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Wind energy in the European Union

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS & MARKETS

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Contents

Abstract

The aim of this report is to provide an update of the state of the art of wind energy technology. This includes utility-scale onshore and offshore wind and, when available, selected findings on technologies at a lower maturity level. Research and development trends are analysed, focussing particularly on the technology progress made in EU-funded research by the end of 2023 in view of SET-Plan targets. This report also assesses the EU's global competitiveness within the wind value chain and identifies potential bottlenecks and supply risks.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (RTD) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal;
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market;
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020);
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform.

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and emerging technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore);
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport;
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis;
- Clean Energy Outlooks: Analysis and Critical Review;
- System Modelling for Clean Energy Technology Scenarios;
- Overall Strategic Analysis of Clean Energy Technology Sector.

More details are available on the CETO web pages.

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Executive Summary

EU wind energy sector: growth and challenges

The revised Renewable Energy Directive (RED III) took effect in 2023, setting a binding target for the EU's renewable energy share to at least 42.5% of final energy consumption by 2030, with an ambition to reach 45% (EC, 2023). In 2022, renewables accounted for 23% of the EU's final energy consumption, with wind energy contributing 9.1%.

The EU installed 16 GW of wind capacity in 2023, comprising 13 GW onshore and 3 GW offshore, bringing the total wind capacity to 220 GW (201 GW onshore and 19 GW offshore). Although these record deployments - representing the best year for offshore installations and the second best year for onshore installation - are encouraging, they fall short of the trajectory needed to reach the ambitious 2030 targets.

Competitive costs

The cost of onshore wind has decreased by a remarkable 69% between 2010 and 2022, resulting in a global weighted average levelised cost of energy (LCoE) of EUR 31 per MWh. This makes onshore wind highly competitive with fossil fuels. Offshore wind, while more expensive (with a global weighted average LCoE of EUR 77 per MWh), offers advantages in terms of energy system integration thanks to the more consistent wind resources at sea, which result in higher capacity factors.

Economic impact and employment

In 2022, the EU wind sector's turnover grew to EUR 43 billion, and the gross value added (GVA) to EUR 19 billion, both representing a 26% increase on 2022. The sector employed between 274 000 and 326 000 full-time equivalents (FTEs), accounting for approximately 30% of the global wind energy workforce.

Global market share and competition

Among the top 10 original equipment manufacturers (OEMs) in 2023, Chinese companies accounted for 55% of the global wind turbine market, followed by European companies at 23% and North American companies at 6%. This trend is primarily due to the rapid growth of the domestic Chinese market. At the same time, European OEMs remain the largest suppliers to the European market, holding an 88% share of the onshore market and 100% of the offshore market.

Meeting future demand: manufacturing capacity and supply chain risks

The Net-Zero Industry Act, adopted in June 2024, aims to ensure that the EU's manufacturing capacity meets at least 40% of the annual deployment requirements needed to meet the EU's 2030 climate and energy objectives and 15% of world production by 2040. In terms of nacelles and blades, the EU wind sector is already achieving these targets in 2023. However, this does not apply to all wind components and the global market may change. To remain on track to meet the 2030 climate objectives using domestically produced components, the EU must closely monitor its manufacturing capabilities.

The EU's reliance on a single non-EU country for critical raw materials (especially the rare earth elements used in turbine generators) poses a significant risk to the wind sector's growth due to potential supply chain disruptions.

R&D leadership

The EU is a leader in public research and development (R&D) investment in wind energy, with Member States accounting for 35% of all public investment in the sector from 2013 to 2022. EU framework programmes Horizon 2020 and Horizon Europe contribute an additional 9%. The EU also leads in private R&D investment, closely followed by China, with a cumulative investment of approximately 40% of total private R&D funding from 2010 to 2020.

Table 1. CETO SWOT analysis for the competitiveness of the EU wind energy sector.

Strengths	**Weaknesses**
• Global leader in wind technological development, with European OEMs at the forefront of R&I. • EU pioneer in floating offshore wind development, with first pre-commercial wind farms installed in EU waters. • Strong manufacturing supply chain, covering 88% of the EU's onshore market for wind turbines (final assembly step). • European companies have a substantial market presence within the EU, as well as a notable share in the global market, contributing to a positive trade balance.	• Administrative barriers, particularly the slow permitting process for new installations. • Rare earth elements used in the permanent magnets are identified as critical raw materials with a high supply risk. • Emphasis required on circularity by design, environmental impact, and human capital agenda. • Need for increased focus on maritime spatial planning (MSP) and coexistence among sectors.
Opportunities	**Threats**
• Annual deployment rates need to increase to reach ambitious 2030 targets. • Floating offshore wind enables Member States (MSs) with steeper shorelines to harvest offshore wind and exploit existing potentials. • Implementing recycling and circularity practices can promote innovation, alleviate supply chain pressures, and enhance public acceptance of wind technology, benefiting the entire value chain. • Offshore wind R&I priorities should focus on system integration, efficient transmission & interconnection, and O&M.	• The EU could face supply chain bottlenecks if production needs to scale up rapidly to meet ambitious climate targets. • Potential bottlenecks and supply risks for critical raw materials (e.g. rare earth elements) and processed materials (e.g. NdFeB magnets, balsa wood). • Risk of increased LCoE (reflecting commodity price inflation, increased transportation costs, and/or supply chain risk). • Trade barriers have the potential to distort trade and cause unintended effects on investment across value chains, hindering the competitiveness of EU companies.

Source: JRC analysis, 2024.

1. Introduction

1.1 Scope and context

The purpose of this report is to offer an up-to-date overview of the current state of wind energy technology, covering onshore wind, offshore wind (including both bottom-fixed and floating offshore), and, when available, findings on wind technologies with lower technology readiness levels, e.g. Airborne Wind Energy Systems (AWES) and Vertical Axis Wind Turbines (VAWT). The report examines the progress in RD&I within EU-funded research, specifically focusing on technology advancements until the end of 2023, in alignment with the SET-Plan targets. Additionally, the report analyses the EU's global competitiveness within the wind energy value chain and identifies potential bottlenecks and supply risks as the industry works towards achieving the goals set by the European Green Deal.

Chapter 2 examines the current status and future development of key technology indicators in the wind energy sector. This chapter is organized as follows: chapter 2.1 introduces the current technology readiness level (TRL) of the main technologies used in the wind energy industry; chapter 2.2 highlights key indicators on deployment and electricity generation, and develops modelling projections at EU and global levels; chapter 2.3 explores present and future cost developments in wind energy, including estimates on Levelised Cost of Energy (LCoE); chapters 2.4 to 2.7 outline competitiveness indicators such as public and private R&D funding, patenting trends, and scientific publications; and chapter 2.8 analyses the impact and trends of EU-supported research and innovation.

Chapter 3 focuses on the wind energy value chain, covering macroeconomic indicators like turnover, Gross Value Added (GVA), employment, and production. This chapter also assesses the role of EU companies in the wind sector, and maps environmental and socioeconomic sustainability indicators.

Chapter 4 provides an overview of the EU's global position and competitiveness in the wind energy industry. It assesses market shares of EU and global market leaders in wind, and examines the trade balance between the EU and its main competitors. Additionally, the chapter investigates supply risks and critical dependencies along the supply chain, looking at the various raw and processed materials used in wind power plants.

1.2 Methodology and data sources

The report has been written following the CETO methodology that addresses three principal aspects:

a) Technology maturity status, development and trends

b) Value chain analysis

c) Global markets and EU positioning.

Annex 1 provides a summary of the indicators for each aspect, together with the main data sources.

2. Technology status and development trends

2.1 Technology readiness level (TRL)

Onshore and bottom-fixed offshore wind turbines are currently at a commercial readiness stage. These wind turbines feature horizontal axis, three-bladed designs with standardized steel or concrete towers and upwind rotors (including three blades, yaw systems, pitch regulation, and drive train systems). Offshore wind turbines rely on various bottom-fixed foundation types, including monopiles, jackets, tripods, tripiles, gravity bases, and suction buckets.

Floating offshore wind technology is rapidly advancing, with the potential to strengthen Europe's position in renewable energy deployment. This technology enables wind farms to be installed in deeper waters, extending the reach of offshore wind projects beyond the limitations of bottom-fixed turbines. Floating offshore wind projects can thus benefit EU countries with deep waters (50-1 000 meters in depth), potentially opening up new markets such as the Atlantic Ocean, the Mediterranean Sea, and the Black Sea.

The main distinctive criterion in the various floating designs is the substructure used to provide the buoyancy, and thus stability to the plant (typologies include Spar-buoy, Semi-Submersible, Tension-leg platform (TLP), Barge and Multi-Platforms substructures). As the technology is still on its way to full commercialisation, no design has yet prevailed over the others; however, the spar-buoy design and the semi-submersible design have already been deployed in pre-commercial projects in the North Sea and the Atlantic Ocean.

Other wind energy technologies generating electricity are at a lower technology readiness level, such as airborne wind energy systems and vertical axis wind turbines.

Airborne wind energy systems (AWES) convert wind energy into electricity using autonomous kites or unmanned aircrafts, linked to the ground by one or more tethers. As compared to conventional wind energy concepts, AWES offer the possibility to harness stronger and steadier winds by flying at higher altitudes. At this stage both fundamental academic research and long-term investments are needed towards commercialisation (Watson, 2019).

Vertical axis wind turbines (VAWTs) use a vertical shaft around which the rotor turns. Due to their low speed and high torque they are less efficient than conventional horizontal axis wind turbines (HAWT), but the technology could gain momentum via hybridisation with floating devices (wave-wind energy) or in small scale wind applications. Currently the integration of a VAWT within a floating platform is still at a low TRL.

Table 2 presents the current TRL of wind energy technologies. Floating wind covers a large range of TRLs, with spar-buoy and semi-submersible designs already achieving TRL 8-9, while the concrete barge design currently stands at TRL 7-8, and tension-leg platform, at TRL 6. Airborne wind energy is at TRL 3-5.

Table 2. Current TRL of wind energy technologies.

	TRL (Technology Readiness Level)								
Sub-Technology	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Onshore wind								■	■
Bottom-fixed offshore wind								■	■
Floating offshore wind						■	■	■	■
Airborne wind energy			■	■	■				

Source: JRC analysis, 2024.

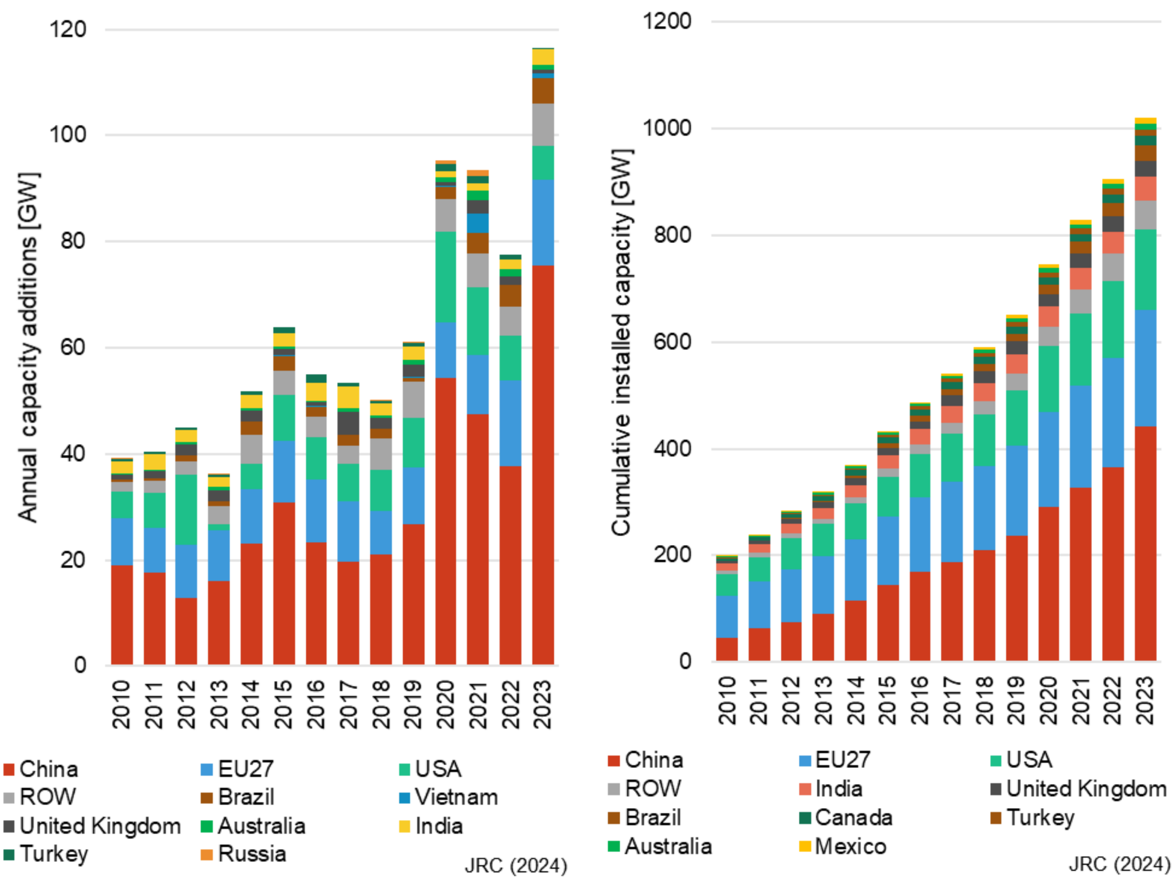
2.2 Installed energy capacity and generation

2.2.1 Global deployment

Total wind (onshore and offshore)

In 2023, the wind global cumulative capacity hit the 1 TW threshold, with over 1 020 GW of installed capacity (**Figure 1**). That year, the deployment of wind power saw significant growth, with onshore capacity reaching an all-time high of over 100 GW and offshore wind breaking the 10 GW mark for the second time (the first being in 2021). Globally, 117 GW of new capacity was installed, with 106 GW onshore and 11 GW offshore.

Figure 1. Global annual capacity additions (left) and cumulative installed capacity (right) of wind energy.



Note: The scale on the right is 10 times larger than the scale on the left.

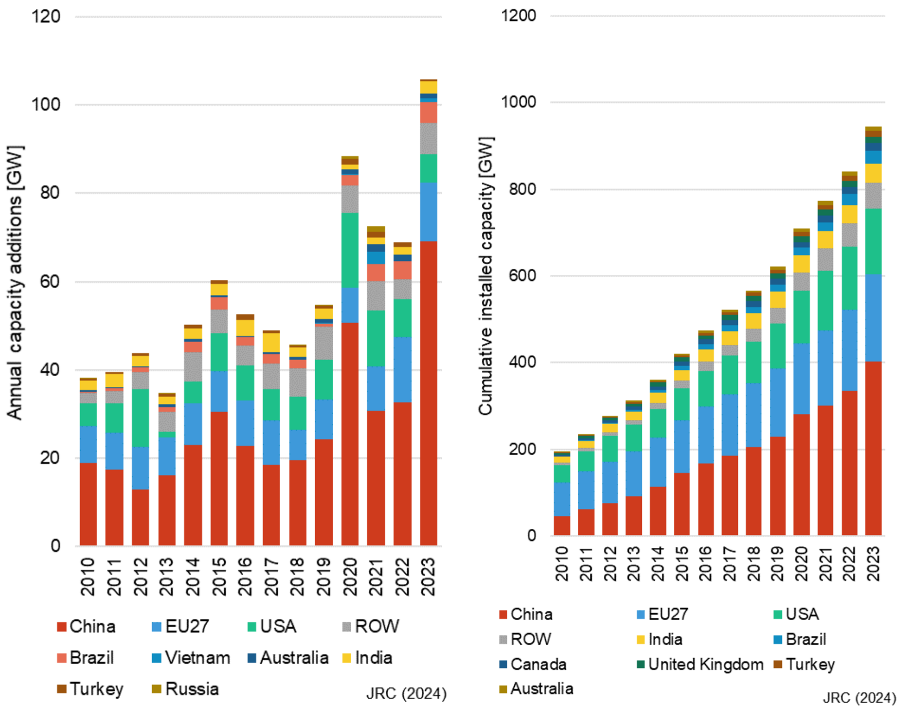
Source: JRC based on GWEC, 2024.

Onshore

Looking specifically at onshore capacity additions, China took the lead with 69.2 GW, followed by the EU with 13.3 GW, and the United States with 6.4 GW (**Figure 2**).

China has held the leading position in global onshore cumulative capacity since 2015, boasting 403 GW of installed capacity in 2023, which represents 43% of all onshore installations. In the same year, the EU's onshore wind market accounted for 21% of the global market with 201 GW of cumulative installed capacity, and the US followed with 16% of the global market, having installed 150 GW (**Figure 2**).

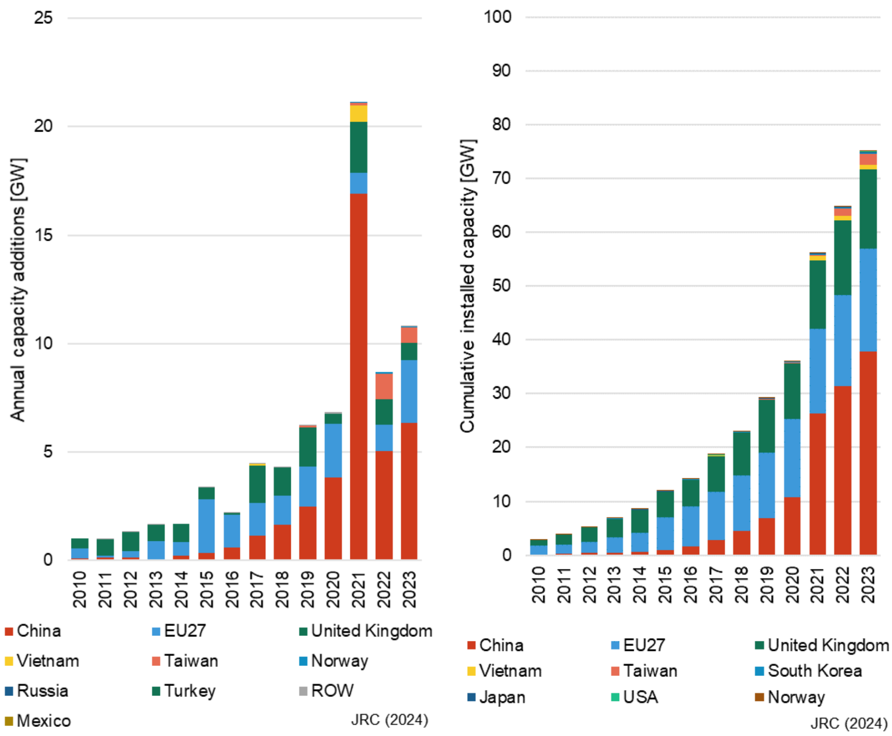
Figure 2. Global annual capacity additions (left) and cumulative installed capacity (right) of onshore wind.



Note: The scale on the right is 10 times larger than the scale on the left.

Source: JRC based on GWEC, 2024.

Figure 3. Global annual capacity additions (left) and cumulative installed capacity (right) of offshore wind.



Note: The scale on the right is 4 times larger than the scale on the left.

Source: JRC based on GWEC, 2024.

Offshore

In the offshore wind sector, China also came first in terms of new capacity additions (6.3 GW), followed by the EU (2.9 GW), while the United Kingdom ranked third (0.8 GW) (**Figure 3**).

Due to China's robust offshore wind deployment in 2021, the country now leads in cumulative offshore wind capacity. In 2023, Chinese offshore cumulative capacity reached 37.8 GW, representing 50% of all offshore installations, followed by the EU with 19.2 GW (25%) and the UK with 14.8 GW (20%) (**Figure 3**).

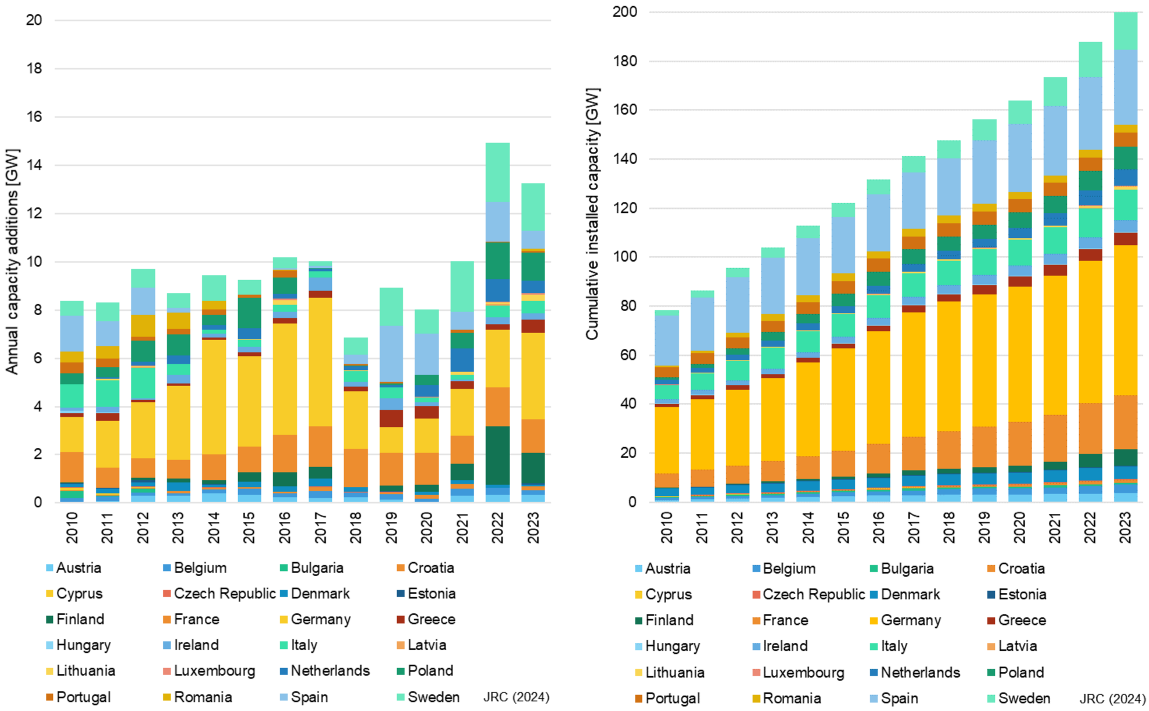
2.2.2 EU 27 deployment

Onshore

In 2023, Member States added 13.3 GW of onshore wind capacity, making it the second strongest year in onshore capacity additions since 2010. In total, 19 countries added new capacity, with Germany in the lead (3.6 GW), followed by Sweden (2.0 GW), France (1.4 GW), and Finland (1.3 GW) (**Figure 4**).

The EU's total installed onshore wind capacity is now 200.9 GW, an increase of 7% on 2022. Among the top countries, Germany leads on total onshore wind deployment with 61.1 GW, followed by Spain (30.6 GW), France (22.0 GW), Sweden (16.2 GW) and Italy (12.3 GW) (**Figure 4**).

Figure 4. EU annual capacity additions (left) and cumulative installed capacity (right) of onshore wind.



Note: The scale on the right is 10 times larger than the scale on the left.

Source: JRC based on GWEC, 2024.

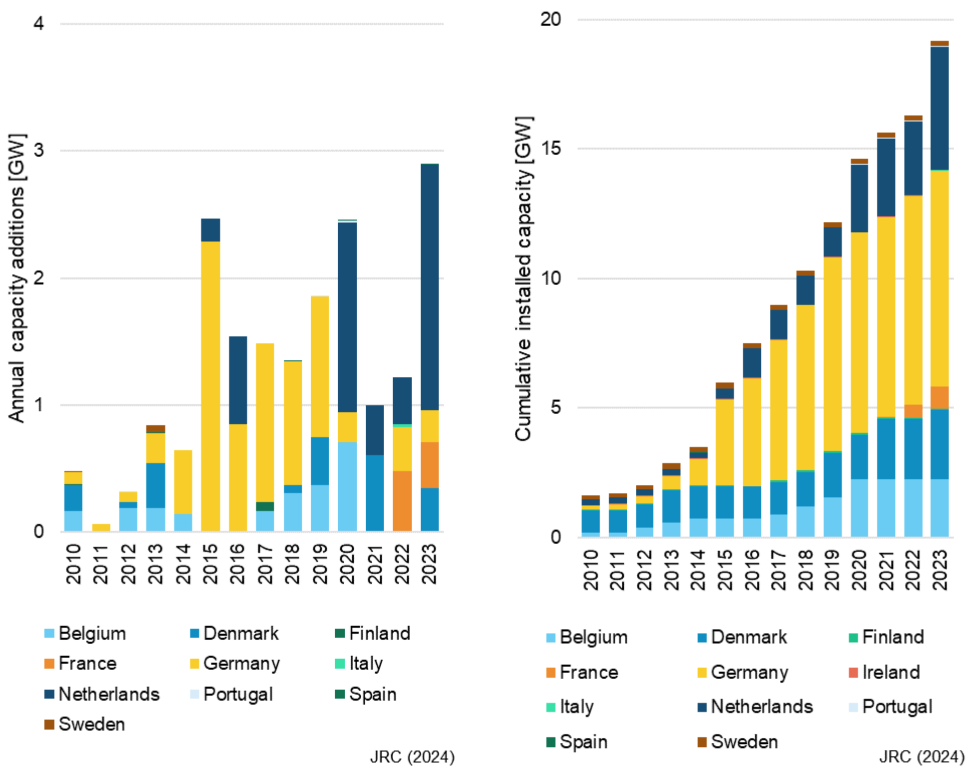
Offshore

The year 2023 also marked a record for offshore wind capacity additions, with 2.9 GW deployed in the EU27. Five Member States contributed to this growth: the Netherlands led in capacity additions with 1.9 GW, followed by France with 0.4 GW, and by Denmark and Germany with 0.3 GW each (**Figure 5**). Additionally, Spain contributed 2 MW to the floating offshore capacity of the EU, highlighting the emergence of this innovative sub-sector within the offshore wind industry.

Cumulative offshore wind capacity reached 19.2 GW in the EU at the end of 2023, with Germany (8.3 GW), the Netherlands (4.7 GW), Denmark (2.7 GW) and Belgium (2.3 GW) in the lead (**Figure 5**). In 2023, European sea basins (including projects installed in the UK and Norway) hosted a total capacity of 34.0 GW.

Building on the growth of the overall offshore wind sector, the floating wind sub-sector is also gaining traction in the EU. By the end of 2023, the EU had 29 MW of installed floating offshore capacity, with WindFloat Atlantic in Portugal being the largest project (25 MW), followed by Floatgen in France (2 MW) and the newly commissioned DemoSATH project in Spain (2 MW). National ambitions for the sector's growth are apparent, with planned auctions in France, Spain, Italy, Portugal, and Greece. It is expected that the installed capacity will reach 3 GW by 2030 and 11 GW by 2035 (EC, 2024 a). However, these projections have been revised downwards in recent years due to policy delays and slow permitting processes in various countries, and the sector relies on government support to enable investments and reduce risk.

Figure 5. EU annual capacity additions (left) and cumulative installed capacity (right) of offshore wind.



Notes: The scale on the right is 5 times larger than the scale on the left.

Floating offshore capacity is included in offshore wind.

Source: JRC based on GWEC, 2024.

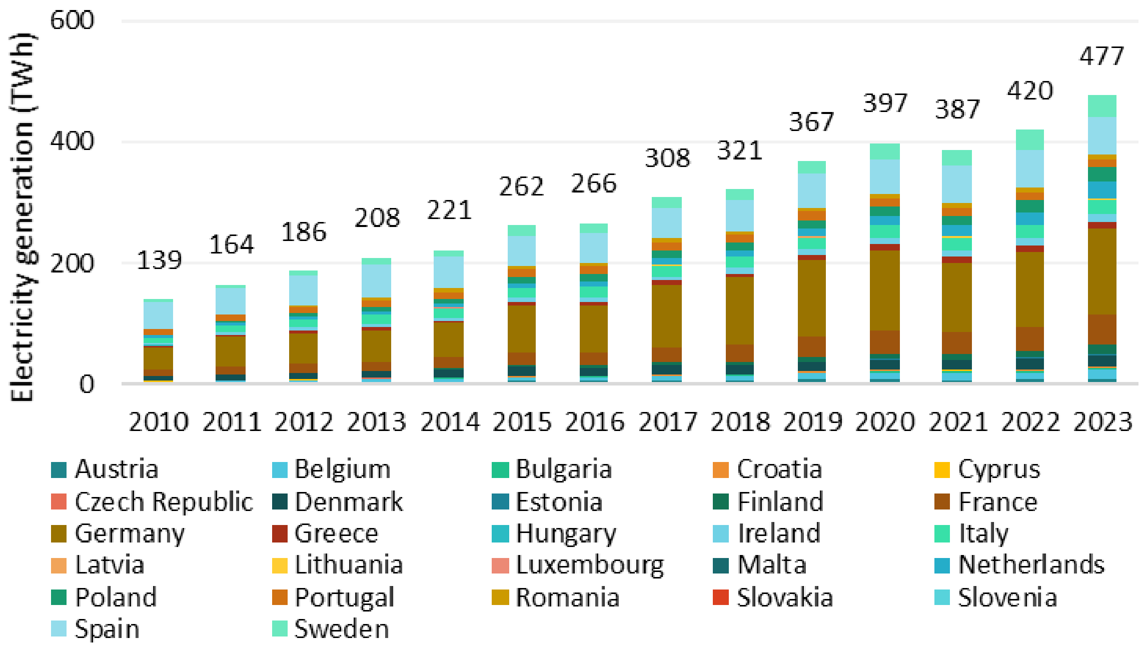
2.2.3 European and global electricity generation

In 2023, wind energy contributed 477 TWh to electricity generation in the EU (see **Figure 6**). This represents a 13.5% increase in electricity generation compared to 2022, which is more significant than the wind capacity additions during the same period (+7.7%).

In 2023, EU wind electricity accounted for 17.5% of the total electricity generation (EC, 2024 b; EMBER, 2024 a), making Europe the continent with the highest share of wind electricity. Among European Member States (MSs), Denmark has the highest wind percentage in its electricity mix at 58%, followed by Ireland (36%), Portugal (29%) and Germany (28%). In comparison, the UK has 28% wind electricity, while the US has 10% and China, 9%. Globally, wind electricity's share was 7.8% in 2023 (EMBER, 2024 b).

In terms of wind power's contribution to primary energy consumption, the numbers are lower: in 2022, wind accounted for 3.3% of global primary energy consumption (OWID, 2023). Denmark and Ireland lead the way, with wind covering 26.2% and 15.6% of their respective primary energy consumption. The EU's share of wind in primary energy consumption stood at 6.8% in 2022. This compares to 10.3% of primary energy consumption in the United Kingdom, 5.7% in Brazil, 4.5% in China, and 4.3% in the United States. We note that 6.8% of the primary energy consumption of the EU is equivalent, in 2022, to 9.1% of the EU's final energy consumption (EEA, 2024).

Figure 6. Wind energy electricity generation of EU MSs, from 2010 to 2023.



Source: JRC based on EurObserv'ER, 2024.

2.2.4 EU 27 and global modelling projections

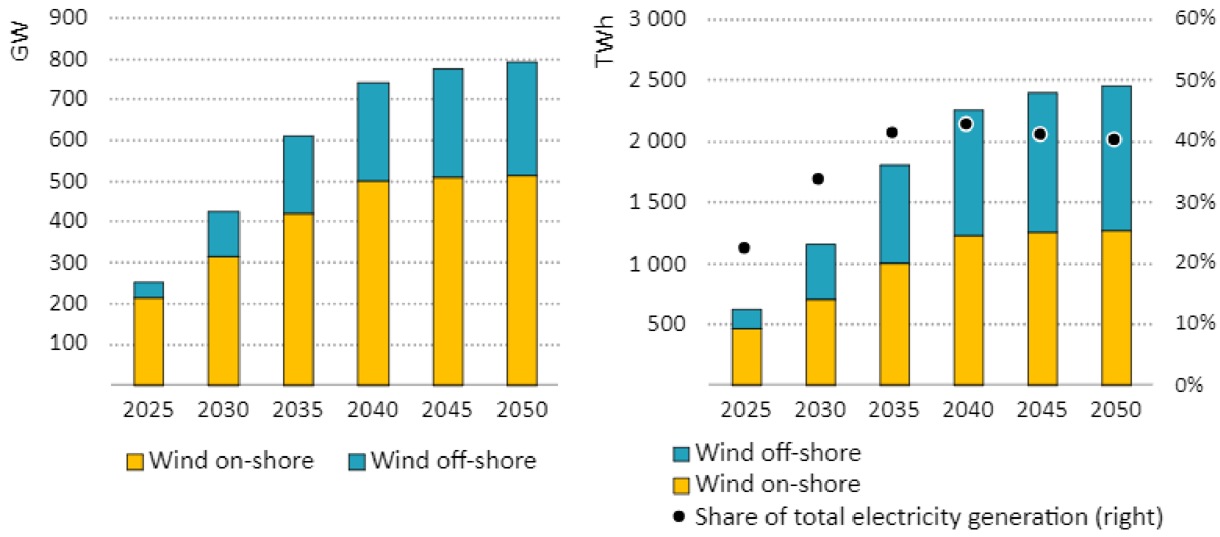
In May 2022, the European Commission introduced the REPowerEU Plan following the global energy market disruptions caused by Russia's full-scale invasion of Ukraine. The revised Renewable Energy Directive (RED III) came into effect in November 2023, aiming to increase the share of renewables in the EU's final energy consumption. Specifically, the Directive raises the binding target for renewable energies to 42.5% by 2030, with an ambition to reach 45% (EC, 2023). With respect to wind energy, this would correspond to over 500 GW.

In the context of the CETO 2024 exercise, the POTEnCIA and POLES-JRC models have been employed to project scenario-specific deployment of onshore and offshore wind until 2050, at the EU and global levels. A short summary about both models and their respective scenario reports can be found in **Annex 3**.

Results of the *POTEnCIA CETO 2024 scenario* show onshore wind installed capacity growing to 317 GW and 514 GW in 2030 and 2050, respectively. A stronger relative increase is projected for offshore wind deployment, with 109 GW in 2030 and 281 GW in 2050 (see **Figure 7**). Under this scenario, wind's share in the EU's electricity mix would rise from 14% (398 TWh) in 2020 to 34% (1 160 TWh) in 2030 and 40% (2 466 TWh) in 2050.

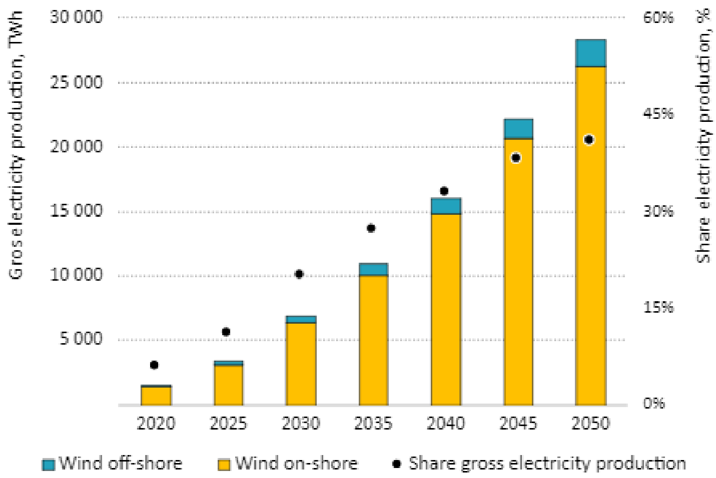
Globally, the POLES-JRC model under the *Global CETO 2°C scenario 2024* projects a significant increase in wind installations, covering 41% of the world's electricity needs by 2050 (**Figure 8**). This is a major increase compared to the previous year's prediction of 27%, aligning with the strengthened ambitions declared at COP 28.

Figure 7: Onshore and offshore installed capacity (left) and gross electricity generation (right) in the EU under the *POTEnCIA CETO 2024 scenario*.



Source: JRC, 2024.

Figure 8. Global gross energy production with wind power according to the *Global CETO 2°C scenario 2024*.



Source: JRC, 2024.

2.3 Technology costs

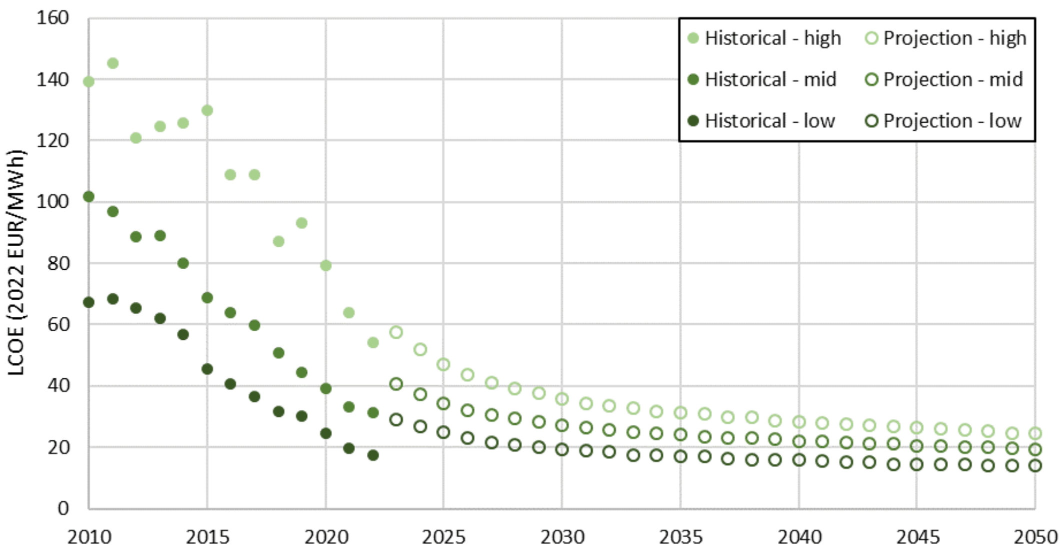
Onshore

The cost of onshore wind decreased by 69% between 2010 and 2022, with a global weighted average LCoE declining from EUR 101 per MWh to EUR 31 per MWh (IRENA, 2023; see **Figure 9**). This cost reduction positions onshore wind as a highly competitive renewable energy source (alongside solar PV) to compete against fossil fuels.

The decline in LCoE is linked to economies of scale (which help decrease the cost of wind turbines down) and to technology improvements (notably the increase in turbine size). Overall, these technology improvements have resulted in a more than one-third improvement in the global weighted average capacity factor of onshore wind, from 27% in 2010 to 37% in 2022 (IRENA, 2023).

According to BNEF, the LCoE of onshore wind is projected to further decrease in the future, reaching EUR 27 per MWh in 2030, EUR 22 per MWh in 2040, and EUR 20 per MWh in 2050 in the median scenario – and even down to EUR 17 per MWh in the low-cost scenario. Interestingly, we observe a discrepancy between the lowest historical LCoE value in 2022 (EUR 17 per MWh, IRENA) and the lowest predicted LCoE in 2023 (EUR 29 per MWh, BNEF), suggesting that the most competitive onshore wind projects have already unlocked the cost reduction expected by BNEF for 2035. The projected cost scenarios for 2023-2050 match, instead, with the median and high-cost historical data.

Figure 9. Range of historical and projected onshore wind LCoE estimates.



Source: JRC, BNEF, IRENA, 2024.

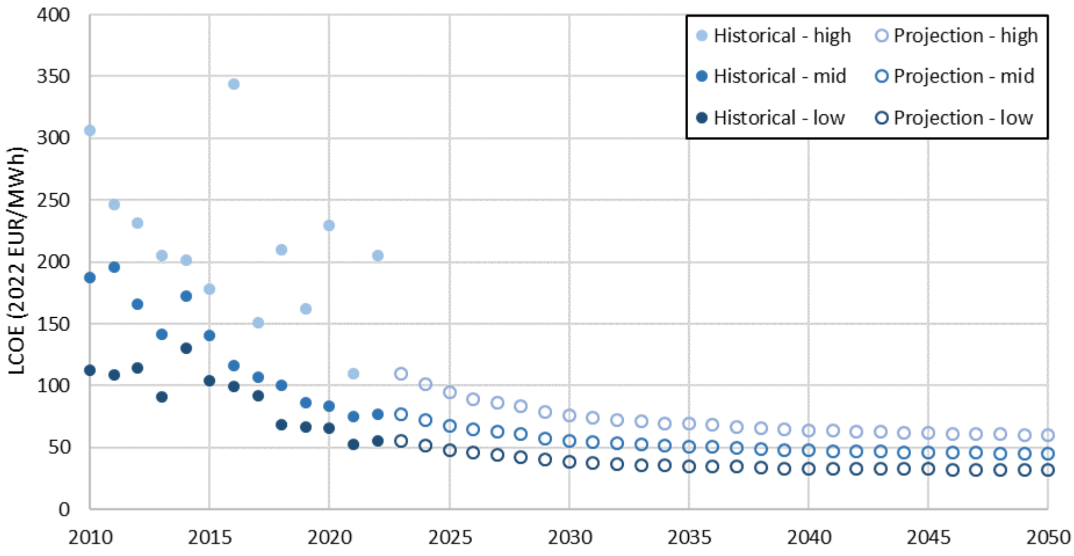
Offshore

Offshore wind saw a 59% decrease in LCoE between 2010 and 2022, from EUR 187 per MWh to EUR 77 per MWh (see **Figure 10**). This improvement is attributed to advancements in wind turbine technology, increased experience, the formation of local and regional supply chains, and strong policy support. As a result, a steady stream of competitive projects has emerged.

Although installation costs for offshore wind are higher than onshore wind, offshore wind offers the dual benefits of economies of scale (with larger wind turbines) and higher capacity factors (due to stronger and more consistent wind resources at sea). Furthermore, European wind generation tends to be higher during winter, which aligns with a higher peak demand. These factors contribute to the large potential for offshore wind in the EU, which have started to materialise (IRENA, 2023).

However, the offshore wind industry is currently facing macroeconomic pressures that have stifled growth and profitability, causing offshore LCoE values to increase in 2022, particularly in Europe. This uncertainty casts doubt on the predicted cost reduction trend depicted in **Figure 10**, which suggests the LCoE could decline from EUR 56 per MWh in 2030 to EUR 45 per MWh in 2050.

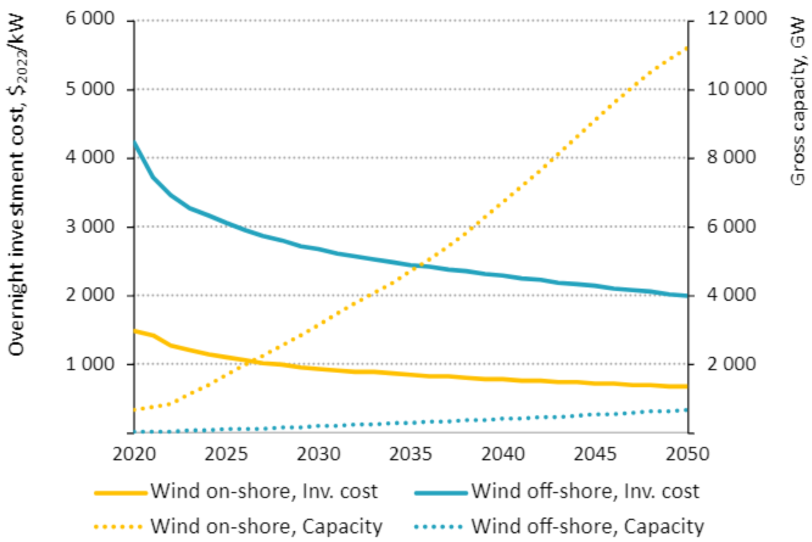
Figure 10. Range of historical and projected offshore wind LCoE estimates.



Source: JRC, BNEF, IRENA, 2024.

As global installations expand both onshore and offshore, costs are projected to decrease. This is reflected in the *Global CETO 2°C scenario 2024*, which shows that onshore wind's overnight investment costs may drop from USD_{2022} 1 274 per kW in 2022, to USD_{2022} 970 per kW in 2030, and USD_{2022} 688 per kW in 2050. For offshore wind, costs could decrease from USD_{2022} 3 461 per kW in 2022, to USD_{2022} 2 730 per kW in 2030, and USD_{2022} 2 031 per kW in 2050 (**Figure 11**). Based on the *Global CETO 2°C scenario 2024*, global installed capacity will grow from the current 1 020 GW in 2023 to 3 032 GW by 2030 (i.e. a tripling of wind energy capacity), to 6 681 GW by 2040, and further to 11 520 GW by 2050. In this scenario, onshore wind represents 94% of the installed capacity in 2050.

Figure 11. Overnight investment costs (in USD) for onshore and offshore installations according to the *Global CETO 2°C scenario 2024*.



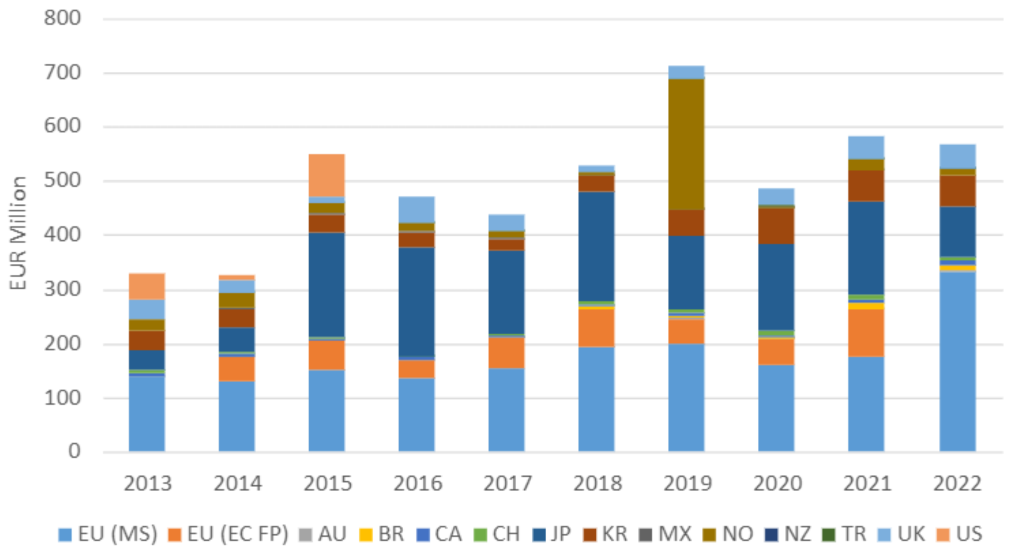
Source: JRC, 2024.

2.4 Public RD&I funding

Public R&D investment is analysed based on the IEA energy technology RD&D budget, which includes data from national investment in the EU MSs and the main OECD countries outside of the EU. Specifically, the analysis takes into account the following R&D IEA classification codes: 321 Onshore wind technologies, 322 Offshore wind techs (excl. low wind speed), 323 Wind energy systems and other technologies and 329 Unallocated wind energy. In addition, EU funding from the Horizon 2020 (H2020) and Horizon Europe Framework Programmes (FP) are included since 2014 (see EC FP).

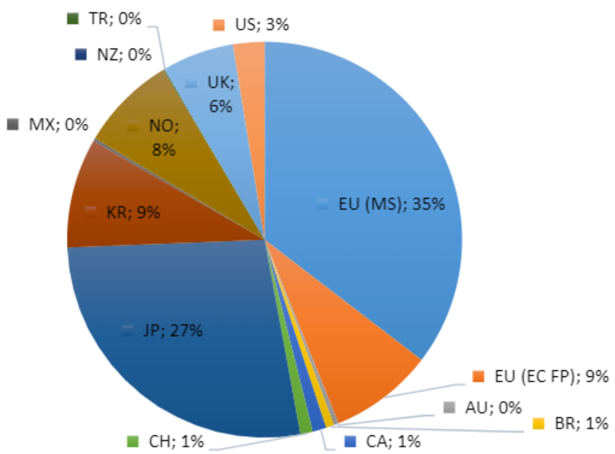
Chapter 2.8.1 also provides a detailed assessment of the evolution of EU R&I funding categorised by R&I priorities for wind energy under the H2020 (2014-2021) and Horizon Europe (2022-present) programmes.

Figure 12. Evolution of public R&I investment in wind energy in the EU and major OECD countries in 2013-2022.



Source: JRC based on IEA, 2024.

Figure 13. Public R&I investment (shares) in wind energy in the EU and major OECD countries in 2013-2022.

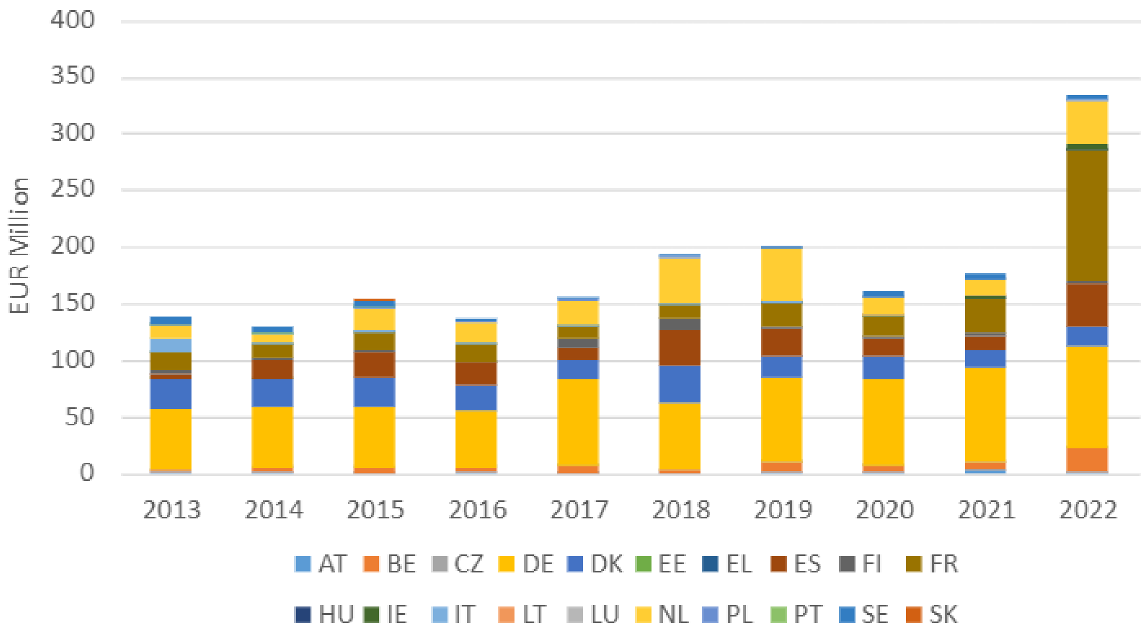


Source: JRC based on IEA, 2024.

The global funding in public R&D reached EUR 568 million in 2022, a small decrease compared to 2021 (EUR 583 million). Since 2013, among OECD members, the EU leads in investment, accounting for 35% of all public investment in wind energy (see **Figure 12** and **Figure 13**).

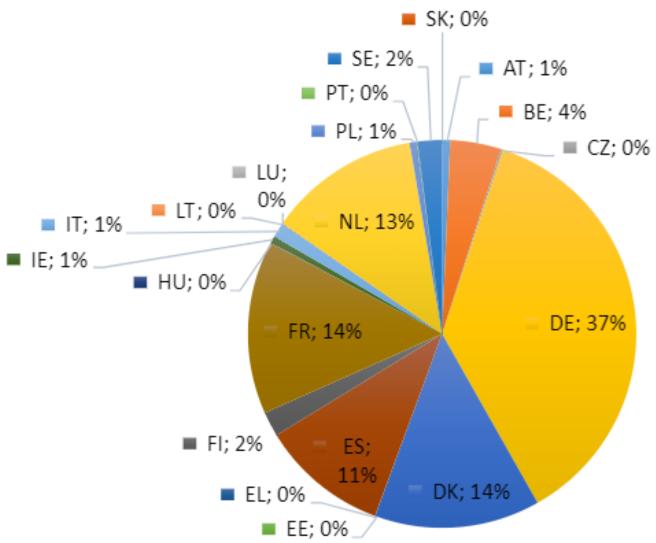
Since 2010, EU MSs spent about EUR 1.82 billion on public R&I in wind energy. Public R&D investment in EU MSs remained roughly constant between 2013 and 2017, at around EUR 120-150 million. The trend subsequently increased, reaching EUR 201 million by 2019, and surged in 2022 to EUR 333 million, when the contributions from France, Spain and Belgium all increased by a factor 3-4 (**Figure 14**). At about 37%, Germany leads in EU public R&D investment in the period 2013-2022, followed by Denmark and France (each at 14%), and the Netherlands (at 13%) (**Figure 15**).

Figure 14. Evolution of public R&I investment in wind energy in the EU in the period 2013-2022.



Source: JRC based on IEA, 2024.

Figure 15. Public R&I investments (shares) in wind energy in EU the period 2013-2022.

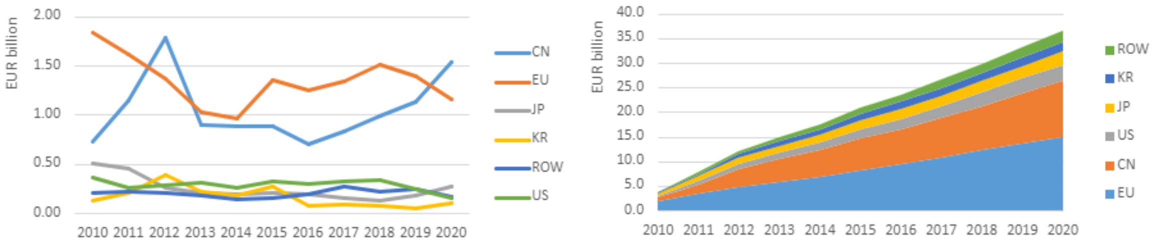


Source: JRC based on IEA, 2024.

2.5 Private RD&I funding

Globally, the EU is at the forefront in private R&D investment in wind energy, closely followed by China. In cumulative terms, for the period 2010-2020 the EU is estimated to lead private R&D investment with about 41% of the total private R&D funding, followed by China (32%) and the US (9%) (**Figure 16**).

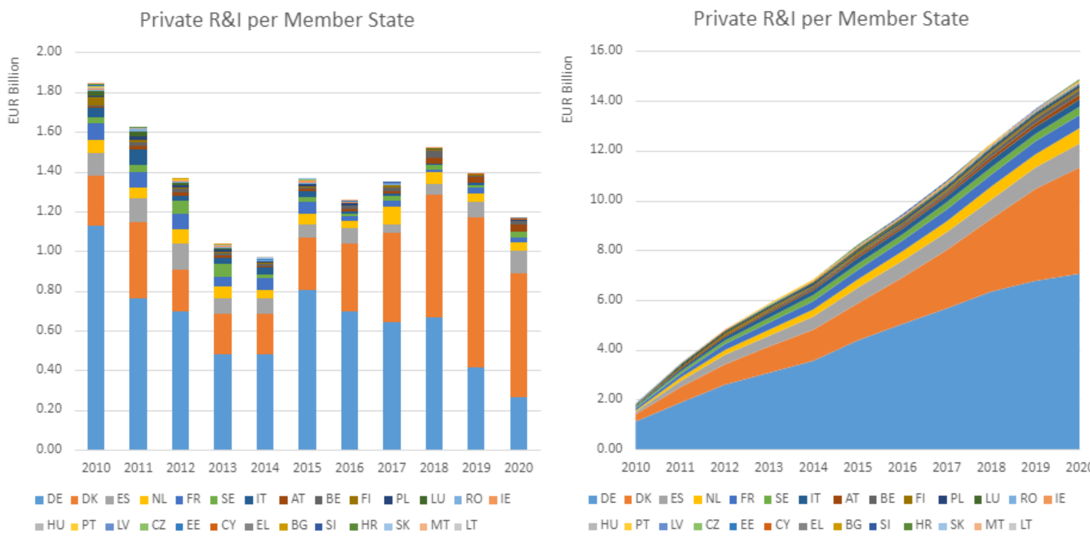
Figure 16. Global private R&D investment in the wind energy sector. Annual investment (left) and cumulative investment (right).



Source: JRC SETIS (Mountraki et al., 2022; Fiorini et al., 2017; Pasimeni, Fiorini, and Georgakaki, 2019), 2023.

Within the EU, private R&D funding is highly concentrated in Germany and Denmark, where the leading European OEMs concentrate their industry and value chain (**Figure 17**). In 2020, private R&D investment from these two MSs reached EUR 618 million for Denmark and EUR 268 million for Germany. In relative terms, their private R&D investment has remained relatively constant in recent years, averaging about 76% of EU corporate funding over the period 2010-2020.

Figure 17. EU private R&D investment in the wind energy sector. Annual investment (left) and cumulative investment (right) per EU MS.



Source: JRC SETIS (Mountraki et al., 2022; Fiorini et al., 2017; Pasimeni, Fiorini, and Georgakaki, 2019), 2023.

EU companies are among the leading investors in R&D. In the period 2015-2019, four EU companies were among the top five global R&D investors in the wind energy sector (see **Table 3**). However, Senvion went into insolvency at the end of 2019, resulting in further market consolidation within the offshore sector and SiemensGamesa RE acquiring Senvion's European onshore service assets (WPM, 2019). Moreover, a strong representation of Chinese OEMs is observed among the top 20 global R&D investors, increasing their shares in recent years. Other competitors include General Electric (US), in fourth position, and Japan's Hitachi, Mitsubishi and NTN Corporation.

Table 3. EU Leading companies (and their origin) in private R&D investment in the period 2015-2019.

Position (2015-2019)	Company	Country
1	VESTAS WIND SYSTEMS AS	DK
2	SENVION GMBH	DE
3	Siemens Gamesa Renewable Energy AS	DK
4	GENERAL ELECTRIC COMPANY	US
5	WOBBEN PROPERTIES GMBH	DE
6	BEIJING GOLDWIND SCIENCE CREATION WINDPOWER EQUIPMENT CO LTD	CN
7	SIEMENS AKTIENGESELLSCHAFT	DE
8	STATE GRID CORPORATION OF CHINA	CN
9	XINJIANG GOLDWIND SCIENCE TECHNOLOGY CO LTD	CN
10	Nordex Energy GmbH	DE
11	SAMSUNG HEAVY IND CO LTD	KR
12	BEIJING GUODIAN SIDA TECHNOLOGY CO., LTD.	CN
13	MITSUBISHI HEAVY INDUSTRIES LTD	JP
14	Siemens Gamesa Renewable Energy Innovation Technology SL	ES
15	HITACHI LTD	JP
16	MING YANG SMART ENERGY GROUP LTD	CN
17	SHANGHAI ELECTRIC WIND POWER GROUP CO LTD	CN
18	ELECTRIC POWER DEVELOPMENT CO LTD	JP
19	NTN CORPORATION	JP
20	ZF Friedrichshafen AG	DE

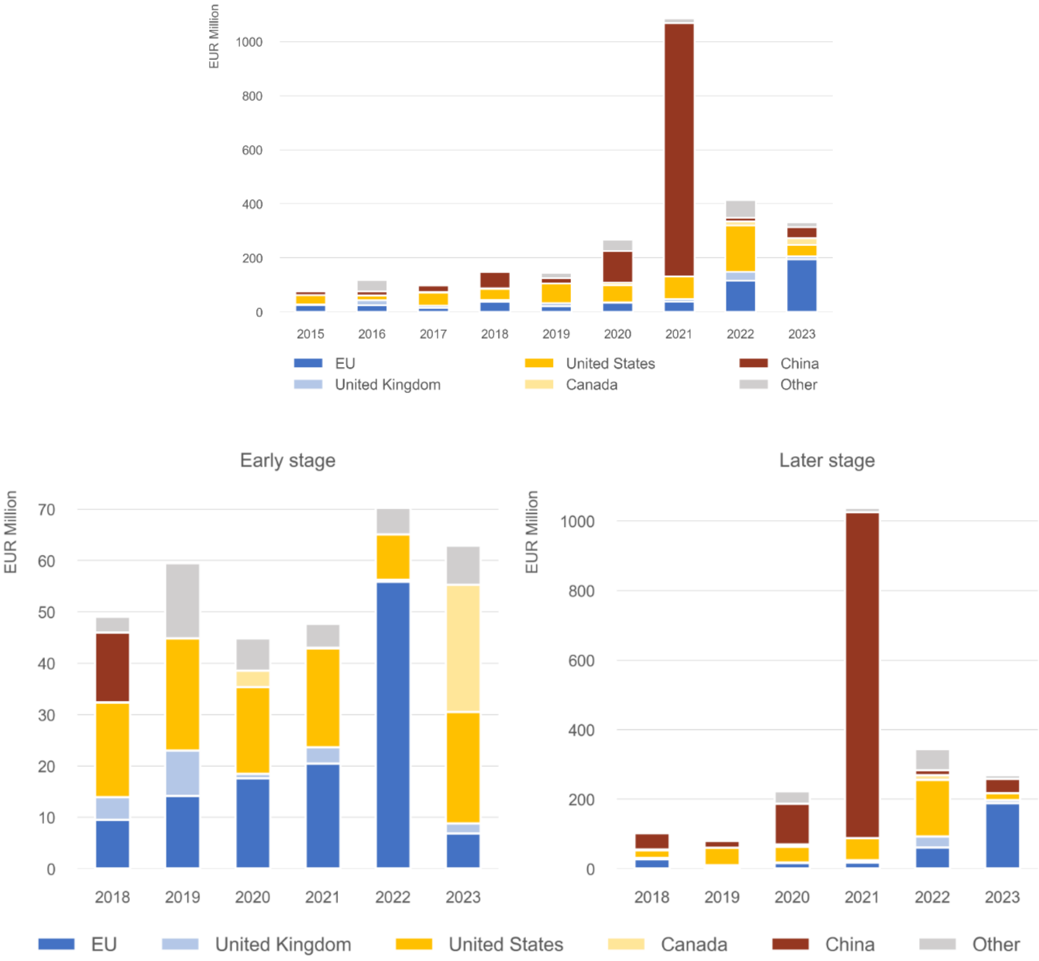
Source: JRC, 2023.

Note: Senvion went into insolvency at the end of 2019

Venture capital (VC) is a type of private equity (PE) financing that investors offer to start-ups and small businesses with high growth potential. It is divided into early stage investment and later stage investment. Early stages include Pre-Seed, Accelerator/Incubator, Angel, Seed, and Early stage VC investments. Later stages involve growth investments for scaling up start-ups or larger SMEs, such as Late Stage VC, Small M&A, and Private Equity Growth/Expansion. By investing in innovative companies, VC and PE firms contribute to the development of new technologies and business models within the wind industry and promote the sector's innovation landscape.

Globally, VC and PE investment in the wind energy sector decreased in 2023 (EUR 332 million) compared to the two peak years recorded in 2021 (EUR 1 086 million) and 2022 (EUR 414 million). However, VC/PE investments remain at an important level, largely above the average EUR 117 million recorded between 2012 and 2019. Focusing on the EU, the share of VC/PE investments has shown a considerable increase in 2023 when it reached EUR 195 million, and the region represents more than half of all investments for that year. Specifically, later-stage deals represent the majority of VC and PE investment. On the other hand, China, after witnessing a large growth in later-stage deals in 2020 and 2021, has seen its investment considerably decrease in 2023, down to less than EUR 42 million (see **Figure 18**).

Figure 18. Global VC/PE investment in the wind energy sector from 2010 to 2023, by region, for all deals (top), early-stage deals (bottom left) and later-stage deals (bottom right).

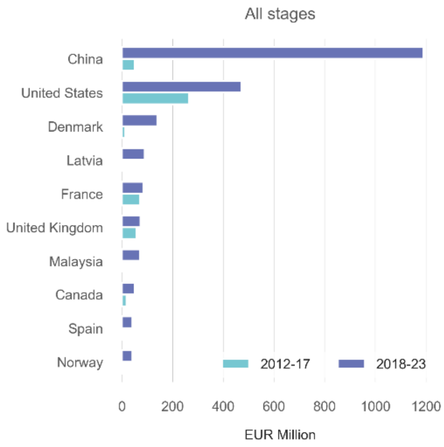


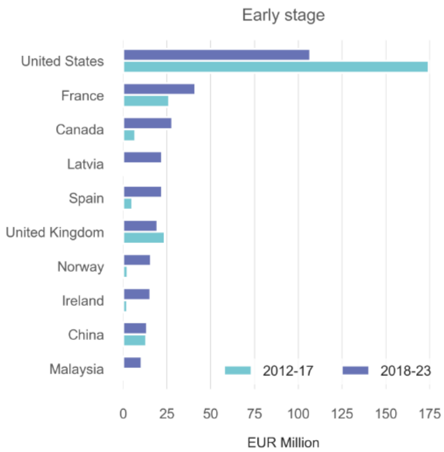
Source: JRC based on Pitchbook, 2024.

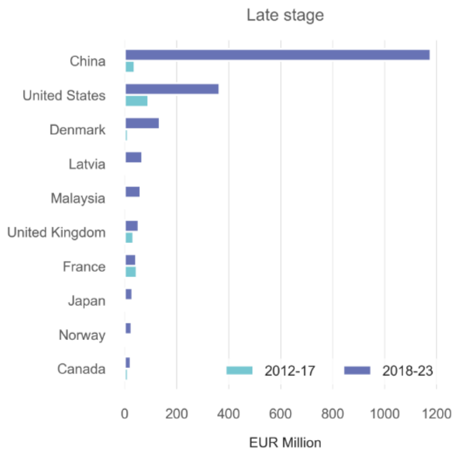
The top 10 beneficiary countries for VC/PE investment in the wind energy sector all show an increase in funding for the period 2018-2023 compared to 2012-2017, with the most substantial evolution visible in China, Denmark and Latvia. Europe is at the forefront of private investment in the wind energy sector. Out of the top 10 beneficiary countries, 4 are part of the EU: Denmark, Latvia, France and Spain, and 2 more are from Europe: the UK and Norway. In terms of early-stage investment deals, the 3 leading countries are the US, France, and Canada; while for later-stage investment deals, the leaders are China, the US and Denmark. Additionally, we find that the funds invested during later stage deals are larger than those invested for early stage deals (see **Figure 19**).

Overall, the EU represents an important share of all-stage investments deals, with 18.4% of global investment deals for the period 2018 to 2023. This proportion is even higher for early-stage investment deals, where the EU represents over 37% of global deals for the time period considered. For late-stage investment deals, the EU represents 15.4% of global investment deals (see **Figure 20**).

Figure 19. VC/PE investment in the top 10 beneficiary countries for all deals (top), early-stage deals (bottom left) and later-stage deals (bottom right), for the periods 2012-2017 and 2018-2023.

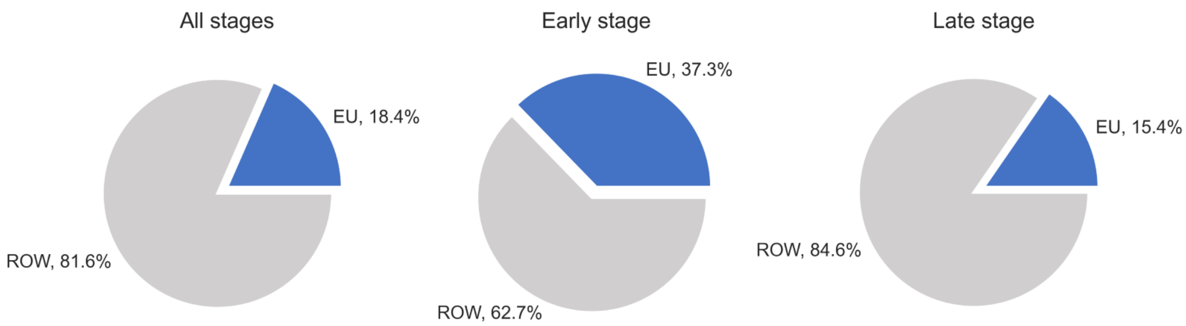






Source: JRC based on Pitchbook, 2024.

Figure 20. VC/PE investment share in the EU and in the ROW, for all deals (left), early-stage deals (centre) and later-stage deals (right), for the period 2018-2023.



Source: JRC based on Pitchbook, 2024.

2.6 Patenting trends

The following section discusses patenting activity and the protection of intellectual property in the wind sector. Key countries and organizations are analysed based on:

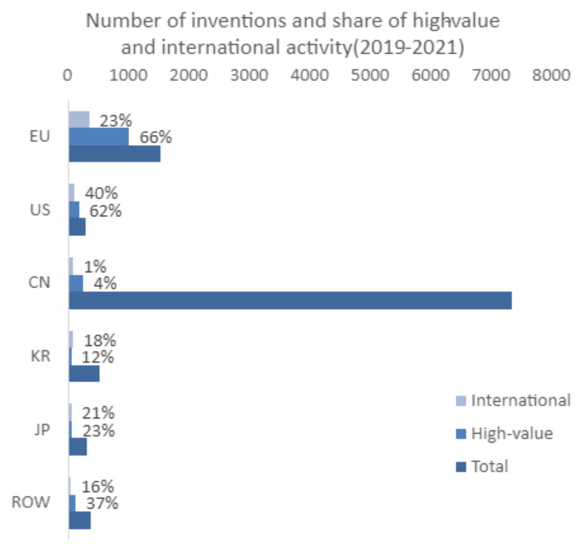
- **Number of inventions:** Patent families represent all relevant documents related to a specific invention, such as applications filed with multiple authorities.
- **International inventions:** Patent applications protected in a country other than the applicant's residence are considered international.
- **High-value inventions:** High-value refers to patent families including patent applications filed in more than one patent office. High-value inventions consider EU countries separately, while international inventions group European countries into a single macro category.

The Cooperative Patent Classification (CPC) codes considered for the evaluation of the patenting activity are: Y02B 10/30, Y02E 10/70, Y02E 10/72, Y02E 10/727, Y02E 10/728, Y02E 10/74 and Y02E 10/76. Data are incomplete for the year 2021, but are still an indication of the trend for the year.

China surpassed the EU in wind energy inventions in 2009, becoming the new global leader by number of inventions. However, Chinese patents mostly focus on the domestic market, with only 1% of them being international, compared to 23% in the EU and 40% in the US. In the 2019-2021 period, only 4% of Chinese wind energy inventions filed were considered high value, while high-value inventions accounted for approximately 66% of all European wind energy inventions filed. The US and Japan have 62% and 23% high-value inventions, respectively, but their absolute numbers are much lower (see **Figure 21**).

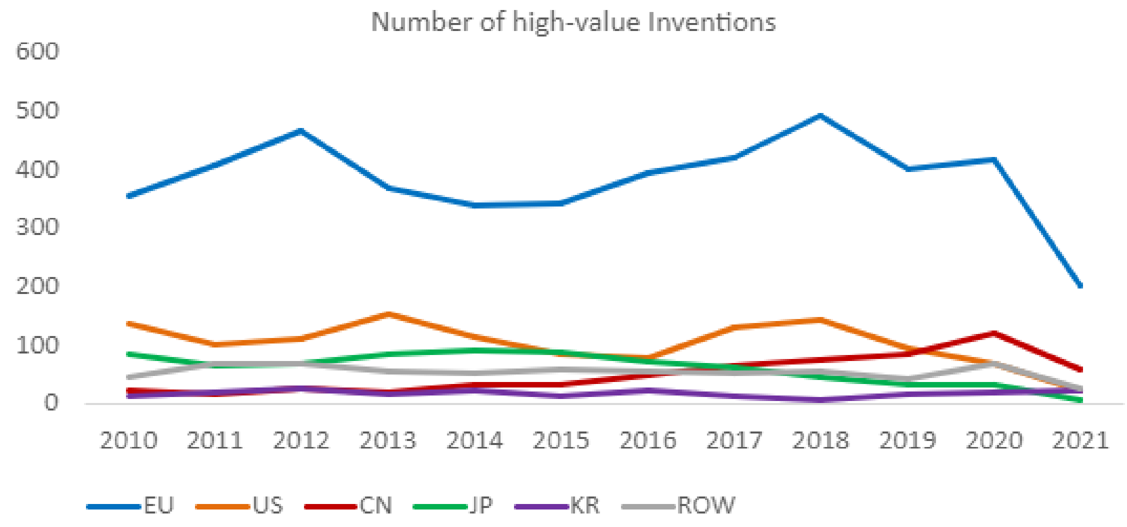
Globally, the number of high-value inventions decreased by half in 2021, going from 734 inventions in 2020 to 341 inventions in 2021. This trend is visible for all major players: the EU saw a decrease from 418 inventions to 204, China from 121 to 61, the US from 70 to 23, and Japan from 35 to 6. The only notable exception is South Korea, which saw its number of inventions increase from 20 to 25 between 2020 and 2021. Overall in the period 2019-2021, the EU's share of high-value inventions was 58%, followed by China (15%), the US (11%), Japan (4%) and South Korea (4%) (see **Figure 22**).

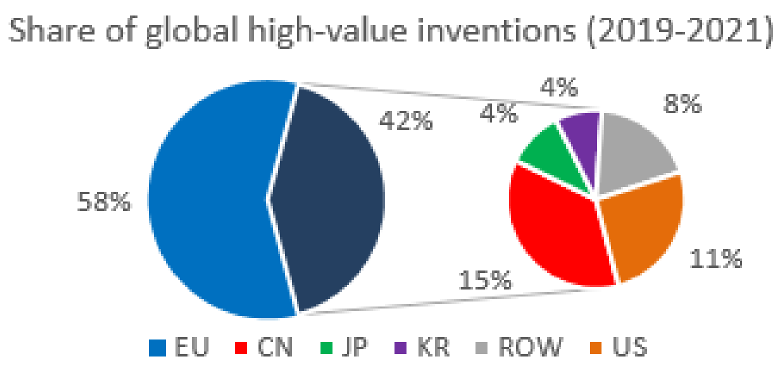
Figure 21. Number of wind energy inventions and share of high-value and international activity (2019-2021).



Source: JRC based on Patstat, 2024.

Figure 22. Number of high-value inventions per region, from 2010 to 2021 (top), and share of high-value activity per region, for the time period 2019-2021.





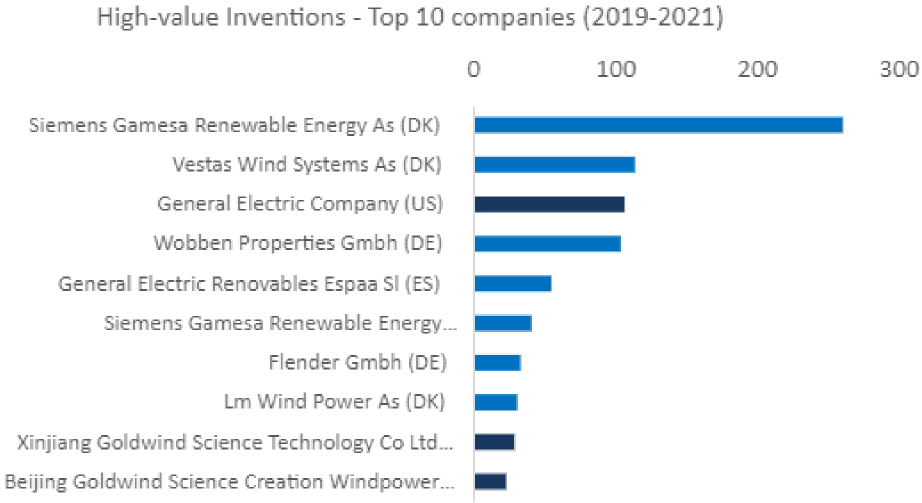
Source: JRC based on Patstat, 2024.

At country level for the period 2019-2021, Denmark leads on high-value inventions (462), followed by Germany (276) and China (267). In total, five EU countries can be found within the top 10: Denmark (462), Germany (276), Spain (125), France (52) and the Netherlands (39). The US and Japan rank fourth and sixth, filing respectively 190 and 76 high-value patents during that period.

During the 2019-2021 period, EU companies maintained their leadership in high-value inventions, with seven out of the top 10 OEMs originating from the EU. These include SiemensGamesa (first), Vestas (second), Enercon (Wobben Properties GmbH) (fourth), Flender (seventh) or Lm Wind Power (eighth). The US and China are also represented in the top 10 OEMs, with General Electric (US) in third position, and Goldwind (China) in ninth position (see **Figure 23**).

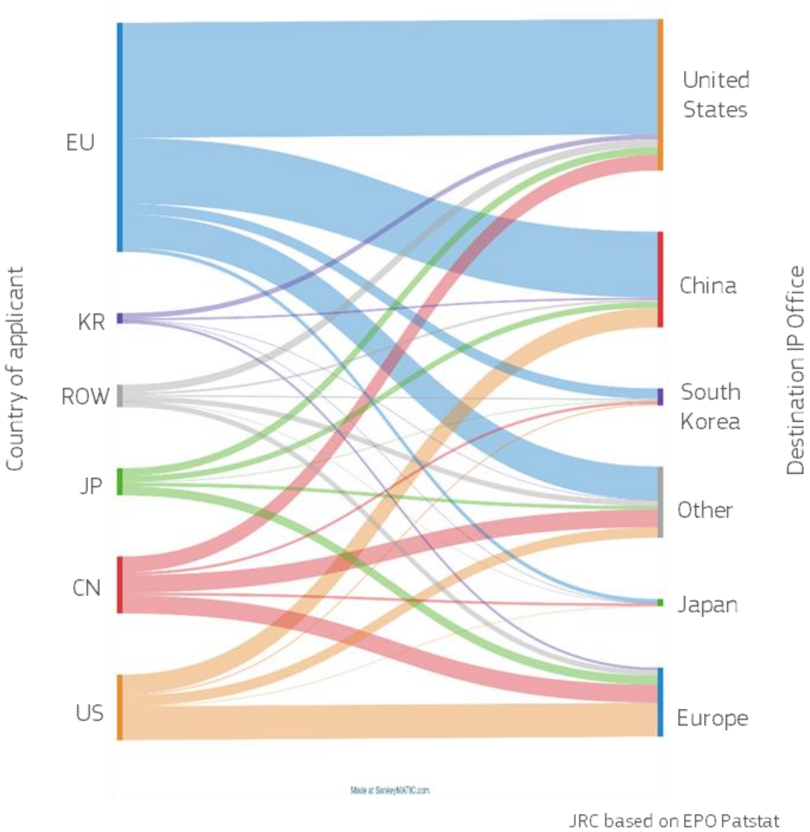
Figure 24 presents the flow of high-value inventions from the major economies to the main patent offices in the period 2019-2021. EU applicants show the highest share of inventions protected in the US (50%) and China (29%), whereas the US protect a substantial share of their inventions in Europe (52%) and China (30%). China, Japan and South Korea protect a significant lower number high-value patents, yet Europe and the US are again the main destinations of IP protection.

Figure 23. Top 10 organisations (global) - Number of inventions and share of high-value and international activity (2019--2021).



Source: JRC based on Patstat, 2024.

Figure 24. International protection of high-value inventions (2019-2021).



Source: JRC based on Patstat, 2024.

2.7 Scientific publication trends

This chapter analyses bibliometric trends in the wind energy sector, specifically:

- the number of peer-reviewed articles per year 2010-2023 (global and EU),
- the number of highly cited papers (top 10% cited, normalised per year and field),
- the FWCI[1] per country, measuring the citation impact of publications as compared to the global average of the research field
- the h-index[2] per country, measuring both the productivity and citation impact of publications,
- the collaboration network among countries[3].

Publications in the wind sector are based on data from Scopus from 2010 to 2023.

Globally, the overall number of wind energy publications grew at a fast pace, rising from 427 articles in 2010 to 3 463 publications in 2023, a more than eightfold increase. In 2023, China leads with the highest number of articles (36%), followed by the EU (17%), the US (8%) and the UK (6%) (**Figure 25**).

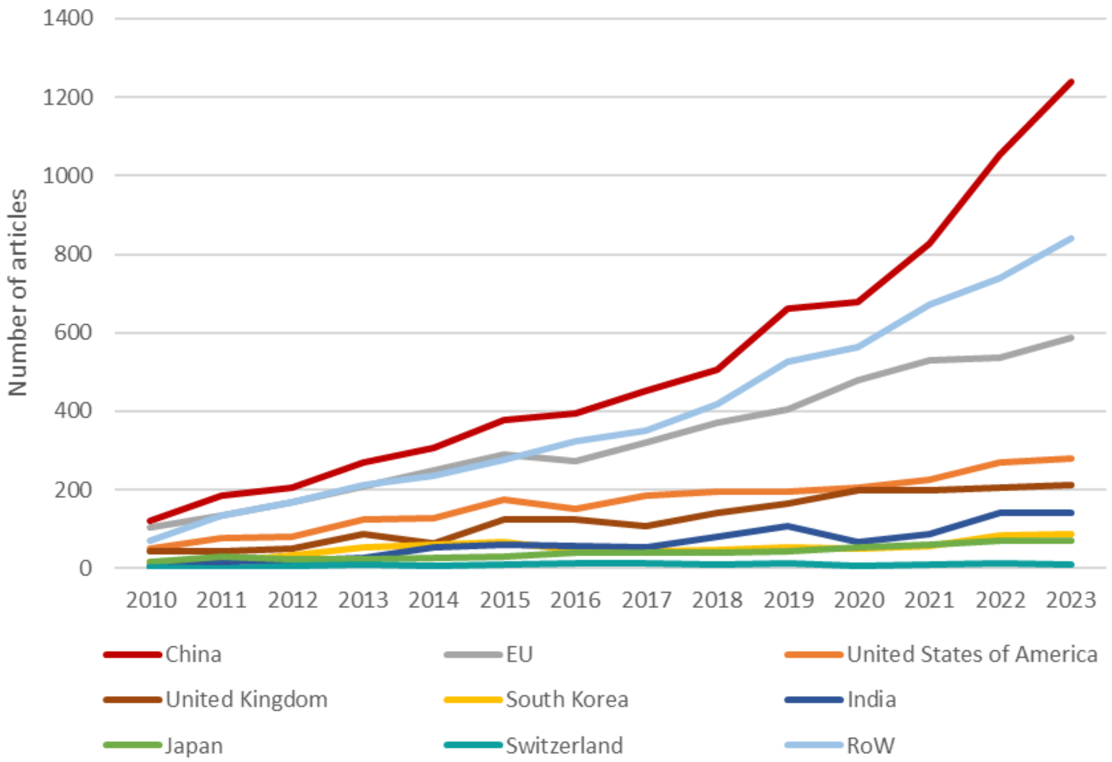
Within the EU, the leading countries in terms of first-mover status also demonstrate the highest publication activity. Since 2010, Germany ranks first in cumulative number of articles (1 029 articles for 2010-2023), followed by Denmark (695), Spain (669), Italy (551) and the Netherlands (429) (**Figure 25**). Research in the wind sector has spread throughout Europe, with all EU MSs showing publishing activity between 2010 and 2023, and 13 countries having over 100 peer-reviewed articles during that period.

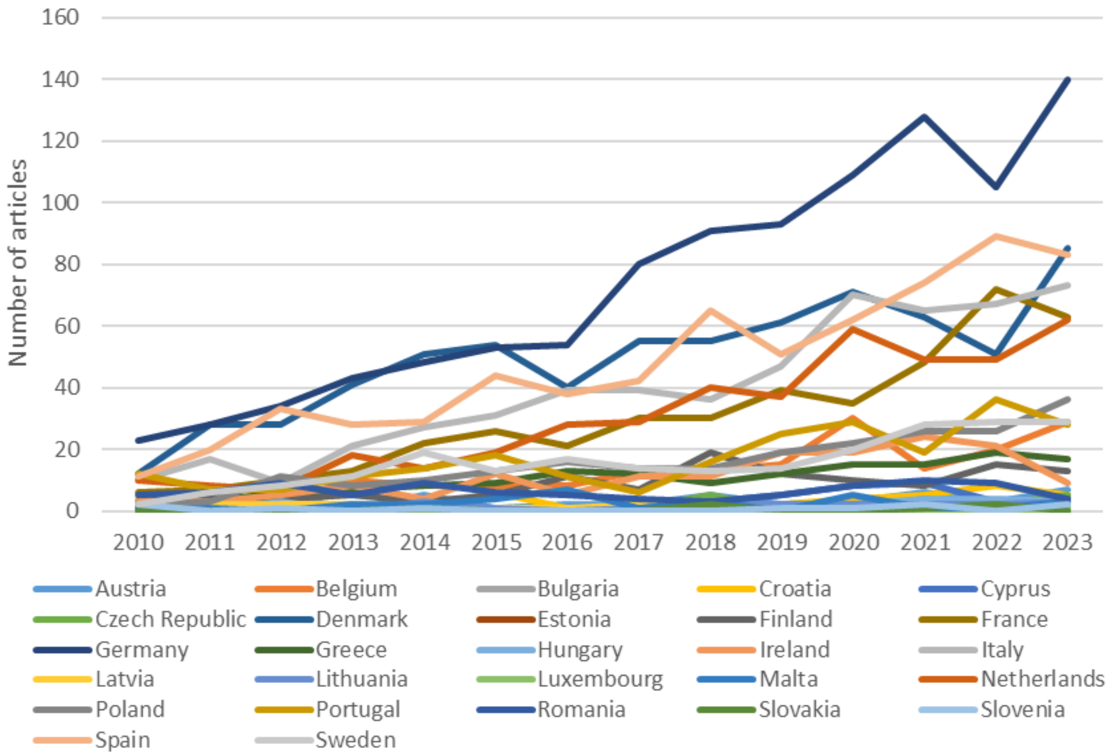
1 Field Weighed citation impact is calculated as the average number of citations the article receive normalised per year and per field. A FCWI of 1 means that the output performs just as expected for the global average (Scopus, 2022).

2 The h-index (also Hirsch-Index) of a country is the largest number h such that at least h articles in that country for that topic were cited at least h times each (Hirsch, 2005).

3 Network graphs show collaboration networks among competitors. The size of the nodes in the graphs indicates the number of documents retrieved for a location. The edges indicate co-publications or co-occurrence n the same document(s). The thickness of the edge is relative to the number of documents in common. Same colours of nodes indicate communities that tend to appear more together than with others

Figure 25. Wind energy - Number of peer-reviewed articles per year (2010-2023) globally (top) and in the EU (bottom).

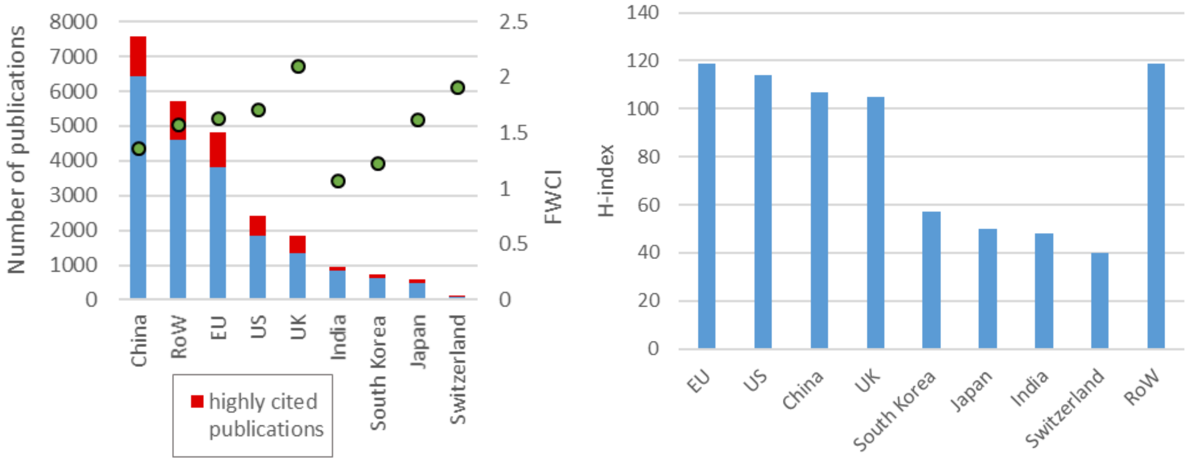




Source: JRC based on TIM, 2024.

Indicators measuring the impact and productivity of peer-reviewed articles in the area of wind energy confirm that the EU can compete with its international counterparts. China leads in highly cited articles (1 164), followed by the EU (986), the US (551) and the UK (501). The FWCI within the research field indicates that EU performs above global average (1.63), ranking fourth behind the UK (2.10), Switzerland (1.91), and the US (1.71), all countries with significantly lower overall publication activity than the EU. Other competitors such as China (1.36), South Korea (1.23) and India (1.07) rank below the global average in FCWI. In terms of citation impact and productivity, the EU leads with a H-index of 119, closely followed by the US (114), China (107) and the UK (105) (**Figure 26**).

Figure 26. Wind energy - Total number of peer-reviewed articles per year (2010-2023), FWCI (left) and H-index (right) of the EU and global competitors.

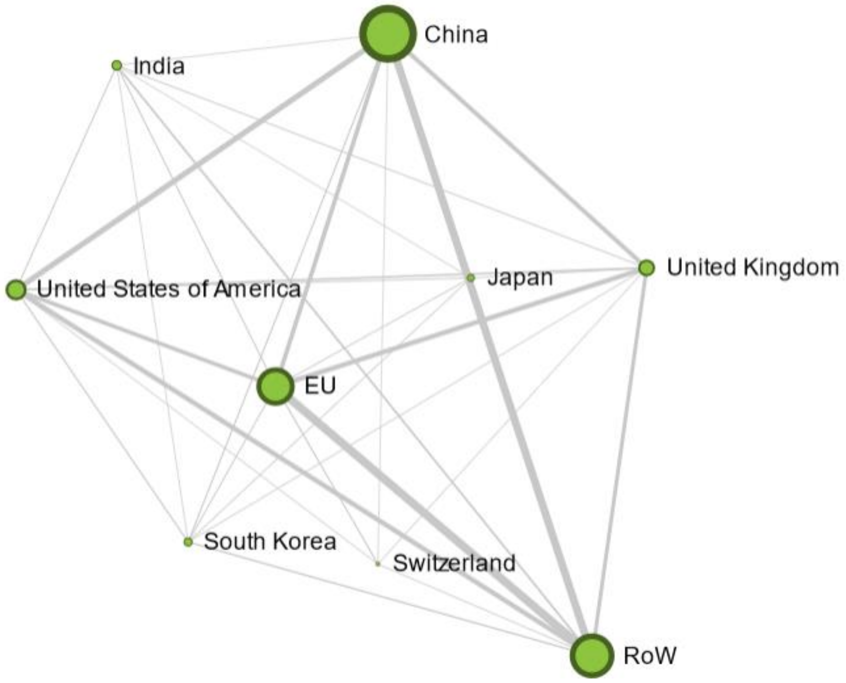


Source: JRC based on TIM, 2024.

In the period 2010-2023, EU organisations show the strongest collaboration ties in publishing peer-reviewed articles with organisations from the UK, China and the US. Similarly strong co-publication activity is observed between China and the US, as well as between China and the UK (**Figure 27**).

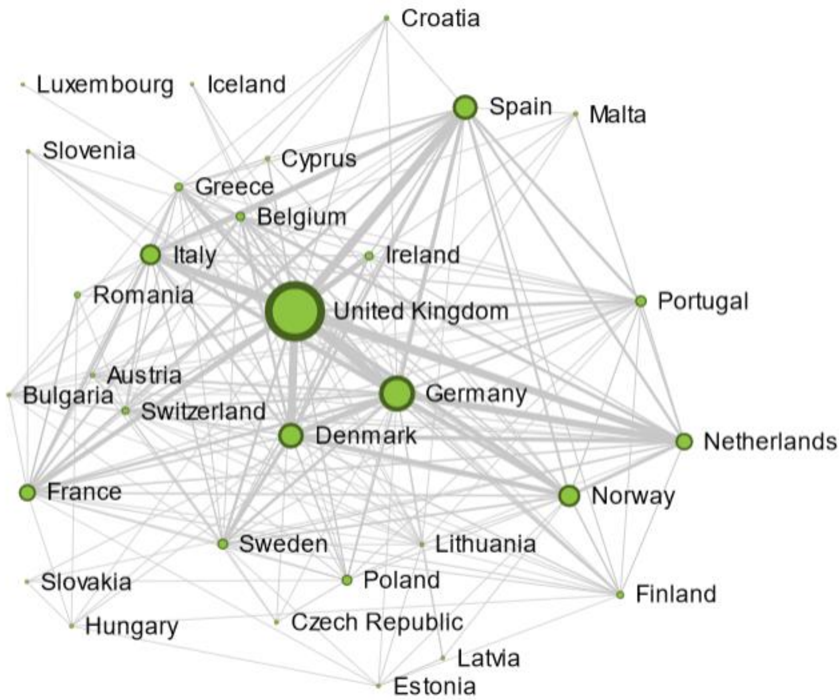
Within the EU, the strongest collaboration networks exist between Germany and the Netherlands, Germany and Denmark, Germany and Italy, and the Netherlands and Denmark. Moreover, Spain, Denmark, Germany and the Netherlands show very strong publication ties with the UK (**Figure 28**).

Figure 27. Global collaboration network for wind energy research, based on peer-reviewed articles from 2010 – 2023.



Source: JRC based on TIM, 2024.

Figure 28. European collaboration network for wind energy research, based on peer-reviewed articles from 2010 – 2023.



Source: JRC based on TIM, 2024.

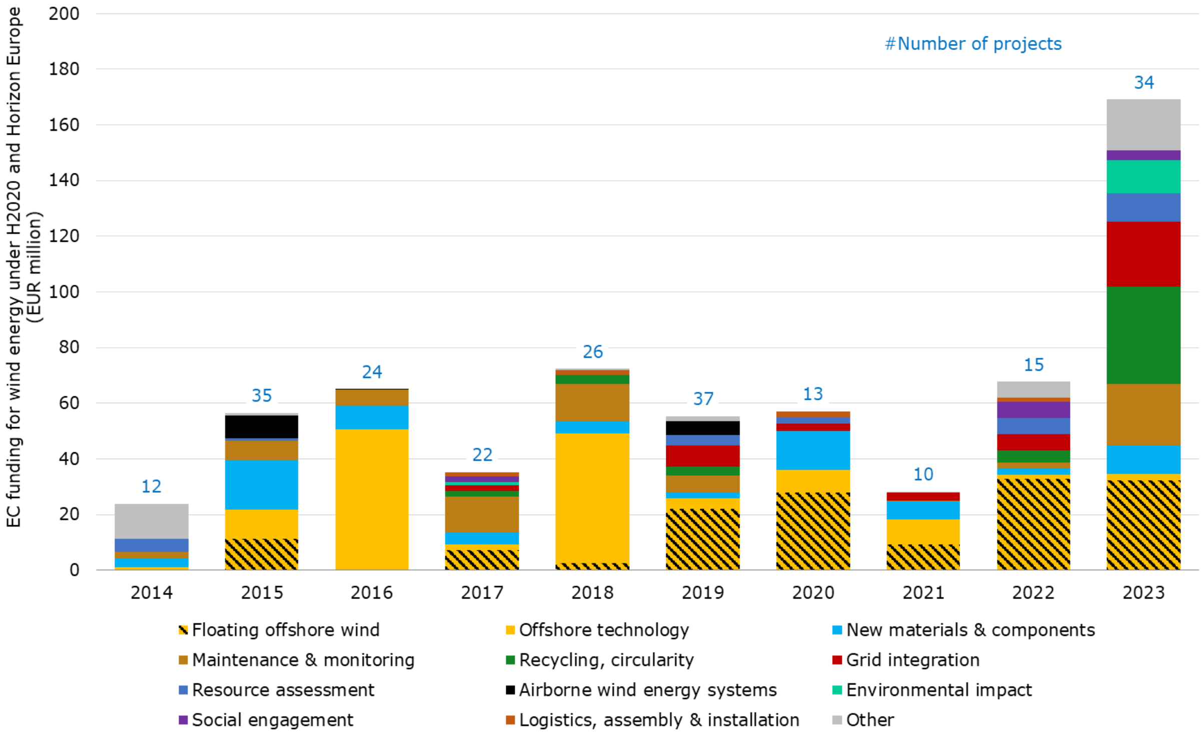
2.8 Impact and trends of EU-supported Research and Innovation

2.8.1 Development and priorities of R&D investment in H2020 and Horizon Europe

H2020 and Horizon Europe, Europe's largest research and innovation programmes, have consistently supported wind energy. The year 2023 marked the best performance since 2014, with 34 new wind energy research projects funded and a cumulative investment of EUR 169.1 million, more than double the amount in 2022 (EUR 67.7 million).

Figure 29 illustrates the development of research and innovation (R&I) funding between 2014 and 2023 through the Horizon Europe and H2020 programmes. In 2023, 21% of the European Union's funding (EUR 34.8 million) went to wind energy projects focused on recycling and circularity. Floating offshore wind projects received 19% (EUR 32.4 million), and grid integration projects received 14% (EUR 23.4 million).

Figure 29. Evolution of EU R&I funding categorised by R&I priorities for wind energy under H2020 (2014-2021) and Horizon Europe (2022-2023) programmes and the number of projects funded in the period 2014-2023.



Notes: Projects specifically on wind energy and those with a significant wind energy component are accounted for. Funds granted refer to the start year of the project.
Source: JRC based on CORDIS, 2024.

In 2023, four new European projects focus on recycling and circularity solutions. Three projects tackle the issue of waste generated from wind turbine blades at the end of their life cycle. The largest of these projects, Blades2Build (EUR 12.4 million), aims to develop recycling solutions for wind turbine blades. REFRESH (EUR 11.5 million) seeks to create a circular, smart system for recycling at least 90% of glass fiber-reinforced composites from wind turbines. EoLO-HUBs (EUR 10 million) will develop and implement efficient circular economies for wind turbine blades. Lastly, the GR4FITE3 project (EUR 960 thousand) aims to establish a sustainable end-to-end supply chain for lithium-ion batteries. This is specifically targeted towards anode active materials used in lithium-ion batteries designed for electric vehicles and power sources like solar and wind farms.

With WHEEL (EUR 16.7 million), BLOW (EUR 15.5 million) and ShareWind (EUR 212 thousand), 3 new projects started in floating energy in 2023. The objective of the WHEEL project is to fully demonstrate and bring to a precommercial Technology Readiness Level (TRL) a novel floating wind technology excellently suited for deep water locations, effective industrialization strategies, breakthrough cost reduction and minimized carbon footprint. Development and demonstration needed to reach the pursued TRL will be achieved through the design, installation, certification and testing of a fully operative 6 MW Pilot unit. BLOW will develop a 5 MW demonstrator in the Black Sea, paving the way to industrial mass production of floating offshore wind farms. ShareWind will study the use of shared anchors to reduce construction costs of floating wind turbines.

7 new projects will focus on grid integration, including WILLOW (EUR 5.8 million) which will develop a data-driven smart curtailment solution; and InterOPERA (EUR 12.7 million) which will improve the grid-forming capabilities of offshore and onshore converters, by transforming future high-voltage direct current systems into mutually compatible and interoperable systems.

Maintenance and condition monitoring systems will be the R&I priority of 5 new projects, including TWAIN (EUR 6 million) which plans to accomplish efficient deployment of AI in wind farm control and asset management in order to optimise operation for cost, performance, and efficiency while also considering environmental and societal aspects.

3 new projects will focus on environmental impacts of wind energy, including ULTFARMS (EUR 9.6 million) which will develop novel designs in six low trophic aquaculture pilots in offshore wind farm locations across the North and Baltic Seas; and off-coustics (EUR 2 million) which aims to achieve a comprehensive understanding of the acoustic repercussions of wind turbines, specifically their potential to negatively impact marine life through acoustic damage.

Resource assessment will be the R&I priority of 2 new projects, including FLOW (EUR 6 million) which will develop new prediction methods for production statistics and load performance of modern GW-scale and 400-metre tall offshore and onshore wind energy systems.

New materials and components will be the R&I priority of 3 new projects, including MADE4WIND (EUR 6 million) which aims to develop and test innovative components for a 15 MW floating wind turbine. Specifically, the project will introduce new designs and manufacturing techniques in lightweight materials, recyclability, and advanced software tools. Nanowings (EUR 2.5 million) aims to improve wind turbine performance and durability by developing nanocoating based on a blended formulation of super-glue polymers combined with nanoparticles and with outstanding anti-icing and anti-fouling properties.

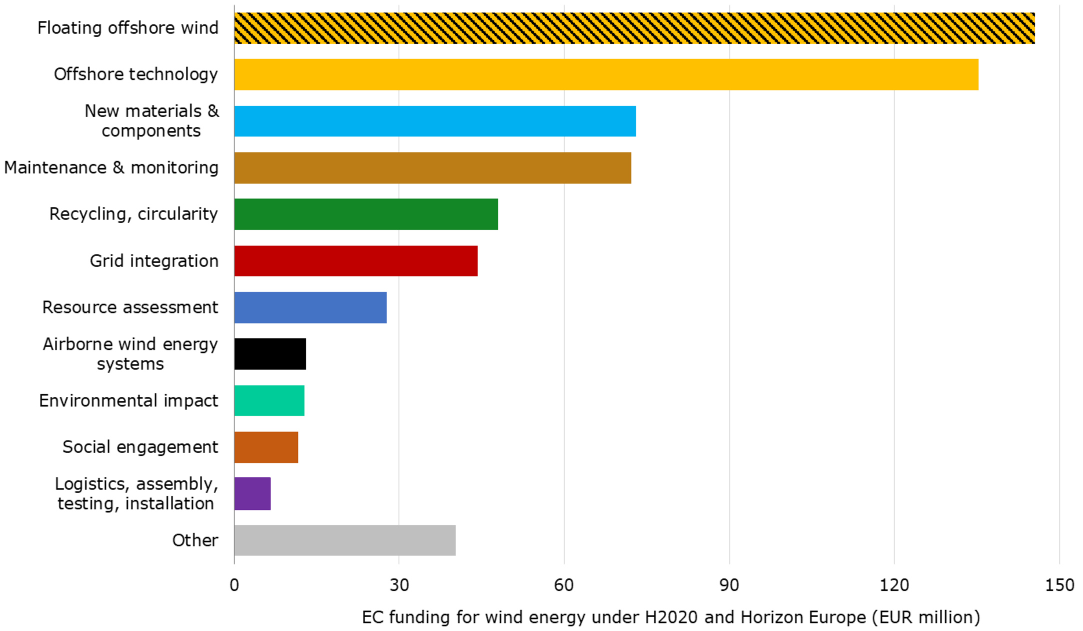
2 new projects will focus on social engagement, including WIMBY (EUR 3.3 million) which will study the drivers and barriers of social acceptance in order to address related challenges so that wind energy gains substantially more popular support. Taking a citizens science approach, it will focus on four geographically, climatically and socioeconomically diverse pilot cases across the EU.

Offshore technology will be the R&I priority of 2 new projects, including DATA-DRIVEN OFFSHORE (EUR 2 million) which aims to revolutionise aerohydroelastic simulations used in wind turbine research and development, specifically integrating experimental data into these simulations.

In the category "other", 3 projects started in 2023, with 2 targeting the shipping sector, which contributes to more than 3% of the total CO_2 emissions in the EU. The Orcelle project (EUR 9 million) will develop and demonstrate a solution involving wind as the main form of propulsion. Orcelle expects to achieve an energy efficiency gain of more than 50% (average savings in full-year operation). The WHISPER project (EUR 9 million) will develop a modular retrofit solution, including a wingsail system to provide wind-assisted propulsion. By developing the novel modular retrofit solution, WHISPER will also test viability by demonstrating efficiency savings of more than 20%.

For a detailed list of the projects, refer to **Annex 4**.

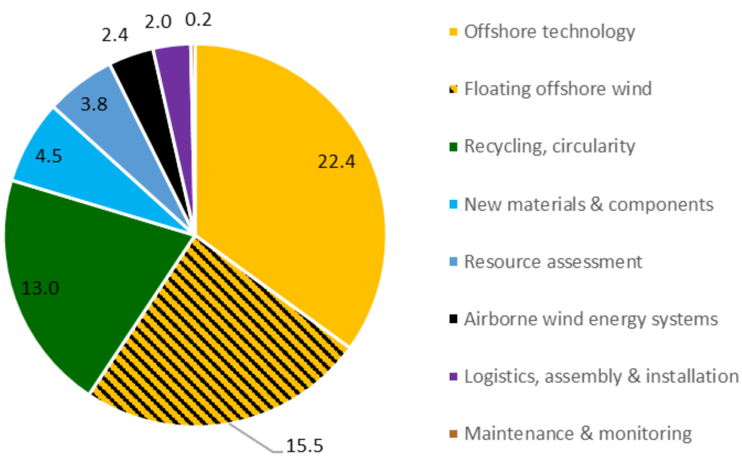
Figure 30. EC funding on wind energy R&I priorities under H2020 and Horizon Europe, for 2014-2023 [EUR million].



Source: JRC based on CORDIS, 2024.

Since 2014, significant funding has been allocated across all wind research R&I priorities. Floating offshore has received the most funding (EUR 146 million), followed by offshore wind (EUR 135 million), and research on new materials and components (EUR 73 million) (**Figure 30**).

Figure 31. Share of wind energy funding under Horizon Europe granted to projects completed in 2023.



Source: JRC based on CORDIS, 2024.

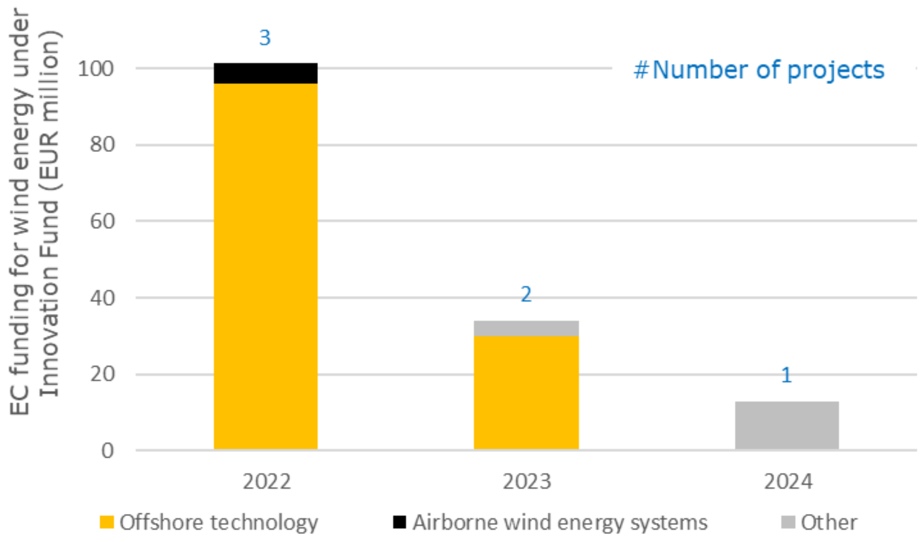
In 2023, 13 projects ended, for a total budget of EUR 64.9 million (**Figure 31**). The largest fundings were allocated to offshore technology (35%, EUR 22.4 million), floating offshore wind (24%, EUR 15.5 million), and recycling and circularity (20%, EUR 13 million).

The i4Offshore project (EUR 19.9 million) aimed to reduce cost barriers in large-scale offshore developments by optimizing low-cost manufacturing through a hybrid-material gravity jacket foundation. Although geotechnical designs for suction buckets and steel jacket structures were developed, the project ended prematurely. The COREWIND project (EUR 5 million) contributed to cost and environmental footprint reductions in floating offshore wind energy systems by utilising digital tools and optimizing designs for station-keeping systems and dynamic cables. This led to significant cost savings primarily due to reductions in oversizing. The SUSMAGPRO project (EUR 13 million) focused on recycling and reusing neodymium-containing magnets from waste, creating a shorter recycling loop with a higher recovery rate (25%) and increased yield compared to conventional methods.

2.8.2 Development and priorities of R&D investment in the Innovation Fund programme

The Innovation Fund is designed to finance demonstrations of cutting-edge, low-carbon technologies. The programme derives its funding from the EU Emission Trading System by auctioning 450 million allowances between 2020 and 2030. The funding is divided into separate calls for small-scale and large-scale projects, with budget requirements below and above EUR 7.5 million, respectively.

Figure 32. Evolution of EU R&I funding categorised by R&I priorities for wind energy under the Innovation Fund programme and the number of projects funded (2022-2024).



Source: JRC, 2024.

In 2020, the first small-scale project call of the Innovation Fund supported two demonstration projects focused on airborne wind energy systems (AWES), both commencing in 2022 (**Figure 32**). The Norse Airborne Wind Energy Project (NAWEP), with a EUR 3.4 million budget, aimed to construct and operate an onshore array of at least twelve 100 kW AWES devices, generating a combined 1.2 MW. The developers targeted 50% lower costs and an 80% reduction in the carbon footprint compared to conventional horizontal axis wind turbines (HAWTs). The Aquilon project, funded at EUR 2 million, served as a demonstrator for both airborne wind energy production at a 160 kW scale and an integrated renewable energy and storage (RES) solution.

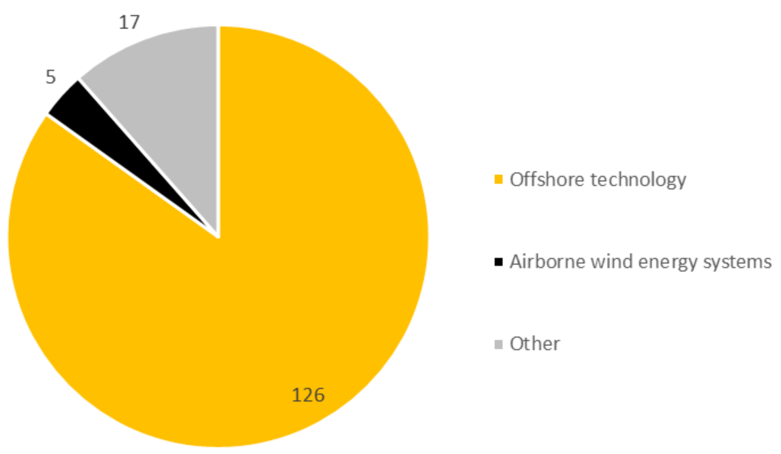
The second large-scale call of the Innovation Fund, launched in 2021, awarded the Nordsee Two Offshore Windfarm Innovation Project (N2OWF) a EUR 96 million budget. N2OWF began in 2022 and aimed to build and operate a first-of-its-kind offshore wind farm with a capacity of 450 MW, combined with on-site production, storage, and offtake of green hydrogen. The innovative technologies included wind turbines (approximately

15 MW), foundations, and a hydrogen technology solution (including a 4 MW electrolyser on the offshore substation).

The second small scale call in 2021 funded the SUSTAIN-SEA project (EUR 4 million) that started in 2023. SUSTAIN-SEA will use wind energy to reduce fuel use and GHG emissions in the maritime transport sector. WIthin the project, the wind propulsion system will be integrated into five large cargo vessels operating mainly in EU waters.

The third large-scale call, in 2022, rewarded HIPPOW (EUR 30 million) and SEAWORTHY (EUR 13 million), commencing respectively in 2023 and 2024. HIPPOW delivered the installation, operation, and testing of the world's most powerful offshore wind turbine prototype, with innovations in nominal power, bearings, electrical systems, blade and tower installation, cooling systems, and maintenance strategies. SEAWORTHY is a commercial-scale demonstration of a technology capable of supplying clean dispatchable offshore power from wind, waves and hydrogen. The demonstrator technology integrates a 4.3 MW wind turbine generator, a 0.8 MW wave energy converter and a hydrogen system (consisting of a 1 MW electrolyser, 48 MWh of energy storage and a 1.2 MW fuel cell).

Figure 33. EC funding on wind energy R&I priorities under the Innovation Fund programme [EUR million], for the period 2022-2024.



Source: JRC, 2024.

From 2022 to 2024, the Innovation Fund allocated EUR 126 million to offshore technology, EUR 5 million to AWES, and EUR 17 million to other R&I priorities, totaling EUR 148 million in funding (Figure 33).

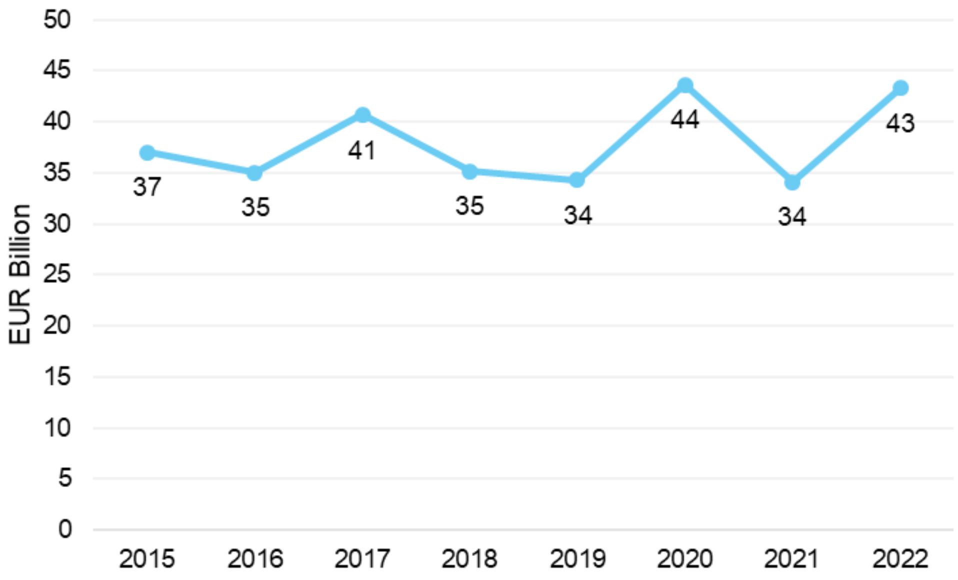
3. Value chain analysis

3.1 Turnover

The turnover, GVA and employment are determined using a method that evaluates the wind industry's economic activity. Specifically, EurObserv'ER considers the monetary flows from the following activities in the value chain: 1) Investment in new installations, 2) Operation and maintenance of existing plants, including newly added plants, and 3) Production and trade of renewable energy equipment (EurObserv'ER, 2024).

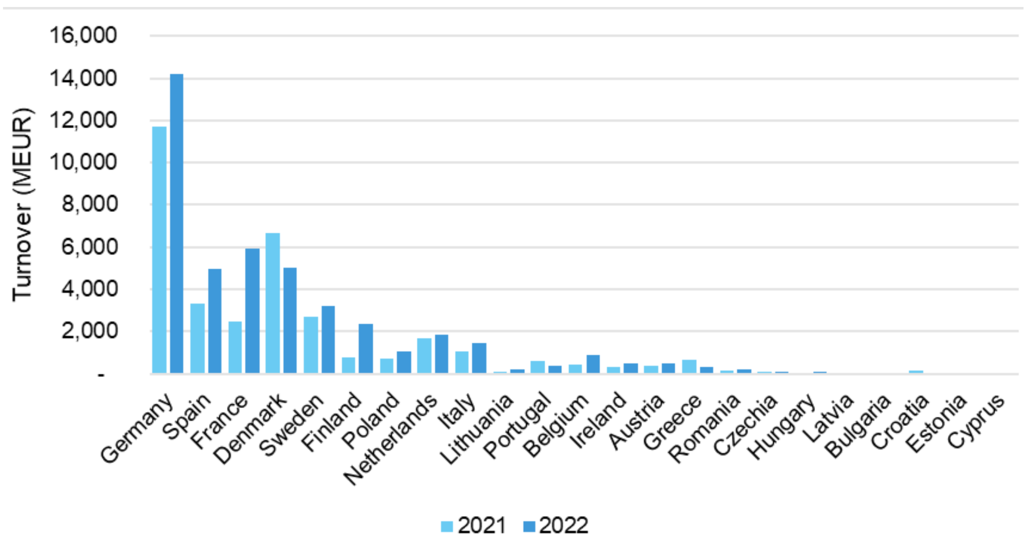
From 2015 to 2022, the EU wind power sector experienced a steady turnover, ranging between EUR 34 billion and EUR 44 billion (see **Figure 34**).

Figure 34. Turnover of the EU wind sector in the period 2015-2022.



Source: JRC based on EurObserv'ER, 2024.

Figure 35. Turnover of the wind sector in EU Member States in 2021 and 2022 for countries with more than EUR 100 million turnover.



Source: JRC based on EurObserv'ER, 2024.

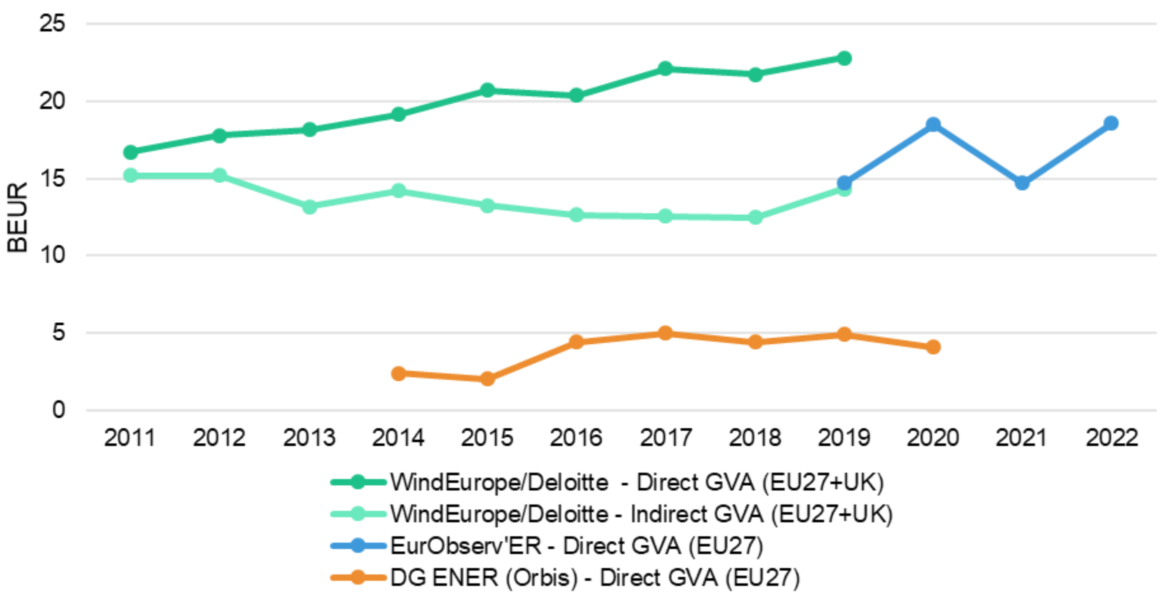
From 2021 to 2022, the total turnover of EU companies increased by about EUR 9 billion, sending it almost back to its levels of 2020. At about EUR 14.2 billion, Germany leads on turnover and is followed by France (EUR 5.9 billion), Denmark (EUR 5.0 billion) and Spain (EUR 5.0 billion) (see **Figure 35**). Additionally, most MSs saw an increase in their turnover from 2021 to 2022, except for Denmark which saw its turnover decrease from EUR 6.7 billion to EUR 5.0 billion.

3.2 Gross value added

Attempts to calculate the gross value added (GVA) in the EU wind sector reveal variations in methodology and geographical coverage. EurObserv'ER's analysis concentrates on the EU27, and calculates direct GVA using the sector's turnover figures and value added/input factors per sector from Eurostat input-output tables. More generally, direct GVA for a specific sector in a country is determined by subtracting the value of intermediate consumption from the value of output. WindEurope/Deloitte's work encompasses the EU27 together with the UK, while a study published by DG ENER focused on the EU27 (however only for the time period from 2014 to 2020) (**Figure 36**).

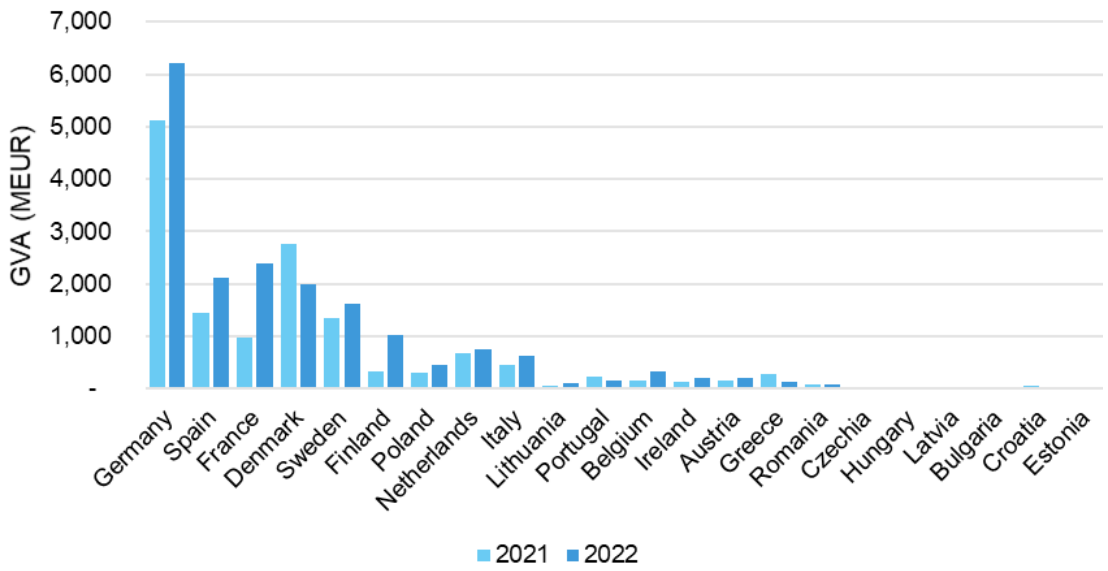
Direct GVA values calculated by EurObserv'ER (2024) increased to 18.6 billion in 2022, a 26% increase on the previous year's figure. With about EUR 6.2 billion, Germany leads in direct GVA, followed by France (EUR 2.4 billion), Spain (EUR 2.1 billion) and Denmark (EUR 2.0 billion) (see **Figure 37**).

Figure 36. Gross Value Added (GVA) of the EU wind sector in the period 2011 to 2022.



Source: JRC based on EurObserv'ER and WindEurope, 2024.

Figure 37. Direct Gross Value Added (GVA) of the EU wind sector in 2021 and 2022.

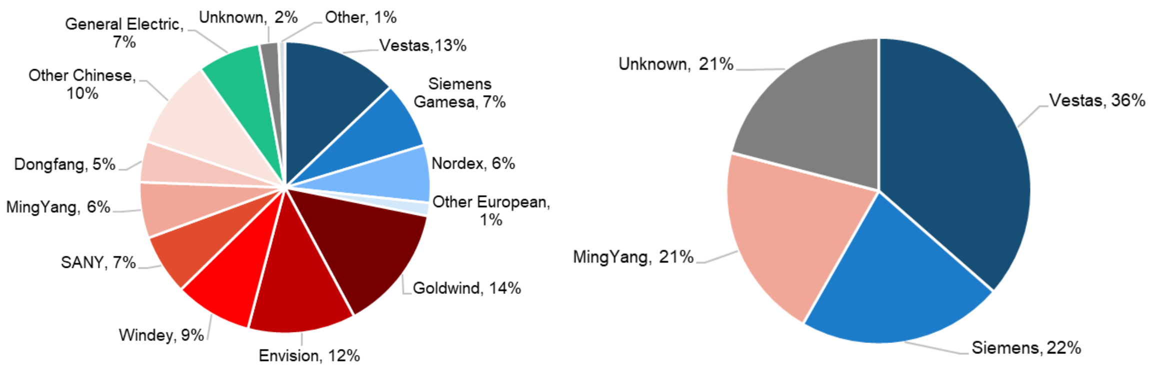


Source: JRC based on EurObserv'ER, 2024.

3.3 Role of EU Companies

The 2023 market shares for wind turbines are presented in **Figure 38**. Chinese OEMs dominate the global onshore market, holding 63% of the share, followed by European OEMs at 27% and American OEMs at 7%. In contrast, European OEMs lead the global offshore market, capturing 58% of the total due to the prominence of Vestas and Siemens.

Figure 38. Global market share of wind turbines for 2023 onshore (left) and offshore (right) installations.

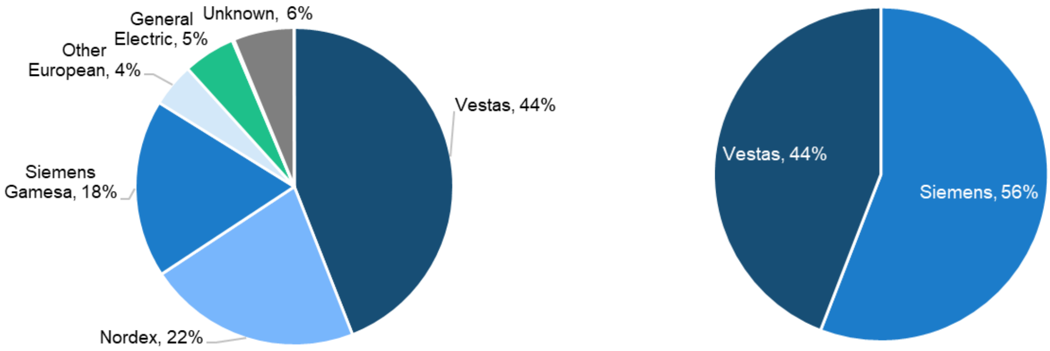


Source: JRC based on GWEC, Wood MacKenzie, 2024.

The market shares within the EU are shown in **Figure 39**. European OEMs dominate the domestic onshore market with an 88% share and monopolize the offshore market entirely.

In terms of components, the EU holds 12% of the global manufacturing capacity for blades and 15% of that for nacelles (**Figure 40**). This capacity corresponds to approximatively 150 to 185% of the deployments in the EU in 2023 (16.2 GW). This remains well below the manufacturing capacity of China, which currently holds 60% of the global manufacturing capacities for blades and 65% for nacelles.

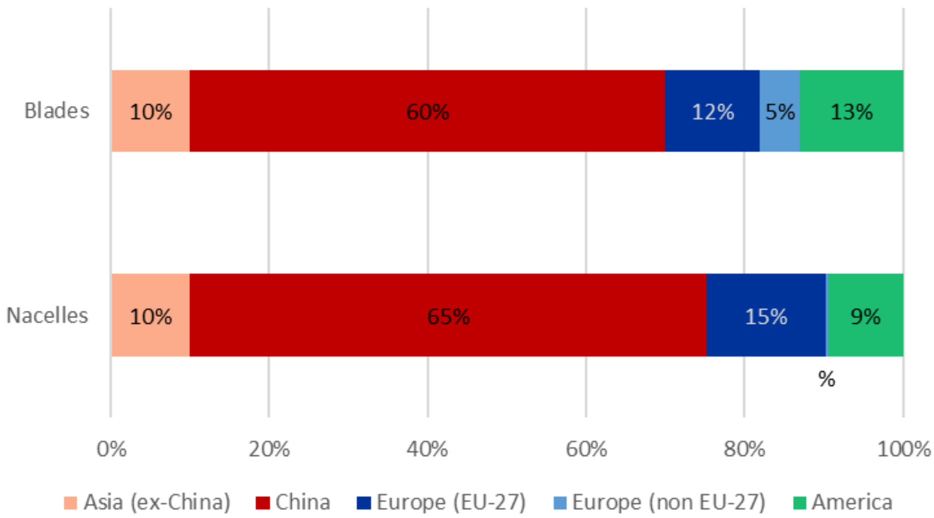
Figure 39. EU market share of wind turbines for 2023 onshore (left) and offshore (right) installations.



Source: JRC based on GWEC, Wood MacKenzie, 2024.

The Net-Zero Industry Act, adopted in June 2024, aims to accelerate the production of net-zero technologies within the European Union and streamline the regulatory environment for these technologies. Its primary goal is to ensure that by 2030, the EU's manufacturing capacity reaches a minimum of 40% of the annual deployment requirements needed to meet the EU's 2030 climate and energy objectives. Additionally, the Act sets a limit on single sources of supply, with a single third-country supply restriction of no more than 50%.

Figure 40. Global manufacturing capacity of major wind components.



Source: JRC based on BNEF, S&P, Rystad Energy, 2024.

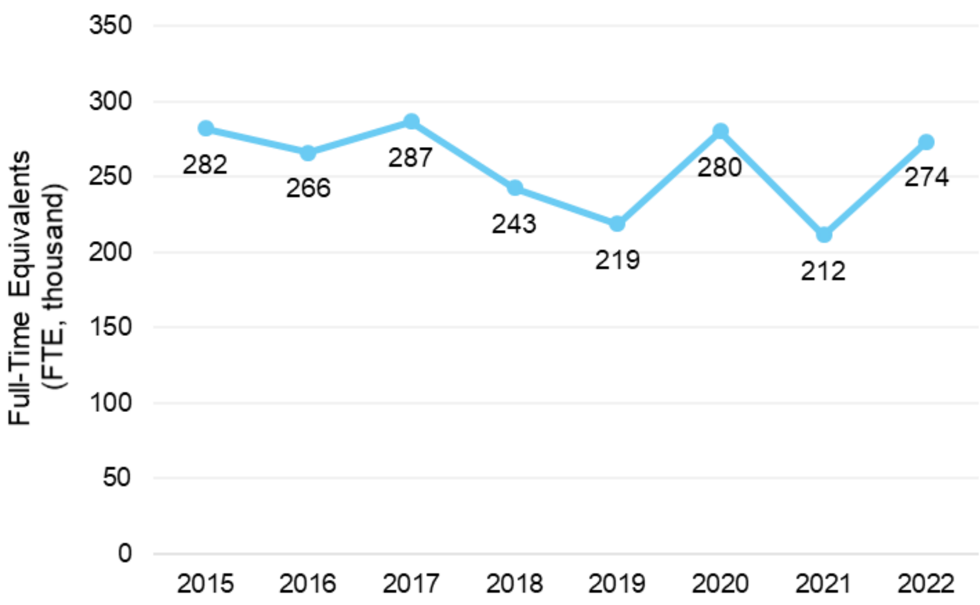
3.4 Employment

Wind is a strategic industry for the EU, employing between 274 and 326 thousand FTEs for the year 2022[4] (EurObserv'ER, 2024; ETIP Wind, 2024). According to EurObserv'ER, the total 274 thousand FTEs represent a 29% increase compared to 2021, when the sector employed 212 thousand FTEs (see **Figure 41**). Germany ranks first in terms of direct and indirect jobs in 2022 (85.6 thousand FTEs), followed by Spain (37.1 thousand

[4] These are estimates using different methods. ETIP Wind estimates the figure to be 326 thousand FTEs in 2022, while EurObserv'ER estimates a total of 274 thousand FTEs in the wind energy sector for the same year.

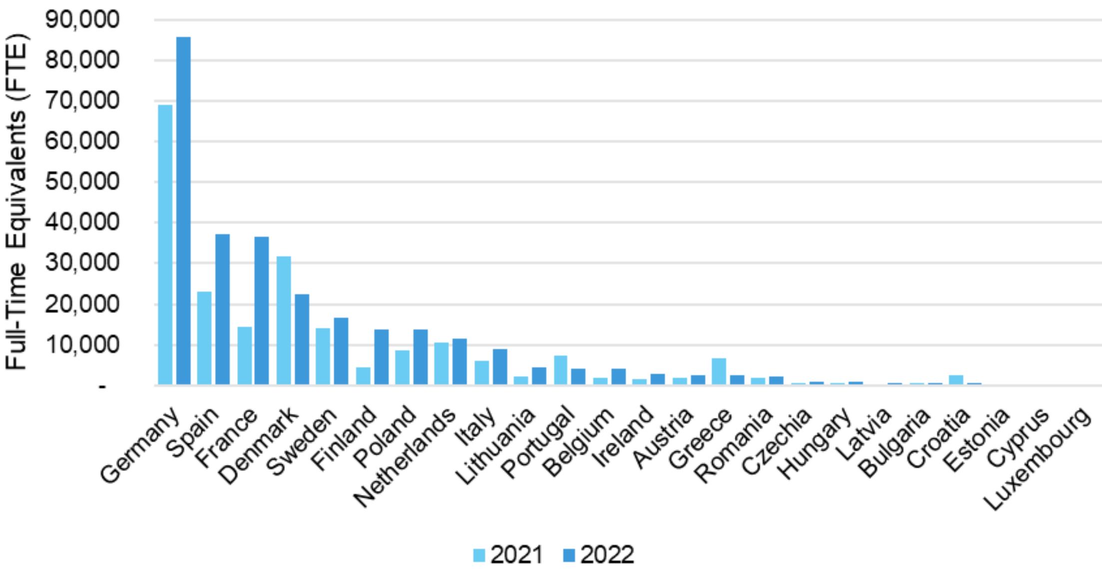
FTEs) and France (36.5 thousand FTEs) (**Figure 42**). Technical, commercial and administrative employees represent 54% of the workforce, while 36% are in management roles and 10% in executive or directive functions. Regarding the distribution of jobs per gender, 18% of workers directly employed in the European wind industry are women, a proportion that has been stable since 2017 (ETIP Wind, 2024). Overall, the European total wind energy workforce forms about 30% of the estimated global employment in the wind energy sector, with the largest proportion of all wind-related jobs located in China (49%) (IRENA/ILO, 2023).

Figure 41. Evolution of direct and indirect jobs in the wind energy sector in the period 2015-2022.



Source: JRC based on EurObserv'ER, 2024.

Figure 42. Employment (direct and indirect jobs) in the wind sector in 2021 and 2022.



Note: Employment is expressed in full-time equivalents (FTE).
Source: JRC based on EurObserv'ER, 2024.

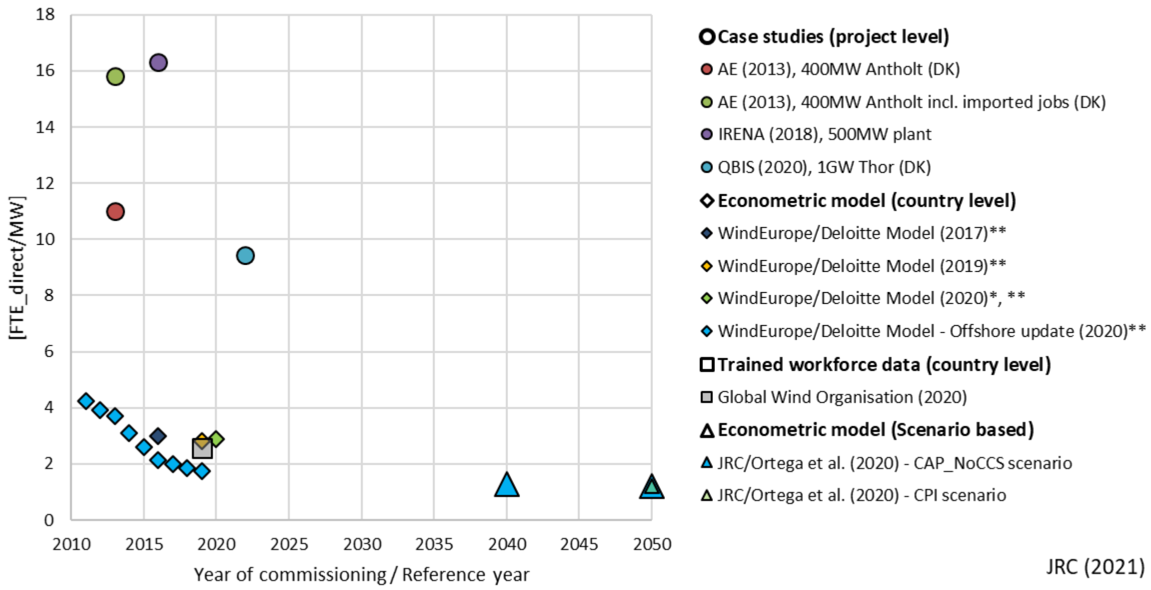
3.5 Labour productivity and energy intensity

Labour productivity. Figures on labour productivity in the offshore wind sector, measured in direct full-time equivalents (FTE) per MW installed, have been declining in recent years as the learning effect improves, with more capacity installed in the sector. Yet the scope and boundary conditions of these studies differ significantly, ranging from case studies at project level to econometric models and scenario-based projections estimating the employment factor at country or sector level (SEE). Direct job estimates for single projects are in the range of 15.8-16.3 FTE/MW for projects in the period 2013-2016 (QBIS, 2020; IRENA, 2018). Due to productivity improvements, some studies estimate a decrease in specific direct labour requirements to 9.5 FTE/MW per project by 2022. Although these numbers show the expected learning effect, they cannot be used to estimate the total number of jobs in the industry as the extrapolation from project-level capacity to installed capacity in the market would lead to double counting and thus an overestimation.

Current econometric models estimating the number of jobs using employment factors, trade data and/or contribution to GDP of the sectors involved shows direct employment figures declining from about 4 $FTE/MW_{Installed}$ in 2010 to a range of 1.8-2.9 $FTE/MW_{Installed}$ in 2020. When including indirect employment effects, 2.2 to 5.1 $FTE/MW_{Installed}$ seems plausible (GWO, 2020; JRC, 2020; Ortega et al., 2020; WindEurope, 2020; Deloitte/WindEurope, 2017). Scenario-based analyses estimate a further decline in direct labour productivity to about 1.2 $FTE/MW_{Installed}$ by 2050.

The onshore wind sector shows a lower specific labour productivity than offshore, based on the latest case studies and econometric models. Direct job estimates for single onshore wind projects are in the range 1.73.0 FTE/MW for projects in the period 2015-2019. Differences in this spread seem to originate in project size and geographical scope (Ejdemo and Söderholm, 2015; Okkonen and Lehtonen, 2016). Econometric models at regional and national levels estimate the number of direct jobs at 0.5-2.3 $FTE/MW_{Installed}$ with European estimates declining to about 0.7 $FTE/MW_{Installed}$ in 2019 (Llera Sastresa et al., 2010; Brown et al., 2012; Dvořák et al., 2017). Long term scenario models estimate future labour productivity for onshore wind at a similar scale, with values ranging from 0.35 to 0.9 $FTE/MW_{Installed}$ (Ortega et al., 2020).

Figure 43. Estimated direct person years (FTE/MW) for offshore wind based on different case studies and modelling approaches.



Note: Employment is expressed in full-time equivalents (FTE).
** Includes direct jobs from wind turbine component manufacturers where a split between onshore& offshore is not possible.*
*** Direct jobs estimated based on contribution to the GDP of the sectors involved in the industry and annual reports.*

Source: JRC, 2021.

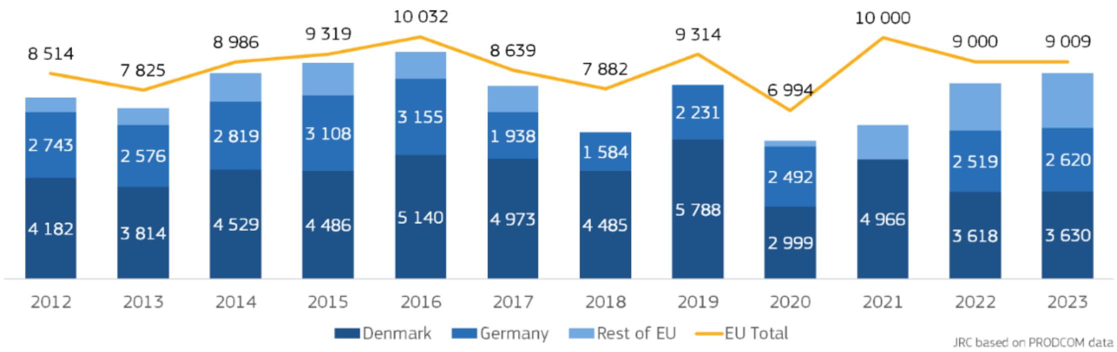
Energy intensity. The energy intensity is analysed based on the cumulative energy demand (CED) along the lifecycle of either onshore or offshore wind. For onshore wind, life cycle analyses from specific case studies and OEM data (SiemensGamesa, Vestas, NordexAcciona) indicate a decrease in the CED from 0.12-0.17 MJ_{input}/kWh_{el} in 2011 to 0.08-0.12 MJ_{input}/kWh_{el} in 2022. For offshore wind, the majority of life cycle analyses find the cumulative energy demand to be between 0.1 and 0.19 MJ_{input}/kWh_{el}, which is comparable to the energy intensity of onshore wind turbines. However, data points on floating offshore show higher values than bottom-fixed offshore wind. Besides the life cycle inventory data used, decisive factors can influence the CED, such as the assumed geographical reference (e.g. countries' electricity mix and wind resource).

3.6 EU industrial production

The Prodcom code 28112400 (Wind turbines - Generating sets, wind-powered) is used as a proxy to monitor the EU's manufacturing output in the wind industry. The PRODCOM code does not distinguish between the size or the use of the turbines; thus, there is no distinction between the onshore and offshore wind sections. The sum of countries' production (boxes) is lower than the 'EU Total' (line) because some Member States keep their production data confidential. However, Eurostat includes confidential data in the 'EU Total' estimates.

In 2023, the EU production value of wind turbines remained stable at EUR 9 billion (**Figure 44**). Denmark and Germany were the top EU producers, holding 40% and 29% of the total EU production, respectively, followed by Spain (18%) and France (8%). In the last 10-year average, Denmark holds 57% of the EU production and Germany 29%.

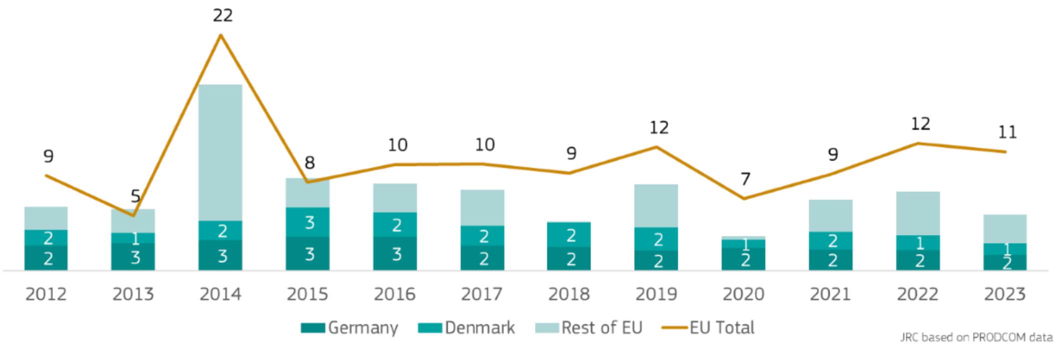
Figure 44. EU production value and top producers among the Member States disclosing data [EUR million].



Source: JRC based on PRODCOM data, 2024.

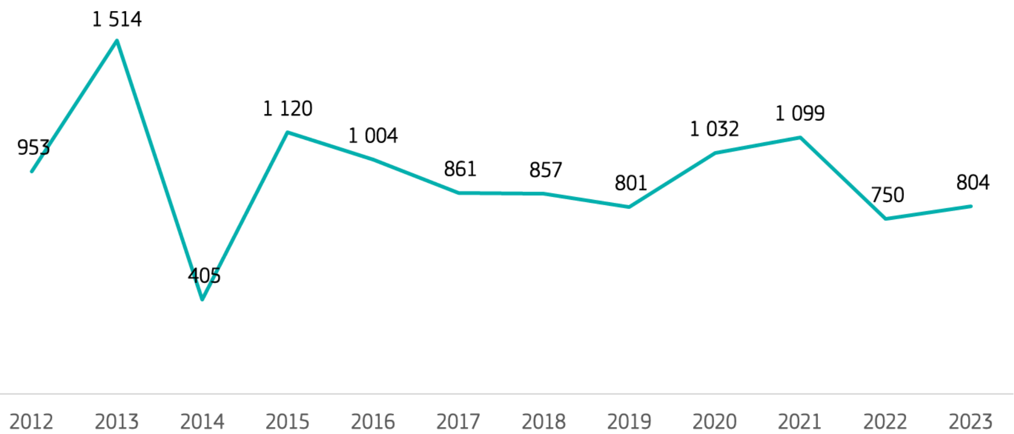
The EU production shrank by -7% in terms of quantities in 2023, at around 11 thousand wind turbine pieces (**Figure 45**). Spain was the top producer, holding one-fourth of the EU production in quantities, followed by Germany (13%) and Denmark (10%), meaning that Denmark and Germany produce wind turbines of higher value. France didn't disclose any data on quantities. In 2023, the average EU production value per piece increased by 7% at around EUR 800 thousand per wind turbine (**Figure 46**).

Figure 45. EU production in quantities [Thousand pieces].



Source: JRC based on PRODCOM data, 2024.

Figure 46. EU production value per wind turbine [Thousand EUR per piece].



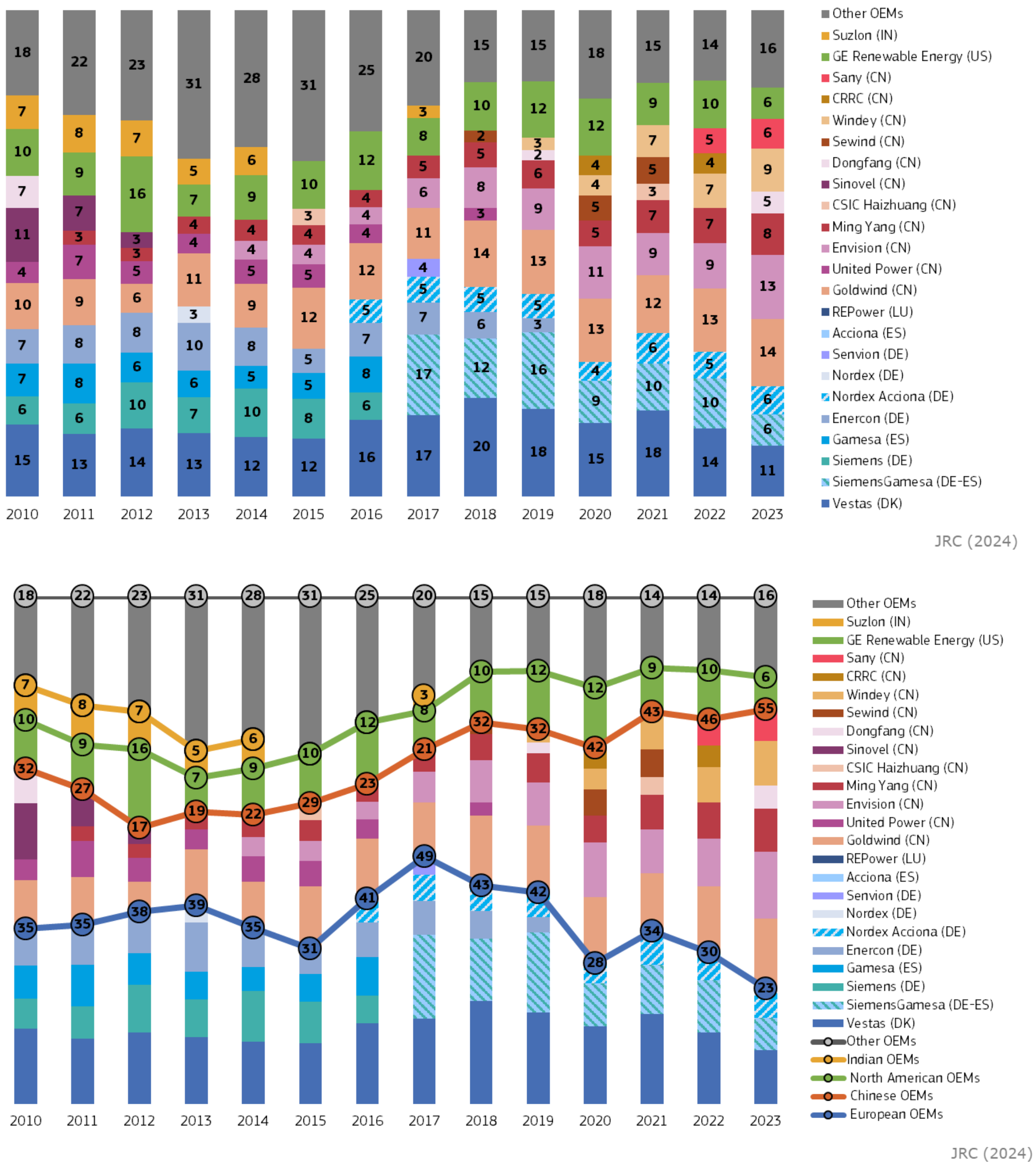
Source: JRC based on PRODCOM data, 2024.

4. EU market position and global competitiveness

4.1 Global & EU market leaders

In the past decade, European original equipment manufacturers (OEMs) have been dominant in the wind energy sector. However, their global market share has gradually declined, and in 2023, they ranked second to Chinese OEMs. Despite this, European OEMs continue to dominate the domestic market (see Chapter 3.3 and **Figure 39**), as the decrease in European OEMs' global market share is primarily due to the rapid growth of the Chinese market, supported by Chinese OEMs. Among the top 10 OEMs in 2023, Chinese companies had the highest global market share at 55%, followed by European companies at 23% and North American companies at 6% (**Figure 47**).

Figure 47. Market share (%) of the top 10 OEMs in wind energy over the period 2010-2023 (top) and their respective origin (bottom).

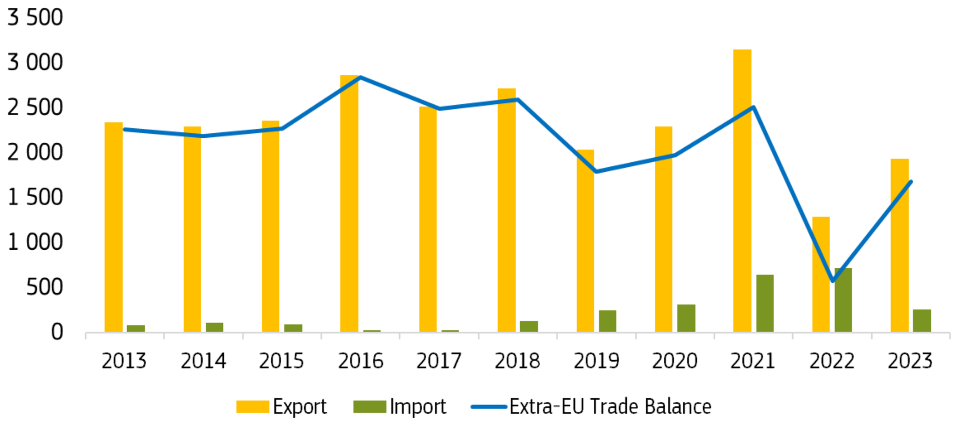


Source: JRC based on GWEC, 2024.

4.2 Trade (import/export) and trade balance

In 2023, the EU presence in the global market of wind generating sets was strengthened as exports increased by 60% (EUR 1.9 billion) and imports decreased by 65% (EUR 250 million) compared to the previous year (**Figure 48**). The increase in the EU exports is followed by an increase in the extra-EU share in global exports in 2021-2023, reaching 74% from 54% in 2020-2022. For the same reference periods, the share of intra-EU imports decreased from 66% to 62%.

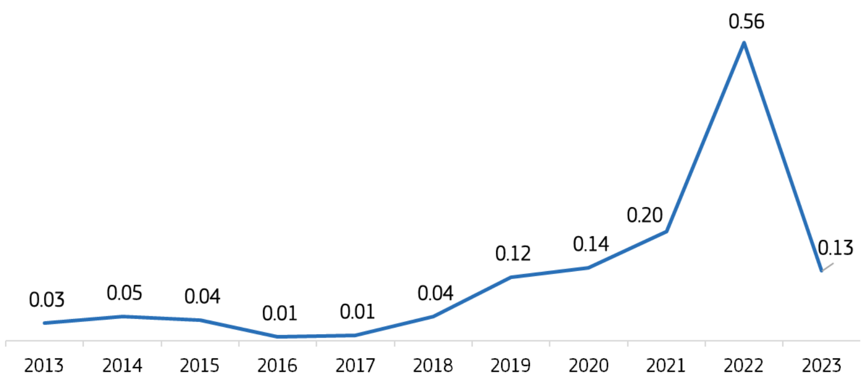
Figure 48. Extra-EU trade for wind generating sets [EUR Million].



Source: *JRC based on COMEXT data, 2024.*

Even though the share in global exports has increased, it is still lower than the pre-pandemic levels (87% for 2017-2019) as is the value of intra-EU imports (93% for 2017-2019). In 2021 exports increased by 38%, yet the imports to exports ratio was higher than the previous years (**Figure 49**). In 2023, the imports to export ratio fell to the pre-pandemic levels but remained higher than 0.1, suggesting that extra-EU imports have captured a share of the EU wind generating sets market.

Figure 49. Extra-EU imports to exports ratio.

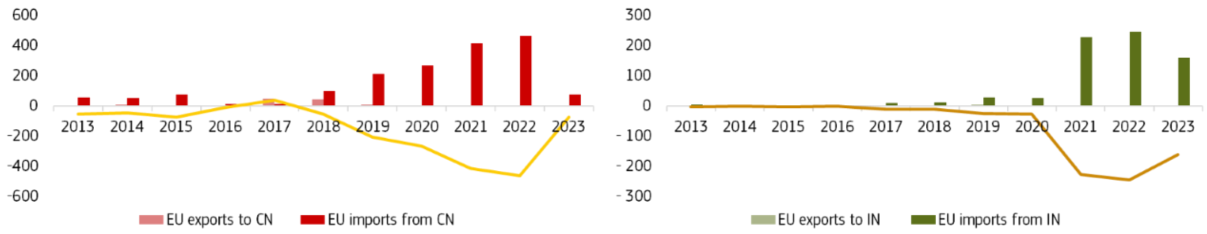


Source: JRC based on COMEXT data, 2024.

In 2023, China and India remained the two main importing partners despite the reduction in imports (-84% and -35%, respectively) (**Figure 50**). The two countries provided over 94% of extra-EU imports value (99% in 2022). China's share plummeted to 30% from 65%, while India's share increased to 64% from 34% in 2022.

The UK (31%), the US (19%), Taiwan (15%) and Türkiye (14%) remained EU's main exporting partners, receiving 79% of the extra-EU exports in total value.

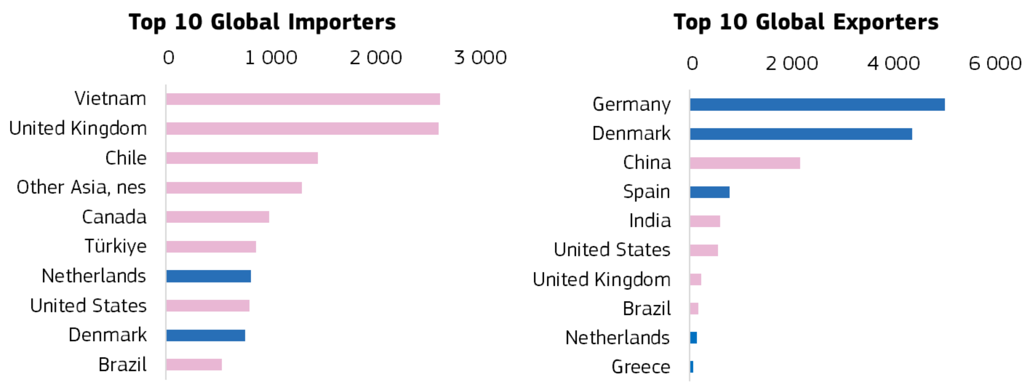
Figure 50. EU trade with China (left) and India (right) [EUR Million].



Source: JRC based on COMEXT data, 2024.

Germany, Denmark, China and Spain remained the top global exporters for 2021-2023, while the Netherlands dropped place from the fifth place to the ninth in 2020-2022 (**Figure 51**). The Netherlands maintained its position amongst the top global importers and Denmark showed up as ninth, but Sweden and Poland fell out.

Figure 51. Top global importers (left) and exporters (right) of wind generating sets (2020-2022) [EUR Million].



Source: JRC based on COMEXT and COMTRADE data, 2024.

The EU captured the import flows of half of the growing markets (EU share greater than 40%) during 2020-2022, and had the smallest share in Colombia, Argentina and Vietnam (**Table 4**).

Table 4. Growing markets based on a 2-year average of import change.

Country	Total import (2020-2022) [EUR million]	% import from the EU
Vietnam	2 805	14%
Other Asia, not elsewhere specified	1 674	88%
United States	998	53%
Canada	737	19%
Kazakhstan	506	41%
Brazil	431	26%
Columbia	395	6%
Japan	339	58%
Argentina	227	8%
Morocco	215	87%

Source: JRC based on COMTRADE data, 2024.

4.3 Resource efficiency and dependence in relation to EU competitiveness

Raw materials used in wind power plants include different rare earth materials, structural materials and metals (see **Table 5**).

Table 5. List of raw materials used in wind power plants.

Raw materials	Dysprosium, Neodymium, Praseodymium, Terbium, Niobium, Borate, Silicon, Chromium, Manganese, Molybdenum, Aluminium, Iron ore, Nickel, Silica sand, Copper, Zinc, Aggregates, Lead, Gadolinium, Balsa wood

Source: JRC, 2023.

The rare earth elements and permanent magnets supply chain contains the most critical bottlenecks and highest supply risk. China dominates the rare earth elements market, which spans the entire value chain of permanent magnets, including extraction, metal refinement, alloying, and magnet manufacturing. Rare earth permanent magnets, specifically dysprosium (Dy), neodymium (Nd), praseodymium (Pr), and terbium (Tb), play a vital role in the electric generators of wind turbines, particularly offshore technologies. These magnets are essential for achieving high efficiency and performance levels. In 2020, almost all offshore wind turbines in the EU and approximately 72% of the globally deployed offshore wind turbines utilised generators with rare earth permanent magnets. Onshore turbines installed in 2020 had a lower adoption rate, with around 13% in the EU and 22% worldwide using permanent magnets (JRC, 2022).

Proposed in March 2023 and adopted in April 2024, the Critical Raw Materials Act aims to ensure a secure and sustainable supply of critical raw materials (CRMs) for Europe's industry, where CRMs are materials of high economic importance for the EU and which present a high risk of supply risk disruption. Besides the rare earth elements mentioned above (Dy, Nd, Pr and Tb), boron (also used for permanent magnets), niobium, aluminium, copper, manganese and nickel are also considered CRMs. The EU production share in raw materials is only 2%, while China leads with 43%.

The material intensity indicates the specific mass of each raw or composite material per unit of installed capacity. An indicative range on the single materials is reported in **Table 6**. A more comprehensive analysis can be found in (Carrara et al., 2023; Telsnig et al., 2022).

Blades are another essential component of wind turbines, and their design and manufacture must balance energy output optimisation (proportional to blade length) with the ability to withstand varying wind speeds and weight containment. Therefore, the materials used must possess a high strength-to-weight ratio, as well as high stiffness and fatigue resistance. Balsa wood is a key material for wind turbine blades, specifically in spar caps and blade cores, due to its low density and high stiffness. Blade manufacturers are experiencing a strong resource dependency as most balsa wood is sourced from Ecuador, which supplies an estimated 75% to 90% of the world's balsa wood demand. The latest uptake in global wind energy markets resulted in a supply bottleneck for balsa wood, over-logging and soaring prices. Countries and manufacturers look for alternatives by planting balsa in their own premises (China), replacing balsa wood with recycled polyethylene terephthalate (rPET) or creating hybrid designs (OEMs). Additionally, various composite materials such as glass fibre, carbon fibre, polymers, and plastics can also be employed.

Table 6. Material intensity estimates in kg/MW for wind turbines in general (ranges) and for the different turbine types (Carrara et al., 2020) and material data on wind turbines released in 2022 (Vestas, 2022 a).

Material	Range	DD-EESG	DD-PMSG	GB-PMSG	GB-DFIG	Vestas V150-4.2MW & V136 – 4.2MW (Type F / GB-SCIG)
		(Carrara et al., 2020)				(Vestas, 2022 a)
Concrete	243 500 - 413 000	369 000	243 000	413 000	355 000	357 390 - 483 590
Steel	107 000 – 132 000	132 000	119 500	107 000	113 000	123 257- 153 447
Polymers	4 600	4 600	4 600	4 600	4 600	3 670 - 4 430
Glass/carbon composites	7 700 - 8 400	8 100	8 100	8 400	7 700	7 530 - 9 350
Aluminium (Al)	500 - 1 600	700	500	1 600	1400	1 660 - 1 740
Boron (B)	0 - 6	0	6	1	0	0.3
Chromium (Cr)	470 - 580	525	525	580	470	560 - 675
Copper (Cu)	950 - 5 000	5 000	3 000	950	1 400	840 - 890
Dysprosium (Dy)	2 - 17	6	17	6	2	1.2
Iron (cast) (Fe)	18 000 - 20 800	20 100	20 100	20 800	18 000	17 473
Manganese (Mn)	780 - 800	790	790	800	780	1 266 - 1 581
Molybdenum (Mo)	99 - 119	109	109	119	99	
Neodymium (Nd)	12 - 180	28	180	51	12	8.7
Nickel (Ni)	240 - 440	340	240	440	430	204
Praseodymium (Pr)	0 - 35	9	35	4	0	
Terbium (Tb)	0 - 7	1	7	1	0	
Zinc (Zn)	5 500	5 500	5 500	5 500	5 500	1 191 - 1 204

Source: JRC, 2022.

Note: For a comprehensive list of the materials in use and assumptions on the figures please refer to (Carrara et al., 2020).

5. Conclusions

This report presents the state of the art in wind energy technology and analyses the R&D development trends and technology progress made in the EU until the end of 2023. It also provides an analysis of the EU's global competitiveness within the wind value chain and identifies potential bottlenecks and supply risks in the push to meet its climate targets.

State of the art of technology and future developments

In terms of technology, both onshore and bottom-fixed offshore wind energy systems are commercially available, while floating offshore wind is rapidly growing and airborne wind energy systems are still at a lower level of development.

The year 2023 saw significant progress in wind energy deployment, reaching over 1 TW of cumulative installed capacity. Onshore wind installations accounted for over 100 GW, and offshore wind installations added over 10 GW, making it a record year. Wind energy now represents 3.3% of primary energy consumption and 7.8% of electricity generation worldwide.

Globally, the EU ranks second after China with 16 GW of new installations, bringing the total capacity to 220 GW, including 201 GW onshore and 19 GW offshore. Within the EU, Germany leads in both onshore and offshore wind deployment (61.1 GW and 8.3 GW), followed by Spain (30.6 GW) and France (22.0 GW) in onshore, and the Netherlands (4.7 GW) and Denmark (2.7 GW) for offshore. In 2023, wind energy contributed 477 TWh to electricity generation in the EU, representing 17.5% of the total electricity generation. According to the *POTEnCIA CETO 2024 scenario*, this figure could grow to 34% (around 1 160 TWh) in 2030 and 40% (2 411 TWh) in 2050.

The LCoE of onshore wind is EUR 31 per MWh, making onshore wind highly competitive against fossil fuels. With a LCoE of EUR 77 per MWh, offshore wind is more expensive, but it offers the advantages of higher capacity factors due to stronger and more consistent wind resources at sea. On top of this, European offshore wind generation tends to be higher during winter, which aligns with a higher peak demand.

The EU leads in public RD&I investment related to wind energy, with Member States accounting for 35% of all public investment in the sector for the period from 2013 to 2022. At about 37%, Germany leads in EU public R&D investment in the period 2013-2023, followed by Denmark and France (each at 14%). Additionally, EU framework programmes Horizon 2020 and Horizon Europe contribute significantly to public funding of wind energy. Within these programmes, the top R&I priorities receiving funding are floating offshore (EUR 146 million), offshore wind (EUR 135 million), and research on new materials and components (EUR 73 million).

However, most RD&I funding comes from the corporate sector, with the EU leading in private R&D investment. For the period from 2010 to 2020, the EU is estimated to lead private R&D investment with about 40% of the total private R&D funding. Within the EU, private R&D funding is concentrated in Germany and Denmark, where the leading European OEMs and their value chains are located. European companies are leaders in terms of innovation, representing 58% of high-value inventions in 2019-2021. In terms of private equity, venture capital investments increased to EUR 195 million in 2023.

From 2010 to 2023, the EU ranked second in the number of articles (19%) related to wind energy, after China (31%); but indicators measuring the impact of peer-reviewed articles show that the EU can compete with its international counterparts. China leads in highly cited articles (1 164), closely followed by the EU (986).

Value chain analysis

In 2022, the wind energy sector experienced a turnover growth, reaching EUR 43 billion, which is at the higher end of the EUR 34-44 billion average between 2015 and 2022. GVA also increased, reaching EUR 19 billion, a 26% increase compared to the previous year's figure. Germany leads in direct GVA with approximately EUR 6.2 billion, followed by France (EUR 2.4 billion), Spain (EUR 2.1 billion), and Denmark (EUR 2.0 billion). Employment in the sector grew as well, with EurObserv'ER estimating that it employed around 274 000 FTEs; however, this number may be underestimated.

EU companies have a significant presence in the wind energy market, accounting for 88% of the onshore domestic market and 100% of the offshore market. In 2023, the EU production value of wind turbines remained stable at EUR 9 billion. Denmark and Germany were the top EU producers, holding 40% and 29% of the total EU production, respectively, followed by Spain (18%) and France (8%).

EU position and global competitiveness

European OEMs rank second in terms of global market shares. This is a consequence of the rapid growth of the Chinese market, but the EU remains the largest supplier of its domestic market.

The EU's presence in the global market for wind generating sets was strengthened in 2023 as exports increased by 60% and imports decreased by 65% compared to the previous year. China and India remained the two main importing partners, despite the reduction in imports. The UK (31%), the US (19%), Taiwan (15%), and Türkiye (14%) were the EU's main exporting partners, receiving 79% of the extra-EU exports in terms of total value.

Potential bottlenecks and supply risks in the wind sector could arise from critical raw materials, with rare earth elements utilised in permanent magnets of turbine generators identified as particularly vulnerable due to their dependence on a single non-EU country for sourcing.

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List of abbreviations and definitions

AWES	Airborne wind Energy Systems
CED	Cumulative Energy Demand
CETO	Clean Energy Technology Observatory
CPC	Cooperative Patent Classification
CRM	Critical Raw Materials
DD-EESG	Direct Drive – Electrically Excited Synchronous Generator
DD-PMSG	Direct Drive – Permanent Magnet Synchronous Generator
DG	Directorate General
EC	European Commission
EIA	Environmental Impact Assessment
EPBT	Energy Pay-Back Time
EU	European Union
FTE	Full-Time Equivalents (employment)
FWCI	Field Weighed Citation Impact
GB-DFIG	GearBox – Doubly-Fed Induction Generator
GB-PMSG	GearBox – Permanent Magnet Synchronous Generator
GB-SCIG	GearBox – Squirrel Cage Induction Generator
GE	General Electric
GVA	Gross Value Added
GW	Gigawatt
HAWT	Horizontal Axis Wind Turbines
IEA	International Energy Agency
kW	Kilowatt
LCA	Life Cycle Analysis
LCOE	Levelised Cost of Energy
MSP	Maritime Spatial Planning

MSs	Member States
MW	Megawatt
MWh	Megawatt hour
NID	Nature Inclusive Design
NNL	No Net Loss
NSNG	North Sea Net Gain
O&M	Operation & Maintenance
OECD	Organisation for Economic Co-operation and Development
OEMs	Original Equipment Manufacturers
OW	Offshore Wind
OWF	Offshore Wind Farm
PET	Polyethylene Terephthalate
R&D	Research & Development
R&I	Research & Innovation
RD&D	Research, Development & Demonstration
RES	Renewable Energy Systems
RNS	Rich North Seas
SDG	Sustainable Development Goal
SET Plan	Strategic Energy Technology Plan
SGRE	SiemensGamesa Renewable Energy
TCP	Technology Collaboration Programme
TLP	Tension-Leg Platform
TRL	Technology Readiness Level
TWh	Terawatt hour
VAWT	Vertical Axis Wind Turbines
VC	Venture Capital
WT	Wind Turbine

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Annex 1 Summary table of data sources for the CETO indicators

Table 7. Data sources.

Theme	Indicator	Main data source
Technology status and development trends	Technology readiness level	JRC
	Installed energy capacity and generation	JRC database, GWEC, EurObserv'ER
	Technology costs	JRC, BNEF, IRENA
	Public and private RD&I funding	JRC based on IEA, JRC SETIS, JRC based on Pitchbook
	Patenting trends	Patstat
	Scientific publication trends	JRC based on TIM
	EU-supported Research and Innovation	JRC based on CORDIS
Value chain analysis	Turnover	EurObserv'ER
	Gross Value Added	EurObserv'ER and WindEurope
	Role of EU companies	JRC database, WoodMackenzie, 4COffshore, BNEF, S&P, Rystad Energy
	Employment	EurObserv'ER
	Labour productivity and energy intensity	IRENA
	EU industrial production	PRODCOM
EU market position and global competitiveness	EU's position in global market share	JRC, GWEC
	EU trade (imports, exports) and trade balance	COMEXT
	Resource efficiency and dependencies	JRC

Annex 2 Sustainability assessment framework

Table 8. Sustainability assessment table.

Parameter/Indicator	***Input***
Environmental	
LCA standards, PEFCR or best practice, LCI databases	*No sector guidelines, but LCA regulated by the ISO 14040 and ISO 14044 standards. LCI data of differing quality available in LCA studies of the main wind turbine manufacturers (Vestas, SGRE). Manufacturers provide no detailed LCA and LCI data on the latest offshore wind turbines.*
GHG emissions	*JRC literature review based on manufacturers LCA, environmental product declarations and case studies from scientific literature.* ***Onshore wind values****: MIN: 4.4 gCO2eqv/kWh; MAX: 12.2 gCO2eqv/kWh; AVERAGE: 7.4 gCO2eqv/kWh* ***Offshore wind values:*** *MIN: 8 gCO2eqv/kWh; MAX: 32 gCO2eqv/kWh; AVERAGE: 17 gCO2eqv/kWh*
Energy balance	*The Energy Pay-Back Time of wind energy systems is dependent on the capacity (MW) of the turbine as well as its geographical location.* ***EPBT of representative wind power plants (industry values):*** *100 MW onshore wind plant with Vestas V136-4.2MW wind turbines* (Vestas, 2022 b)*:* *Net energy payback time: 6.1 months* *Primary energy payback time: 2 months (assuming primary energy input of EU average grid* *640 MW offshore wind plant with SGRE SG 8.0MW-167 DD wind turbines (data based on EPD not full LCA study)* (SGRE, 2022) *Net energy payback time: 7.4 months* ***EPBT of wind power plants in scientific literature (exemplary):*** (Bonou, Laurent, and Olsen, 2016; Wagner et al., 2011)*:* *Onshore wind plants (Turbine rated capacity 2.3MW – 3.2MW):* *Energy payback time: 5.2 – 6.2 months* *Offshore wind plants (Turbine rated capacity 4MW – 6MW):* *Energy payback time: 10 – 11.1 months* *Offshore wind plants (Turbine rated capacity 5MW):* *Energy payback time: 6.1 – 9.5 months*
Ecosystem and biodiversity impact	*Cooper et al. (2022) find that the roll out of Offshore Wind Farms (OWFs) across the North Sea may present opportunities for biodiversity enhancement or so-called North Sea Net Gain (NSNG).* *The EU's Biodiversity Strategy provides a plan to protect nature and reverse the degradation of ecosystems. The strategy promotes the concept of No Net Loss (NNL) of biodiversity. The Netherlands aim to follow this concept by implementing a policy of Nature Inclusive Design (NID), whereby offshore wind developers are required to 'take measures to increase the suitable habitat for species naturally occurring in the North Sea'. Moreover the Rich North Seas (RNS) initiative (https://www.derijkenoordzee.nl/en/our-approach) that seeks to develop solutions which can be adopted by OWF developers, including the introduction of reef structures to promote colonisation by naturally occurring reef forming species (e.g. European oyster – Ostrea edulis , horse mussel – Modiolus modiolus, tube worms – Sabellaria spinulosa). OWFs*

	may also provide benefits for benthic biodiversity through reductions in fishing pressure, either as a result of exclusion or avoidance by boats, facilitating natural recovery of the seabed. To help support the expansion of offshore wind (OW), and to assess whether there is evidence of NSNG, there is an urgent need for high resolution maps depicting benthic biodiversity, and for development of approaches to assess temporal change. This is important given the placing of turbines (or their anchoring equipment, in the case of floating devices), hard substrate scour and cable protection on the seabed. These maps could go on to support licensing decisions and provide a benthic faunal baseline against which changes resulting from the development (positive or negative) can be assessed (Cooper, Downie, and Curtis, 2022).
Water use	***Exemplary 100 MW onshore wind plant with Vestas V136-4.2MW wind turbines*** (Vestas, 2022 b)*:* ***Blue water consumption*** *(net balance of water inputs and outputs of freshwater throughout the lifecycle:* *19-43 g_water/kWh (0.019-0.043 m3/MWh) (mainly during manufacturing, minimal water requirements during operation)* ***Contribution to water scarcity*** *based on AWARE (available water remaining) water scarcity footprint method* (Boulay et al., 2018)*:* *454-681 g_water/kWh (0.454-0.681 m3/MWh)* ***Estimated water consumption NdFeB Permanent Magnet Production*** *(1 kg of NdFeB Magnet)* (Marx et al., 2018)*:* *Resource depletion water: 0.345-0.905 m3/kg_NdFeB*
Air quality	*Impact category related to air quality:* *Human toxicity potential (HTP) covers the impacts on human health of toxic substances present in the environment* (Guinée et al., 2001). ***Exemplary 100 MW onshore wind plant with Vestas V136-4.2MW wind turbines*** (Vestas, 2022 b)*:* *Human toxicity potential (HTP): 5121 mg DCBeq/kWh (mainly during manufacturing stage)*
Land use	***Installed power densities:*** *For onshore projects, estimates indicate a range from 6.2-46.9 MW/km2.* *For offshore projects, estimates indicate a range from 3.3 to 20.2 MW/km2.* (Enevoldsen and Jacobson, 2021)
Soil health	*Exemplary 100 MW onshore wind plant with Vestas V136-4.2MW wind turbines* (Vestas, 2022 b)*:* ***Impact categories related to soil health:*** *Acidification potential (AP): 22 mg SO2eq/kWh (mainly manufacturing stage)* *Eutrophication potential (EP): 2.7 PO4eq/kWh (mainly manufacturing stage)* *There is no direct soil pollution caused by wind turbines operation and maintenance* (Hamed and Alshare, 2022).
Hazardous materials	*No information*
Economic	
LCC standards or best practices	*Levelised cost of electricity*

Cost of energy	***EU onshore wind LCoE range**: 36-51 EUR/MWh* ***EU offshore wind LCoE range:** 61-95 EUR/MWh* *Please see levelised cost of electricity range in chapter 2.3*
Critical raw materials	*Dysprosium, Neodymium, Praseodymium, Terbium, Gadolinium and Borate show a high supply risk*
Resource efficiency and recycling	*Most materials of wind turbines can be recycled however composite waste poses challenge. Beyond the current approaches to keep composite waste from wind turbine blades out of landfill, innovations and measures for circular economy strategies are observed in other wind turbine components (e.g. components such as the tower, mooring, nacelle housing and grid integration technologies)* *No dedicated recycling infrastructure for NdFeB magnets as volumes are currently too low* (AMEC, 2014; Patil et al., 2022).
Industry viability and expansion potential	*Yes, see chapter 0 (on future deployments) and chapter 3.4 (on the industrial value chain)*
Trade impacts	*Yes, see chapter 4.2 on trade*
Market demand	*Yes, see chapter 0 (on future deployments) and chapter 3.4 (on the industrial value chain)*
Technology lock-in/innovation lock-out	*No dominant technology or technology provider*
Tech-specific permitting requirements	*Article 16 of the 2018 Renewable Energy Directive sets the regulatory framework for wind energy with clear requirements to Members States on the organisation and duration of the permit-granting process* (EP, 2018). *Administrative barriers, in particular in the granting of permits, have long been identified as a common bottleneck for the deployment of renewable energy projects which discourage potential investors. While the 2018 Renewable Energy Directive introduced rules on the organisation (single contact points) and maximum duration of the permit-granting process, stakeholders have underlined how additional guidance, such as the sharing of good practice, would help provide further improvement on the ground* (EC, 2022). *Example offshore wind:* *Established offshore wind markets (Denmark, Germany, UK, Netherlands) build on a 'one-stop shop' model to speed up the permitting process in which government agencies (and not the developers) are responsible for site selection in either a zonal or site-specific approach, pre-site investigations, licensing, Environmental Impact Assessment (EIA), grid connection and decommissioning.*
Sustainability certification schemes	*No information*
Social	
S-LCA standard or best practice	*No information*
Health	I. Selected examples on research on noise related impacts ***Perception and impact of wind energy related noise on humans:** (IEA Wind TCP - Task 39 (2022) summarises as follows: Psycho-medical studies have reported that, at high enough levels of low frequency noise (LFN), like for any other sound at high levels, humans can be affected in the form of annoyance, stress, irritation, unease, fatigue, headache, possible nausea and*

disturbed sleep. However, it must be remembered that the LFN emissions from a wind turbine, when heard at residential locations at a few hundred meters, are comparable with, or often below, the natural ambient levels. Although LFN can be measured in the immediate vicinity of a wind turbine and sometimes far away as well, there is no evidence that wind turbine noise can cause direct physical effects on people living nearby, considering the low levels involved at distances equal or larger than the typical minimum legal distances between wind turbines and dwellings. Typically, LFN and infrasound from wind turbines falls well below the level of audibility. A resident's attitude to wind turbines is an important factor in their response to them and annoyance certainly plays a role here (IEA Wind TCP Task 39, 2022).

Possible Perceptual and Physiological Effects of Wind Turbine Noise:
Carlile et al. (2018) analyse perceptual effects of laboratory exposure to low-frequency sound (LF) and infrasound (IS) stressing: A number of laboratory studies have directly exposed human listeners to IS and LF either directly recorded from wind turbines or synthesised to reproduce key elements of these recordings. A range of exposure symptoms have been reported but no systematic or significant effects of IS and LF have been demonstrated. [...] Although not an exhaustive survey of this literature, this review indicates that there are questions relating to the measurement and propagation of LF and IS and its encoding by the central nervous system that are relevant to the possible perceptual and physiological effects of wind turbine noise but for which we do not have a good scientific understanding. There is much contention and opinion in these areas that, from a scientific perspective, are not well founded in the data, simply because there are little data available that effectively address these issues. This justifies a clear call to action for resources and support to promote high-quality scientific research in these areas (Carlile et al., 2018).

Infrasound and low frequency noise from wind turbines: exposure and health effects:
Bolin et al. 2011 analyses: Three cross-sectional questionnaire studies show that annoyance from wind turbine noise is related to the immission level, but several explanations other than low frequency noise are probable. A statistically significant association between noise levels and self-reported sleep disturbance was found in two of the three studies. It has been suggested that LFN from wind turbines causes other, and more serious, health problems, but empirical support for these claims is lacking (Bolin et al., 2011).

II. Exposure to electromagnetic fields (EMF):

There is public concern on possible health hazards with respect to exposure to electromagnetic fields (EMF) generated by wind turbines. EMF exposure measurements performed by Alexias et al. (2020) indicate that EMF levels are similar or even lower compared to those in urban areas and well below international safety limits (Alexias et al., 2020).

III. Shadow flicker

Wind rotors can periodically cast shadows onto surrounding buildings during sunny intervals which can impact residents and their perception of wind energy. In order to prevent this, OEMs use shadow flicker protection systems integrated into the control system of a wind turbine (a light detection sensor system, such as the Vestas Shadow Detection System (VSDS)) taking into account the position of the sun and other meteorological data (DNV, 2022; Vestas, 2022 c).

Public acceptance	*Scherhaufer et al (2017) find that local opposition to/public acceptance of wind energy in Austria is caused by a complex set of individual and collective preferences ([...] with landscape-related impacts remaining significant) rooted in institutional and socio-political arrangements* (Scherhaufer et al., 2017). ***Drivers with respect to wind energy repowering projects:*** *Kitzing et al. (2020) demonstrate that for wind pioneer in Denmark, only 67% of the capacity removed in repowering projects was related to the physical space needed for a new turbine. Other factors that drive repowering include regulation (for example, noise-related, 8–17%), development principles (for example, aesthetics, 7–20%) and political bargaining (4–13%)* (Kitzing et al., 2020). *Frantál (2015) finds that disruption to local landscape was detected as the main factor behind opposition against repowering wind turbines in Czechia* (Frantál, 2015). *Ziegler et al. (2018) finds that public acceptance for lifetime extension of existing wind farms is perceived to have less local opposition than repowering with larger rotors and hub heights (investigating these factors in Germany, Spain, Denmark, and the UK)* (Ziegler et al., 2018).
Education opportunities and needs	*See chapter 3.5 good practices in revitalizing and repurposing workforce towards the wind energy sector*
Employment and conditions	*For employment data see chapter 3.5*
Contribution to GDP	*See chapter 3.2*
Rural development impact	*No information*
Industrial transition impact	*See chapter 3.4 for impacts and potential bottlenecks in the transition of the wind energy industry*
Affordable energy access (SDG7)	*No information*
Safety and (cyber)security	*Offshore wind: affecting navigational safety and air defence capabilities* *Cyber security: see for example cyber-attack on remote control of Enercon turbines in 02/2022*
Energy security	*No information*
Food security	*No information*
Responsible material sourcing	*No material was identified in relation to EU REGULATION (EU) 2017/821 requirements*

Source: JRC, 2022.

Annex 3 Energy system models and scenarios: POTEnCIA and POLES-JRC

AN 3.1 POTEnCIA model

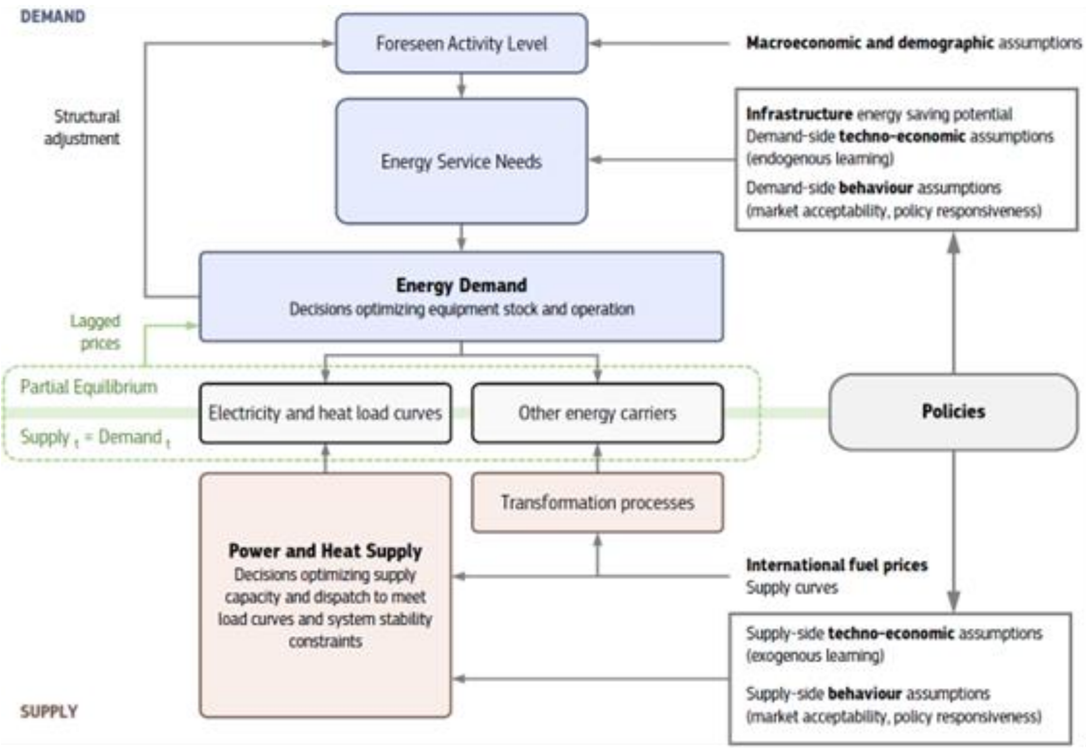
AN 3.1.1 Model overview

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed in-house by the European Commission's Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA allows for the joint evaluation of technology-focused policies, combined with policies addressing the decision-making of energy users. To this end:

- By simulating decision-making under imperfect foresight at a high level of techno-economic detail, POTEnCIA realistically captures the adoption and operation of new energy technologies under different policy regimes;
- By combining yearly time steps for demand-side planning and investment with hourly resolution for the power sector, POTEnCIA provides high temporal detail to suitably assess rapid structural changes in the EU's energy system;
- By tracking yearly capital stock vintages for energy supply and demand, POTEnCIA accurately represents the age and performance of installed energy equipment, and enables the assessment of path dependencies, retrofitting or retirement strategies, and stranded asset risks.

The core modelling approach of POTEnCIA (Figure 1; detailed in Mantzos et al., 2017, 2019) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies.

Figure 52. The POTEnCIA model at a glance.



Source: JRC adapted from Mantzos et al., 2019.

This core modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO_2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System (JRC-IDEES; Rózsai et al., 2024).

AN 3.1.2 POTEnCIA CETO 2024 scenario

The technology projections provided by the POTEnCIA model are obtained under a Climate Neutrality Scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU GHG emissions by 55% by 2030 and 90% by 2040, both compared to 1990, and reaches net zero EU emissions by 2050. To model suitably the uptake of different technologies under this decarbonisation trajectory, the scenario includes a representation at EU level of general climate and energy policies such as emissions pricing under the Emissions Trading System, as well as key policy instruments that have a crucial impact on the uptake of specific technologies. For instance, the 2030 energy consumption and renewable energy shares reflect the targets of the EU's Renewable Energy Directive and of the Energy Efficiency Directive. Similarly, the adoption of alternative powertrains and fuels in transport is consistent with the updated CO_2 emission standards in road transport and with the targets of the ReFuelEU Aviation and FuelEU Maritime regulations. A more detailed description of the *POTEnCIA CETO 2024 scenario* will be available in the forthcoming report (Neuwahl et al., 2024).

AN 3.2 POLES-JRC model

AN 3.2.1 Model overview

POLES-JRC (Prospective Outlook for the Long-term Energy System) is a global energy model well suited to evaluate the evolution of energy demand and supply in the main world economies with a representation of international energy markets. It is a simulation model that follows a recursive dynamic partial equilibrium method. POLES-JRC is hosted at the JRC and was designed to assess global and national climate and energy policies.

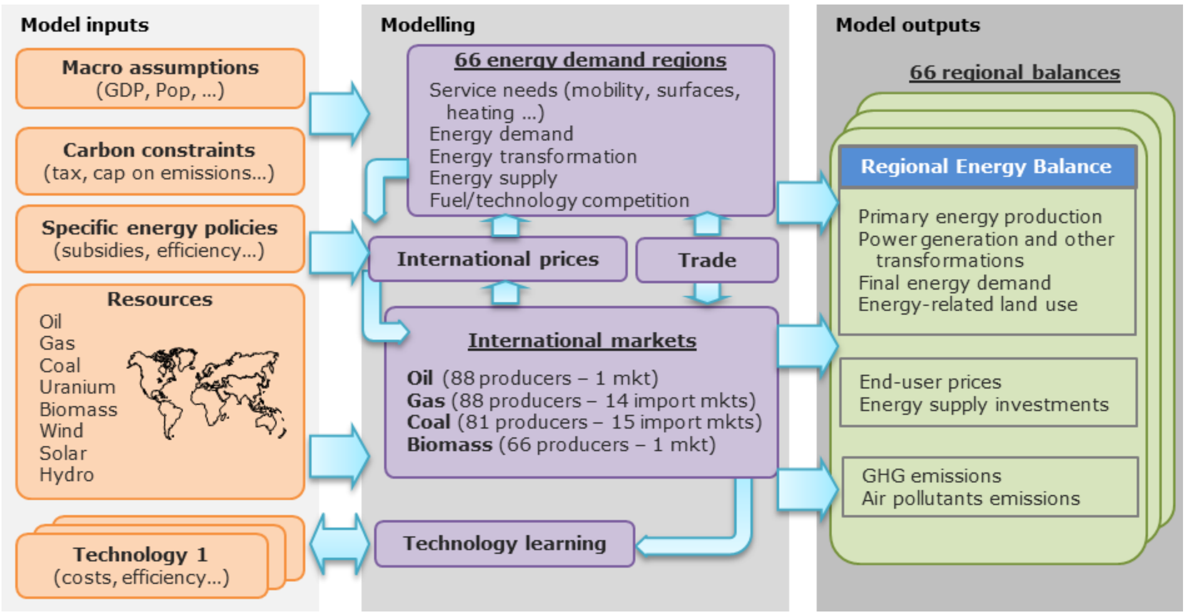
POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables) to transformation (power, biofuels, hydrogen and hydrogen-derived fuels such as synfuels) and final sectoral demand (industry, buildings, transport). International markets and prices of energy fuels are calculated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all detailed OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global frame: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2100 and is updated yearly with recent information.

The POLES-JRC model applied for the CETO project is specifically enhanced and modified to capture learning effects of clean energy technologies.

POLES-JRC results are published within the series of yearly publications "Global Climate and Energy Outlooks" – GECO. The GECO reports along with detailed country energy and GHG balances and an on-line visualisation interface can be found at: https://joint-research-centre.ec.europa.eu/scientific-activities-z/geco_en

A detailed documentation of the POLES-JRC model is provided in (Després et al., 2018).

Figure 53. Schematic representation of the POLES-JRC model architecture.



Source: POLES-JRC model .

AN 3.2.2 POLES-JRC model description

Power system

The power system considers all relevant power generating technologies including fossil, nuclear and renewable power technologies. Each technology is modelled based on its current capacities and techno-economic characteristics. The evolution of cost and efficiencies are modelled through technology learning.

With regard to the power technologies covered by CETO, the model includes solar power (utility-scale and residential PV, concentrated solar power), wind power (on-shore and off-shore), hydropower and ocean power. Moreover, clean thermal power technologies are taken into account with steam turbines fuelled by biomass, biomass gasification, CCS power technologies and geothermal power. Furthermore, electricity storage technologies such as pumped hydropower storage and batteries are also included.

For solar and wind power, variable generation is considered by representative days with hourly profiles. For all renewables, regional resource potentials are considered.

Electricity demand

Electricity demand is calculated for all sectors taking into account hourly fluctuations through the use of representative days. Clean energy technologies using electricity consist of heat pumps (heating and cooling), batteries and fuel cells in transport, and electrolysers.

Power system operation and planning

Power system operation allocates generation by technology to each hour of representative days, ensuring that supplying and storage technologies meet overall demand, including grid imports and exports. Capacity planning considers the existing power mix, the expected evolution of electricity demand as well as the techno-economic characteristics of the power technologies.

Hydrogen

POLES-JRC takes into account several hydrogen production routes: (i) low temperature electrolysers using power from dedicated solar. wind and nuclear plants as well as from the grid, (ii) steam reforming of natural gas (with and without CCS), (iii) gasification of coal and biomass (with and without CCS), (iv) pyrolysis of gas and biomass as well as (v) high temperature electrolysis using nuclear power.

Hydrogen is used as fuel in all sectors including industry, transport, power generation and as well as feedstock for the production of synfuels (gaseous and liquid synfuels) and ammonia. Moroever, hydrogen trade is modelled, considering hydrogen transport with various means (pipeline, ship, truck) and forms (pressurised, liquid, converted into ammonia).

Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM-G4M model (IIASA, 2024). This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass-for-energy potential, production cost and reactivity to carbon pricing.

Biomass is used for power generation, hydrogen production and for the production of 1st and 2nd generation of liquid biofuels.

Carbon Capture Utilization and Storage (CCUS)

POLES-JRC uses CCUS technologies in:

- Power generation: advanced coal using CCS, coal and biomass gasification with CCS, and gas combined cycle with CCS.
- Hydrogen production: Steam reforming with CCS, coal and biomass gasification with CCS, and gas and biomass pyrolysis.
- Direct air capture (DAC) where the CO_2 is either stored or used for the production of synfuels (gaseous or liquid).
- Steel and cement production in the industrial sector.
- Second generation biofuels production.

The deployment of CCS technologies considers region-specific geological storage potentials.

Endogenous technology learning

The POLES-JRC model was enhanced to capture effects of learning of clean energy technologies. To capture these effects, a one-factor learning-by-doing (LBD) approach was applied to technologies and technology sub-components, aiming at endogenising the evolution of technology costs.

POLES-JRC considers historical statistics and assumptions on the evolution of cost and capacities of energy technologies until the most recent year available (this report: 2022/2023). Based on the year and a capacities threshold, the model switches from the default time series to the endogeneous modelling with the one-factor LBD approach. Within the LBD, the learning rate represents the percentage change of the cost of energy technology based on a doubling of the capacity of the energy technology.

This generic approach is applied on a component level to capture spillover effects as well. For instance, a gasifier unit is used as component for several power generating technologies (e.g. integrated gasification combined cycle, IGCC) as well as for several hydrogen production technologies (e.g. gasification of coal and biomass). Therefore, the component-based LBD approach allows to model spillover effects not only across technologies, but also across sectors. Also, it allows to estimate costs for emerging technologies for which historical experience does not yet exist.

Moreover, for each component a floor cost is specified which marks the minimum for the component's investment cost and serves as limitation for the cost reduction by endogenous learning. Cost reductions by learning in POLES-JRC slow down when the investment cost approaches the floor cost.

The described method above applies not only for the overnight investment cost of energy technologies, but as well for operation and maintenance (OM) costs, which also decrease as technologies improve, and for efficiencies. In the model, OM costs diminish synchronously to the decrease of total investment cost of the technology. The efficiency of renewables is implicitly taken into account in the investment cost learning and the considered renewable potentials. For most technologies the efficiencies are endogenously modelled.

AN 3.2.3 Global CETO 2°C scenario 2024

The global scenario data presented in the CETO technology reports 2024 refers to a 2°C scenario modelled by the POLES-JRC model in a modified and enhanced version to address the specific issues relevant for the CETO project.

The *Global CETO 2°C scenario 2024* and its specific POLESJRC model configuration is described in detail in the forthcoming report "*Impacts of enhanced learning for clean energy technologies on global energy system scenario*" (Schmitz et al., 2024).

The *Global CETO 2°C scenario 2024* is designed to limit global temperature increase to 2°C at the end of the century. It is driven by a single global carbon price for all regions that reduces emissions sufficiently so as to limit global warming to 2°C. This scenario is therefore a stylised representation of a pathway to the temperature targets. This scenario does not consider financial transfers between countries to implement mitigation measures. This is a simplified representation of an ideal case where strong international cooperation results in concerted effort to reduce emissions globally; it is not meant to replicate the result of announced targets and pledges, which differ greatly in ambition across countries.

As a starting point, for all regions, it considers already legislated energy and climate policies (as of June 2023), but climate policy pledges and targets formulated in Nationally Determined Contributions (NDCs) and Long-Term Strategies (LTSs) are not explicitly taken into account. In particular, the EU Fit for 55 and RePowerEU packages are included in the policy setup for the EU. Announced emissions targets for 2040 and 2050 for the EU are not considered.

The *Global CETO 2°C scenario 2024* differs fundamentally from the *Global CETO 2°C scenario 2023* used in the CETO technology reports in 2023 in various aspects[1]:

- The version of the POLES-JRC model used for the *Global CETO 2°C scenario* has been further enhanced and modified to capture effects of endogenous learning of clean energy technologies and, furthermore, several technology representations were further detailed, e.g. DAC (composition of renewable technologies, batteries and DAC unit), fuel conversion technologies (for hydrogen transport) and batteries in transport.
- The techno-economic parameters have been thoroughly revised and updated taking into account the expertise of the authors of the CETO technology reports.

As a result, major scenario differences occur in the *Global CETO 2°C scenario 2024* regarding DAC, synfuels, CCS power technologies, wind power and ocean power.

AN 3.3 Distinctions for the CETO 2024 scenarios - POLES-JRC vs. POTEnCIA

The results of both models are driven by national as well as international techno-economic assumptions, fuel costs, as well as policy incentives such as carbon prices. However, on one side these two JRC energy system models differ in scope and level of detail, on the other side the definitions of the POTEnCIA and POLES-JRC scenarios presented in this document follow distinct logics, leading to different scenario results:

The *Global CETO 2°C scenario 2024* (POLES-JRC) scenario is driven by a global carbon price trajectory to limit global warming to 2°C, where enacted climate policies are modelled, but long-term climate policy pledges and targets are not explicitly considered. Scenario results are presented for the global total until 2100.

The *POTEnCIA CETO 2024 scenario* is a decarbonisation scenario that follows a trajectory for EU27's net GHG emissions aligned with the general objectives of the European Climate Law (ECL) taking into consideration many sector-specific pieces of legislation. Scenario results are presented for the EU27 until 2050

Annex 4 R&I projects funded under the Horizon Europe programme

Table 9. R&I projects funded under the Horizon Europe programme and started in 2023.

Project Acronym	Start Year	Project DOI	EU Financial Contribution (EUR)	Wind share	Research area
FUNnY-SUMO	2023-12-01	10.3030/101108665	181 153	100%	Offshore technology
WINDACCEPT	2023-01-01	10.3030/101061882	283 439	100%	Social engagement
ShareWind	2023-07-01	10.3030/101106921	211 755	100%	Floating offshore wind
AptWind	2023-09-01	10.3030/101119550	4 221 677	100%	Resource assessment
MLSITDAIAFWT	2023-08-01	10.3030/101108745	210 911	100%	Environmental impact
Nanowings	2023-01-01	10.3030/101099620	2 495 626	100%	New turbine materials, components
flying factory	2023-03-01	10.3030/190125421	1 254 225	100%	Maintenance, condition monitoring systems
WILLOW	2023-10-01	10.3030/101122184	5 816 861	100%	Grid integration
FLOW	2023-01-01	10.3030/101084205	5 995 209	100%	Resource assessment
SUDOCO	2023-10-01	10.3030/101122256	5 769 120	100%	Maintenance, condition monitoring systems
TWAIN	2023-11-01	10.3030/101122194	5 998 643	100%	Maintenance, condition monitoring systems
WHEEL	2023-01-01	10.3030/101084409	16 663 951	100%	Floating offshore wind
BLOW	2023-01-01	10.3030/101084323	15 483 361	100%	Floating offshore wind
MADE4WIND	2023-12-01	10.3030/101136096	6 003 276	100%	New turbine materials, components
ICONIC	2023-12-01	10.3030/101122329	3 897 448	100%	Maintenance, condition monitoring systems
PhyDAWN	2023-07-01	10.3030/101107634	214 934	100%	Grid integration
DeP2WIND	2023-05-01	10.3030/101061320	210 911	100%	Other
AIRE	2023-01-01	10.3030/101083716	5 424 916	100%	Maintenance, condition monitoring systems
Blades2Build	2023-01-01	10.3030/101096437	12 362 240	100%	Recycling, circularity
EoLO-HUBs	2023-01-01	10.3030/101096425	9 994 682	100%	Recycling, circularity
Orcelle	2023-01-01	10.3030/101096673	8 989 978	100%	Other
WHISPER	2023-01-01	10.3030/101096577	8 991 483	100%	Other
off-coustics	2023-10-01	10.3030/101086075	1 992 500	100%	Environmental impact
DATA-DRIVEN OFFSHORE	2023-04-01	10.3030/101083157	2 000 000	100%	Offshore technology
WIMBY	2023-01-01	10.3030/101083460	3 346 455	100%	Social engagement
ULTFARMS	2023-01-01	10.3030/101093888	9 590 771	100%	Environmental impact
REFRESH	2023-01-01	10.3030/101096858	11 462 602	100%	Recycling, circularity
AdvanSiC	2023-01-01	10.3030/101075709	3 242 373	50%	Grid integration
InterOPERA	2023-01-01	10.3030/101095874	50 720 449	25%	Grid integration
D-STANDART	2023-01-01	10.3030/101091409	3 330 617	50%	New turbine materials, components
OCEANBATTERY	2023-07-01	10.3030/190140124	2 499 999	50%	Grid integration
Clean(S)tack	2023-02-01	10.3030/190155898	1 680 875	50%	Grid integration
NEXTBMS	2023-06-01	10.3030/101103898	4 998 318	20%	Grid integration
GR4FITE3	2023-05-01	10.3030/101103752	4 798 586	20%	Recycling, circularity

Source: JRC based on CORDIS, 2024.

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