents about a third of global renewables investment.**
- Global investment in wind power capacity **reached USD 217 billion in 2023**, with **35% allocated to offshore wind** which emerges as a strong growth area.
- In Europe, wind project acquisition activity hit **€16.3 billion in 2022** driven by onshore wind, with Sweden, Italy, and Spain witnessing the largest amounts.

Wind power project financing structure

- Wind project financing typically involves a **special purpose vehicle (SPV) structure** to reduce risks. Projects are financed by a combination of debt, equity, and, in some cases, tax equity.

Regional financing trends

- European wind financing in 2022 saw reduced activity, marked by fewer final investment decisions in **large-scale offshore projects.**
- **Refinancing** of operational wind farms remained robust, driven by lower risks and favorable interest rates, particularly for **onshore projects.**

Wind power purchase agreements (PPA)

- Power purchase agreements play a crucial role in **providing price certainty** to both wind power investors and offtakers.
- Corporate PPAs have gained momentum, particularly among **heavy industry and IT companies**.
- Although **solar PPAs** have grown significantly in recent years, wind still **cumulatively accounts for two-thirds of Europe's total contracted capacity, approximately 16 GW**.
- Using PPAs increases wind project developers' ability to compete in **subsidy-free auctions.**

Investment in research and innovation

- Investments in research and innovation for wind energy have been falling, with **2022 registering the lowest investments since 2011.**
- **Offshore technology and floating offshore wind** received more than half of the public research funding in 2022.

Global investment is driven by onshore wind, but offshore is capturing most of the growth in 2023

Wind technology costs are declining, with each dollar invested in 2023 delivering 2.5 times more energy output than a dollar invested a decade ago.

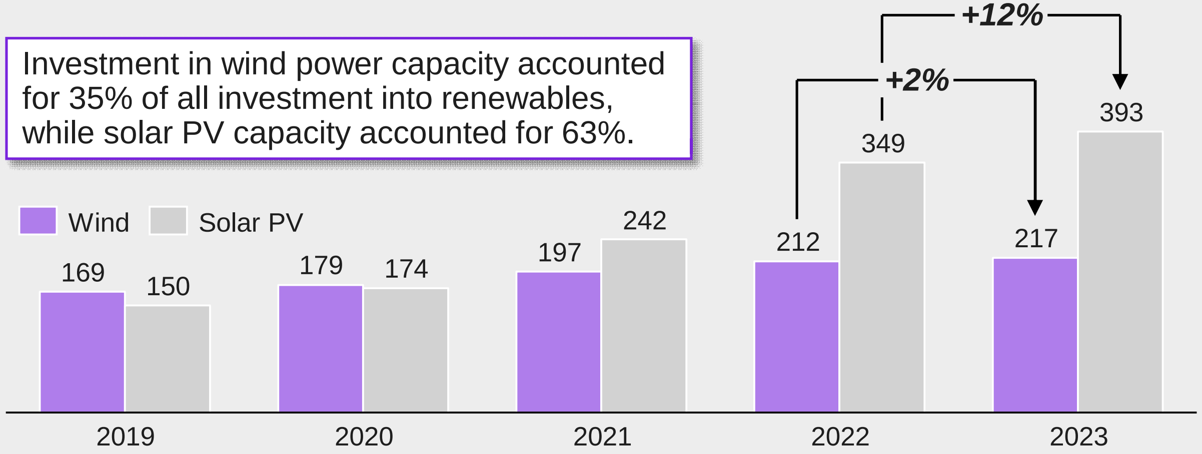
Global investment in wind power capacity lags behind investment in solar PV capacity. Macroeconomic challenges affected wind market investment in recent years, reducing investment.

6.1 Global wind power investment

Global investment in wind and solar PV power

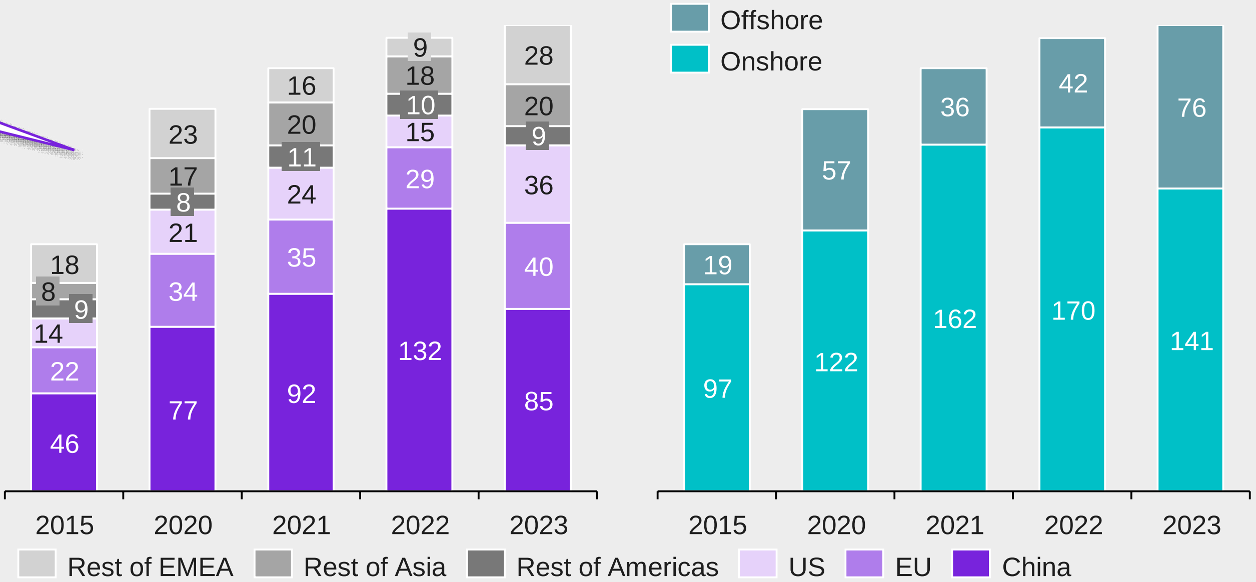
USD billion, 2019–2023

Investment in wind power capacity accounted for 35% of all investment into renewables, while solar PV capacity accounted for 63%.



Wind power investment differs by region and technology

USD billion, 2023



Sources: REN21, 2024, Global Status Report Collection; IEA, 2023, Renewable Energy Market Update June 2023; IEA, 2024, World Energy Investment 2024; BNEF, 2024, Energy Transition Investment Trends; BNEF, 2024, Renewable Energy Investment Tracker 1H 2024; Kearney Energy Transition Institute analysis

Macroeconomic challenges affected wind markets globally

Growth in the wind power sector in 2022 was slowed due to **increasing cost of equipment, inflation, higher costs, and supply chain constraints**.

As a result, projects were canceled, and some auctions received limited if no bids. One-sixth of renewable energy auction volumes went unallocated in 2022. Capacity undersubscription rates for wind power auctions were highest in Europe.

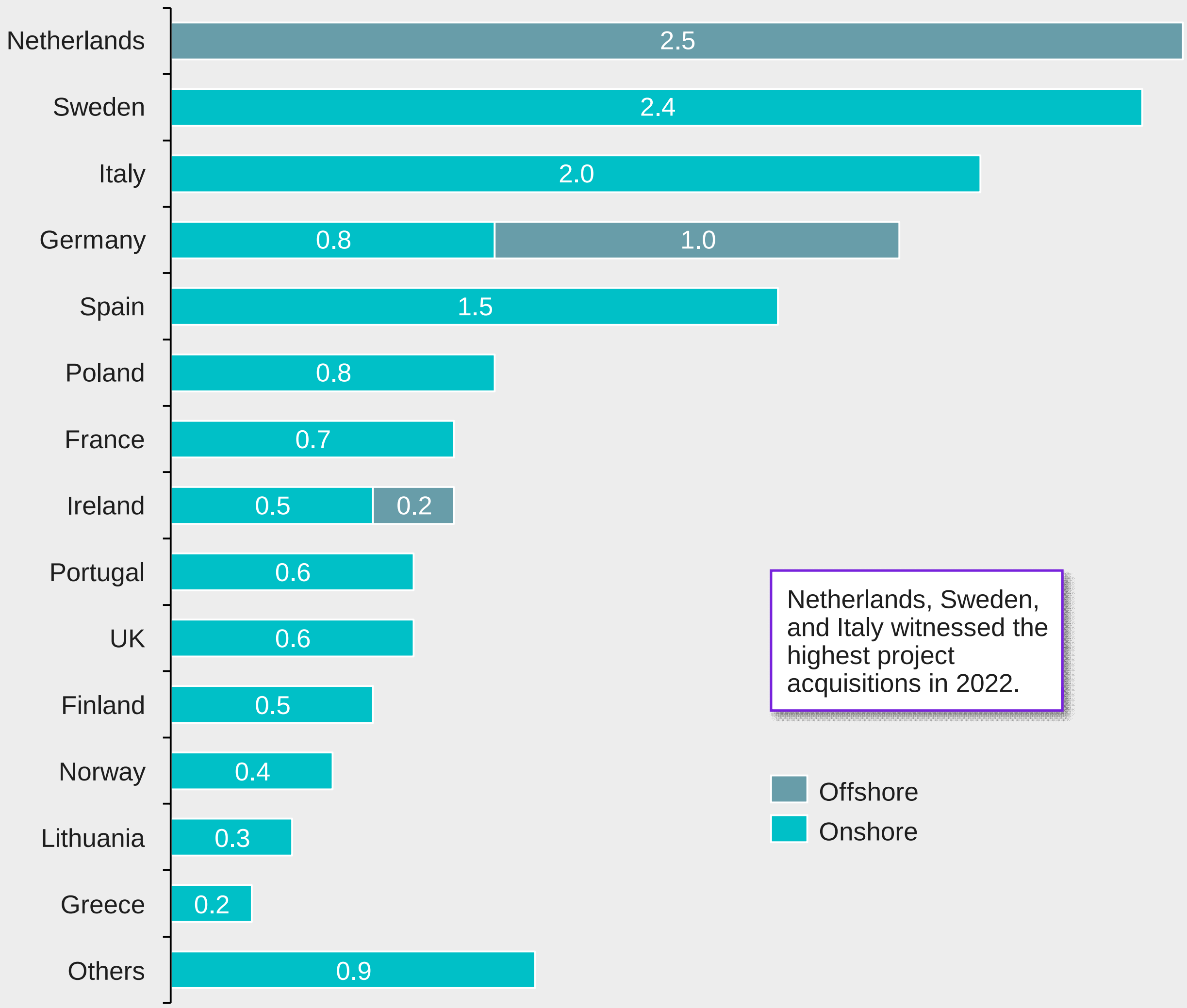
Since then, countries have adjusted their auction mechanisms to encourage bidding and investment into new projects.

European wind project acquisition activity continues to increase, driven by onshore wind

Europe

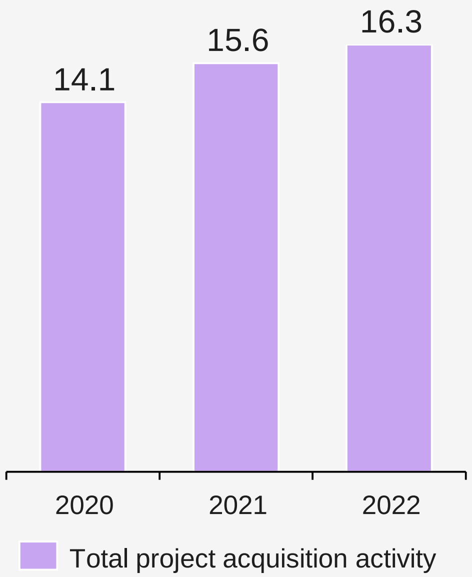
6.1 Global wind power investment

Wind project acquisitions by country
EUR billion, 2022



Sources: WindEurope, 2023, Financing and investment trends: The European wind industry in 2022; Kearney Energy Transition Institute analysis

Wind project acquisitions
EUR billion, 2020–2023



Total project acquisition activity hit €16.3 billion in 2022, surpassing the totals of €14.1 billion in 2020 and €15.6 billion in 2021.

Wind power project financing is commonly structured through a special purpose vehicle

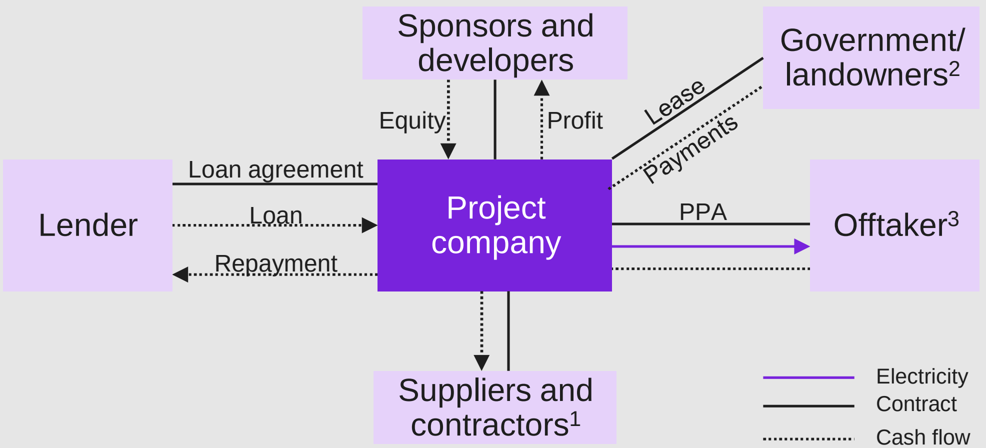
Illustrative

Special purpose vehicles (SPVs) legally separate the project from its sponsors. Projects are financed through a combination of **debt**, **equity**, **and tax equity** if the project is receiving tax credits. Financing contracts are complex and bespoke.

6.2 Wind project financing structures

Special purpose vehicles are used to reduce risk

Typical wind power project finance structure



An **SPV** is a legal entity created for the purpose of developing a wind power project.

An SPV creates a **project company** that is separate from the project sponsors. This financing structure is also known as **limited-recourse** or **non-recourse financing**.

Under this arrangement, lenders cannot claim payment from the balance sheet of the sponsors, which reduces risk for the sponsors (though payment can be claimed from sponsors if a back-leveraged debt structure is used, as is common for US tax equity financing).[4]

Full-recourse financing is an alternative to a special purpose vehicle

Under **full-recourse (corporate balance sheet) financing**, the project remains on the balance sheet of the sponsor. Lenders can claim payment from the balance sheet of the sponsor.

Full-recourse financing can be used by **established companies with investment grade rated debt**, but it creates additional risk and opportunity cost for the project sponsor.

Financing comes from a combination of debt and equity

Tax equity financing is used in the US for projects receiving tax credits. A lender provides equity in exchange for the rights to the generated credits. Back-leveraged debt and changes in tax benefit allocations over the project's lifetime are commonly used.

Under **cash equity financing**, investors provide equity and become partial owners of the project. Cash equity typically complements debt or tax-equity financing.

Debt financing involves debt contributions from lenders which the project company must pay back.

[1] Suppliers and contractors include services such as operations and management and engineering, procurement, and construction.
[2] Leases and payments take on different forms depending on whether the project is built on private or public property, with regulations dependent on country. Government payments can include subsidies to projects.
[3] Payments can be bidirectional depending on the price mechanism.
[4] Under a back-leveraged debt arrangement, a lender lends above the project company level to reduce their risk.
Sources: GWEC, 2024, Global Offshore Wind Report 2024; Stoel Rives LLP, 2024, Project Finance for Wind Power Projects; Kearney Energy Transition Institute analysis

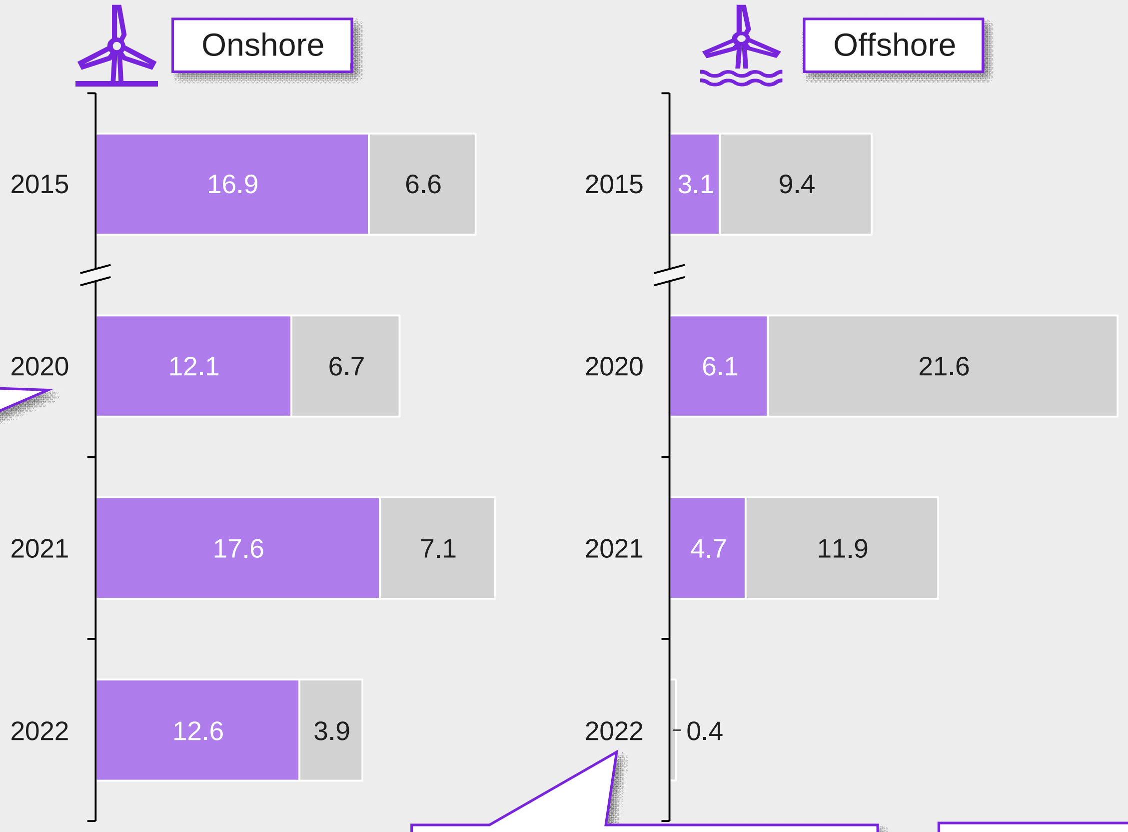
European wind financing highlights shifts in corporate investments and project debt

Europe

Due to the large scale of offshore projects, few developers can fund them on their balance sheets, making project finance structures essential.

Project finance debt: new investments and refinancing

EUR billion, 2015–2022



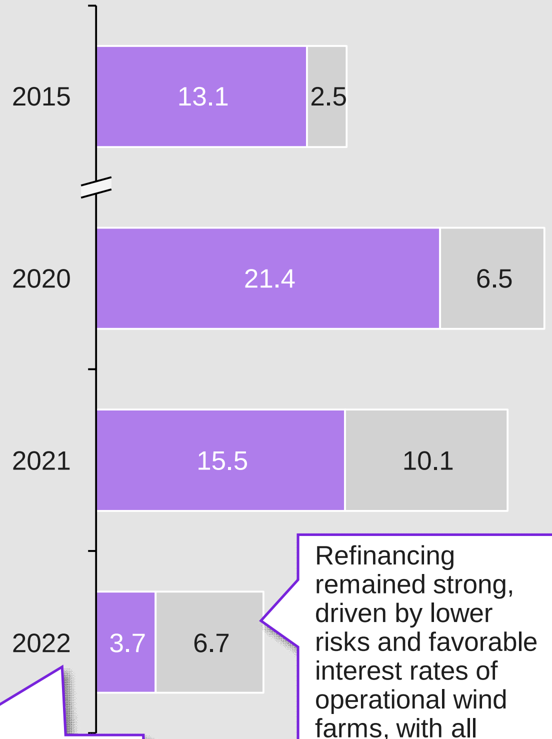
In 2022, higher interest rates and bank margins increased borrowing costs, complicating project finance deals and prolonging negotiation times.

The lack of FIDs in large-scale offshore and the lowest project financed onshore capacity since 2013 led to just €3.7 billion of total investments.

Project finance
Corporate finance

Onshore and offshore wind corporate and project financing

EUR billion, 2015–2022



Refinancing remained strong, driven by lower risks and favorable interest rates of operational wind farms, with all activity focused on onshore.

Refinanced project financed debt
Project financed debt for new investments

Sources: WindEurope, 2023, Financing and investment trends: The European wind industry in 2022; Kearney Energy Transition Institute analysis

6.3 Regional financing trends

Power purchase agreements provide price certainty to wind power projects and offtakers

Power purchase agreements (PPAs) **reduce the need for government revenue support** to create certainty for project investors. For offtakers, PPAs avoid exposure to electricity market prices and can allow the offtaker to meet decarbonization goals.

6.4 Wind power purchase agreements

PPAs de-risk wind power project revenue but must meet certain conditions

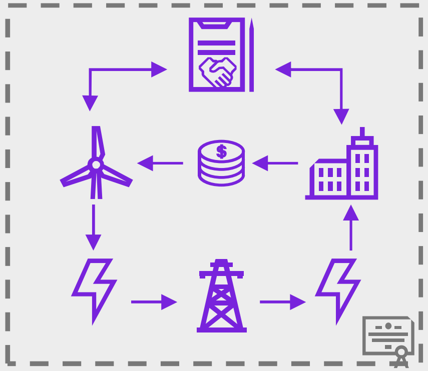
PPAs **specify a set quantity and price** for electricity which will be purchased from the wind farm by an offtaker, creating **revenue certainty**. The price can be **indexed** to certain indicators to account for market uncertainties over the duration of the contract. PPAs can be **physical** or **virtual**.

PPAs may take up the entirety of the wind project capacity or a fraction of available capacity. Remaining capacity is sold on the wholesale electricity market.

The **offtaker must be sufficiently creditworthy** and likely to fulfill the contract obligations.

Physical PPAs deliver electricity to the buyer

Physical PPAs involve a direct exchange: an offtaker pays a producer for the delivery of renewable power. The offtaker directly receives electricity and a guarantee of origin or renewable energy credits (RECs).[1]



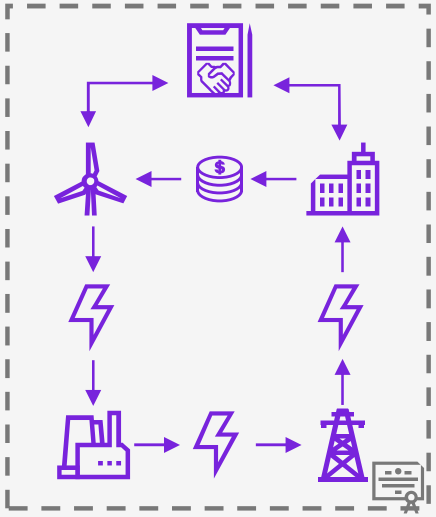
Virtual PPAs involve a financial transaction

Virtual PPAs (also known as **financial** or **synthetic PPAs**) are a **financial hedging transaction**.

Financial PPAs take place in **deregulated electricity markets** and are typically defined as a **contract for difference (CfD)**.

The CfD requires the buyer to pay the difference between the electricity market price and a pre-determined strike price to the seller. In exchange, the buyer receives RECs or a guarantee of origin.

No power is directly delivered from the producer to the buyer. The producer injects electricity into the grid, and the buyer procures market-priced electricity.



[1] Guarantees of origin and RECs are used to track that a certain quantity of electricity was produced with renewable energy.

Sources: IEA, Renewable Energy Market Update – June 2023; EPA, 2023, "Financial PPA"; DNV, (n.d.), "How do you finance projects in a zero-subsidy world?"; Kearney Energy Transition Institute analysis based on desktop research

Power purchase agreements involving corporations as offtakers are gaining popularity

Power purchase agreements (PPAs) provide corporations with stable energy prices and the means to decarbonize. **Heavy industry** and **information technology sector** companies drive corporate PPA procurement.

6.4 Wind power purchase agreements

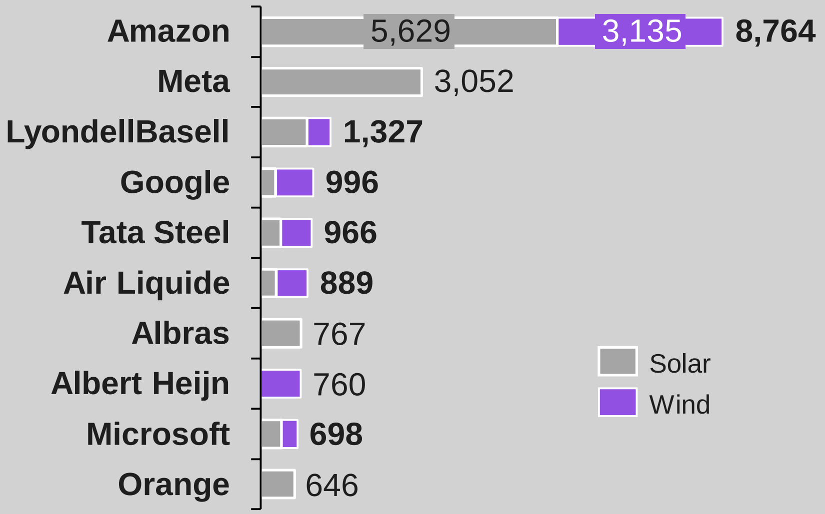
Corporations turn to PPAs to meet electricity needs

Driven by corporations' desire for stable electricity prices and to reach decarbonization goals, **55 GW of renewable energy corporate PPAs** were announced in 2023, which included **12 GW of onshore and offshore wind PPAs.**

Wind PPAs are more expensive than solar PPAs (USD 67.81/MWh and USD 56.76/MWh in the fourth quarter 2024). In recent years, wind PPA prices have increased significantly, notably 13.5% year-on-year by the end of June 2024 in North America, though prices had moderated in Europe. **Wind PPAs were less procured than solar PV PPAs**, comprising around 1/3 of reported procured capacity.

Top corporate buyers of clean energy

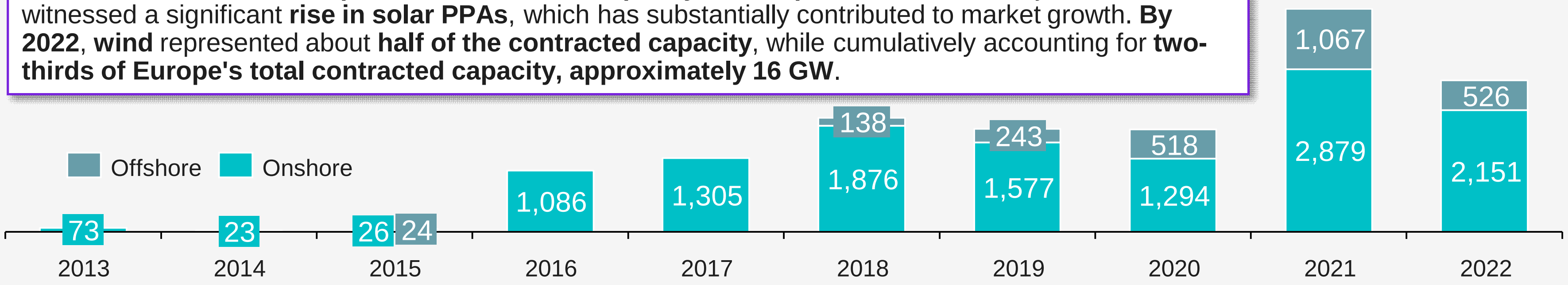
2023, MW



Onshore and offshore wind corporate sourcing through PPAs in Europe

MW, 2013–2022

Before 2018, wind made up 90% of contracted capacity in Europe. However, recent years have witnessed a significant **rise in solar PPAs**, which has substantially contributed to market growth. **By 2022**, **wind** represented about **half of the contracted capacity**, while cumulatively accounting for **two-thirds of Europe's total contracted capacity, approximately 16 GW**.



[1] At the time of the final investment decision in March 2023, 335 out of 960 MW were under PPA contracts.

Sources: IEA, Renewable Energy Market Update – June 2023; DNV, (n.d.), "How do you finance projects in a zero-subsidy world?"; Blackburne, A. and Naschert, C., 2023, "Germany's He Dreiht forges blueprint for subsidy-free offshore wind," S&P Global; BNEF, 2024, "Corporate Clean Power Buying Gew 12% to New Record in 2023, According to BloombergNEF"; Penrod, E., 2024, "Solar PPA prices flat, wind prices continue to rise: LevelTen Energy," UtilityDive; WindEurope, 2023, Financing and investment trends: The European wind industry in 2022; Kearney Energy Transition Institute analysis based on desktop research

Using PPAs increases wind project developers' ability to compete in subsidy-free auctions

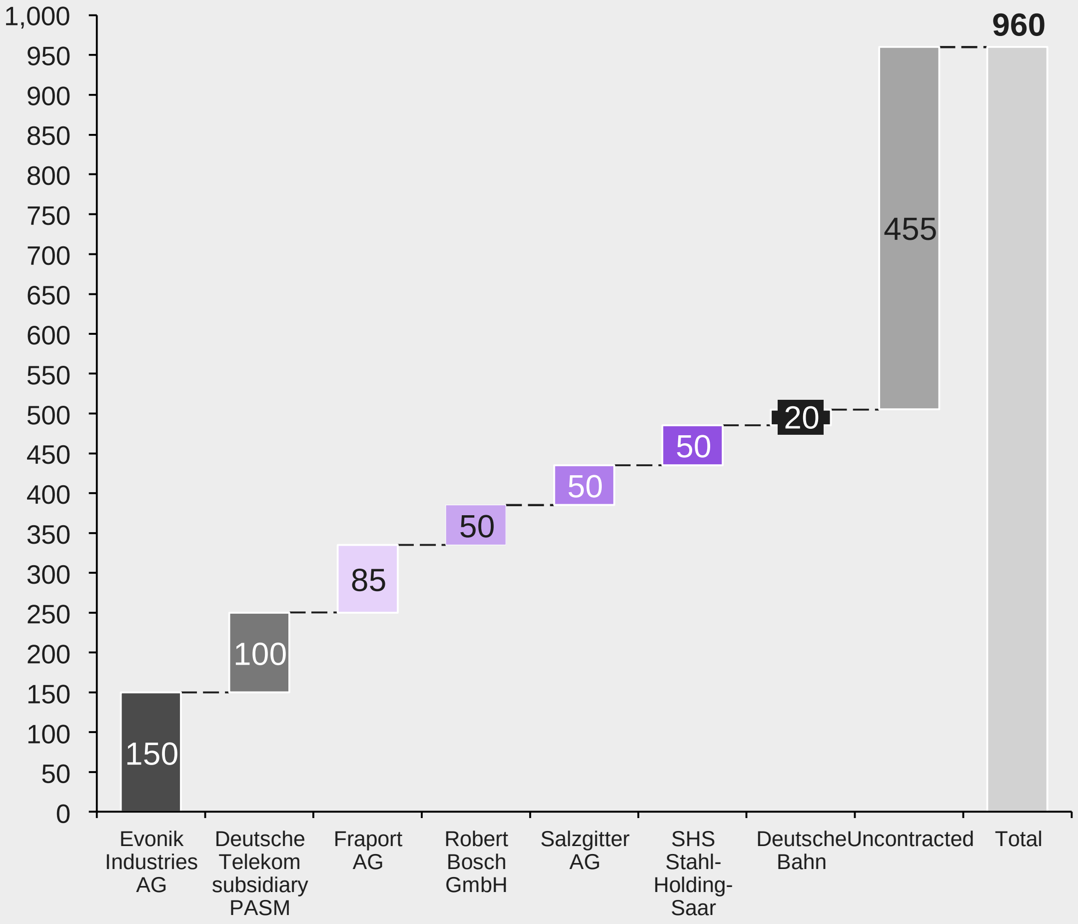
Example

6.4 Wind power purchase agreements

PPAs support subsidy-free bids in wind project auction

He Dreiht offshore wind farm PPAs

Contracted capacity (MW)



[1] At the time of the final investment decision in March 2023, 335 out of 960 MW were under PPA contracts.
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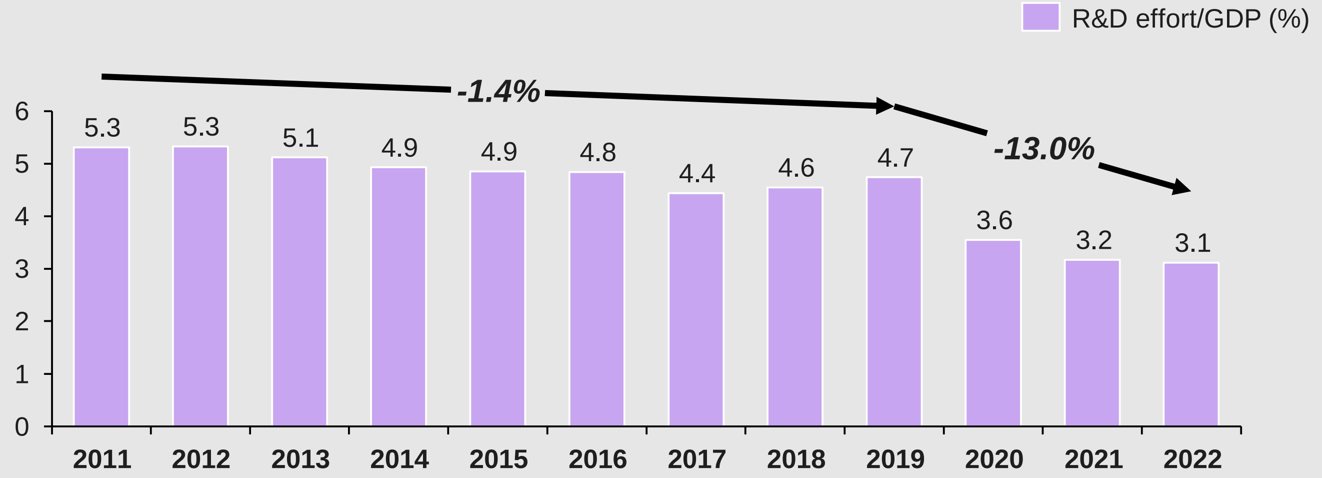
Key points

- In some auctions, the signing of PPAs by proposed wind power projects can even be **considered auction non-price criteria** by governments, such as in Germany's auctions for centrally pre-surveyed offshore wind sites.
- The right to build Germany's **He Dreiht offshore wind farm** was secured by EnBW in a 2017 zero-subsidy auction. As of 2024, EnBW had signed PPAs for 505 MW of the wind farm's 960 MW total capacity, some of which were signed after a final investment decision was taken.[1]
- Construction began in 2024, with commissioning expected by the end of 2025.

Investments in wind energy research and development have been falling globally, while public funding has remained steady

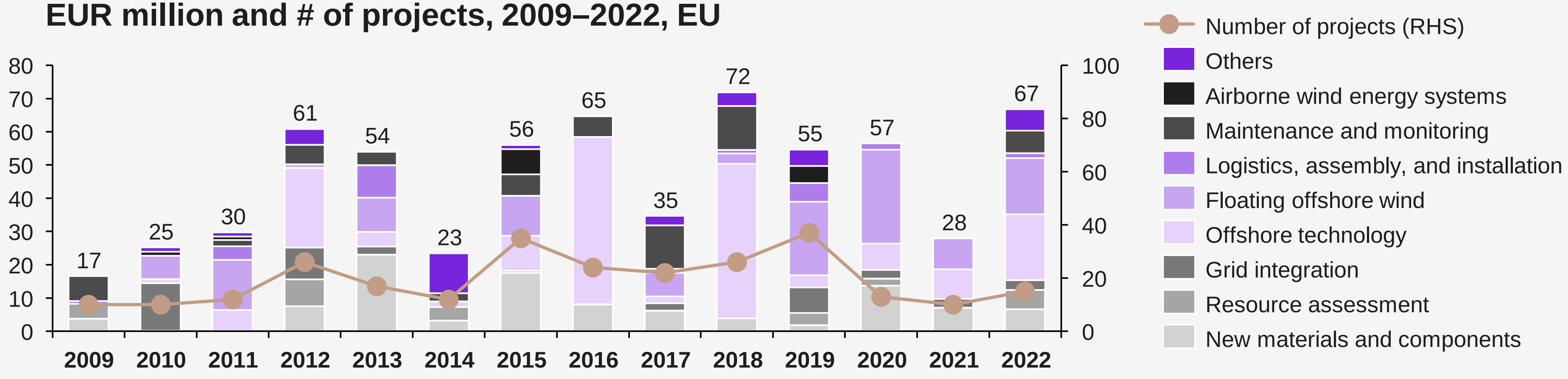
R&D efforts of the wind energy industry
% of industry's contribution to EU GDP, 2011–2022, EU



- Historically, in the 2010s, R&D investment averaged between 4.5 and 5% of the industry's contribution to EU GDP.
- However, investments declined sharply in the 2020s and 2022 was the lowest year for research and innovation investments since 2011.

Offshore technology and floating offshore wind receive a large chunk of the public research funding.

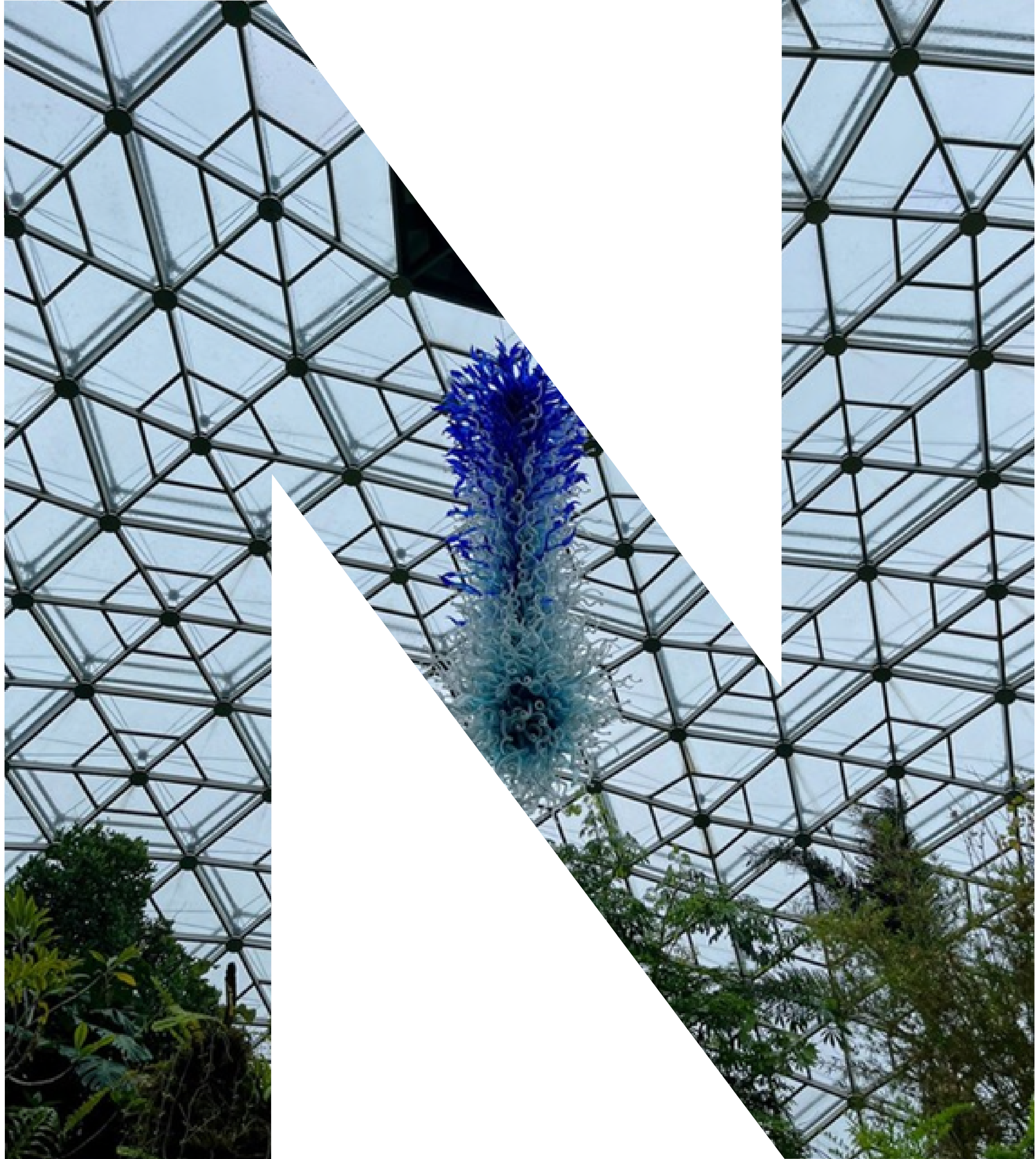
European commission public budget for wind energy
EUR million and # of projects, 2009–2022, EU



6.5 Investment trends in research and innovation

Sources: ETIPWind, 2023, Strategic research & innovation agenda 2025-2027; Kearney Energy Transition Institute analysis

7. Research, development, and innovation



Research, development, and innovation

Research and development efforts **focus mainly on floating systems,** with less emphasis on fixed-bottom offshore and even less on onshore wind. Floating systems need significant innovation, whereas onshore require incremental advancements.

7.0 Chapter summary

Key research priorities for the wind industry include:

Scaling up and industrialization

- Adopting advanced manufacturing techniques and design, such as 3D printing and automation, which enable and support large scale production
- Strengthening reliability in wind turbine designs
- Engineering new turbines and systems resilient to extreme weather events
- Installation solutions, such as robotics, to aid rapid deployment

Optimizing operations and maintenance (O&M)

- Improve O&M of assets through AI, digitization, and tools such as lasers and autonomous equipment
- New approaches to limit the displacement of large parts of wind turbines, ensuring local maintenance and improved transport conditions

Wind energy system integration

- Optimizing existing grid infrastructure and modeling future system needs to enable integration of rapid scale-up of wind energy

Advancing sustainability

- Materials research is exploring **new chemistries and alternative materials** to enable longer, lighter, and lower-cost blades.
- Development of new recycling technologies, innovative materials, and manufacturing processes are targeting the remaining **10–15% of unrecyclable material** in a wind turbine.
- Extending current lifetime and developing novel decommissioning solutions to reduce environmental impact.

Offshore patents

- Patents filed **for floating foundations** have grown almost **tenfold since 2002**.
- Annually, **78%** of the patents filed for offshore foundations are dedicated to floating foundations.
- European and Japanese companies have taken the lead in floating wind foundations research.

Key research and innovation themes

Non-exhaustive

1 Scaling up and industrialization

Addressing design, manufacturing, and supply chain gaps needed for scaling up wind energy

- Mass production through automation
- Design for large volume manufacturing
- Design for reliable and lasting products
- Extreme weather-resilient turbines
- Improved installation

2 Optimizing operations and maintenance (O&M)

Adopting new technologies and methods to improve operations and maintenance

- Digitalization and AI
- Advanced tools
- Replacement and transport of large parts
- Autonomous O&M

3 Wind energy system integration

New set of solutions to integrate large amounts of wind energy while making grid more flexible and resilient

- Modeling future system needs
- Advanced grid capabilities
- Interoperability
- Manage curtailment
- System integration of co-located assets
- Direct current grid solutions

4 Advancing sustainability

Research on the next-generation chemistries and development of superior recycling processes

- Material research
- New recycling methods
- Lifetime extension
- New decommissioning tools and methods

Improving reliability, quality, and sustainability while reducing costs

Sources: ETIPWind, 2023, Strategic research & innovation agenda 2025-2027; Kearney Energy Transition Institute analysis

Advance manufacturing techniques can enhance wind turbine production capabilities

Mass production of wind turbine components and turbines will be based on gigafactory concepts.

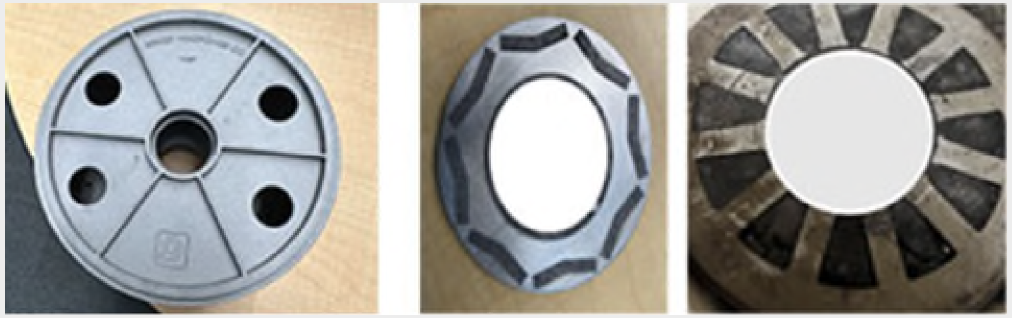
Gigafactories of high volume and serial production will require a high degree of automation.

7.2 Scaling up and industrialization

3D printing

Printing large-scale, structural components for wind turbine blades

- NREL and Oak Ridge National Laboratory are collaborating on 3D printing the structural cores required to support a 13-meter technology demonstrator blade.
- Revolutionary designs needed to modernize turbine blades can be produced.



Manufacturing and additive design of electric machines

- Traditional approaches to designing and manufacturing direct-drive electric generators result in prohibitively expensive and heavy powertrains.
- 3D printing of electric machines can enable next-generation, lightweight offshore wind turbine generators with reduced use of critical materials.
- MADE3D project is leading the design, fabrication, and verification of the world's first fully additively manufactured direct-drive electric generator.[1]

Automation and robotics

Robots have been used by the wind energy industry to paint and polish blades, but automation has not been widely adopted in wind turbine production (especially blade).

- NREL has successfully demonstrated the use of robots in post molding manufacturing (to trim, grind, and sand blades).
- This can help in elimination of difficult working conditions for humans and has the potential to improve the consistency of the product.
- Benefits: Lower costs, higher quality, increased reliability, better performance, increased annual energy production, and lower LCOE.

[1] Manufacturing and Additive Design of Electric Machines by 3D Printing project by NREL
Sources: NREL, 2024, NREL Invites Robots To Help Make Wind Turbine Blades; Press search, Kearney Energy Transition Institute analysis

Designs which enable large-volume production and higher reliability should be key focus areas for future research

1. Scaling up and industrialization
2. Optimizing O&M
3. Wind energy system integration
4. Advancing sustainability

Improvements in installation methods can help scale up wind energy faster and safely.

Design for large-volume manufacturing

Manufacturing of wind turbine components still requires a large amount of manual labor, especially for components such as blades, drivetrains, castings, and offshore foundations.

Research should accelerate modularization to speed up the deployment of wind energy while cutting down on operating costs.

Key research themes
Developing innovative design, testing, and certification methods for modular blades, offshore foundations, drive trains, and drive train components
Developing innovative design concepts and materials for modularization of wind turbines, testing, and certification
Demonstrating modular wind turbine technology (manufacturing and assembly)
Focusing on materials that enable large-scale manufacturing

Enabling more effective designs for wind turbine manufacturing and balance of plant will mean new testing methods, updated design tools, and demonstration projects, with focus on low capex automation methods.

Design for reliable and lasting products

Strengthening reliability in wind turbine design allows material consumption to be optimized and helps cut down on investment costs. Key research areas include:

- Development and validation of reliability prediction tools for large components
- Investigating possible standardization of wind-related load cycles while also accounting for ambient operating conditions
- Development of innovative health monitoring systems
- Development of components to cope with growing wind turbines sizes (e.g., bearings, etc.)

Improved installation

The upscaling and acceleration of onshore and offshore wind calls for novel installation solutions to boost efficiency while ensuring safety and reducing environmental impact:

- Use robotics to enable faster and safer lifting operations through improved motion control when working at heights under difficult environmental conditions
- Develop and demonstrate innovative installation and low noise piling methods for offshore substructures
- Effective underwater noise mitigation technology

Sources: ETIPWind, 2023, Strategic research & innovation agenda 2025-2027; Kearney Energy Transition Institute analysis

New wind turbines are more resistant to the extreme weather events which are becoming more common

The tropical cyclone intensity has increased in the past 40 years (as per US Environmental Protection Agency) highlighting the need for higher resilience in offshore wind projects.

7.2 Scaling up and industrialization

Dual-rotor wind turbine

OceanX, the world's first dual-headed wind turbine, was introduced in the southern Chinese port city of Guangzhou with capacity of 16.6 MW in 2024.

– Designed to withstand typhoons and category 5 hurricanes with a turbulence intensity of 0.135 (which can damage conventional offshore wind turbines), improving the safety and longevity.
– It can operate in deep waters over 115 feet (35 meters) and is capable of enduring winds up to 161 mph (260 km/h) and 98-foot (30-meter) waves.
– Features a unique V-shaped structure with twin counter-rotating rotors. The platform is stabilized by high-tension cable stays and mounted on a Y-shaped floating base, weighing approximately 16,500 tons (15,000 tonnes).

Recent (anti-cyclone) developments in offshore wind

Blade

– **Failure mechanism:** Overloading due to abnormal characteristics of cyclones
– **Design implication:** Aerodynamic shape optimization, carbon fiber materials, anti-cyclone airfoils

Tower

– **Failure mechanism:** Local inelastic buckling due to steel yielding
– **Design implication:** Structural strengthening

Foundation and mooring system

– **Failure mechanism:** Overturning due to cyclic load (fixed), large drift motion due to broken mooring system (floating)
– **Design implication:** Accurate coupling dynamic simulation tool

Control system

– **Failure mechanism:** Power grid failure, mechanical failure
– **Design implication:** Control strategy optimization, Smart communication Cyclone Resistance Control System

The northwest Pacific Ocean has the highest frequency of cyclones in the world, and China has the most cyclone landings in the world. Consequently, most of the research and innovation in anti-cyclone technology is originating in China.

Sources: Li, J. et al., 2022, Typhoon Resistance Analysis of Offshore Wind Turbines: A Review; Press search, Kearney Energy Transition Institute analysis

AI paired with digital twins offers improvements on the entire fleet of wind farms, while also delivering detailed insights at wind farm level and for each individual wind turbine

AI applications across the project life cycle

Site selection

– Many companies are leveraging AI's ability to assess and analyze massive amounts of relevant geographic and environmental data to identify sites with the most favorable wind resources and conditions.

Design and production

– AI based technology can capture complex nonlinear aerodynamic effects 100X faster than alternative wind turbine design approaches.[1]

– GE Vernova is employing AI to inspect the raw materials before molding and assembly.

Logistics

– In April 2022, GE Vernova announced the development of an AI-based tool to analyze installation logistics.

– A targeted 10% reduction in the installation costs can result in potential savings of $25 billion over 10 years for the whole industry.

O&M

– AI can ease the execution of O&M activities by uncovering patterns which signal the need for future maintenance and repair by monitoring wind conditions and referencing data from records of prior maintenance.

Virtual modeling and digital twin

Digital twins can be a powerful tool to optimize wind turbine design, in proactive operation and maintenance (O&M) and to potentially extend the turbines' lifetime

– Digital twins use real-time and historical data to represent the past and present and simulate predicted futures. Continuous recording of operating data and analysis of this data enables optimization of wind projects which is difficult in the real physical world.

– As a software representation of the physical asset, it allows the digital design, simulation, and testing of wind power plants before commencing production, saving time and costs, increasing quality, and ensuring safety.

[1] NREL's Inverse Network Transformations for Efficient Generation of Robust Airfoil and Turbine Enhancements (INTEGRATE) project is developing a new inverse-design capability for wind turbine rotors using invertible neural networks.
Sources: NREL, 2022, Enabling Innovation in Wind Turbine Design Using Artificial Intelligence; GWEC, 2024, Global wind report; Press search, Kearney Energy Transition Institute analysis

Tools, such as lasers and autonomous equipment, present opportunities to increase efficiency and lower costs

1 Scaling up and industrialization

2 Optimizing O&M

3 Wind energy system integration

4 Advancing sustainability

Projects are under way to fly autonomous drones and apply X-ray technology to scan blades and predict maintenance needs.

Lasers

Manufacturing

During blade manufacturing, precision laser techniques minimize waste

- Laser trimming removes excess material, resulting in smooth, aerodynamic surfaces.
- Laser cutting shapes the complex blade profiles with precision.

Measurement and monitoring

Lasers can enhance wind turbine performance

- LiDAR (Light Detection and Ranging) technology uses laser pulses to accurately measure wind speed and direction. This data is valuable for optimizing turbine performance and minimizing downtime.
- Remote laser inspections can help detect potential faults in wind turbines and laser scanners can identify microscopic cracks or structural weaknesses.

Operation and maintenance

Precision laser-based systems can remove corrosion, contaminants, paint, and residues with a high-energy laser beam.

- Blade cleaning: traditional cleaning methods often involve chemicals and labor-intensive processes, which can potentially damage the turbine blades' surfaces, whereas lasers can remove dirt, ice, and other surface coatings without damaging the underlying material of the blades.

Autonomous underwater vehicles (AUV)

In the offshore wind sector, AUVs can be used for maintenance and repair of wind turbines and to plan their decommissioning:

- AUVs can be paired with AI technology to conduct complex underwater inspections without any human intervention, significantly increasing the efficiency and reducing the costs of underwater surveys and inspections.
- Beam, a leader in high-tech offshore wind services, had successfully deployed this solution for inspecting jacket structures at Seagreen wind farm—Scotland's largest offshore site and a joint venture between SSE Renewables, TotalEnergies, and PTTEP.

Sources: GWEC, 2024, Global wind report; Press search, Kearney Energy Transition Institute analysis

New approaches to limit large parts displacements and improve their transport are considered to impact economics

1 Scaling up and industrialization

2 Optimizing O&M

3 Wind energy system integration

4 Advancing sustainability

Key challenges

- Mobilizing large cranes, to lift larger turbines and taller towers.
- Transporting large components to hard-to-access areas (mountains, deep offshore).
- Long mobilization of different vessels to disconnect and reconnect mooring lines and inter-array cables and to tow the foundation to port.
- Operating wind assets and infrastructure for component disposal/recycle are located at a significant distances. In the US, some waste blades may have to travel upwards of 1,600 miles to reach their end-of-life destination.

Innovation focus areas

Research themes
Improving large component repairs for in situ repair and/or crane-less exchange
Developing quick connect/disconnect systems for mooring lines and inter-array cables
Optimization of wind turbine design for easier transport and installation, including concepts for separable rotors, frames, nacelles, housing

Siemens Gamesa and Vestas have announced a collaboration to standardize equipment for transportation of wind turbine towers.

Effect on transport infrastructure

Research and innovation for wind turbines logistics can inform development of transport infrastructure:

- Optimize port logistics enabling faster load-out, efficient use of port space
- Design waterways specifically for very wide offshore wind component transport
- Hasten the integration of technologies for automation and digitalization in ports
- Encourage solutions to incorporate new fuel alternatives, such as battery charging systems and hydrogen fueling facilities in ports
- Contribute to road planning by indicating future trends and challenges associated with the transport of very large components

Sources: ETIPWind, 2023, Strategic research & innovation agenda 2025-2027; Kearney Energy Transition Institute analysis

Focus is on optimizing existing grid infrastructure and modeling future system needs

1 Scaling up and industrialization
2 Optimizing O&M
3 Wind energy system integration
4 Advancing sustainability

Key research and innovation themes

Themes	Description	Key actions	Long-term focus areas
Modeling future system needs	Wind energy services must be redefined to reflect potentially new system services and market mechanisms to handle advanced capabilities.	– Analysis of interdependencies between grid developments and increased system services requirements – Design impacts on wind turbine components	– Refining the planning and optimization of onshore and offshore power grid
Advanced grid capabilities	Enable the demonstration of the provision of grid forming, black start, and other ancillary services via wind farms.	– Black start modeling and demonstration across multiple markets – Grid ancillary service development involving manufacturers, developers, and TSOs	– Refine and provide wind energy with new technical solutions to meet grid code requirements
Interoperability	Large-scale offshore plants will require infrastructure interoperability and robustness to ensure security, reliability, and controllability.	– Digital twin for wind and hybrid power plants – Cyber resilience and cybersecurity – Interoperability of models and testing platforms	– Interoperability needs of wind power-to-x projects and infrastructure
Solutions to effectively manage curtailment	Countries with wind penetration levels over 30% have witnessed higher levels of curtailment.	– Assessment of interdependencies between the share of wind generation and curtailments – Adoption of virtual power plants concepts – Deployment of storage to limit curtailment, increase value-capture, and manage system variability	– Managing curtailment at different spatial scales and across larger regions – Integrating hydrogen and storage
System integration of assets	Combining wind energy with other assets such as energy storage, hydrogen production, or the co-location with other renewables.	– Analysis of system integration needs – Integrating wind with storage and hydrogen – Development of offshore wind hybrid projects	– Ongoing development of energy islands to promote hybrid and co-located projects
Direct current (DC) grid solutions	Demonstrate rollout of DC grid solutions to connect wind farms over long distances.	– Grid topology option assessment and development – Assess technology equipment – Large-scale demonstrations	– Fast-track solutions to help operate and design offshore wind farms installed very far offshore (including floating wind)

Sources: ETIPWind, 2023, Strategic research & innovation agenda 2025-2027; Kearney Energy Transition Institute analysis

7.4 Wind energy system integration

Materials research is focused on higher recyclability while enabling longer, lighter-weight, and lower-cost blades

New chemistries

Larger wind turbine blades require composite materials that effectively retain their shape and strength when subjected to various stressors.

- Currently, blades are manufactured from a combination of glass and/or carbon fiber composite materials with a thermoset resin.
- Thermoset composite materials, such as epoxies, polyesters, and vinyl esters, have no economically viable recycling options and hence, most of these blade materials end up in landfills.
- Scale-up of new polymer chemistries that are recyclable by design is a key focus area.
- Utilizing a thermoplastic resin system (which can be melted and recast at end-of-life), including the use of thermal welding to bond blade components, will enable lower-cost and recyclable wind turbine blades. Other promising alternative is recyclable thermosets.

Plant-based resins

Novel **PECAN (PolyEster Covalently Adaptable Network)** resin-based 9-meter prototype wind turbine blade

- The resin can be designed using biobased chemicals that can be easily extracted from plant waste.
- Easily recyclable using mild chemical processes (the blade was broken down in ~6 hours).
- Composites held their shape, withstood accelerated weatherization validation, and could be made within a timeframe similar to the existing cure cycle or how wind turbine blades are currently manufactured.

Alternative materials

Development of alternative materials is crucial to reduce the environmental footprint of products and solutions. Material scarcity and supply chain constraints are other key drivers for the research on these materials

- Generators: Alternatives to permanent magnets with no or lower rare earth content
- Electrical and grid components: Alternative materials for valves, conductors, and power conversion applications, replacement of lead and PFAS (Per- and polyfluoroalkyl substances), alternatives for gas-insulated equipment like switchgear

Sources: ETIPWind, 2023, Strategic research & innovation agenda 2025-2027; NREL, 2024, NREL Advances Method for Recyclable Wind Turbine Blades; Press search, Kearney Energy Transition Institute analysis

Further research and innovation is needed to propel the wind sector toward 100% recyclability

1 Scaling up and industrialization
2 Optimizing O&M
3 Wind energy system integration
4 Advancing sustainability

About 85% to 90% of the mass of a wind turbine is made of materials that can already be commercially recycled. The bulk of the unrecycled materials is composed of fiber-reinforced composites (carbon fiber and fiberglass).

7.5 Advancing sustainability

Research areas

Recycling should include manufacturing waste as well as end-of-life waste, particularly for composite materials which represent a large volume of waste stream

– Additionally, emphasis should also be on reusing recycled materials in a number of industrial sectors, guaranteeing the creation of a well-established value chain and exploring the closed-loop circularity approach as well.

– Validation and certification procedures for secondary materials use should also be developed in parallel.

Broader scope of recycling

Themes
Development and demonstration of recycling of wind turbine composite components as well as manufacturing waste (from blade manufacturing)
Development of recycling processes for permanent magnets (composite materials and neodymium) and other components (like lubricants and greases)
New solutions to use recycled content in the design of wind components

Enhanced recycling processes

Development of new recycling technologies, innovative materials, and manufacturing processes to target remaining **10% to 15% of unrecyclable material** in turbine

– Experimental pyrolysis, or thermal decomposition, method of reclaiming fiberglass from wind turbine blades. The recovered fiberglass will be used for new blade construction, and to manufacture second-generation composites for the automotive, consumer products, marine, and aerospace industries.

– Developing commercial-scale recycling of rare earth elements (including the neodymium and dysprosium magnets used in generators).

Cross-industry synergies

Cross-industry partnerships and knowledge sharing should be explored to address recycling.

– For example, in Europe, collaboration with the European Boating Association (for composite recycling) and the European Composites Industry Association (EuCia) is possible.

Refer to slides 112–114 for more on waste and recycling.

Sources: ETIPWind, 2023, Strategic research & innovation agenda 2025-2027; Kearney Energy Transition Institute analysis

Lifetime extension and novel decommissioning practices can lead to more sustainable wind farms

1 Scaling up and industrialization
2 Optimizing O&M
3 Wind energy system integration
4 Advancing sustainability

In addition to recyclability and waste prevention, repowering (replacing aging wind turbines) is an economical choice for increasing efficiency and electricity output, as well as extending lifetime of the wind farm.

7.5 Advancing sustainability

Lifetime extension of wind turbine components

The lifetime estimate for wind farms has already risen from **20–25 years to 30–35 years.**

Strategies for achieving lifetime extension of wind turbines are crucial, as waste prevention strategies, including the repurposing and recycling of components, are not fully integrated and adopted at an industrial scale.

Environmental assessments of lifetime extension strategies achieved by reuse or refurbishment should be performed and compared with alternative methodologies, e.g., the use and direct replacement of non-recyclable or bio-sourced turbine components.

Key research actions
Development of supply chain infrastructure and prototype processes for refurbishment of wind turbine components and associated grid equipment
Assessment of most prominent wind turbine component failure modes that require further technology development to achieve lifetime extension, e.g., blades (fatigue), gearbox (wear), generator (bearing failure)
Digital twinning, advanced sensor technologies, and use of AI for lifetime extension through hotspot detection and health monitoring

New decommissioning tools and methods

Decommissioning procedures are quite standardized for onshore wind farms, but innovative solutions are needed for offshore farms. Current decommissioning process should be improved to allow:

- Easier reuse and recycling of components and materials
- Reduction of environmental impact
- Creating new supply chains

Key research actions
Development of solutions for monopile extraction and new cutting tools for subsea bed cutting
Development of new technologies for effective and environmentally friendly decommissioning
Development of decommissioning vessels specifically suited to offshore wind, building on experiences from the oil and gas sector

Sources: ETIPWind, 2023, Strategic research & innovation agenda 2025-2027; Kearney Energy Transition Institute analysis

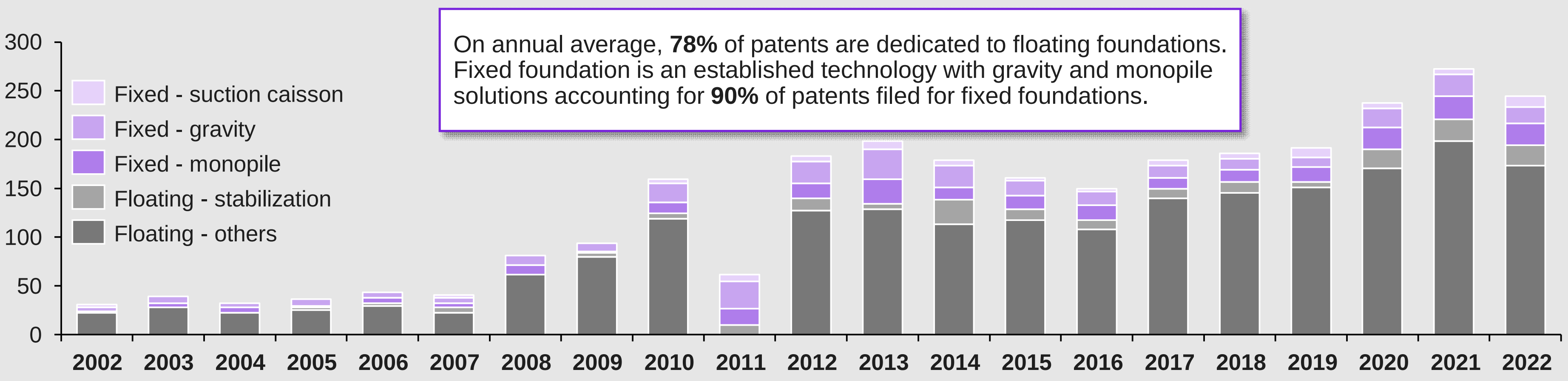
Patents filed for floating foundations have grown almost tenfold since 2002

European and Japanese companies are taking the lead in filing patents for floating solutions.

7.6 Offshore patents

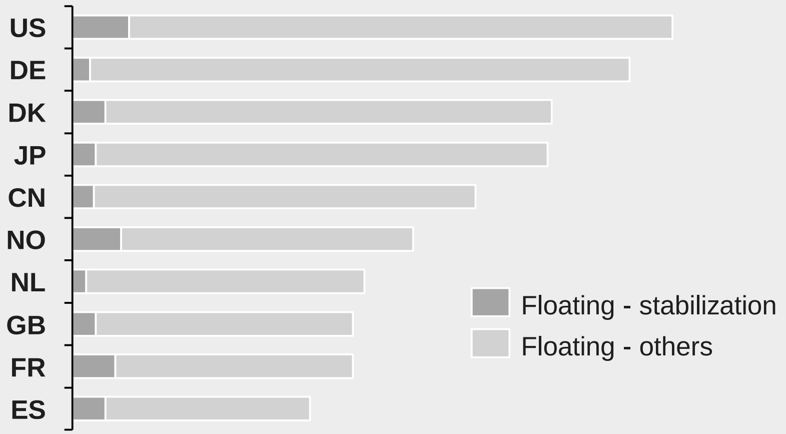
Offshore wind foundation patent trends

of international patent families, 2002–2022[1]



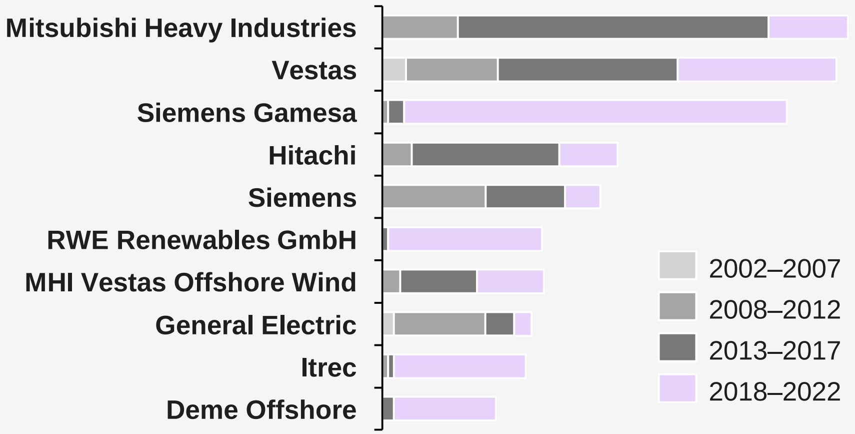
Top 10 patenting countries (floating wind)

of international patent families, 2002–2022



Top 10 patenting companies (floating wind)

of international patent families, 2002–2022



[1] International patent families (IPF) are patents that have more than one country in the list of publications, assignees, inventors, or first-priority countries.
Sources: IRENA, 2024, Floating offshore wind outlook; Kearney Energy Transition Institute analysis

8. Environmental and social impact

Environmental and social impact

Environment impact

- Wind power has one of the lowest GHG emissions within renewables and low-carbon sources with median emissions of about **12 gCO_2e per kWh** over its full life cycle.
- **Foundation and tower** contribute significantly to the carbon footprint of the wind turbine.
- The generator, **due to copper use**, has a significant impact assessment from mineral and metals.
- Wind energy's land use intensity can vary significantly depending on whether spacing is considered or not. If spacing is considered, it has one of the **highest land use intensities**. However, the footprint of turbines on wind farms is negligible and **land can be used for other uses.**
- Wind power has the **lowest water consumption** compared to other electricity sources making it a favorable choice for the areas with high water stress.

Waste and recycling

- **86%–94%** of the turbine's above-ground mass, mainly **towers and hubs**, is highly recyclable while **blades and components such as nacelle covers** are more difficult to recycle.
- Decommissioned and repowered capacity are expected to grow fourfold by 2030.
- Recycling processes need to carefully be evaluated, as emissions from recycling may outweigh the benefits of the recycled product.

Social acceptance

- Onshore and offshore wind energy projects affect communities by **altering landscapes, changing land and sea usage, impacting marine ecosystems, and creating economic opportunities.**
- Surveys show **64%** of Europeans support onshore wind and **63%** support offshore wind, with higher acceptance when projects create local jobs.

Wind misinformation

- **Misinformation** about wind technology disrupts policymaking, causing delays, higher costs, and reputational damage, hindering wind energy expansion.

Wind sector employment

- The wind sector's job creation potential is significant, with **manufacturing and construction representing the largest share of jobs at 28% and 36%**, respectively.
- **More than 60%** of roles require minimal training, with STEM roles representing 28% for onshore and 21% for offshore.
- Human resource requirements are substantial, with a need for **2,888 person-days/MW for onshore and 4,200 person-days/MW for offshore projects**.

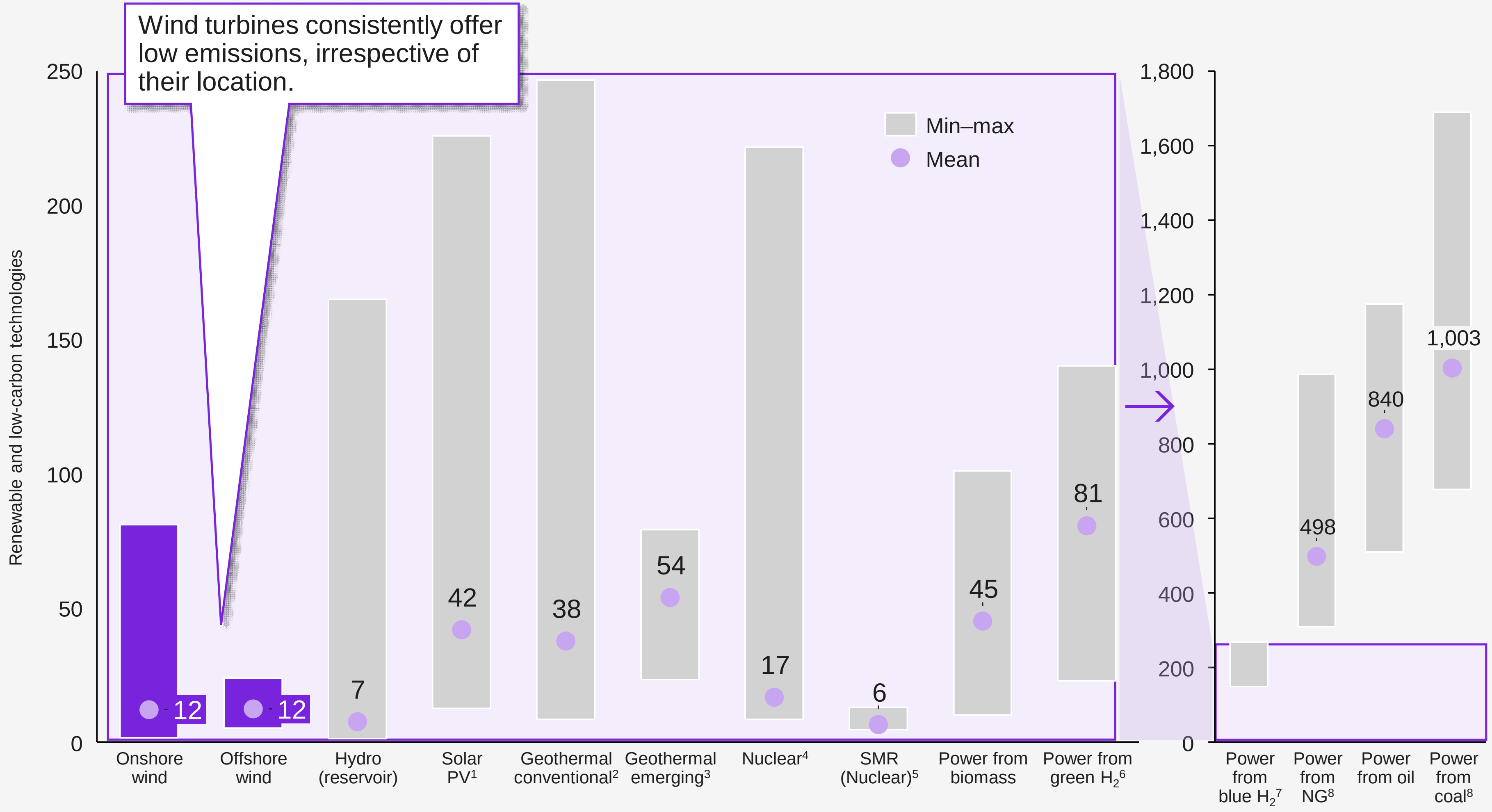
Wind power has one of the lowest GHG emissions within renewables and low-carbon sources

LCA results for various electricity sources show high variability in terms of related carbon footprint, which should be considered when assessing other value chains embodying energy inputs.

8.1 Environmental impact

Life cycle assessment (LCA) – carbon footprint

gCO_2e/kWh, 2021

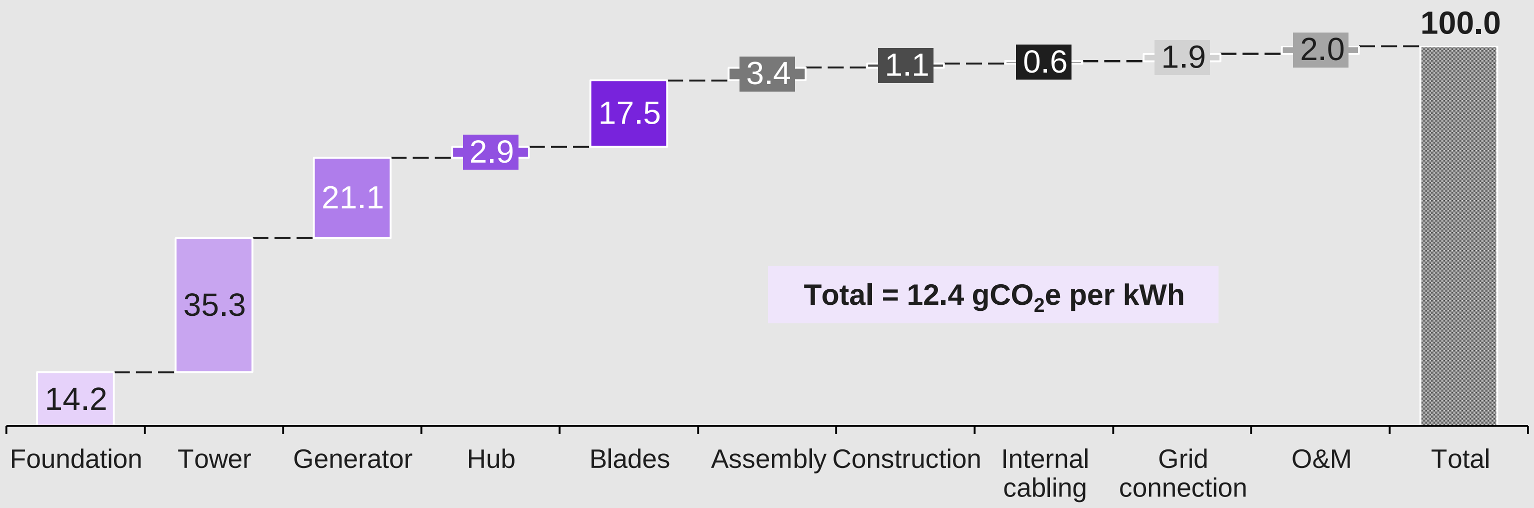


[1] Crystalline silicon, thin film; [2] Flashed steam; [3] Geothermal emerging technologies only include data on EGS. AGS data is unavailable in the literature as the technology is in its early commercialization phase, but it is known to produce no operational CO_2 emissions; [4] LWR, PWR, and BWR; [5] Small modular reactors; [6] Green hydrogen values based on electrolysis from wind electricity with an overall yield of the power to hydrogen to power value chain of 22.8%; [7] Blue hydrogen values based on methane steam reforming with 93% carbon capture (with 0.2% fugitive methane emissions) with an overall yield of hydrogen to power value chain of 40.2%. Combustion turbine and combined cycle; [8] Combustion turbine and combined cycle; [9] Subcritical, IGCC, fluidized bed, and supercritical.

Sources: NREL, 2021, Life Cycle Assessment Harmonization; Malek, A.E. et al., 2022, Techno-economic analysis of Advanced Geothermal Systems (AGS), Renewable Energy; Kearney Energy Transition Institute analysis

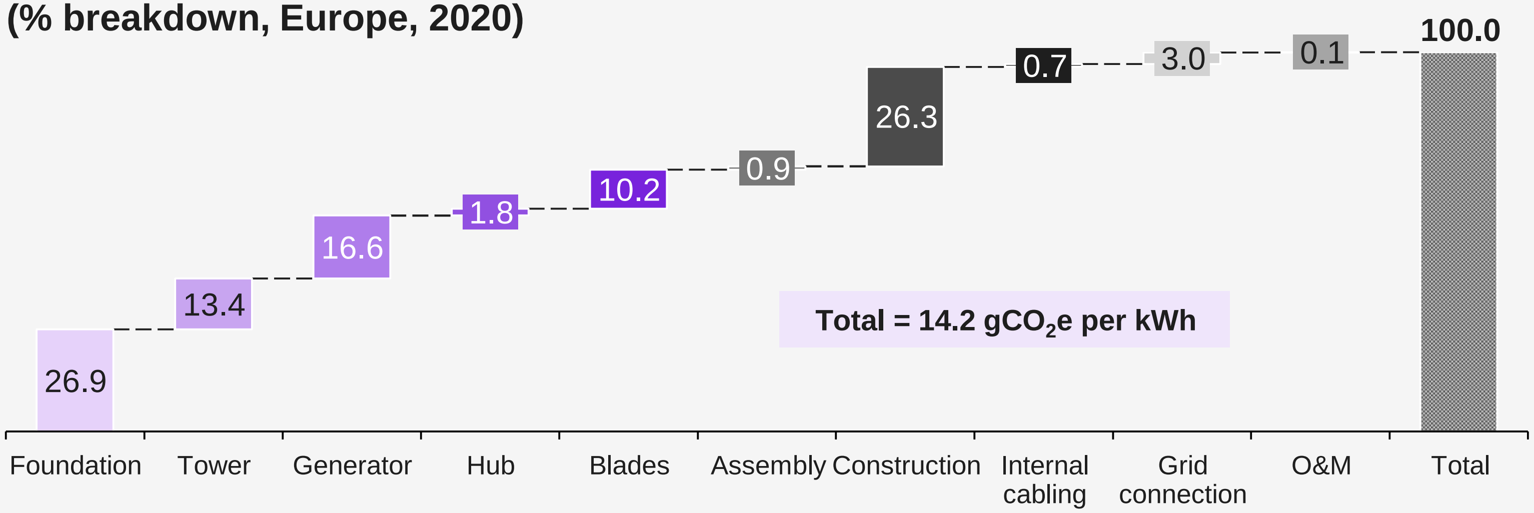
Foundation and tower contribute significantly to the carbon footprint of the wind turbine

Lifecycle carbon footprint – onshore
(% breakdown, Europe, 2020)



Foundation and tower are responsible for **nearly half** of the carbon footprint for onshore projects.

Lifecycle carbon footprint – offshore, gravity based
(% breakdown, Europe, 2020)



In addition to foundation and tower, **ship operations** for construction of offshore wind turbines emerge as a significant factor.

8.1 Environmental impact

Sources: UNECE, 2022, Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity; Kearney Energy Transition Institute analysis

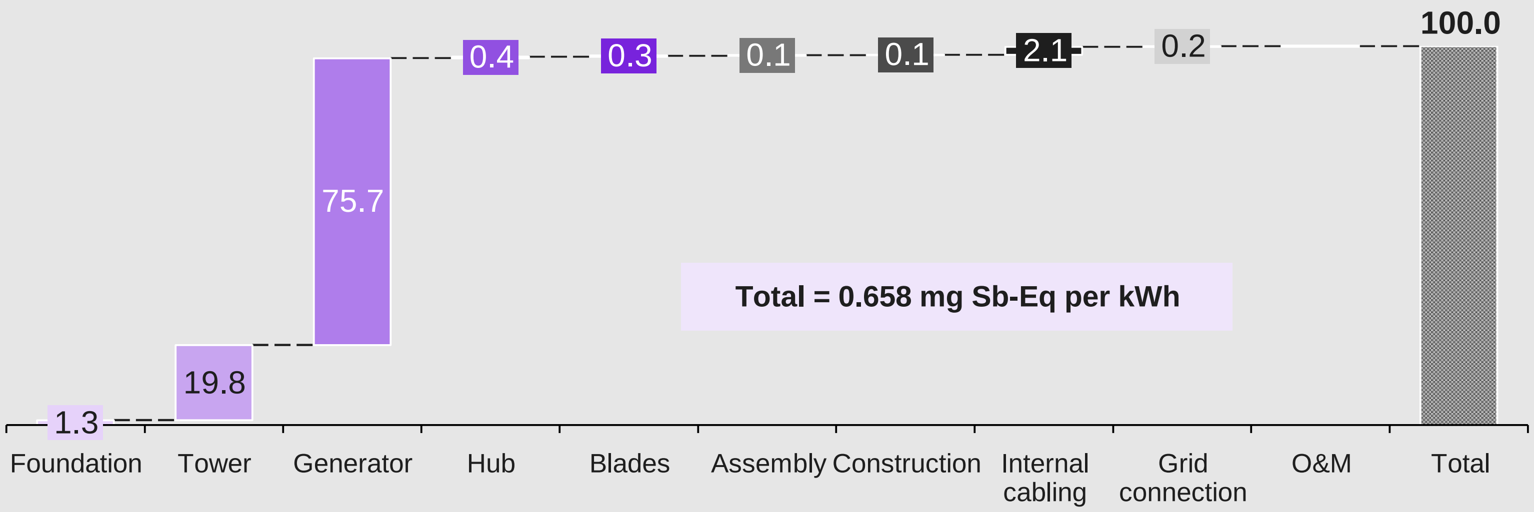
Offshore wind places a higher requirement on minerals and metals resources than onshore wind

How to read the units:

In LCA literature, resource requirement is defined in the terms of depletion (per extraction rate and estimated reserves) of nonliving (abiotic) resources such as fossil fuels, minerals, clay, and peat measured in mass of antimony (Sb) equivalents. The reference substance for this calculation is by default antimony.

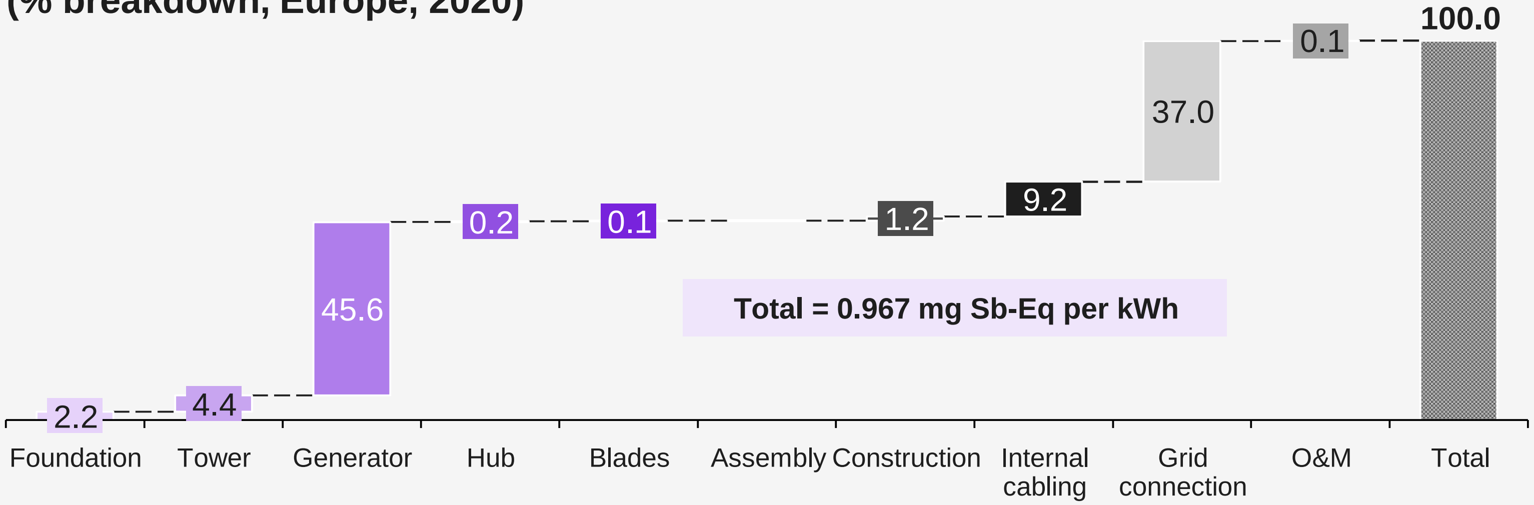
8.1 Environmental impact

Minerals and metals – onshore
(% breakdown, Europe, 2020)



Generator is the dominant contributor, due to copper use.

Minerals and metals – offshore, gravity based
(% breakdown, Europe, 2020)



Apart from generator, **grid connection** is a key impact factor for offshore wind projects.

Sources: UNECE, 2022, Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity; Kearney Energy Transition Institute analysis

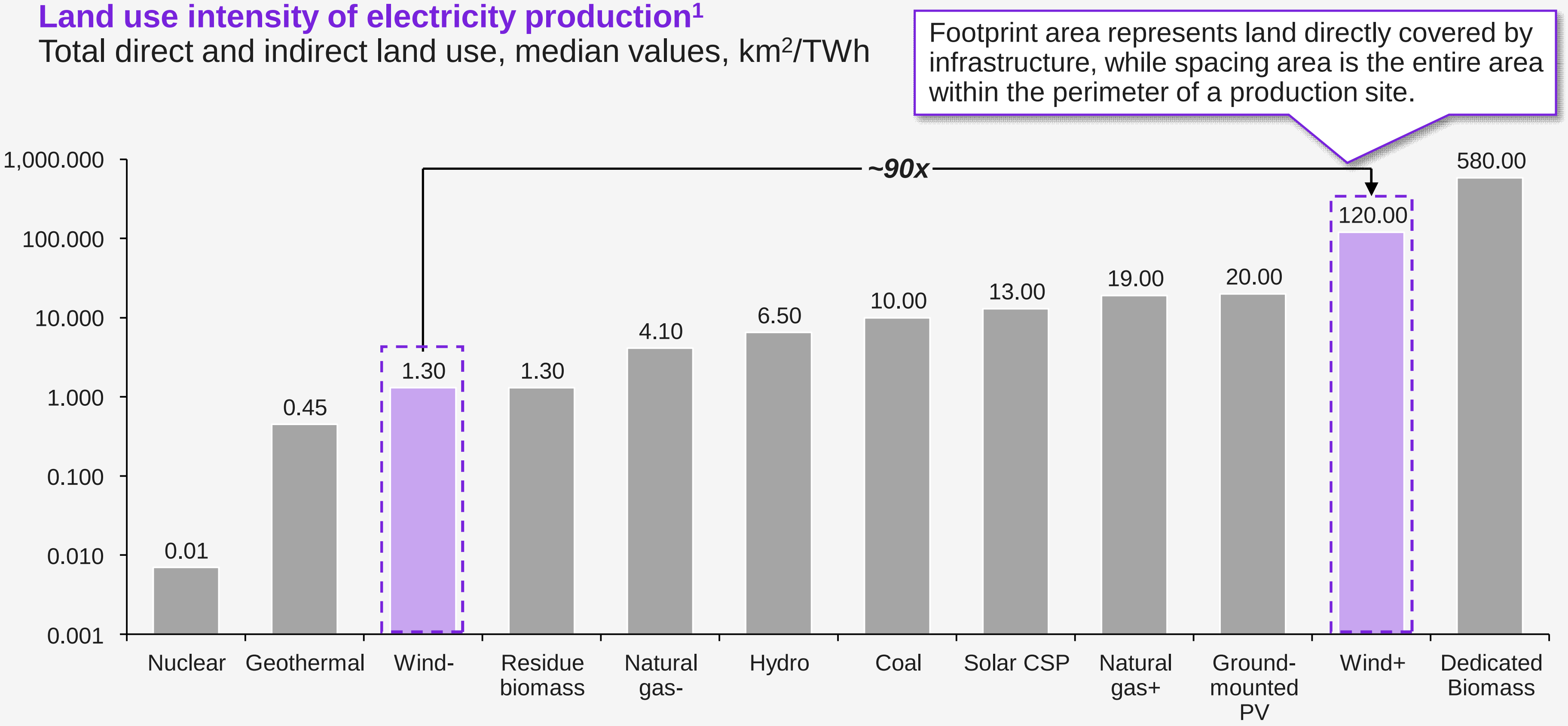
Wind energy's land use intensity can vary significantly depending on whether spacing is considered or not

Land required for electricity transmission infrastructure (e.g., high voltage transmission corridors), offshore area impacts (for wind farms and natural gas drilling), and underground impacts (for geothermal, natural gas, and coal mining) is excluded.

8.1 Environmental impact

Land use intensity of electricity production[1]

Total direct and indirect land use, median values, km^2/TWh



Land use characteristics for wind

– Due to higher land use intensity, large-scale deployment of onshore wind could considerably increase energy sprawl and loss of natural habitat.

– Wind turbines can be built on degraded, contaminated, or on top of agricultural land. Hence, this feature allows electricity production without requiring additional land (unlike some other electricity sources).

– ~99% of the surface area of a wind farm is physically undisturbed. Farming or fishing is possible, although no habitation can be built without it suffering visual disturbance.

[1] "–" denotes excluding spacing and "+" denotes including spacing.
Sources: Lovering et al., 2022, Land-use intensity of electricity production and tomorrow's energy landscape; Kearney Energy Transition Institute analysis

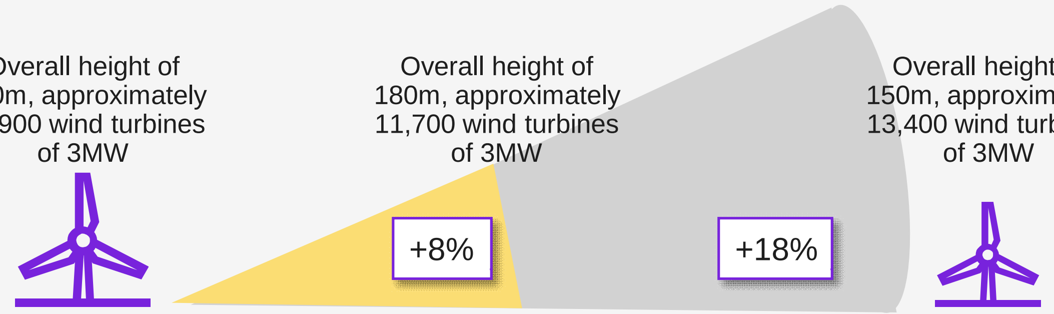
Wind has a lower capacity density than solar, but the footprint of turbines on wind farms is negligible and means the land may be put to other uses

The footprint of turbines on wind farms is negligible and land can be used for other uses

Land-use comparison for two 330 MW-equivalent renewable-power plants

- The total plant area (defined as the convex hull containing all turbines) is very large because wind turbines must be erected at a minimum distance to each other in order to avoid the drop in wind speed in the shadow of upwind turbines.
- About 99% of the surface area of a wind farm is physically undisturbed. Farming or fishing is possible, although no habitation can be built without it suffering visual disturbance.
- The direct land impact consists mainly of service roads (80%) and turbine pads (10%).

For the same electrical output, taller wind turbines require less land footprint



For the same electricity output, taller WTGs require fewer turbines and therefore less land, meaning extra land, while shorter WTGs need more turbines and additional land.

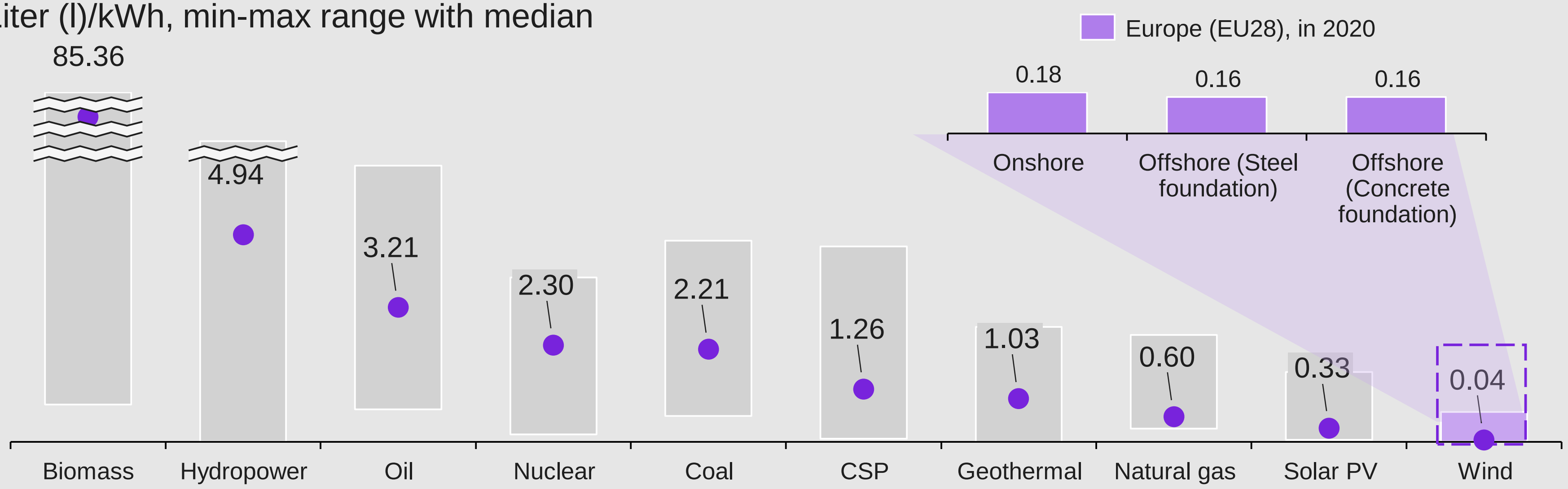
[1] The weighted average capacity density of 172 existing US onshore wind farms is 35 ± 22 hectare/MW, whereas land directly impacted averaged 0.3 ± 0.3 ha/MW according to NREL (2009) “Land-Use Requirements of Modern Wind Power Plants in the United States.” Such a plant would meet the need of roughly 2.2, 6, and 0.8 million households in China, Brazil, and Germany, respectively.
[2] According to the US DOE, modern solar PV plants require 10 to 20 km² per GW of capacity installed, depending on the latitude. 10km² /GW in this example.
Sources: NREL (2009) “Land-Use Requirements of Modern Wind Power Plants in the United States”; IPCC (2014), “Technology-specific cost and performance parameters”; NREL(2013), “Land-Use Requirements for Solar Power Plants in the United States”; Fachagentur Windenergie an Land, 2019, Overview Onshore Wind Energy; Kearney Energy Transition Institute analysis

Wind power has the lowest water consumption compared to other electricity sources

Wind energy development is ideal for regions with **scarce water resources** because during operations water use is very small.

Water consumption comparison[1]

Liter (l)/kWh, min-max range with median

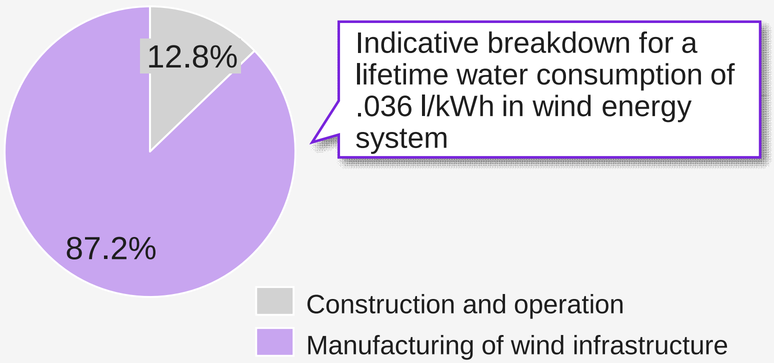


Water consumption characteristics

- Water consumption in the **operational stage** of wind power is negligibly small (mainly for blade cleaning).
- Even in the largest turbines, most inverters, transformers, and generators will use air **instead of water cooling.**
- Water consumption in manufacturing and transportation is larger than in operations.

Water consumption in wind power

By category, in %



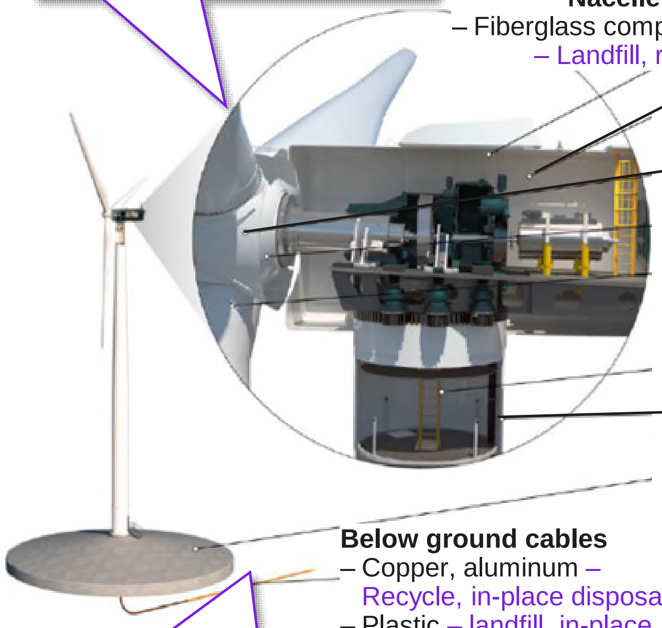
8.1 Environmental impact

[1] Water consumption is defined as the volume of water required to produce 1 kWh of electricity.
Sources: Jin et al., 2019, Water use of electricity technologies: A global meta-analysis, Renewable and Sustainable Energy Reviews; UNECE, 2022, Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity; Kearney Energy Transition Institute analysis

Recycling potential varies across wind turbine materials

Towers, hubs, and various internal components of wind turbines are constructed from metal materials that **are highly recyclable**, making up **86%–94% of the turbine's above-ground mass.**

Blades and components such as **nacelle covers** are composed of composite materials, which are more difficult to recycle, accounting for **6%–14% of a wind turbine's above-ground mass.**



Foundations and underground cables, made from materials such as concrete, plastic, and metals, **are often recyclable. However, they are frequently left partially buried in the ground.**

Rare earth elements (REE), used in permanent magnets for wind turbine generators, **are difficult to recycle.**

8.2 Waste and recycling

Blade waste treatment methods, from more to least preferred

1. Blade waste can be **prevented** through design improvements focused on **reduction and substitution** (for example, **reducing blade mass** and designing **modular or segmented blades).**

2. Blades should be used and **reused** as long as possible before waste treatment, with **routine servicing and repairs** ensuring their **full design lifetime.**

3. **Repurposing** involves reusing blade parts for different, typically **lower-value applications**.

4. When repurposing is not feasible, **recycling** is the next option, **transforming blade waste into new materials or products** for similar or different uses, though it requires energy and resources.

5. **Recovery** involves **converting waste into fuel or thermal energy** after extracting reusable blade components.

6. **Landfilling or incinerating blades** without energy recovery are the **least preferred waste treatment methods**, as they **provide no material or energy reclamation.**

Sources: WINDExchange U.S. DOE and NREL, 2024, Winding Down: End of Service and Recycling for Wind Energy; Vestas, 2020, The Vestas Sustainability Report 2019; Tota-Maharaj, K. and A. McMahon, 2021, Resource and Waste Quantification Scenarios for Wind Turbine Decommissioning in the United Kingdom; Cefic, WindEurope and EuCIA, 2020, Accelerating Wind Turbine Blade Circularity; WindEurope, 2020, How to build a circular economy for wind turbine blades through policy and partnerships; Kearney Energy Transition Institute analysis

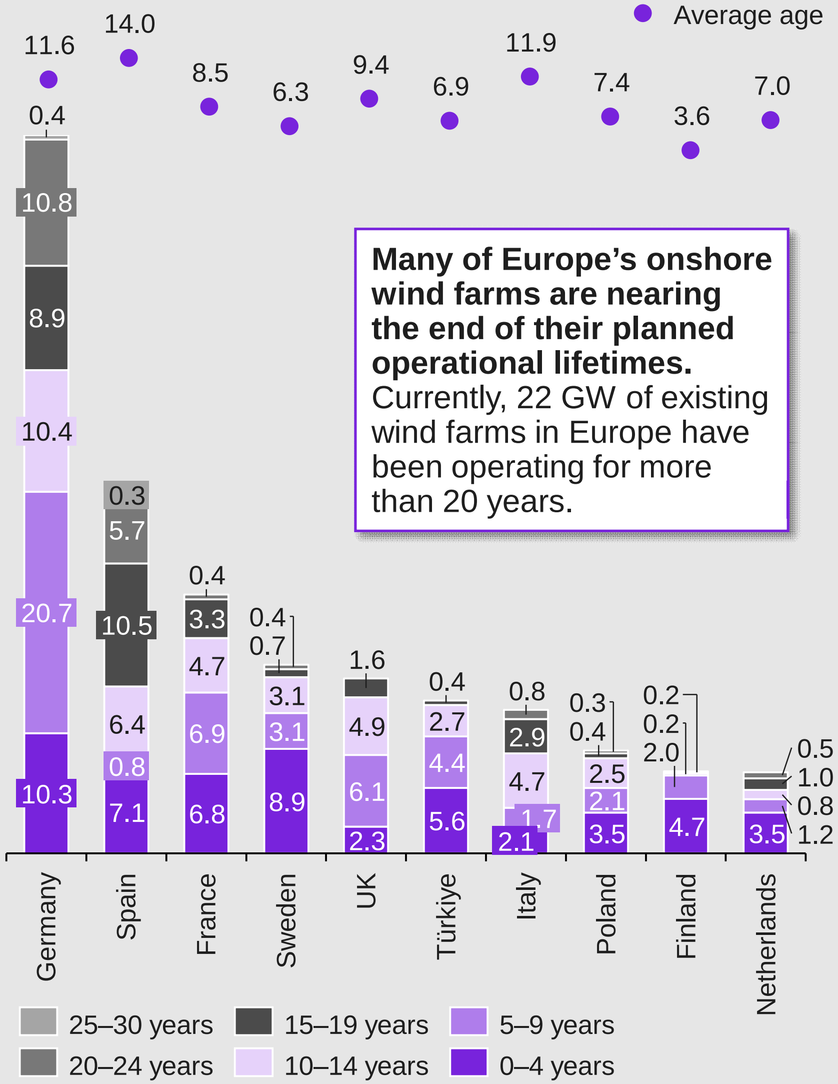
The wind energy recycling supply chain should evolve to meet energy and climate targets

Europe

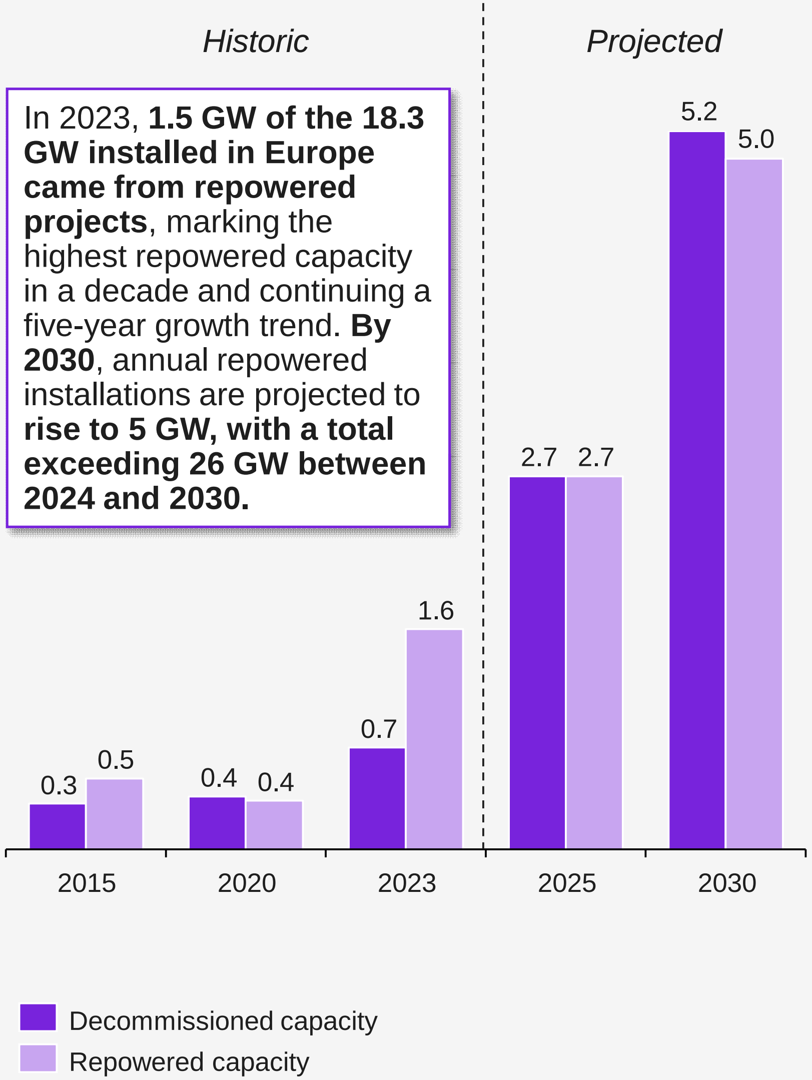
Most wind farms at the end-of-life stage now choose some form of lifetime extension, not only due to the current economic situation but also because legislative frameworks for repowering are often not yet in place.

8.2 Waste and recycling

Average age of onshore wind farms in Europe
GW, 2023



Decommissioned and repowered capacity in Europe
GW, 2014–2023

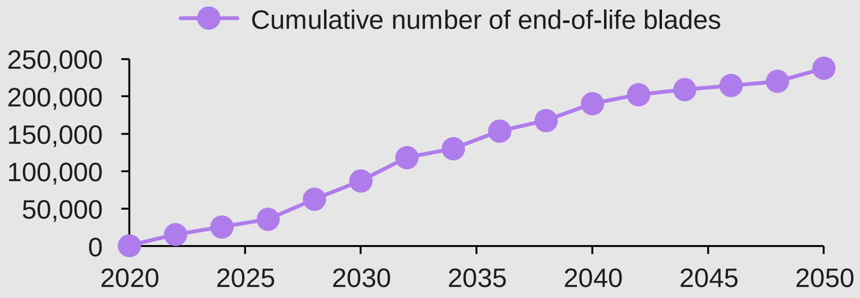


Sources: WindEurope, 2024, Wind energy in Europe – 2023 Statistics and the outlook for 2024-2030; Kearney Energy Transition Institute analysis

Kearney XX/ID

Recycling can reduce life cycle emissions of blade materials

US blade waste estimates
(Number of blades, 2020–2050)



On average, **3,000–9,000** blades reach end-of-life per year in the United States. This number is forecasted to increase to **10,000–20,000** blades per year by 2040.

Challenges in blade landfilling

Most wind turbine blades are currently disposed of in landfills due to lower cost, more proximate to project site, more processing capacity, etc.

However, blades take up a large amount of landfill space and can require **specialized equipment, capacity, and personnel.**

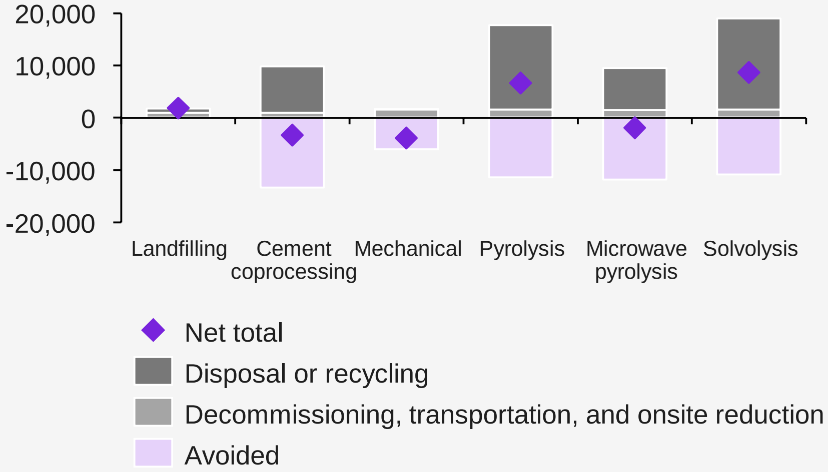
Some communities have enacted **landfill bans**, and some landfill operators may not accept blades.

Several countries have banned landfilling of blades (e.g., Austria, Germany, Finland, and the Netherlands).

Life cycle analysis for blade processing

Recycling processes tend to be energy intensive and produce greenhouse gas emissions themselves and for some processes, these extra emissions **may outweigh the benefits of the recycled product they create.**

GHG emissions, $kgCO_2e$/blade



Different recycling options include:

- **Mechanical recycling** grinds or shreds blades into materials that are repurposed for use in other manufacturing processes. **Cement coprocessing** is a common mechanical recycling method.
- **Pyrolysis or thermal decomposition recycling** uses heat to recover glass fibers that can then be upcycled into new composite-based materials.
- **Solvolysis or chemical decomposition recycling** separates glass fiber from other components through dissolution.

Sources: NREL, 2024, Winding down: End of service and recycling for wind energy; Kearney Energy Transition Institute analysis

8.2 Waste and recycling

Onshore and offshore wind energy projects affect communities by altering landscapes, changing land and sea usage, and creating economic opportunities

	Negative impact	Positive impact
Space use	– Can interfere with radar and aircraft navigation systems	**Offshore wind installations can affect marine ecosystems and environments**, including changes in sediment movement that impact the ecosystem.
Habitat	– Birds and bats collision, disturbance or habitat damage could occur	
Economic	– Potential loss of real estate and tourism income if turbines are very close to living zones	– Yearly additional incomes from tax and land-lease payments to local communities – Employment and business opportunities for local communities in the supply chain – Access to clean energy and possibility to invest in wind farm projects
Aesthetic and comfort	– Dominance of wind turbines over the landscape altering visual aesthetics – Disturbance from night light and light signals – Visual and noise disturbance from rotor movement – Shadow flicker	**Onshore turbines** are increasing in size and **being installed in new locations**, making them **more noticeable in the landscape**, potentially altering natural scenery and disrupting views.

Sources: US DOE, Advantages and challenges of wind energy, accessed January 2025; Local Government Association, UK, Benefits and potential impacts of wind energy, accessed January 2025; Unesco World Heritage Convention, 2024, Impact of Wind Energy Projects and their Assessment; Kearney Energy Transition Institute analysis

64% and 63% of Europeans surveyed support new onshore and offshore wind turbines in their area, respectively

- Support
- Oppose
- Don't know

Example Europe

YouGov polling on renewable energy was commissioned by the European Climate Foundation, carried out online and the total sample size was 10,547 adults.

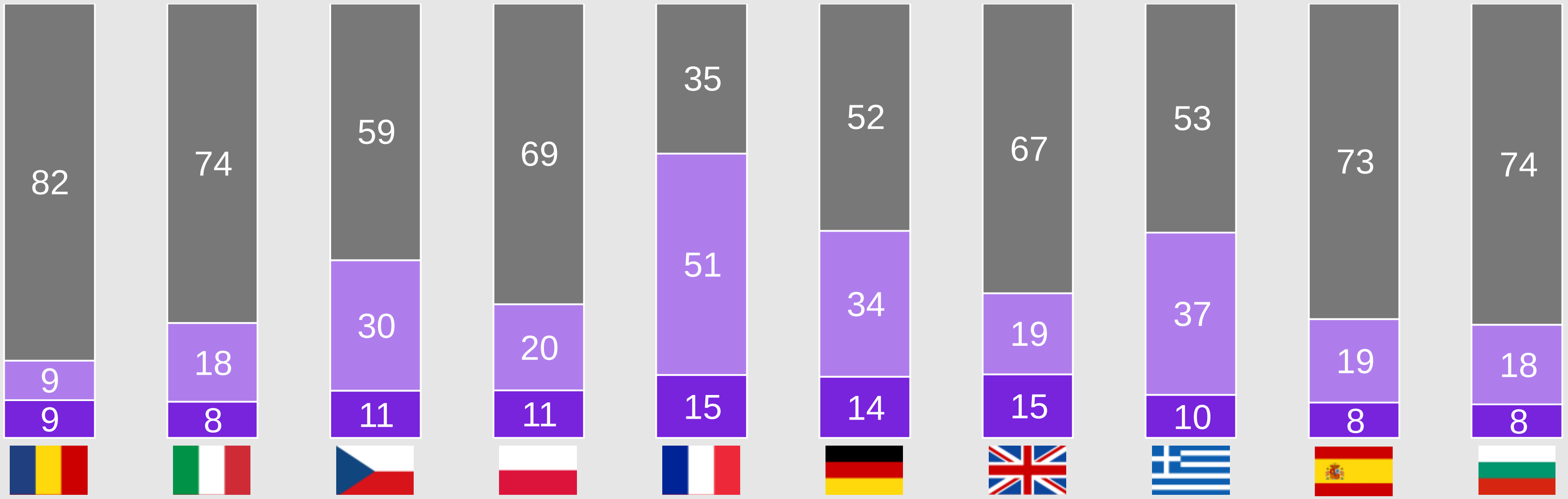
Sources: YouGov, 2021, Cross-EU polling on renewable energy; Kearney Energy Transition Institute analysis based on desktop research

8.3 Social acceptance

Social acceptance of onshore wind farms in Europe

%, 2021

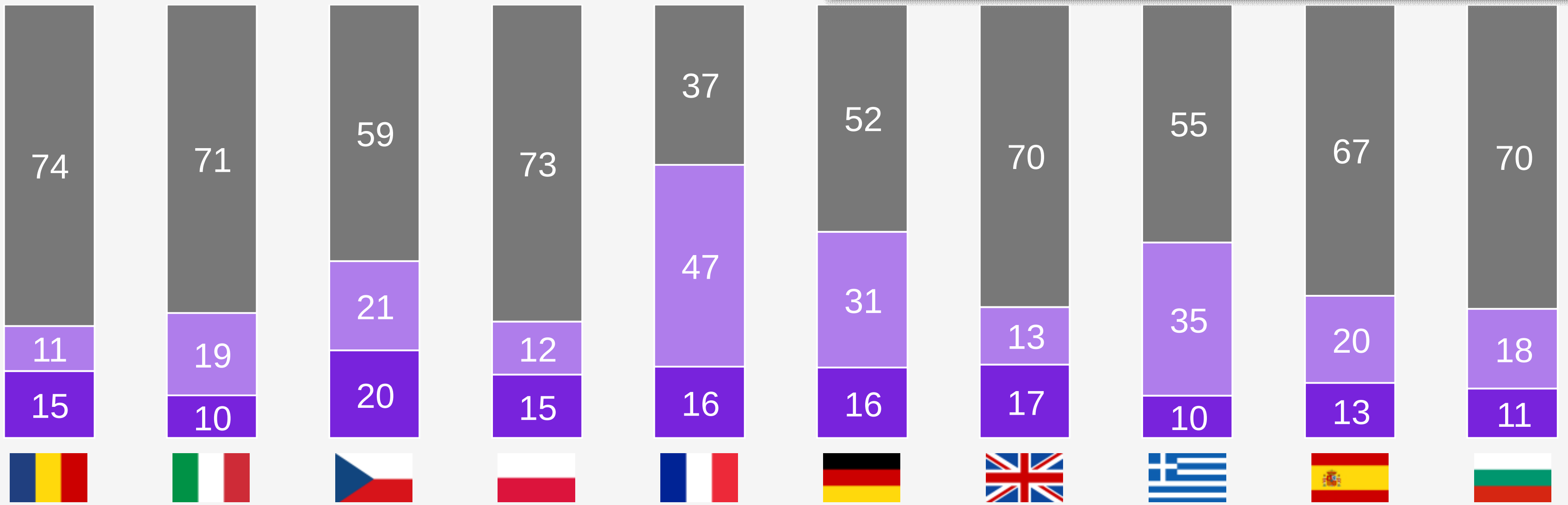
82% and 87% of Europeans questioned do not live near an onshore or offshore wind farm, respectively.



Social acceptance of offshore wind farms in Europe

%, 2021

67% of Europeans said they would be more likely to support wind farm construction if it created local jobs, while 65% felt the same if profits were shared with the community.



Kearney XX/ID

Social acceptance is a key factor in the success of wind energy projects across diverse geographies

Example

Evolution of the project	Kinangop wind park (KWP) project	Fosen wind farm project	Mareña Renovables / Eólica del Sur project	Northern California's Humboldt energy area
	Lack of community involvement during the land acquisition led to distrust.	**Disrupted Sami reindeer farming** and connection to the land.	**Indigenous communities opposed due to impacts on biodiversity**, fishing activities, and their way of life.	**The 206-square-mile wind farm area overlaps vital fishing zones**, raising concerns over access and marine ecosystem disruption.
	Use of unsecured private land excluded some groups; farmers feared coercion and health risks, sparking protests for fair engagement and compensation.	**In 2021, the Court sided with the Sami**, highlighting the tension with green energy goals.	**Insufficient transparency** and disregard for community autonomy fueled opposition.	**Local fishermen fear** that the wind turbines may **reduce catches and harm livelihoods.**
	Local politics amplified opposition, turning the project into a campaign issue.	Sami activists **staged high-profile protests**.	**Halted in 2013 after clashes**; relocated and renamed Eólica del Sur in **2014 with FPIC consultation.**[1]	**Fishermen are dissatisfied with limited consultation**, feeling their expertise and livelihoods are overlooked.
Final outcome of the project	**Protests caused delays**, exhausted funds, and **led to cancellation.**	In 2024, an agreement **compensated the Sami with energy shares, a new grazing area, and a NOK 5 million cultural grant.**	Despite tensions, **inaugurated in 2019**.	**Regulators approved the project for lease sale**, with the California Coastal Commission **mandating safe passage for fishing vessels and an independent fisheries liaison.**

[1] Free, prior, and informed consent

Sources: GWEC, 2024, Global Wind Report; Kearney Energy Transition Institute analysis based on desktop research

Misinformation creates unpredictability in policy and decision-making for wind energy projects, causing delays, higher costs, and reputational damage

Example

Technological performance

Narratives critiquing wind turbines often misrepresent their capabilities and those of wind-dependent power systems, focusing on themes like **reliability, sustainability, and cost**.

South Korea: "Many people believe that variability of renewable energy sources will destabilize the power system."

Economic impacts

Critics often exaggerate the economic downsides of wind energy, highlighting **perceived losses to established industries like fisheries, agriculture, and tourism**.

Japan: "Residents are concerned the sight of wind turbines in the bay could have a negative impact on Ishikari's scenery, damaging the local environmental tourism industry."

Greece: "Villages are trying to block wind turbines, arguing they will turn away tourists—Greece's main source of income."

Quality-of-life impacts

Narratives about wind energy's impact on quality of life focus on **health, community character, and property values**, often citing "damaged views" or landscape "industrialization."

Spain: "As a local, I am mostly concerned about the fishing… But also about the cultural spirit of Cadaqués, the landscape that inspired Dali."

Environmental impacts

Narratives about wind energy's environmental impact, such as **effects on wildlife and land**, often rely on outdated information to challenge its green credentials.

United States: "Despite a lack of scientific evidence, they have blamed a recent spike in whale deaths on exploration devices that use sonar to seek wind turbine sites."

Sources: GWEC, 2024, Global Wind Report; Kearney Energy Transition Institute analysis based on desktop research

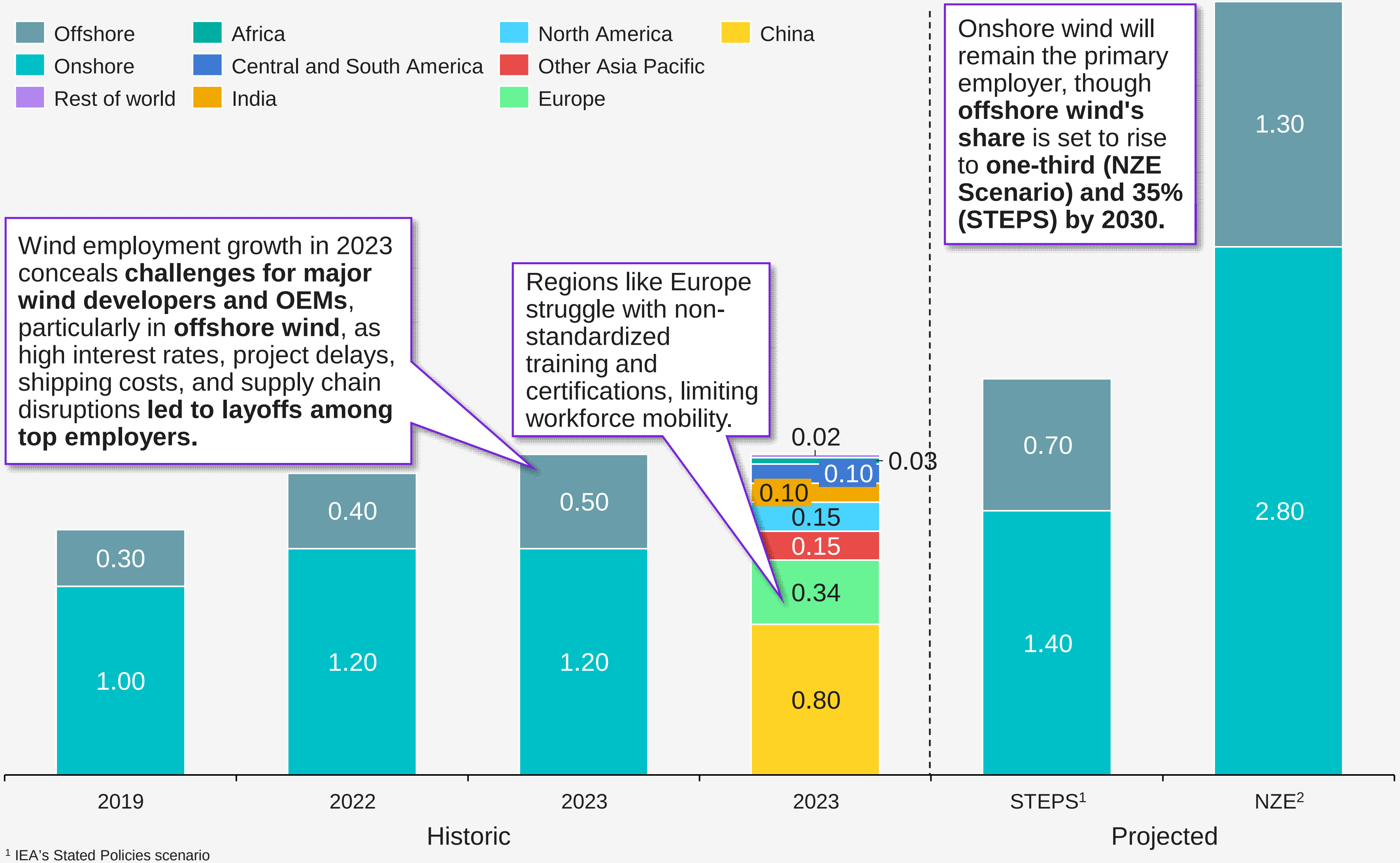
Manufacturing and construction represent the largest share of wind sector jobs at 28% and 36%, respectively

Professional roles in design, planning, maintenance, and grid integration comprise 27%, while wholesale and transport account for 10%.

8.5 Wind employment

Employment in wind by region and by scenario

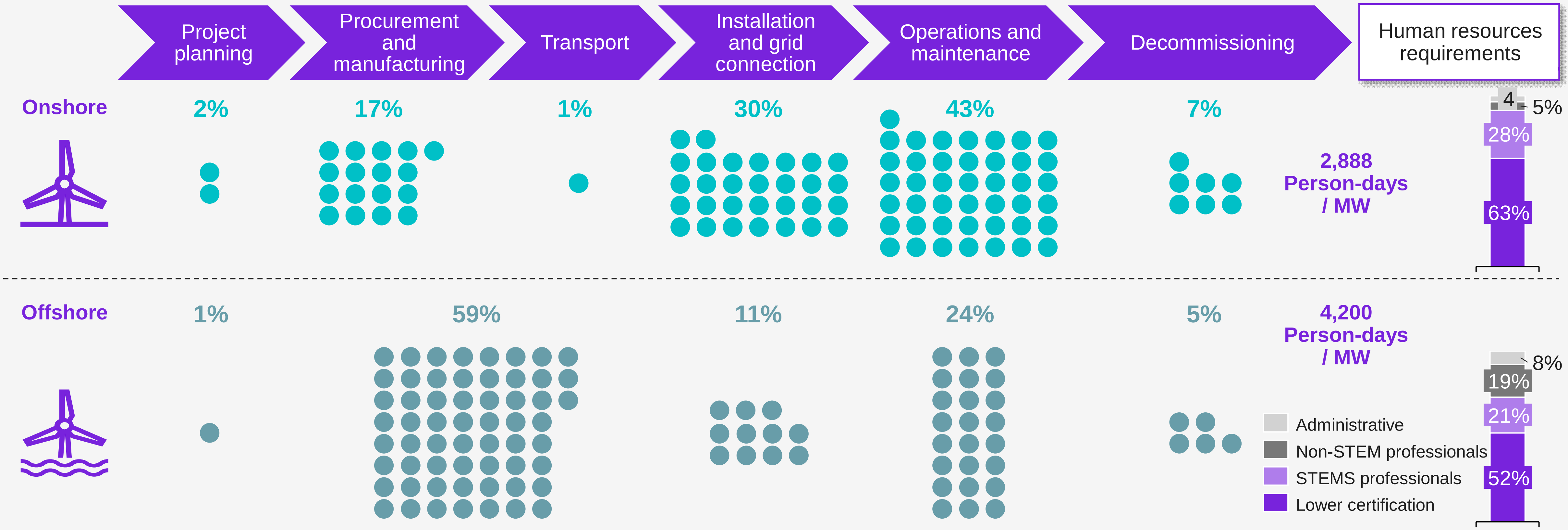
million, 2019–2030



[1] IEA's Stated Policies scenario
[2] IEA's Net Zero Emissions scenario
Sources: IEA, 2024, World Energy Employment 2024; Kearney Energy Transition Institute analysis

Over 60% of the wind energy workforce requires minimal training, with STEM roles making up 28% in onshore and 21% in offshore, and non-STEM professionals accounting for 5% and 20%, respectively

Human resources and occupational requirements for 50 MW onshore and 500 MW offshore fixed-bottom offshore wind projects
Person-days



Sources: GWEC, 2024, Global Wind Report; IRENA, 2017, Leveraging local capacity for onshore wind; IRENA, 2018, Leveraging local capacity for offshore wind; Kearney Energy Transition Institute analysis

9. Regulations and policies

Regulations and policies

Policies overview

– A **combination of policies**, including **price-based, quantity-based, and indirect instruments**, is essential for creating a favorable environment for wind energy. Mechanisms such as **tenders and auctions** remain central tools, while **power purchase agreements** (PPAs) are growing and play an important role in financing and securing revenue for wind projects globally.

Direct price-based mechanisms

– **Price-based support mechanisms**, defined by government policy, ensure revenue certainty de-risks investments and lower financing costs, particularly for **onshore wind projects**. **Offshore wind**, being a less mature market, relies more heavily on **feed-in tariffs (FITs) and PPAs** (including corporate and state-backed) to encourage capacity growth compared to onshore projects.

Direct quantity-based mechanisms

– Countries also use **quantity-based targets** to drive wind energy growth, with current national targets falling short. **As markets mature, zero-subsidy wind power auctions have emerged**, particularly in competitive regions. **New trends include negative bidding**, seen in European offshore wind auctions, where **developers pay governments for project rights**.

– Additionally, **non-price criteria are being introduced in auctions to evaluate projects beyond price**, though these criteria can inflate developer costs.

Indirect mechanisms

– **Indirect instruments play a supportive role by addressing challenges such as grid access**, accelerated permitting, and supply chain development.

Development frameworks

– Wind project development frameworks define the approval and implementation processes, combining both direct and indirect policies. **Onshore wind, being the most mature, is typically developer-led**, whereas **offshore wind requires significant government involvement** due to marine spatial planning. Offshore frameworks are often centralized but vary across countries, with some adopting decentralized approaches.

Country policy highlights

– Countries worldwide have introduced dedicated wind policies to meet renewable energy targets. In the EU, renewable support has evolved since the 2009 Renewable Energy Directive, with the 2023 Wind Power Action Plan addressing industry challenges and promoting higher targets.

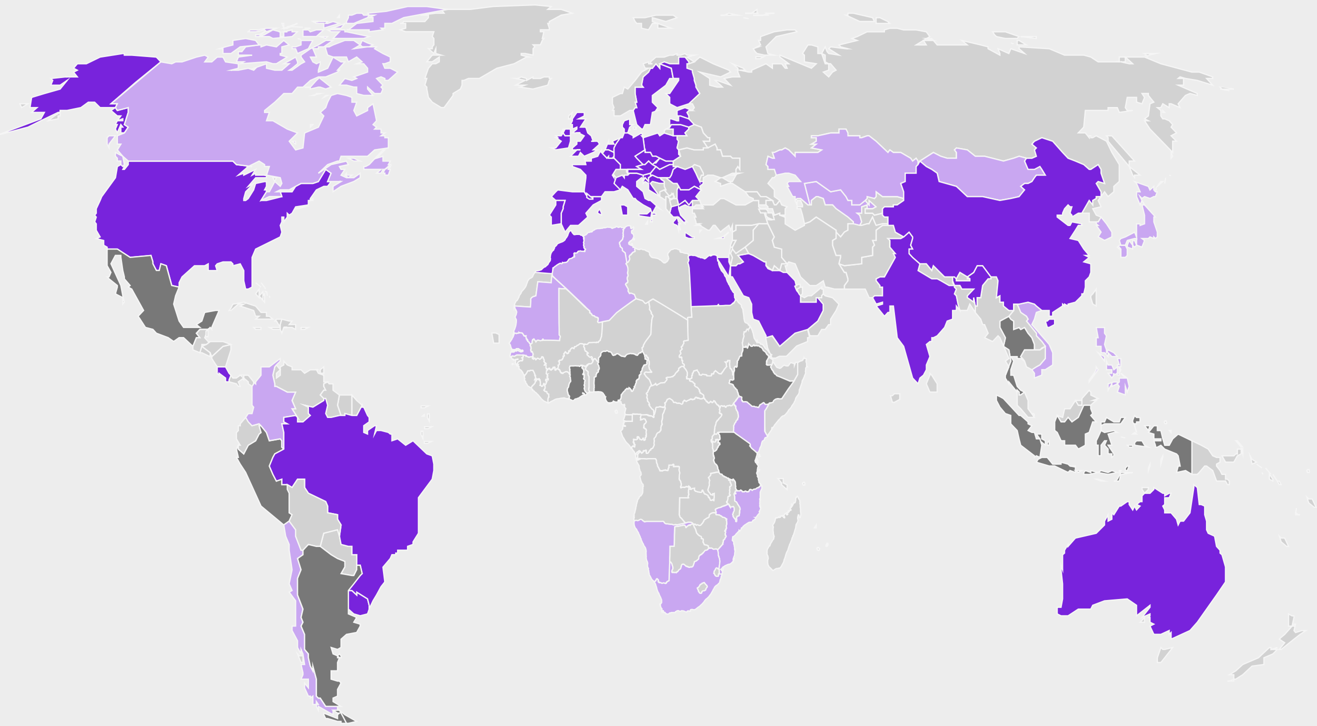
The combination of policies in a country is key in determining a favorable environment for wind power development

Recent political events are modifying policies and major changes are expected to be observed in various regions.

9.1 Policies overview

Status of policies for wind development

2022



- Strong capacity increase, new ambitious targets, and/or policy improvements
- Adequate targets and policies, but not matched by expected progress
- Lack of progress or regression

National governments, national electricity regulators, regional governments, municipalities, supranational entities, and financial institutions can set policies to incentivize wind energy.

Policy options[1]

1 Price-based instruments

Feed-in tariffs (FITs)	Tax incentives or credits
Market premiums	Direct subsidies
Contract for difference (CfD)	Power purchase agreements

2 Quantity-based instruments

Binding targets	Non-binding targets
Tenders and auctions	Quotas with tradable certificates

3 Indirect instruments

Grid access and improvement	Permitting/ regulation
Electricity market rules	Carbon pricing
Development of other sectors	Supply chain support/ mandates
Transmission rights	

[1] This is not an exhaustive list but covers most of the policies implemented globally. There may be some overlap between different policies listed above, and in some cases the same name can mean different things depending on the country or state.
Sources: GWEC, 2023, Global Wind Report 2023; Kearney Energy Transition Institute analysis

Price-based mechanisms have been providing revenue certainty for new onshore wind projects

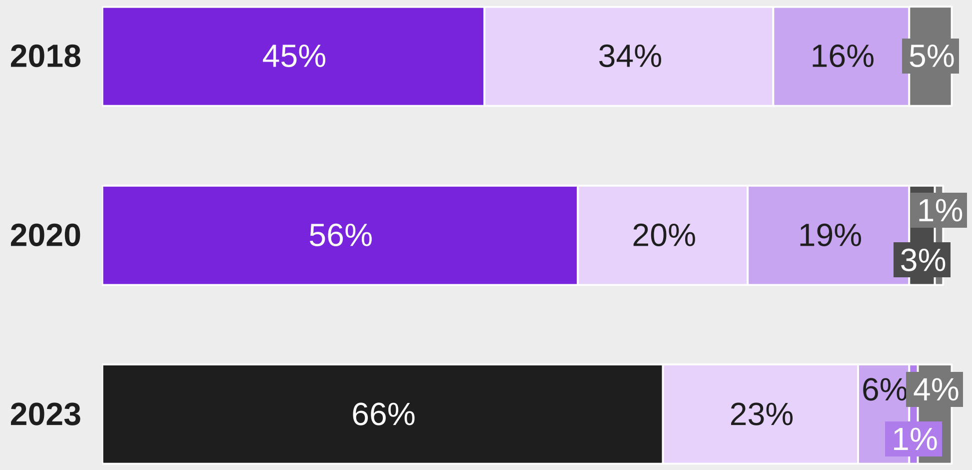
1. Price-based instruments
2. Quantity-based instruments
3. Indirect instruments

Support mechanisms are defined by government policy. **Revenue certainty provides investors with confidence**, de-risking the project and allowing a lower cost of capital to be used.

9.2 Direct price-based mechanisms

Onshore wind power: new annual capacity by market support mechanism

Share %



Year	New capacity	Mechanisms
2018	46.8 GW	FIT (China); Market-based auctions/tenders; PTC (US); Other
2020	86.9 GW	FIT (China); Market-based auctions/tenders; PTC (US); Other; Green certificates
2023	105.8 GW	Grid parity (China); Market-based auctions/tenders; PTC (US); Other; FIT

Sources: GWEC, 2024, Global Wind Report 2024; GWEC, 2021, Global Wind Report 2021; GWEC, 2019, Global Wind Report 2018; Kearney Energy Transition Institute analysis based on desktop research

Main differences between market support mechanisms

A **feed-in tariff** (FIT), defining a set price per amount of electricity produced, or a government **power purchase agreement** (PPA), defining a set price and the quantity purchased of electricity, are common mechanisms to guarantee revenue for projects.

As electricity markets become more established, governments may hold **market-based auctions or tenders**, in which developers compete to propose the lowest price, such as through a **contract for difference** (CfD).

Other mechanisms, like **renewable energy (green) certificates** or **tax incentives**, e.g., a **production tax credit** (PTC), may also support projects.

Previously, China used a **FIT** to incentivize wind development. As the market matured, China switched to a **grid-parity** mechanism, which remunerates wind energy at the same regulated price as coal power.

China's FIT/grid-parity mechanism, market-based auctions, and the US PTC held **95% of market share** for new onshore wind in 2023.

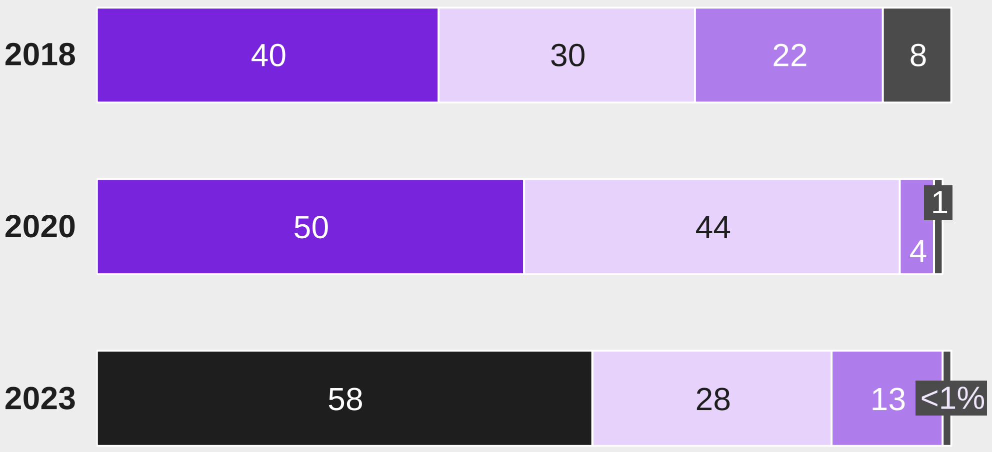
The price-based mechanisms used for offshore wind, and the capacity installed, reflect that offshore wind is a less mature market

1. Price-based instruments
2. Quantity-based instruments
3. Indirect instruments

Offshore wind power is a less mature market than onshore wind. Compared to onshore capacity additions, a greater fraction of support mechanisms for offshore capacity additions involve FITs and state PPAs.

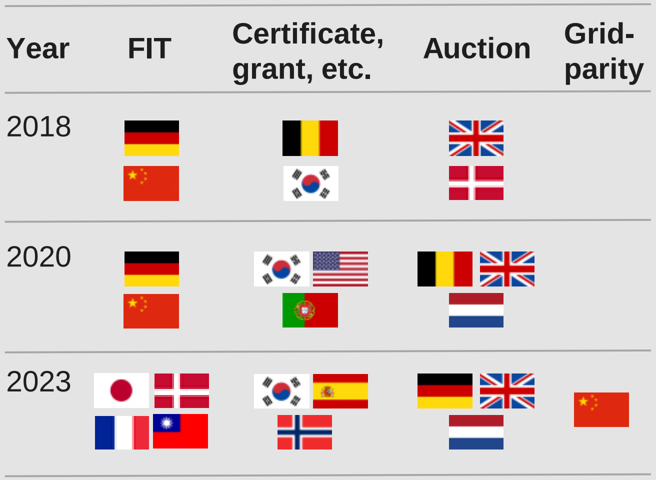
Offshore wind power: new annual capacity by market support mechanism[1]

%



Year	New capacity	Mechanisms		
2018	4.5 GW	FIT (China)	Market-based auction	FIT (Germany)
		Green certificates, grant, subsidy, or prototype		
2020	6.1 GW	FIT (China)	Market-based auction	FIT (Germany)
		Green certificates, grant, subsidy, or prototype		
2023	10.8 GW	Grid parity (China)	Market-based auction	FIT/ state PPA
		Green certificates, grant, subsidy, or prototype		

Offshore wind support mechanisms used for commissioned projects in selected years by country[2]



In **emerging wind markets**, projects are likely to be supported by **grants** for early demonstration or prototype projects, **FITs**, or **state PPA agreements**.

Like new onshore wind capacity, China's **grid parity** mechanism supports most of new offshore wind capacity, followed by **market auctions**. FITs and state PPA agreements make up a greater fraction of offshore support mechanisms than for onshore mechanisms.

[1] Wind projects may be supported by multiple price support mechanisms; the primary price support mechanism is used to classify capacity additions.
[2] Only countries that commissioned offshore wind projects in the selected years are included.
Sources: GWEC, 2024, Global Wind Report 2024; GWEC, 2021, Global Wind Report 2021; WindEurope, 2021, Offshore Wind in Europe: Key trends and statistics 2020; GWEC, 2019, Global Wind Report 2018; Kearney Energy Transition Institute analysis based on desktop research

Among other policy options, countries have defined a variety of quantity-based targets for wind power

Non-exhaustive

1. Price-based instruments
2. **Quantity-based instruments**
3. Indirect instruments

The 2023 COP28 agreed to triple global renewable capacity. However, current government targets are only set to double capacity, despite 24 updated national renewable energy targets in 2023.

9.3 Direct quantity-based mechanisms

Installed capacity and national wind power targets (2023)

Country	Installed capacity (GW)[1] Onshore	Installed capacity (GW)[1] Offshore	Deploying renewables faster than 2030 target	Target (2030 unless otherwise specified)
China	405	37	●	800 GW wind[2]
United States	148	0.04		334 GW onshore wind[2] 35 GW offshore wind[2]
Germany	61	8		115 GW onshore wind 30 GW offshore wind
India	45	0		110 GW wind[2]
Spain	31	0	●	59 GW onshore wind 3 GW offshore wind
Brazil	29	0	●	31 GW of wind
United Kingdom	15	15		29 GW onshore wind[2] 48 GW offshore wind[2]
France	20	0.5	●	33 GW onshore wind 4 GW offshore wind
Australia	13	0	●	34 GW wind[2]
Japan	5	0.2	●	18 GW onshore wind 10 GW offshore wind
Vietnam	5	1		22 GW onshore wind 6 GW offshore wind
Egypt	2	0		7 GW wind[2]
Morocco	2	0	●	4 GW wind[2]
Saudi Arabia	0.4	0		16 GW wind

● Deploying renewables faster than 2030 target

[1] Total installed capacity at year-end 2023; [2] Implicit target sourced from official projections, road maps, or third-party studies; [3] The Esbjerg Declaration was signed by Belgium, Denmark, Germany, and the Netherlands. The Ostend Declaration was additionally signed by France, Luxembourg, Norway, the United Kingdom, and Ireland; [4] The Marienborg Declaration was signed by Germany, Denmark, Poland, Finland, Sweden, Estonia, Latvia, and Lithuania.

Sources: IRENA, 2024, Tracking COP28 outcomes: Tripling renewable power capacity by 2030; IRENA, Power capacity and generation from IRENASTAT, accessed December 2024; GWEC, 2024, Global Wind Report 2024; GWEC, 2024, Global Offshore Wind Report 2024; REN21, 2024, Renewables 2024 Global Status Report Collection; Ember, 2024, 2030 Global Renewable Target Tracker, accessed on December 2024; Ember, 2023, Tracking national ambition towards a global tripling of renewables; Kearney Energy Transition Institute analysis based on desktop research

Other regional and state offshore wind targets

North Sea: The 2022 Esbjerg Declaration set a target to develop 65 GW of offshore wind by 2030, and 150 GW by 2050 in the North Sea. The 2023 Ostend Declaration increased these targets to 120 GW by 2030 and 300 GW by 2050.[3]

Baltic Sea: The 2022 Marienborg Declaration set a target to develop 19.6 GW offshore wind by 2030 in the Baltic Sea.[4]

Australia: 9 GW offshore wind by 2040 in the state of Victoria.

United States: 84 GW of state level offshore wind targets between 2031 and 2045.

Few countries currently have developed floating offshore wind, but more are creating targets and supportive policies

Non-exhaustive

1. Price-based instruments
2. Quantity-based instruments
3. Indirect instruments

At the end of 2023, the global floating offshore wind (FOW) capacity reached **236 MW across seven countries**, while 244 GW were in the pipeline.[1] To support FOW, countries have set **targets** and are using a **variety of direct and indirect mechanisms.**

9.3 Direct quantity-based mechanisms

Leading floating offshore wind countries use a variety of policies to support the sector

Current capacity (MW)	2030 Target (GW)	Details
Norway: 101	30 (offshore)[2]	Norway has the **largest operating FOW project**, Hywind Tampen, of 88 MW. A 1.5 GW FOW was due to be awarded in 2023, but it was delayed to 2025 after the government decided to switch to a **qualitative criteria selection with state subsidies**.
UK: 80	5	The UK's offshore projects are awarded **via auctions with supporting CfD**.[3] The expected 2024 AR6 auction raised CfD ceiling prices to GBP 176/MWh for FOW.
Portugal: 25	10 (offshore)	Portugal installed the EU's first FOW project, WindFloat Atlantic (25 MW) in 2020. The capacity will be awarded via **auctions**, though the auction schedule has been delayed.
China: 23	800	China's first FOW project, **CNOOC Guanlan**, became operational in 2023. Leveraging existing wind industry expertise, China's ambitions are rising significantly with a 1 GW FOW farm in Hainan Province expected to be commissioned in 2027.
Japan: 5	10 (offshore)	Japan is committed to scale up FOW with government allocations for **manufacturing investments** (USD 220M) and **demonstration project grants** (USD 550M). 2024 **legal changes** permitted FOW to be constructed in Japan's EEZ.[5] While the Goto project (Japan's first large FOW farm) commissioning was delayed to 2026, additional **demonstration projects** were announced June 2024.

Key themes to developing floating offshore wind

IRENA identified five areas to prioritize for FOW development:

1. Political
   - Accelerate international cooperation.
   - Promote stakeholder awareness.
2. Regulation
   - Develop and adopt suitable frameworks for FOW.
3. Hydrogen production
   - Couple FOW with hydrogen development.
4. Sustainability
   - Address FOW environmental impacts.
   - Prioritize co-existence with fishing industry.
5. Technology and infrastructure
   - Commercialize and standardize technology.
   - Expand grid and port infrastructure.

[1] Estimates for operational floating offshore wind capacity as of year-end 2023 range from 236 MW (GWEC) to 270 MW (IRENA); [2] Offshore wind. Norway's 30 GW offshore wind target is for 2040; [3] Contract for difference; [4] 800 GW is a projection of all wind power capacity, as China does not have a separate target for offshore wind; [5] Exclusive economic zone

Sources: GWEC, 2024, Global Offshore Wind Report 2024; IRENA, 2024, Floating Offshore Wind Outlook; Ember, 2024, 2030 Global Renewable Target Tracker; offshoreWind.biz, 2024, Norway Postpones Floating Wind Tender to 2025 as Gov't Establishing 'Common State Aid Model; Kearney Energy Transition Institute Analysis based on desktop research

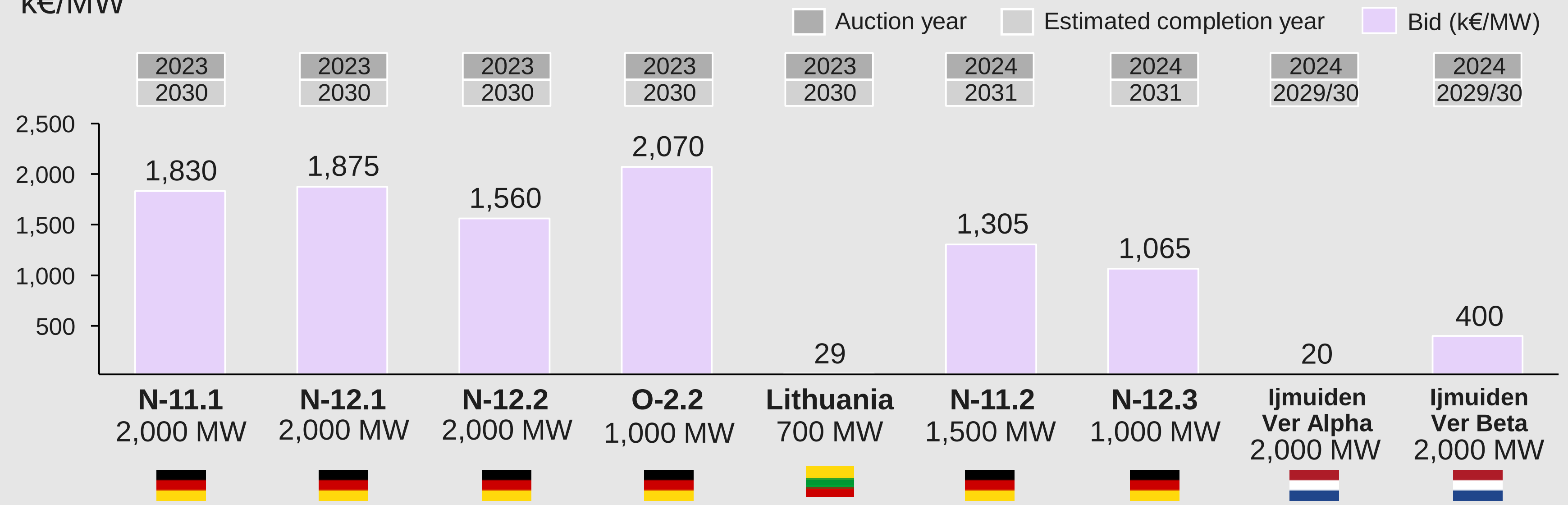
Latest developments in offshore wind auctions have seen the use of negative bidding in some European countries

Non-exhaustive

1. Price-based instruments
2. Quantity-based instruments
3. Indirect instruments

Negative bidding indicates competitiveness of the market and sets a high barrier to entry for developers.

Negative bid prices for awarded offshore wind projects
k€/MW



The future of negative bidding is not yet clear as it is criticized by industry players and may not be suitable for all countries

In negative bid auctions, developers compete on how much they will pay the government for the rights to build a project. Negative bid profits are typically used for **environmental initiatives** or to **reduce electricity tariffs**.[1]

Negative bid auctions are criticized for **incentivizing a "race to the bottom" that leaves developers vulnerable to price fluctuations, puts stress on suppliers, and may raise prices for consumers**.

Germany adopted uncapped negative bidding called **dynamic bidding** in 2023.[2] The **Netherlands** used **capped negative bidding** in its 2024 offshore wind auction. A feed-in premium is used for onshore projects in both countries. **Denmark** will use **uncapped negative bidding** in its announced 2024 offshore wind auction.

Although **Lithuania** used negative bidding in 2023 for its first offshore wind auction, it will use a contract-for-difference mechanism for its second auction in 2024 due to a lack of interested bids.

[1] The payment terms imposed on winning projects differ by country.
[2] Germany uses dynamic bidding for non-centrally pre-surveyed wind sites. For centrally pre-surveyed wind sites, a different auction mechanism is used that ranks projects based on both bid price and non-price criteria. Further details can be found on the Germany policy DeepDive.
Sources: GWEC, 2024, Global Wind Report 2024; GWEC, 2024, Global Offshore Wind Report 2024; WindEurope, 2024, Wind energy in Europe: 2023 statistics and the outlook for 2024-2030; WindEurope, 2022, Negative bidding in wind auctions is bad for consumers and bad for the supply chain; Kearney Energy Transition Institute analysis based on desktop research

Non-price criteria in auctions help to judge projects beyond price criteria but risk inflating prices for developers

1 Price-based instruments
2 Quantity-based instruments
3 Indirect instruments

Non-price criteria (NPC) are defined by governments in the auction mechanism and ask developers to **invest in areas outside of direct project development**. NPC are used to score and select bids complementary to price criteria.

9.3 Direct quantity-based mechanisms

Non-price criteria vary by country but are more common for offshore wind projects

Wind project auctions typically involve at least some non-price criteria, either as **prequalification criteria** to determine participation eligibility, or as **award criteria** to rank submitted bids. NPC are more common for **offshore wind** projects due to their complexity.

NPC may require the implementation of mitigation, avoidance, and offset measures identified in an **Environmental and Social Impact Assessment**.

NPC differ greatly between countries. However, it is good practice for governments to make NPC **transparent, clear, and as non-subjective** as possible.

NPC award criteria may count for a fraction of the score that project bids receive in auctions.[1] NPC are **gaining importance in zero-subsidy auctions**, where they can be used to rank projects beyond price criteria.

Pros: NPC address criteria that pure cost criteria do not address. NPC can create synergistic effects during project development and ensure projects are executed responsibly and successfully.

Cons: Having to invest in additional NPC measures means that project costs go up for developers. Auctions may become subjective and require additional time.

NPCs may involve a variety of criteria

Project sustainability
- Using recycled content
- End-of-life plans
- CO_2 emissions tracking

Community benefit
- Financial remuneration and equity shares
- Stakeholder communication and participation
- Educational outreach programs

Biodiversity
- Reducing disturbances to marine life
- Monitoring wildlife habitats
- Nature preservation projects

Technology development
- Co-development of synergistic technology, like solar, hydrogen, or energy storage
- Testing of next-generation wind technology
- Providing system integration or ancillary services

Economic development
- Sponsoring work and reskilling programs
- Local/domestic sourcing requirements

Project viability
- Quality of risk analysis
- Experience of the developer
- Pre-signed PPAs

[1] The fraction of the bid score that NPC account for varies country to country. However, for auctions approved under the EU's Climate, Energy, and Environmental Aid Guidelines (CEEAG), the NPC cannot make up more than 30% of the auction score.
Sources: GWEC, 2024, Global Wind Report 2024; ESMAP, 2021, Key Factors for Successful Development of Offshore Wind in Emerging Markets; European Commission, 2022, Guidelines on State aid for climate, environmental protection and energy; WindEurope, 2022, WindEurope position on non-price criteria in auctions; Kearney Energy Transition Institute analysis based on desktop research

Indirect policy instruments are used to influence stakeholders and processes in wind power development

Non-exhaustive

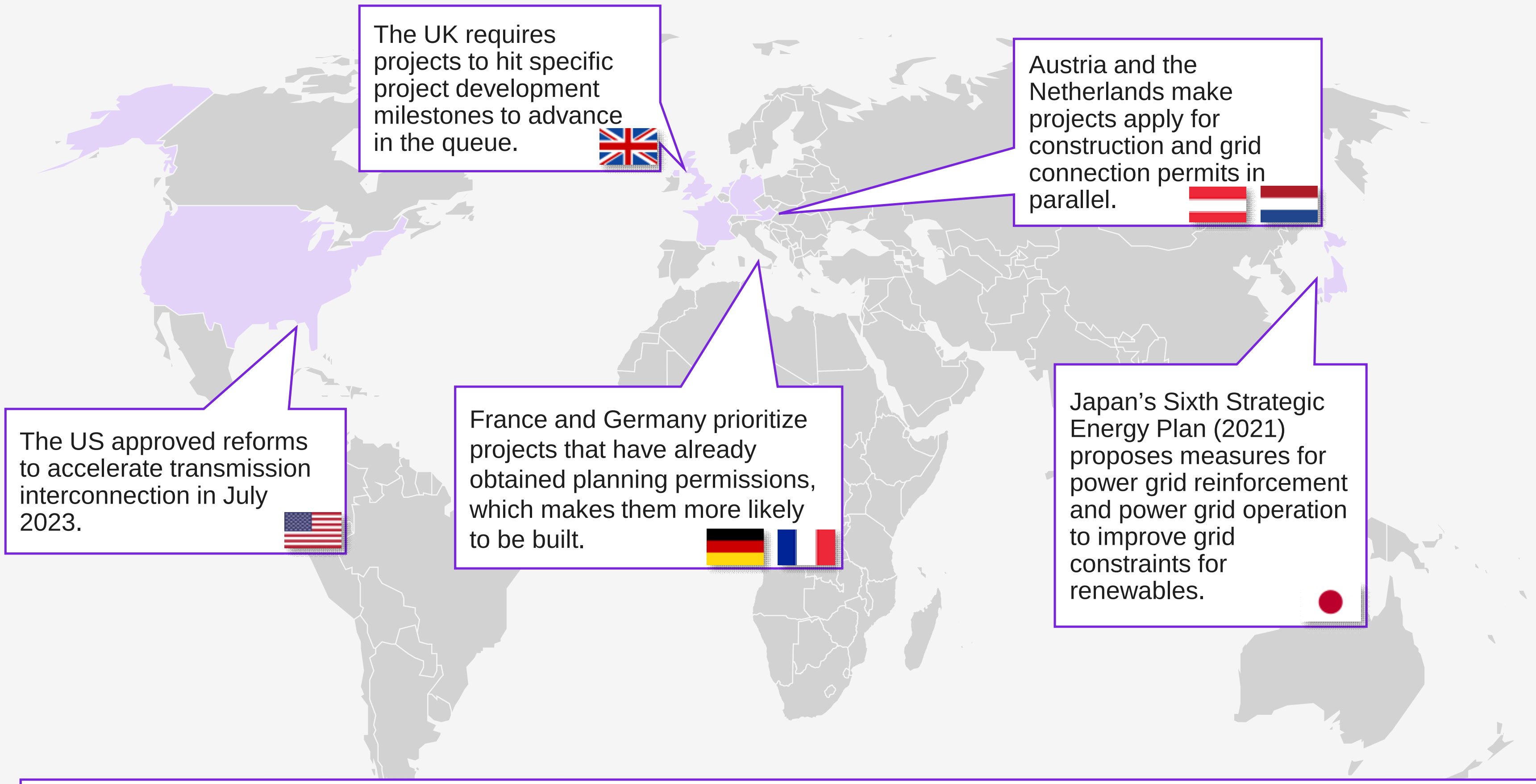
1. Price-based instruments
2. Quantity-based instruments
3. Indirect instruments

Indirect instruments **create favorable conditions** for wind power development. This may include **grid access, accelerated permitting, and supply chain development**.

9.4 Indirect mechanisms

Grid and permitting-focused policies can address grid interconnection queues

Accelerating grid development and interconnection has become a policy focus



- Wind grid interconnection queues total more than **1,000 GW** globally according to 2023 IEA estimates.
- Project interconnection is delayed by complex approval processes, by "phantom" projects that are stuck in early development phases but remain in the queue, and inadequate investment in grid capacity and expansion for new projects.
- Accelerating grid development and interconnection has become a policy focus to continue developing renewables.

Sources: IEA, 2023, Renewable Energy Market Update; GWEC, 2024, Global Offshore Wind Report 2024; IEA, 2023, Electricity Grids and Secure Energy Transitions; Japan Agency for Natural Resources and Energy, 2022, "Here's more about the 6th Strategic Energy Plan;" TenneT, 2024, The offshore bidding zone – a blueprint by TenneT; BNEF, 2023, A Power Grid Long Enough to Reach the Sun Is Key to the Climate Fight; T. Grimwood, Utility Week; 2023, Connections queue blocked by 62GW of 'phantom' projects; Kearney Energy Transition Institute analysis based on desktop research

Project development frameworks define the process of project development, using both direct and indirect policy mechanisms

Project development frameworks define the steps and approval processes to be followed when developing wind power projects. **Onshore wind project development** is typically deployed on private land and is developer-led.

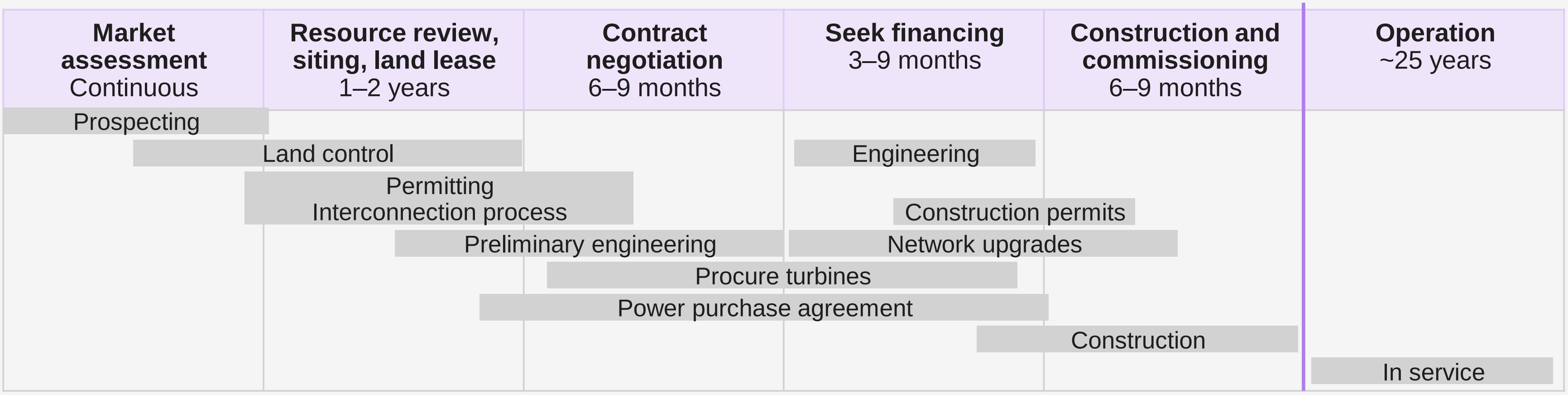
9.5 Development frameworks

Key themes in project development framework policies

- **Project development frameworks differ greatly by country**, depending on the existing government structures.
- **Frameworks are often distributed among a complex approval system**. Federal, state, and local governments may all have separate requirements or permits that must be met.
- **A strong legal system** is key to underpin project development.
- **Frameworks should be transparent, timely, fair, robust, and consistent** to deliver projects on time and prevent delays.

In onshore wind markets, a decentralized, developer-led project framework is common

Wind project development process over approximately 4 years[1]



[1] Timeline assumes optimal project development without delays. Timelines can vary greatly among countries and individual projects, sometimes requiring over 10 years for development.
Sources: ESMAP, 2021, Key Factors for Successful Development of Offshore Wind in Emerging Markets; Lawrence Berkeley National Laboratory, Wind Project Development & EPC — Descriptive Information, accessed on August 2024; Kearney Energy Transition Institute analysis

Offshore projects are developed in zones requiring increased government involvement

Illustrative

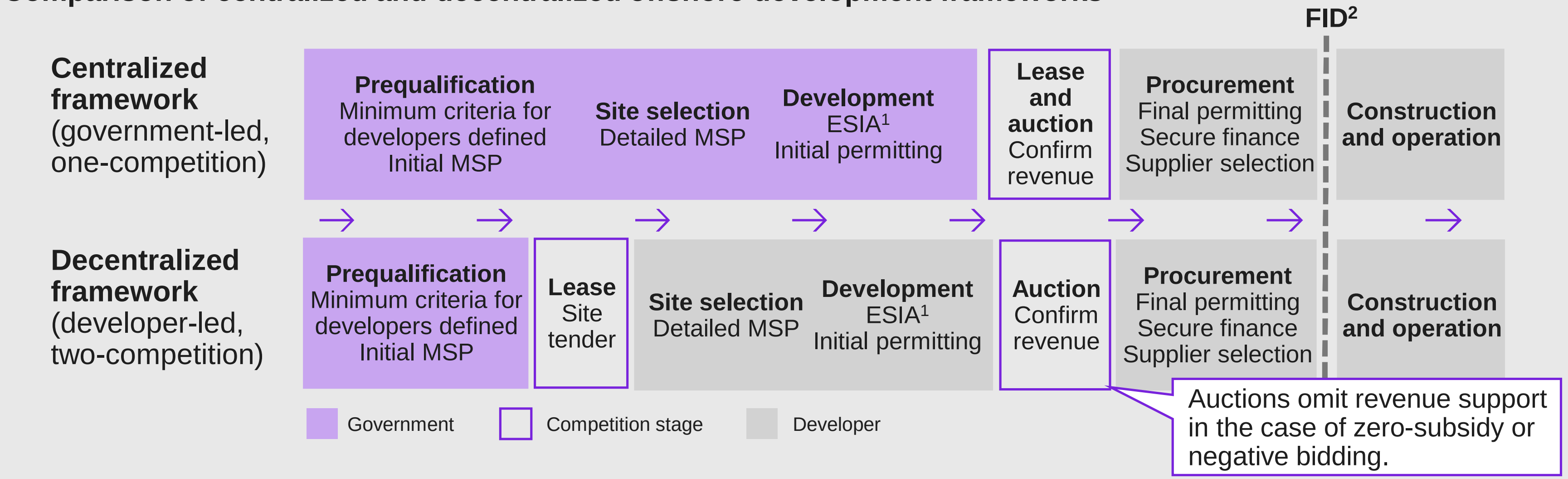
Because marine spatial planning is required before the development of offshore wind power, **centralized development frameworks are more common.** Country frameworks vary significantly and range from centralized to decentralized.

9.5 Development frameworks

Offshore development begins with spatial planning and seabed leasing

Marine spatial planning (MSP) considers the diverse interests of marine stakeholders, such as energy, fishing, shipping, military, conservation, and recreation. It is used to identify suitable areas for offshore wind development.
Seabed leasing grants offshore wind developers the rights to develop a seabed.

Comparison of centralized and decentralized offshore development frameworks



Differences between a centralized and a decentralized development framework

In a **centralized framework**, lease rights and revenue support are allocated in the same stage.

Pros: Less risk to developers. Permitting process for developers is typically simplified due to government interaction with stakeholders.

Cons: Places a larger burden on the government to develop expertise; may take longer in some contexts.

In a **decentralized framework**, lease rights and revenue support are allocated in two separate stages.

Pros: Project developers use their expertise to select project sites. In some contexts, the project may move quicker. Less burden on the government.

Cons: Greater risk to developers. Can lead to permitting delays in face of strong opposition by stakeholders.

[1] Environmental and social impact assessment
[2] Final investment decision
Sources: IRENA and GWEC, 2023, Enabling frameworks for offshore wind scale up; GWEC, 2024, Global Wind Report 2024; Wind Europe, 2023, Industry position: Key elements for offshore wind auction design; EWEA, 2015, Design options for wind energy tenders; Kearney Energy Transition Institute analysis

Development frameworks are highly country-specific

Non-exhaustive

Countries' wind project development frameworks exist on a scale from centralized to decentralized. Wind farm development frameworks differ from frameworks for planning and constructing offshore transmission infrastructure.

9.5 Development frameworks

Example offshore frameworks in established markets

Wind farm and transmission interconnection frameworks

Wind farm	Area selection	Site selection	Site analysis	Permitting	Construction	Operation
United Kingdom	Seabed manager (auction)	Developer			(auction) Developer	
United States	Seabed manager (auction)	Developer			(auction) Developer	
Belgium	Maritime authority		(auction) Developer			
Denmark	Energy agency		TSO (auction)	Developer		
Germany[1]	Maritime authority		(auction) Developer			
Netherlands	Enterprise agency				(auction) Developer	

Transmission infrastructure	Develop export system	Construct system	Operation
United Kingdom[2]	Developer		(auction) Owner
United States	Developer		
Belgium	Developer		TSO
Denmark	Developer/TSO	Developer	
Germany	Developer/TSO	TSO	
Netherlands	TSO		

Legend: Government led; Developer led; Transmission system operator (TSO) led; Export system owner led; Auction

Modalities if different frameworks

- **Hybrid models** combine aspects of a centralized and decentralized model. Governments run initial stages, while developers take over as investment and know-how required increase.
- **Two-track models** use both government and developer-led models. Denmark used this model until its **open-door framework** ended in 2023.[3] Germany currently uses such a model, with two offshore auction mechanisms.
- **Transmission system operators** (TSOs) may be involved in the process.
- As wind markets mature, the need for centralized coordination increases. Governments may take on a greater role to conduct strategic planning and coordination of offshore infrastructure and system integration.

[1] Representative of Germany's non-centrally pre-surveyed offshore wind mechanism; [2] Representative of the UK's decentralized offshore transmission framework prior to Offshore Transmission Network Review. Offshore transmission infrastructure is built by developers and then auctioned off to separate entities called Offshore Transmission Owners.
[3] Denmark's open-door model, launched in 2021, allowed developers to independently pursue and propose offshore wind projects. The framework was suspended in 2023 to comply with EU regulations.

Sources: IRENA, 2023, Enabling frameworks for offshore wind scale up; ESMAP, 2021, Key Factors for Successful Development of Offshore Wind in Emerging Markets; GWEC, 2024, Global Wind Report 2024; UK Department for Energy Security & Net Zero, 2023, Offshore Transmission Network Review: Future Framework; Kearney Energy Transition Institute analysis

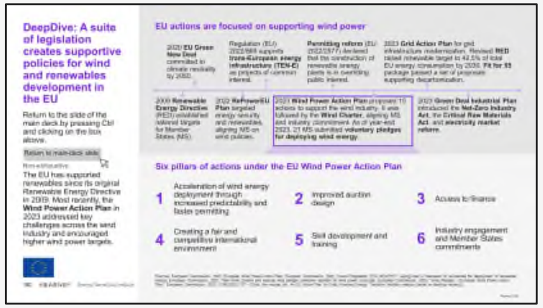
Countries around the world have established dedicated wind policies

Navigate to a country of interest by pressing Ctrl and clicking on the relevant page.

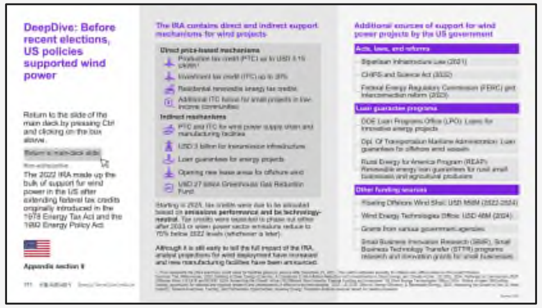
9.6 Country policy highlights

Overview of wind policies by country

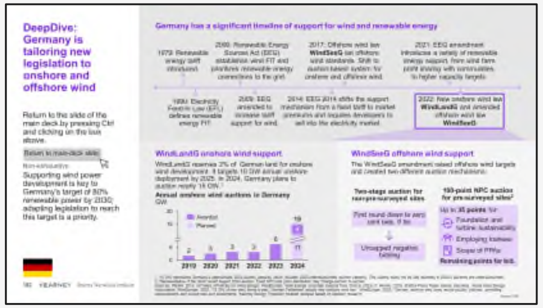
European Union



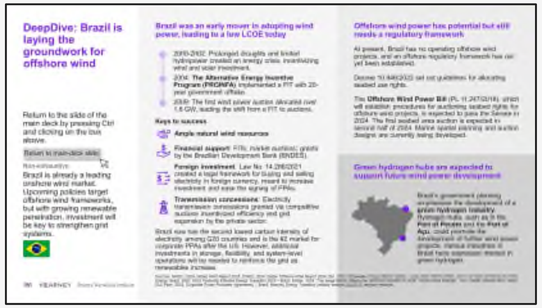
United States



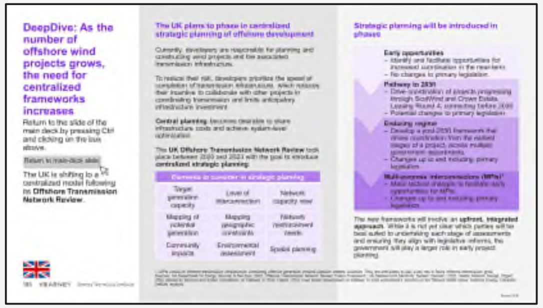
Germany



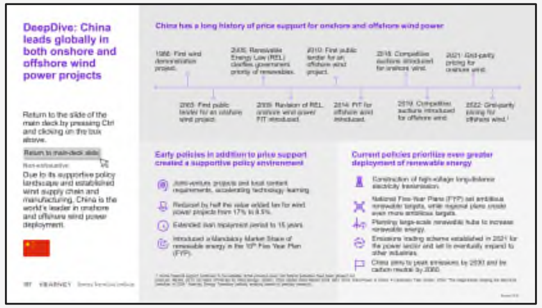
Brazil



United Kingdom



China



Sources: Kearney Energy Transition Institute analysis based on desktop research

10. Glossary, bibliography, and photo credits

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Acronyms (1/2)

AC	Alternating current
APS	Announced pledges scenario
AUV	Autonomous underwater vehicles
C&I	Construction and installation
CfD	Contract for difference
CFPR	Carbon-filament reinforced plastics
CoC	Cost of capital
CSP	Concentrated solar power
CTVs	Crew transfer vessels
DC	Direct current
DD	Direct-drive
DFIG	Doubly fed induction generator
DSO	Distribution system operator
E&D	Engineering and development
EESG	Electrically excited synchronous generator
EEZ	Exclusive economic zone
EHV	Extra high voltage
EoL	End-of-life
EPC	Engineering, procurement, and construction
EuCia	European composites industry association
EUR	Euro
FIDs	Final investment decisions
FiT	Feed-in tariff
FOW	Floating offshore wind
FTE	Full time equivalent
GB	Gearbox
GBP	British pound sterling
gCO2-eq	Grams of carbon dioxide equivalent
GDP	Gross domestic product
GFPR	Glass fiber reinforced plastics
GW	Gigawatt
HLVs	Heavy lift vessels
HV	High voltage
kt	Kilotonne
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt-hour
LCA	Life-cycle assessment
LCOE	Levelized cost of electricity
LiDAR	Light detection and ranging
mgSb-eq	Milligrams of antimony equivalent
MSP	Marine spatial planning

Acronyms (2/2)

Mt	Million tonnes
MV	Medium voltage
MW	Megawatt
MWh	Megawatt-hour
NPC	Non-price criteria
NZE	Net zero emissions
O&M	Operations and maintenance
OEM	Original equipment manufacturer
OW	Offshore wind
PFAS	Per- and polyfluoroalkyl substances
PMSG	Permanent magnets synchronous generator
PPA	Power purchase agreement
PTC	Production tax credit
PTFE	Polytetrafluoroethylene
PWh	Petawatt-hour
RECs	Renewable energy credits
REE	Rare earth elements
RFP	Request for proposal
RoW	Rest of world
SCIG	Squirrel cage induction generator
SOVs	Service operations vessels
SPAR	Single point anchorage buoys
SPV	Special purpose vehicle
STEM	Science, technology, engineering, and math
STEPS	Stated policies scenario
TLP	Tension leg platform
TSO	Transmission system operator
TW	Terawatt
TWh	Terawatt-hour
USD	United States dollar
VALCOE	Value-adjusted levelized cost of electricity
W	Watt
WACC	Weighted average cost of capital
WRIG	Wound rotor induction generator
WTG	Wind turbine generator
WTIV	Wind turbine installation vessels

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