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Abstract

The aim of this report is to provide an update of the state of the art of wind energy technology. This includes onshore and offshore wind and, when available, selected findings on wind technologies at lower technological readiness levels (e.g. research and innovation information on airborne wind energy systems, vertical axis wind turbines and downwind rotors). Research and development trends are analysed, focussing particularly on the technology progress made in EU-funded research by the end of 2022 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 (R&I) 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 inventive 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 of 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

Onshore wind and bottom-fixed offshore wind turbines have reached commercial readiness, but technology developments are still ongoing to improve their performance. 2022 marks another record year in global wind energy deployments, with additions of 68 GW of onshore wind and 9 GW of offshore wind (the second strongest year after 2021). In 2022, EU Member States (MSs) added 15 GW of onshore wind capacity, making it the strongest year in onshore capacity additions since 2010. EU offshore annual deployments saw only 1.2 GW of offshore wind capacity deployed in 2022. In EU MSs, a total of 189 GW of onshore wind is installed, while European sea basins (including projects installed in the UK and Norway) host a total capacity of 30 GW.

Both onshore and offshore wind show a continuous reduction in costs and costs are expected to further reduce towards 2050 as a consequence of scaling effects and technology development. However, since the outbreak of the COVID19 pandemic, an increase in the levelised cost of energy (LCoE) has been observed as a consequence of commodity price inflation, increasing transportation costs and supply chain disruptions. In the last quarter of 2022, inflation and commodity prices started decreasing, however this is not reflected in the LCoE values in 2022. Moreover, financing costs vary considerably among EU countries. BNEF estimates the LCoE of onshore wind in EU countries at between EUR 33.4 and EUR 47.5 per MWh in 2022, depending, for example, on location and financing conditions. The latest estimates on EU offshore LCoE suggest a range of EUR 62.6 to EUR 138 per MWh.

Regarding international competitors, the EU is at the forefront in private R&D investment in wind energy, closely followed by China. In cumulative terms, the EU is estimated to lead private R&D investments with about 40% of the total private R&D funding in the period 2010-2020. Globally, in the period 2018-2020, the EU's share of high-value inventions was 59%, followed by the US (15%), China (13%), Japan (4%) and Korea (2%). EU companies keep the lead in terms of high-value inventions filed in the period 2018-2020.

In terms of scientific publications, the EU is leading in highly cited papers as well as in citation impact and productivity, measured by the H-index. EU organisations show the strongest collaboration ties in publishing peer-reviewed articles with organisations from the UK, China and the US.

The wind energy sector has evolved into a global industry with about 800 manufacturing facilities worldwide. The majority of wind factories operate in China (45%) and Europe (31%), followed by India (7%), Brazil (5%) and North America (4%). The European manufacturing supply chain is constituted mainly by companies from EU Member States. Current manufacturing capabilities in the EU easily cover the current EU demand in major wind energy components. However, as annual deployment rates need to increase significantly to reach the ambitious 2030 targets, supply chain bottlenecks might emerge if components are sourced from EU MSs only. With regard to offshore wind, deployment needs in EU MSs are expected to increase to about 8-9 GW/year by 2030 and up to an estimated 12-13 GW by 2050, necessitating additional investment in the offshore wind supply chain. This includes a significant increase in the provision of offshore wind components and hence manufacturing capabilities at EU ports as well as the investment in new vessels capable of installing next-generation wind turbines and substructures.

Among the top 10 OEMs in 2021, Chinese OEMs led with a 50% market share, followed by European (30%) and North American (10%) companies. The EU traditionally has a positive trade balance in wind-related goods to countries outside the EU, however in 2022 there was a large decrease in exports and an increase in imports compared to 2021. Since China's restrictive wind market policy (local content requirements, import tariffs and VAT exemption for domestic manufacturers), the trade balance clearly leans towards China, with a record surplus (trade deficit for the EU) of EUR 464 million for China in 2022. The EU also showed a negative trade balance with India, seeing imports from that country surging to about EUR 241 million in 2022. The EU has a positive trade balance with the UK and US amongst others. In the last decade, the US has remained reliant on imports from the EU.

However, local content requirements over imported content that were introduced by individual countries has the potential to distort trade and cause unintended effects on investment across value chains.

Potential bottlenecks and supply risks might arise in the wind sector with regard to critical raw materials. This applies particularly to rare earth elements, which are used in the permanent magnets of turbine generators and within wind turbine towers. Rare earth elements have been identified as critical in terms of supply risk since they present a high import reliance on third countries, particularly in China, which dominates the global processing capacity.

With regard to processed materials, the supply risk is highest for balsa wood which is used in blades, NdFeB permanent magnets and polyurethane. 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). For wind energy components, the supply risk of manufactured NdFeB magnets is critical. It is estimated that China's manufacturing capacities of permanent magnets are, reaching 94% of global production. Particularly in offshore wind, permanent magnets replace conventional rotor windings in generators at a much faster pace as they enable a higher power density, along with reduced size and weight.

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

Strengths	**Weaknesses**
• Onshore and offshore wind reached commercial readiness with EU players at the forefront of R&I • Cost competitiveness in both onshore and bottom-fixed offshore wind • Leading in floating offshore wind development with first pre-commercial wind farms in EU waters • Strong EU manufacturing supply chain • EU companies hold a very strong market share in the EU and a good market share globally, contributing to a positive trade balance	• Stronger emphasis needed on Marine spatial Planning (MSP)and coexistence among sectors • Stronger emphasis needed on circularity by design, environmental impact and human capital agenda • Varying financing costs among MSs • Potential bottlenecks and supply risks for critical raw materials (REE) and processed materials (e.g. NdFeB magnets, balsa wood)
Opportunities	**Threats**
• Floating offshore wind enabling MSs with steeper shorelines to harvest offshore wind and exploit existing potentials • Other offshore wind R&I priorities should focus on system integration, efficient transmission & interconnection, O&M • Niche wind technologies (VAWT, downwind rotors, AWES, small-scale wind) • Investment in manufacturing capabilities, EU ports and new vessels	• Administrative barriers (e.g. organisation and duration of the permit-granting process) • Increased LCoE (commodity price inflation, increased transportation costs, supply chain risk) • Potential EU supply chain bottlenecks in effort to meet ambitious climate targets • 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, 2023

1. Introduction

1.1 Scope and context

The aim of this report is to provide an update on the state of the art of wind energy technology. This includes onshore wind, offshore wind (both bottom-fixed and floating offshore wind) and, where available, selected findings on wind technologies with lower technology readiness levels (e.g. R&I information on AWES, VAWT and downwind rotors). It provides an analysis of R&D development trends, focussing particularly on the technology progress made in EU-funded research until the end of 2022 in view of the SET-Plan targets. It also analyses the EU's global competitiveness within the wind value chain and identifies potential bottlenecks and supply risks in the push to meet the targets of the European Green Deal.

The report analyses the status of the main technology indicators and their future development. Chapter 2 introduces the current technology readiness level (TRL) of the main technologies in the wind energy sector. This is followed by an analysis of key indicators on deployment and electricity generation, and an outline of modelling projections at EU and global levels. Chapter 2.2.5 provides an outlook on European and global offshore wind capacity targets and estimated installed capacities towards 2030 and 2050. Chapter 2.3 analyses present and future cost developments in wind energy with the latest estimates on LCoE, CAPEX, OPEX and WACC. Competitiveness indicators measuring public & private R&D funding, patenting trends and scientific publications are presented in chapters 2.4 to 2.7, followed by an analysis of the impact and trends of EU-supported research and innovation.

Chapter 3 focuses on the wind energy value chain and includes an analysis of macroeconomic indicators (turnover, Gross Value Added (GVA), employment and production data) and a mapping of indicators on environmental and socioeconomic sustainability. It provides an in-depth assessment of the role of EU companies in the wind sector, detailing their relative position in the global supply chain, the origin and location of manufacturing of Tier 1 and Tier 2 component suppliers, the estimation of potential bottlenecks in the EU supply chain, the component sourcing strategy of the main EU original equipment manufacturers (OEMs) and an analysis of UK-EU supply chain dependencies.

Chapter 4 gives an insight into the EU's global position and competitiveness by assessing the market shares of EU and global market leaders in onshore and offshore wind. The trade balance between the EU and its main competitors is also scrutinised. Analysing the types and quantities of the main raw and processed materials used in wind power plants, chapter 4.3 investigates the supply risks and critical dependencies along the supply chain.

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

Currently the dominating technologies for both onshore and offshore wind turbines are horizontal axis, three-bladed turbines. These wind turbines have reached commercial readiness status and use standardised/large-scale components such as steel/concrete towers, an upwind rotor (including three blades, yaw system, pitch regulation and a drive train system). Offshore wind turbines that have reached commercial readiness build on various bottom-fixed foundation types (e.g. monopiles, jackets, tripods, tripiles, gravity base and suction buckets).

Floating offshore wind is a growing sector that is strengthening Europe’s leadership in deploying renewable energy. Floating applications seem to be becoming a viable option for EU countries and regions with deep waters (depths between 50-1 000 metres) and could open up new markets such as the Atlantic Ocean, the Mediterranean Sea and potentially the Black Sea. Semi-submersible and spar-buoy technologies have already reached TRL 8-9, while the Floatgen pilot project in France upgraded the concrete barge technology to TRL 7-8. The tension-leg platform is being tested with a prototype (TRL 6) launched off the coast of the Canary islands by the X1 Wind project. At the end of 2022, EU MSs deployed 27 MW of floating offshore wind in EU sea basins while the global cumulative installed capacity totals about 123 MW. The main distinctive criterion in multiple 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 the way to full commercialisation, no concept has yet prevailed over the others; however, the spar-buoy concept and the semi-submersible concept have already been deployed in pre-commercial projects in the North Sea and the Atlantic Ocean (in 2020 the 25 MW WindFloat Atlantic project was installed off the Portuguese coast, as the first semi-submersible floating wind farm). **Table 2** presents the current TRL of wind energy technologies.

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								■	■
Offshore wind								■	■
Floating wind						■	■	■	
Airborne wind energy			■	■	■				

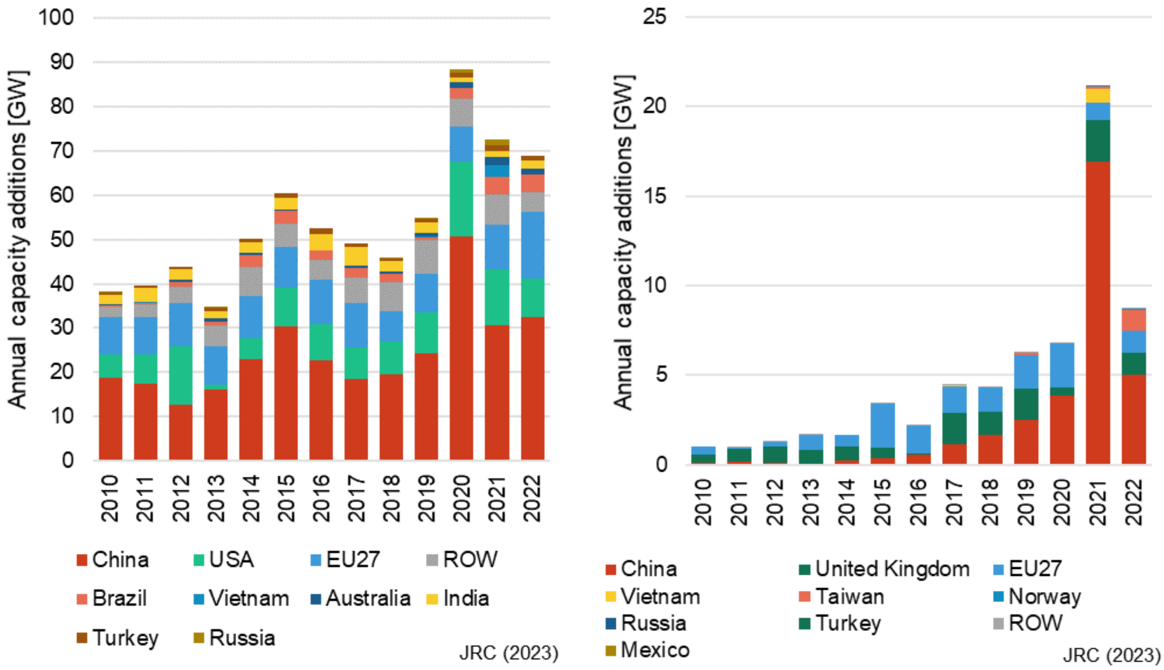
Source: JRC analysis

2.2 Installed Capacity and Production

2.2.1 Global deployment

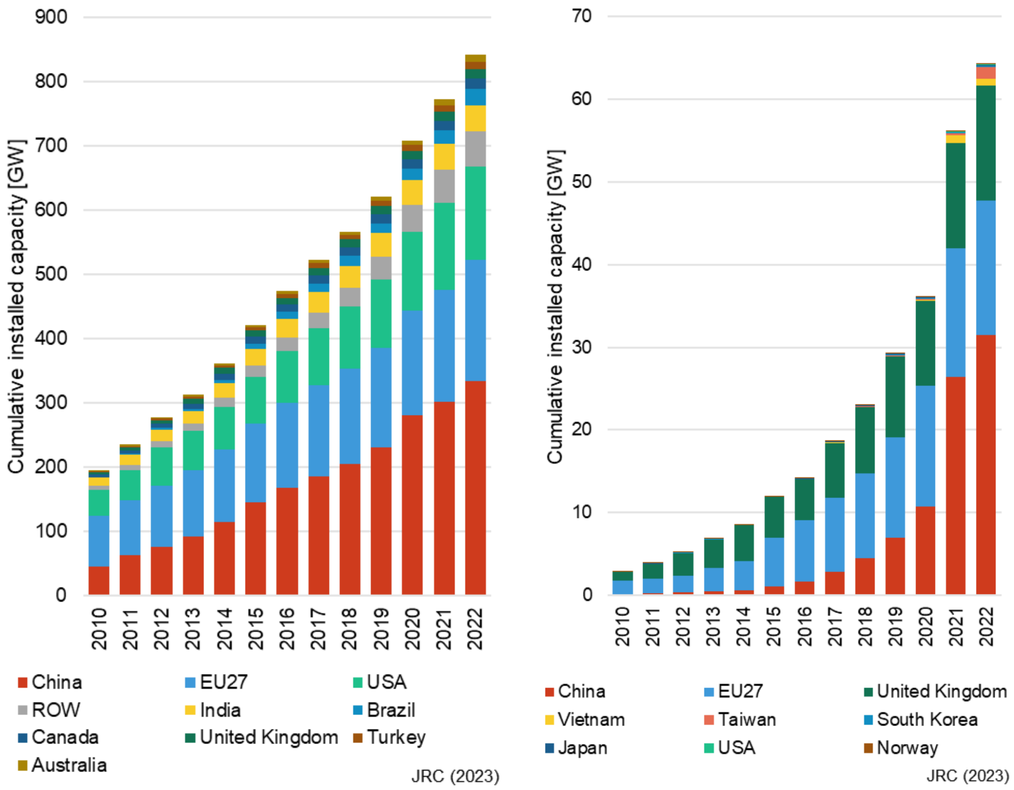
2022 marked another year of strong deployment, both onshore and offshore. In total, 77 GW of new capacity were installed globally, split between 68 GW onshore and 9 GW offshore. That is a reduction of 17% compared to 2021, mainly attributed to the big reduction of offshore deployment by China. Still, for both onshore and offshore wind, China is leading in newly added capacity, with 32.6 GW and 5 GW, respectively. The EU follows with 15 GW onshore and 1.2 GW offshore, while the US is third in terms of new onshore installed capacity (8.6 GW) and the UK is third for offshore (1.1 GW). Taiwan’s new offshore capacity is also worth noting at 1.1 GW (**Figure 1**).

Figure 1. Global annual capacity additions of onshore wind (left) and offshore wind (right).



Source: JRC based on GWEC, 2023.

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



Source: JRC based on GWEC, 2023.

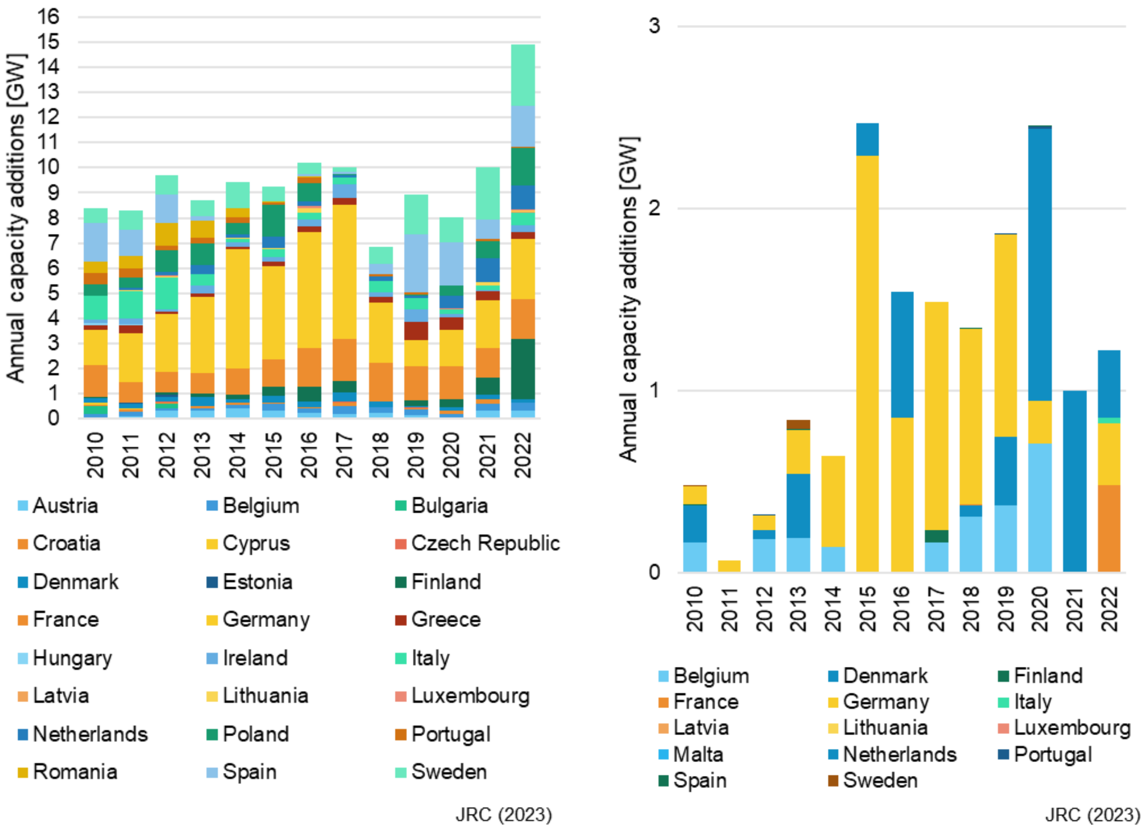
In terms of cumulative global capacity (onshore/offshore), as a consequence of China's strong deployment in 2021, the country is leading in cumulative offshore wind deployment with 31.4 GW, followed by the EU (16.2 GW) and the UK (13.9 GW). As shown in **Figure 2**, China has led in cumulative wind onshore deployment since 2015, further strengthening its lead with 334 GW of total installed capacity (39% of all offshore installations in 2022). In 2022, the EU onshore wind market represented 22.4% (188.9 GW) of the global market in terms of cumulative installed capacity, followed by the US with 17% (144.1 GW).

2.2.2 EU 27 deployment

In 2022, EU Member States (MSs) added another 15 GW of onshore wind capacity, making it the strongest year in onshore capacity additions since 2010. In total, 16 countries added new capacity, with Sweden in the lead (2.44 GW), followed by Germany (2.4 GW) and Finland (2.4 GW).

2022 saw only 1.2 GW of offshore wind capacity deployed in EU 27 countries. Only four EU MSs added additional offshore projects. France led in capacity additions with 0.48 GW, followed by the Netherlands, which added 0.37 GW (**Figure 3)**.

Figure 3. Annual capacity additions of onshore wind (left) and offshore wind (right) in the EU.



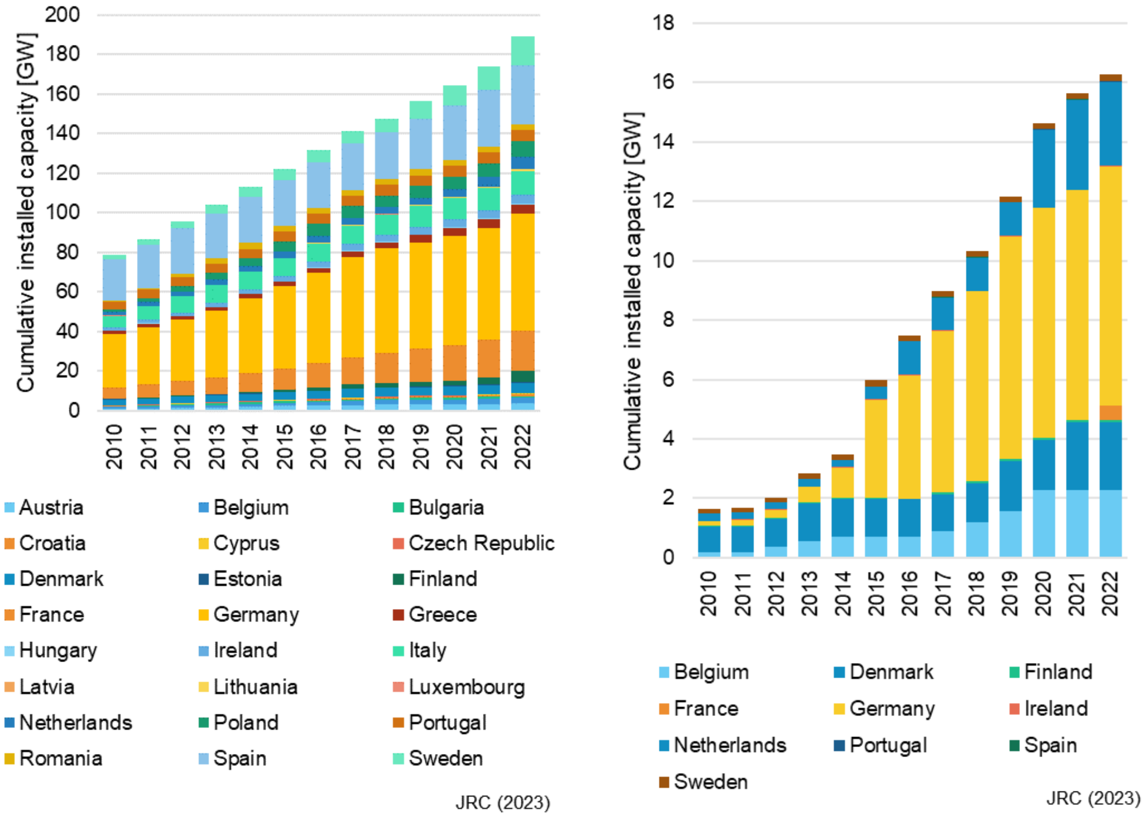
Source: JRC based on GWEC, 2023.

In EU MSs, a total of 188.9 GW of onshore wind is installed, an increase of 6% on 2020 and more than double the 2010 figure (with an additional 141%). Among the top countries, Germany leads on total onshore wind deployment with 59 GW, followed by Spain (29.8 GW), France (20.7 GW), Sweden (14.4 GW) and Italy (11.8 GW).

Cumulative offshore wind capacity in EU MSs at the end of 2022 is at about 16.2 GW, with Germany (8 GW), the Netherlands (3 GW), Denmark (2.3 GW) and Belgium (2.3 GW) in the lead (**Figure 4**).

In 2022, all European sea basins (including projects installed in the UK and Norway) hosted a total capacity of 30.2 GW.

Figure 4. Cumulative installed capacity of onshore wind (left) and offshore wind (right) in the EU.



Source: JRC based on GWEC, 2023.

In terms of floating wind, WindFloat Atlantic, located off the coast of Viana do Castelo, Portugal, with an installed capacity of 25 MW, is the first floating wind farm in continental Europe. 4cOffshore forecasts that 14 GW of floating wind will commence installation globally by 2030, and 46 GW by 2035, which corresponds to 8 GW operational by 2030 and 38 GW by 2035. Compared with the previous forecast in May 2022, the forecasts for 2030 and 2035 have both been reduced by about 2 GW. The decrease reflects continued policy delays and slow permitting in multiple countries.

Despite high ambitions from developers, with several companies having floating projects pipelines greater than 10 GW, development will slow without tangible government support and actions.

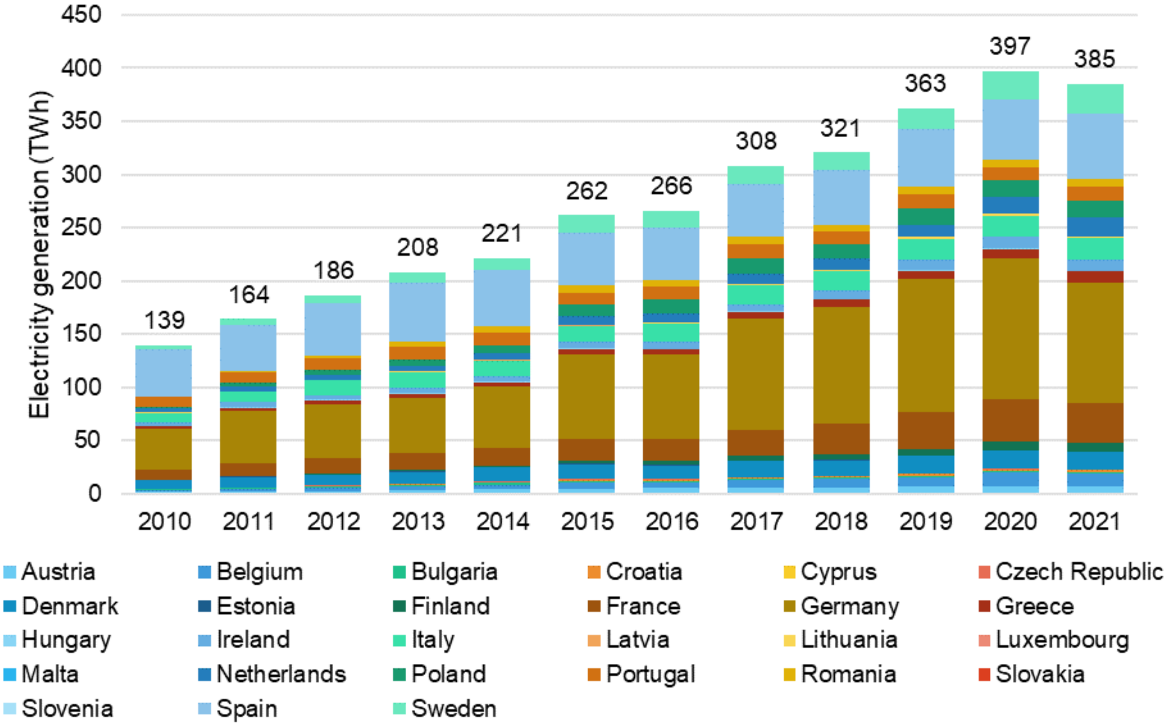
The leading countries are South Korea and the US with around 10 GW each by 2035. Europe remains the leading region with 18 GW by 2035, closely followed by Asia Pacific region with 17 GW (including China). The forecast is contingent on effective cost reductions of floating wind and clearer government support to enable investment and reduce risk.

2.2.3 European and global electricity generation

EU wind electricity accounted for about 14% of total electricity generation in 2021. Denmark has the highest wind electricity share in its electricity mix at 44%, followed by Ireland (31%), Portugal (26%), Spain (24%) and Germany (23%). Most eastern European countries have lower wind shares, as a consequence of lower deployment rates.

In 2021, about 385 TWh was generated from wind energy in EU MSs (see **Figure 5**). Despite an additional 11 GW (+6% in cumulative installed capacity) of wind capacity added in EU MSs, electricity generation from wind energy fell by 3% in 2021 as compared to 2020.

Figure 5. Wind energy electricity generation of EU MSs in 2021.



Source: JRC based on EurObserv'ER, 2023.

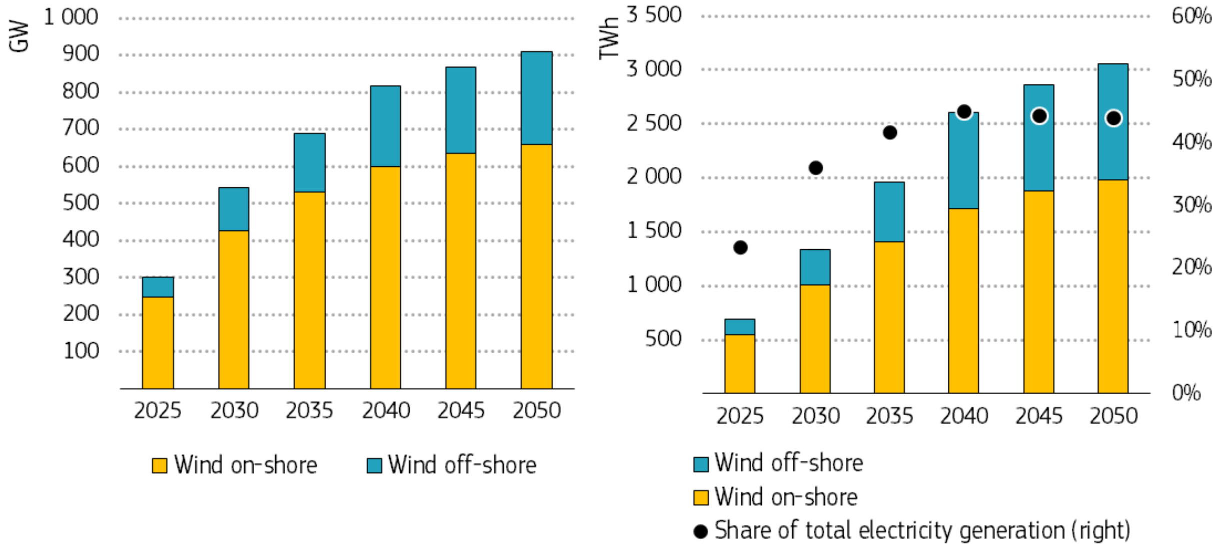
2.2.4 EU 27 and global modelling projections

In May 2022, the EC presented the REPowerEU Plan in response to the global energy market disruption caused by Russia's invasion of the Ukraine. Among other measures, the plan foresees an accelerated rollout of renewables, increasing the target from 40% to 45% by 2030. With respect to wind energy, the REPowerEU Plan proposes an installed capacity of 510 GW by 2030 (EC, 2022).

POTEnCIA and POLES-JRC models can evaluate the expected deployment of onshore and offshore wind until 2050 at the EU and global level respectively. An overview and details about both models can be found in **Annex 4**. Results of the POTEnCIA model under the CETO Climate Neutrality scenario show onshore wind installed capacity surging to 425 GW and 660 GW in 2030 and 2050, respectively. An even stronger relative increase is projected for offshore wind deployment, with around 120 GW in 2030 and almost 250 GW in 2050 (see **Figure 6**). Based on these figures, the share of wind in EU electricity mix will rise from 14% (2021) to 36% (around 1 330 TWh) in 2030 and 44% (3 060 TWh) in 2050.

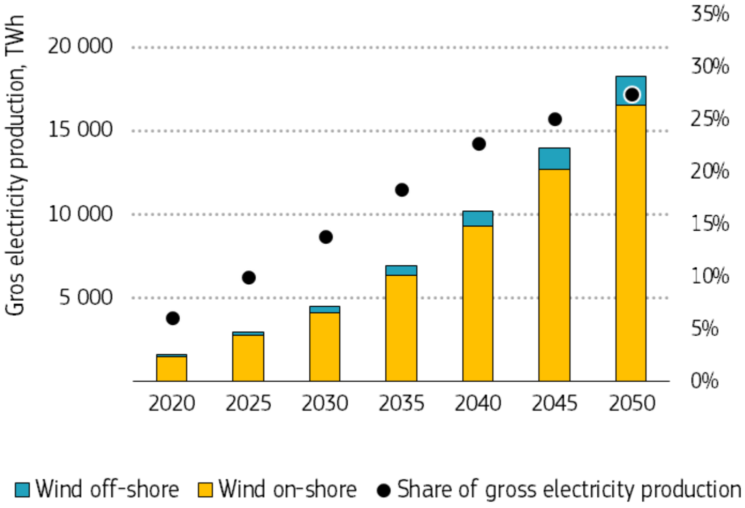
Globally, results of the POLES-JRC model show a surge in onshore installations that would lead to covering 27% of the world's electricity needs by 2050 (see **Figure 7**).

Figure 6: Onshore and offshore installed capacity (left) and gross electricity generation (right) in the EU under the POTEnCIA CETO Climate Neutrality Scenario



Source: JRC, 2023

Figure 7. Global gross energy production according to POLES-*JRC* model



Source: JRC, 2023

2.3 Technology Costs

Onshore

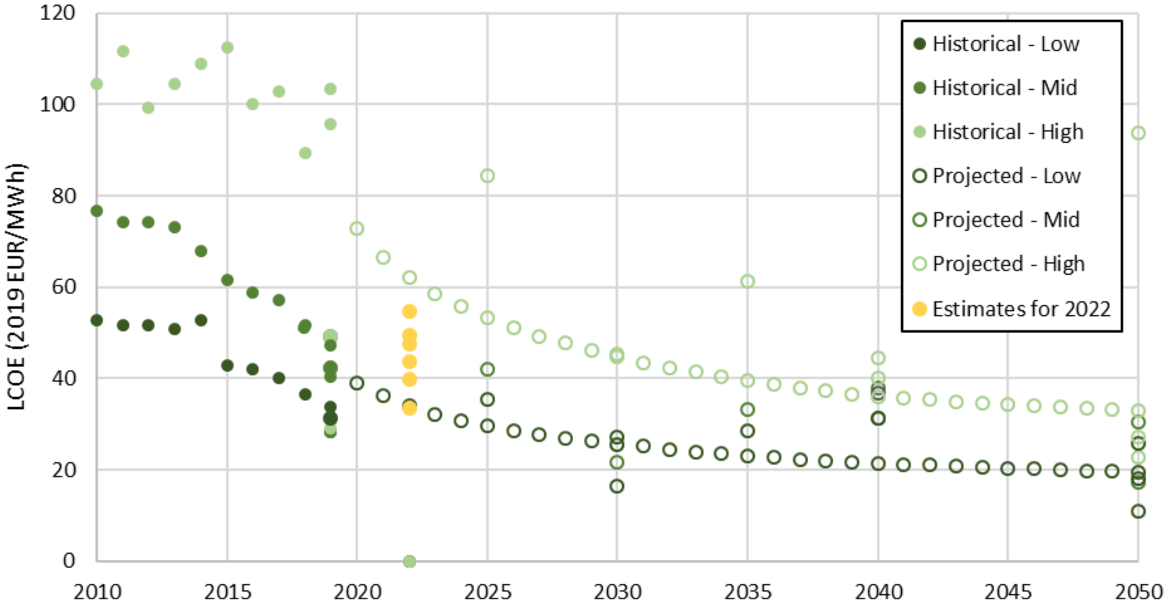
Based on the main cost estimates and projections for onshore wind, **Figure 8** identifies an LCoE range spanning from EUR 33 to EUR 74 per MWh in the period 2019-2022, which is expected to decline further in the long term to values between EUR 19 and EUR 33 per MWh in 2050.

According to WindEurope data, the LCoE of onshore wind will decrease from EUR 40 per MWh in 2019, to EUR 26 in 2030, and EUR 19 in 2050.

Commodity price inflation, increasing shipping costs and supply chain disruptions have led to increasing wind turbine prices since 2020. In early 2023, WindEurope (2023) reports that due to inflation in commodity prices and other input costs, the price of wind turbines increased by up to 40% over the last two years. As a consequence of cost inflation pressure and declining margins, OEMs increase turbine prices, implement cost-cutting programmes and incorporate cost inflation clauses into their contracts. In 2022, commodity price inflation further increased following Russia's invasion of Ukraine, with commodity prices surging. In the last quarter of 2022 and early 2023 there are signs of ease in the inflation and of commodity prices decreasing. For example, at the end of 2022, the price of steel has decreased by 46% since March 2022, Neodymium by 40% since February 2022, while copper has increased by 30% compared to 2019 (BNEF, 2023).

CAPEX for onshore wind projects range in the established European markets between EUR 1 060 and EUR 1 425 per kW. Current projections see onshore wind CAPEX decreasing by 8% and 18% until 2030 and 2050, respectively (BNEF, 2023). Within this time period, an even stronger decrease is expected for OPEX, which range currently between about EUR 18 and EUR 36 per MWh, decreasing by 14% by 2030 and up to 30% in the long term (2050).

Figure 8. Range of historical, current (European estimates 2022) and projected onshore wind LCoE estimates.

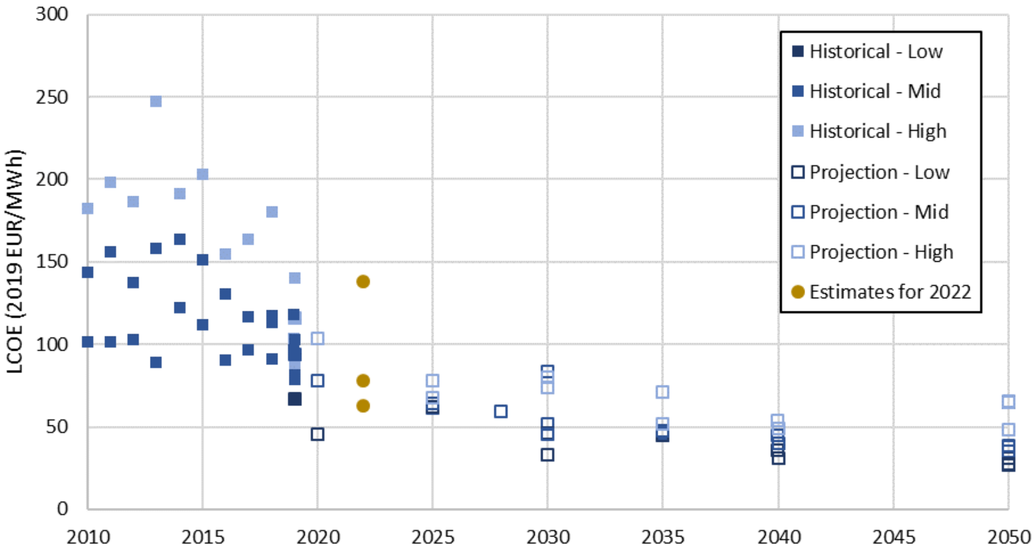


Source: JRC, BNEF, Beiter et al, 2021 (chart reproduced from Beiter et al.), 2023.

Offshore

Estimates of bottom-fixed offshore wind LCoE have declined rapidly to today's values, ranging from EUR 61 per MWh to EUR 140 per MWh (see 2019-2022 range in **Figure 9**). Particularly since 2014, an upscaling in project and turbine size can be observed in order to capitalise on economies of scale. Following current projections on the future costs of bottom-fixed offshore wind, LCoE levels can be expected of EUR 30 to EUR 60 per MWh in 2050. The cost of offshore wind installations is therefore reaching similar levels as that of onshore installations.

Figure 9. Range of historical, current (European estimates 2022) and projected offshore wind LCoE estimates.

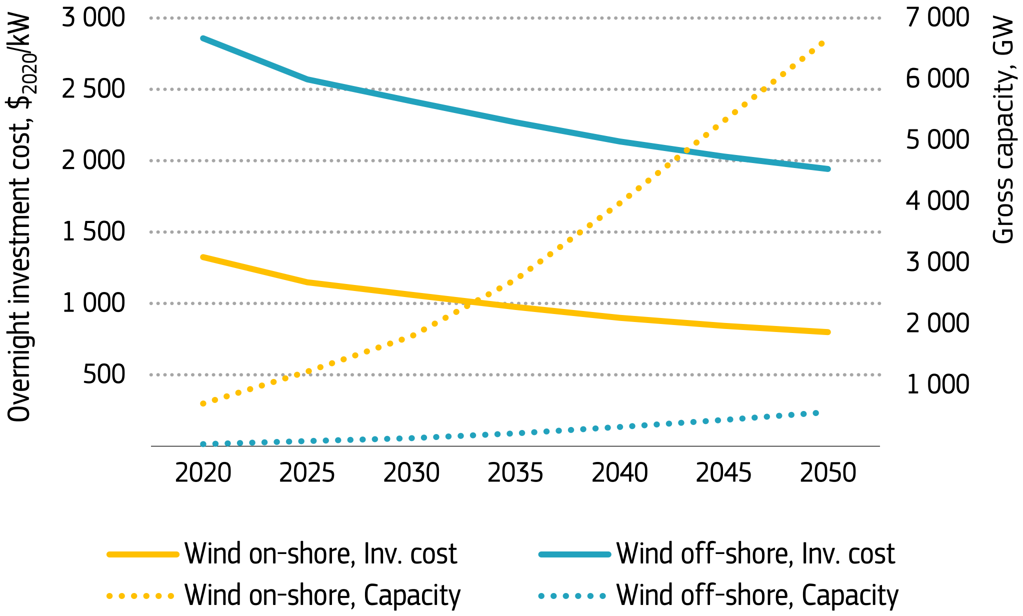


Source: JRC, BNEF, Beiter et al, 2021 (chart reproduced from Beiter et al.), 2023.

Operation & maintenance costs (O&M) are decreasing. The EU's average annual O&M costs for offshore wind range between EUR 50 and EUR 80 per kW in 2022, and are projected to go down by one third by 2030, and to EUR 35-40/kW by 2050 (a decrease of 40% compared to 2021) (BNEF, 2023). These reductions will mainly be due to economies of scale, industry synergies, digitalisation and technology development, including optimised maintenance concepts (IEA, 2019).

Costs are expected to reduce as installations increase, both onshore and offshore. According to the POLES-JRC model, by 2050 overnight investment costs are expected for fall to EUR 753 perkW for onshore wind and EUR 1 628 perkW for offshore wind (**Figure 10).**

Figure 10.Overnight investment costs (in USD) for onshore and offshore installations according to the POLES-JRC model



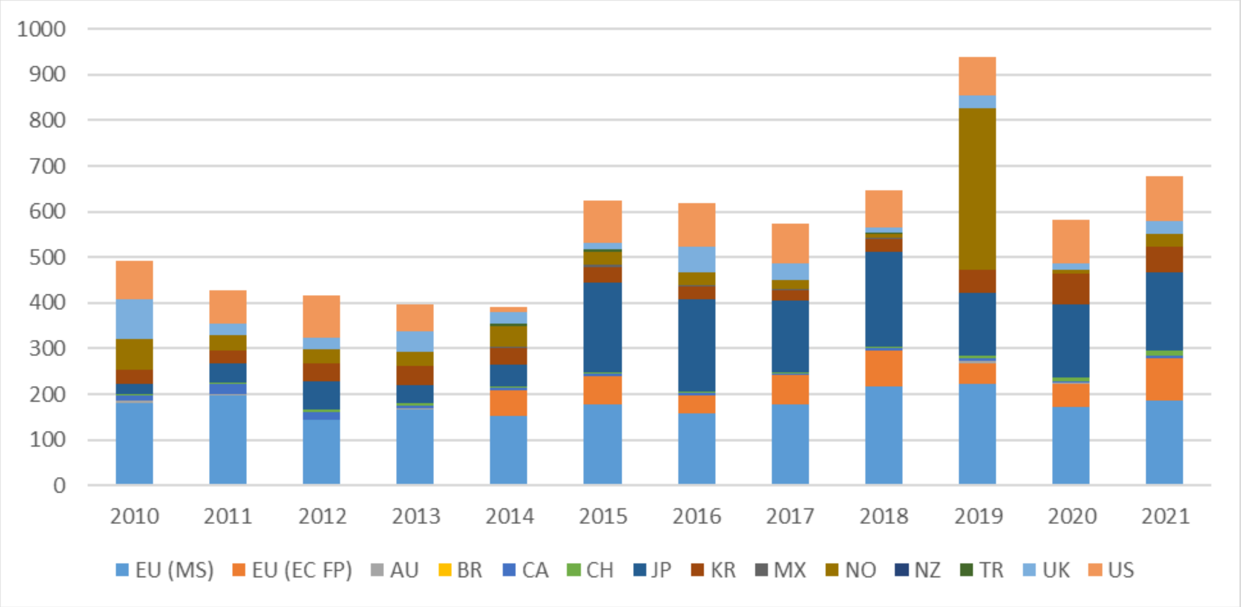
Source: JRC, 2023

2.4 Public RD&I Funding and Investments

Public R&D investment is analysed based on the IEA energy technology RD&D budget and includes data from national investment in the EU and the main OECD countries outside of the EU. In addition, EU funding since 2014 from the H2020 framework programme (see EC FP) is included in Telsnig et al., (2022). 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 FP7 (2009-2013), H2020 (2014-2021) and Horizon Europe programmes.

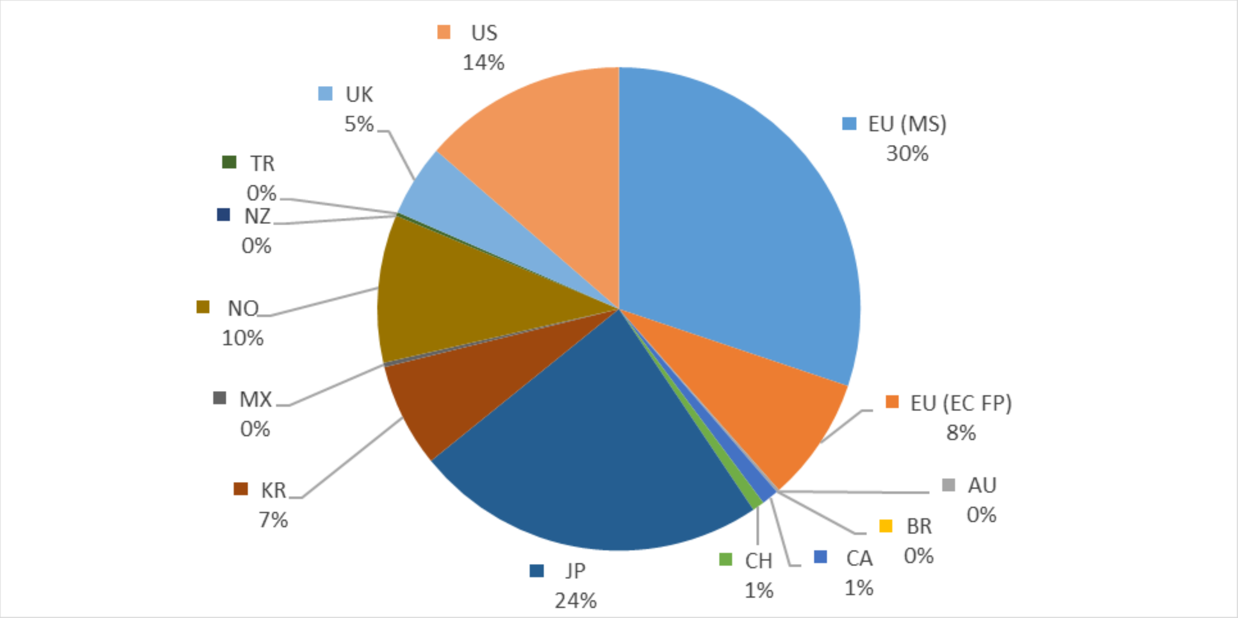
Since 2012, among OECD members the EU leads in investment in public R&D, accounting for 38% of all public investment in wind energy, followed by Japan (24%) and the US (14%) (see **Figure 11** and **Figure 12**).

Figure 11. Evolution of public R&I investment in wind energy in the EU and major OECD countries in 2010-2021.



Source: JRC based on IEA, 2023

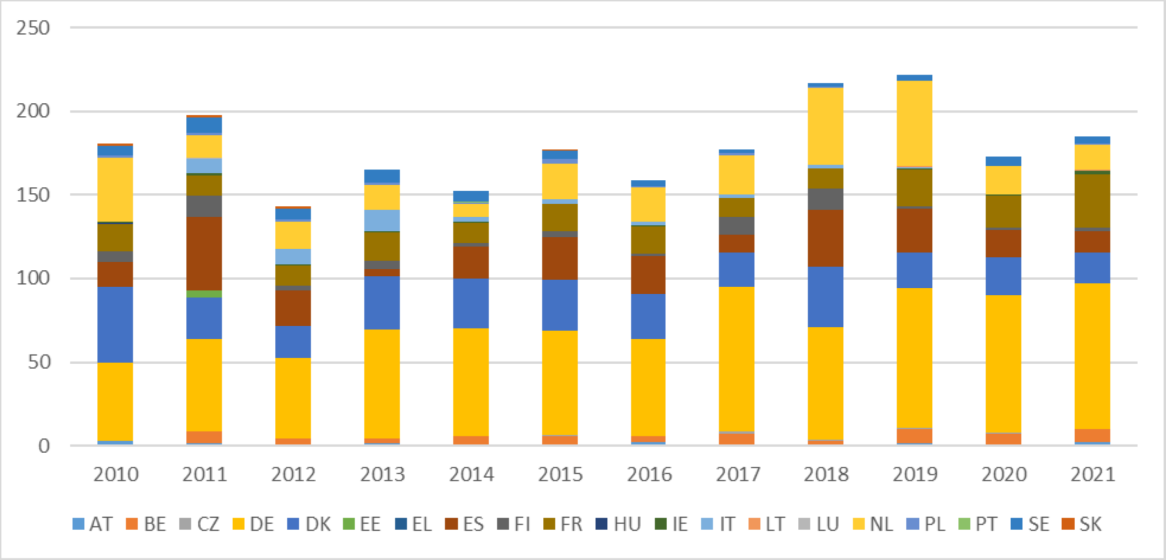
Figure 12. Public R&I investment (shares) in wind energy in the EU and major OECD countries in 2012-2021.



Source: JRC based on IEA, 2023.

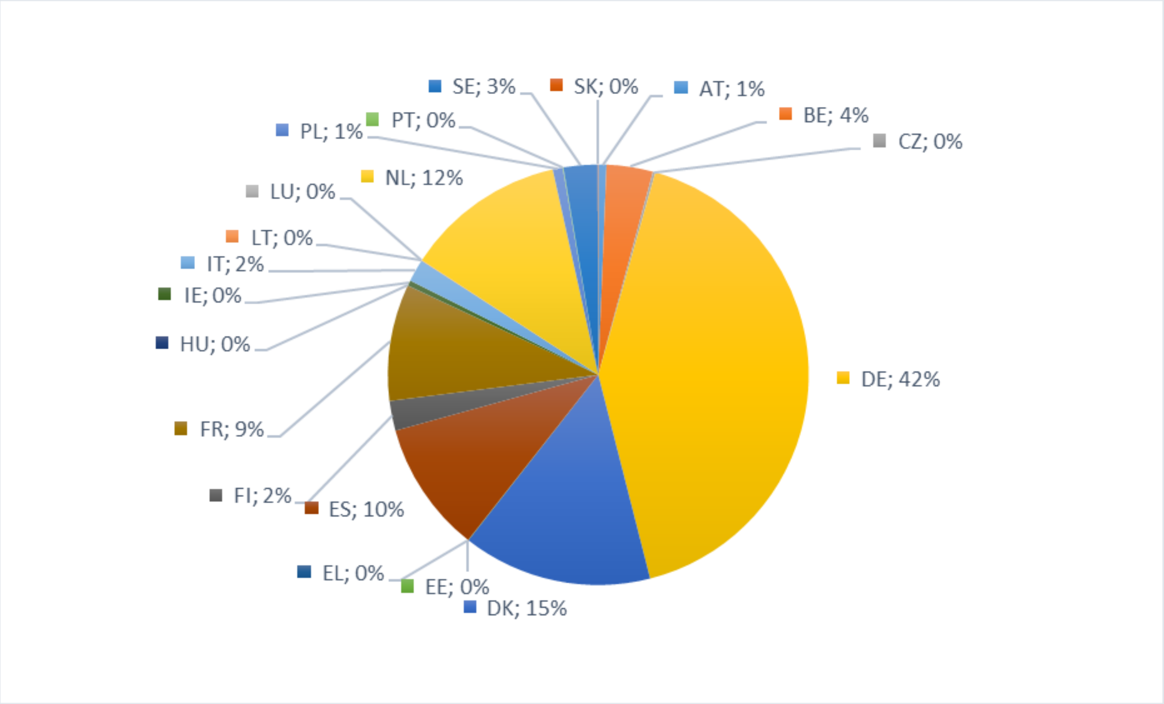
Since 2010, EU MSs spent about EUR 1.42 billion on public R&I in wind energy. Public R&D investment in EU MSs remained roughly constant between 2012 and 2016, at around EUR 120-145 million. The trend subsequently increased, reaching EUR 179 million by 2019. This equates to a 32% increase in public R&D investment since 2010 (**Figure 13**). At about 42%, Germany leads in EU public R&D investment, followed by Denmark (15%) and the Netherlands (12%) in the period 2010-2021 (**Figure 14**). Analysing the evolution of annual shares in public R&I investment reveals that the Netherlands has increased its spending since 2014, with record years in 2018 and 2019. Germany, Spain and Denmark show no clear trend (**Figure 13**).

Figure 13. Evolution of public R&I investment in wind energy in the EU in the period 2010-2021. This figure 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, 329 Unallocated wind energy.



Source: JRC based on IEA, 2023

Figure 14. Public R&I investments (shares) in wind energy in EU the period 2012 – 2021



Source: JRC based on IEA, 2023

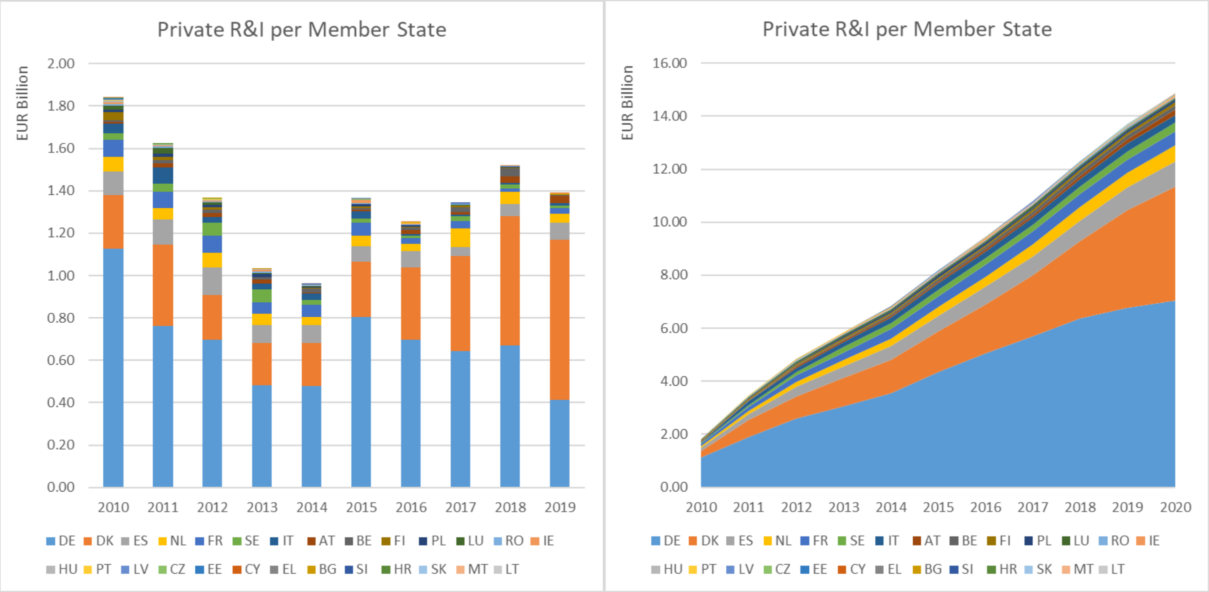
2.5 Private RD&I funding.

EU R&D funding in wind energy comes predominantly from the corporate sector. Since 2015, the share of private R&D funding ranged between 91% and 94% as compared to public funding (6% and 9%).

Within the EU, private R&D funding is highly concentrated in Denmark and Germany, where the leading European OEMs concentrate their industry and value chain (**Figure 15**).

In 2019, the private R&D investment from these two MSs reached EUR 755million and EUR 414million respectively. In relative terms, their private R&D investment has remained relatively constant in recent years, averaging about 75% and 69% of EU corporate and total R&D funding annually over the period 2010-2019.

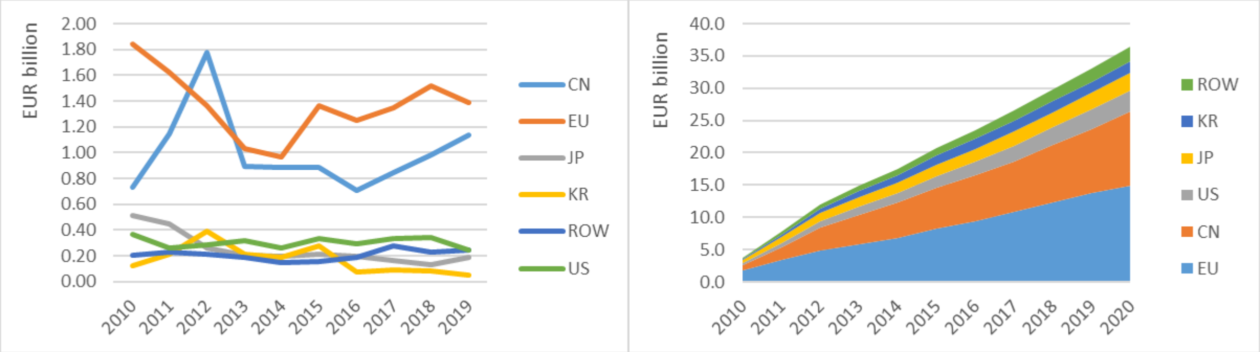
Figure 15. EU private R&D investment in the wind energy sector. Annual investment (left) and cumulative investment (right) per EU MS.



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

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 40% of the total private R&D funding in the period 2010-2020, followed by China (30%) 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.

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

2.5.1 Early and later stage private investment

Analysis of early and later stage venture capital (VC) investment[1] in wind energy-related innovations identifies about 400 companies that can be divided into corporates and venture capital companies. The EU hosts about 41% of all innovators, of which about 40% are venture capital companies and 60% are corporates, in similar proportions to the rest of the world (42% and 58/% respectively). Countries showing a significantly higher number of venture capital companies active in the wind sector are the US (54% of all innovating companies are venture capital companies), the UK (67%), Spain (54%), the Netherlands (65%) and Canada (100%) (see **Figure 17**).

Five countries host almost 80% of identified innovators. The US (first) and the UK (fifth) have a very strong base of venture capital companies while most of the innovators in Germany (second), China (third) and Japan (fourth) are corporate innovators. Within Europe (hosting 41% of identified companies), France, Spain and the Netherlands report a strong share of venture capital companies.

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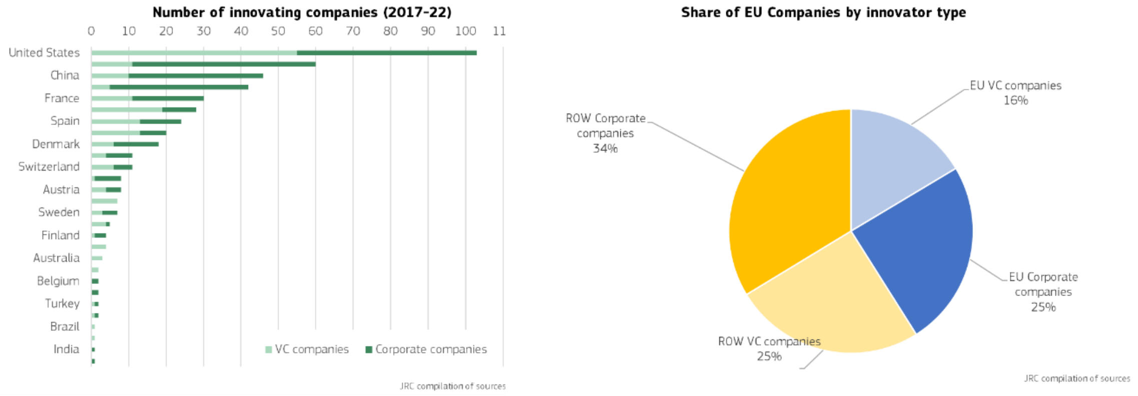
[1] Venture capital (VC) is a form of private equity and a type of financing that investors provide to start-up companies and small businesses that have long-term growth potential. The early stages indicator include Pre-Seed, Accelerator/Incubator, Angel, Seed and Early stage VC investments. The later stages indicator reflects growth investments for the scale-up of start-ups or larger SMEs. It include Late Stage VC, Small M&A and Private Equity Growth/Expansion.

Figure 17. Number of innovating companies in the wind energy sector (2017-2022) by country of origin (left) and by innovator type (right).



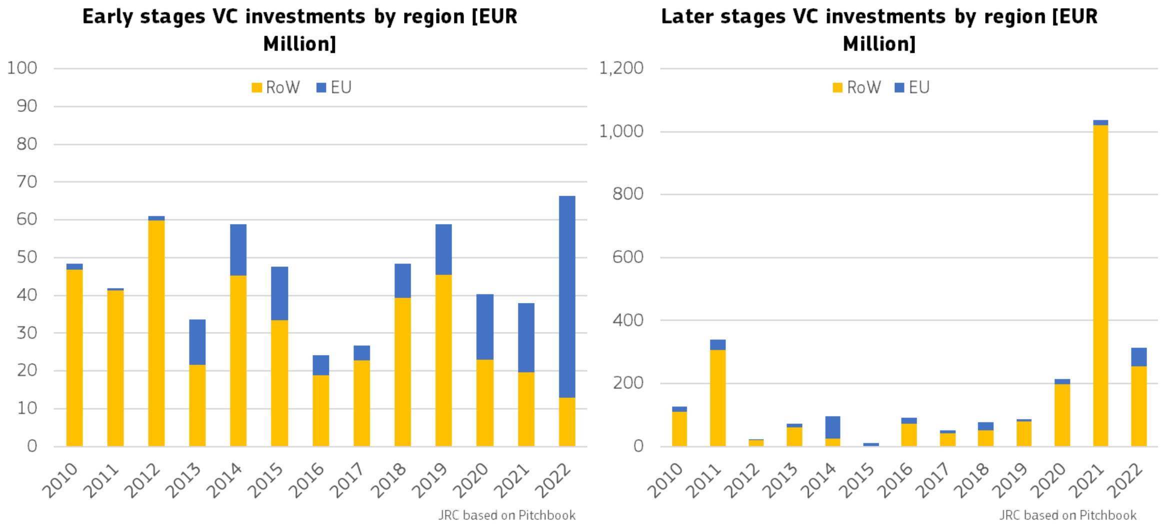
Source: JRC, 2023.

In the period 2017-2022, global early stage VC investment in the wind sector represented only 12% of all VC investment and while it declined from about EUR 48 million in 2018 to EUR 38 million in 2021, in 2022 there was a sharp increase in investment to about EUR 66 million (**Figure 18**).

The US secured most of the investment by far (32%) in early ventures over the 2017-2022 period, followed by France (15%) and the UK (7%). Investment in the EU is distributed across Latvia, Spain, Ireland, Sweden and the Netherlands.

In terms of later stage investment, China dominates the leader board, with 62% of the total investment in 2017-2022, having increased from EUR 14 million in 2011-2016 to EUR 1 billion in 2017-2022. The US follows, accounting for 19% of later stage investment. Investment in the EU is distributed over several countries, with France, Latvia, Sweden, Germany, Spain, Austria and Portugal in the top 15 countries in terms of later stage investment in 2017-2022.

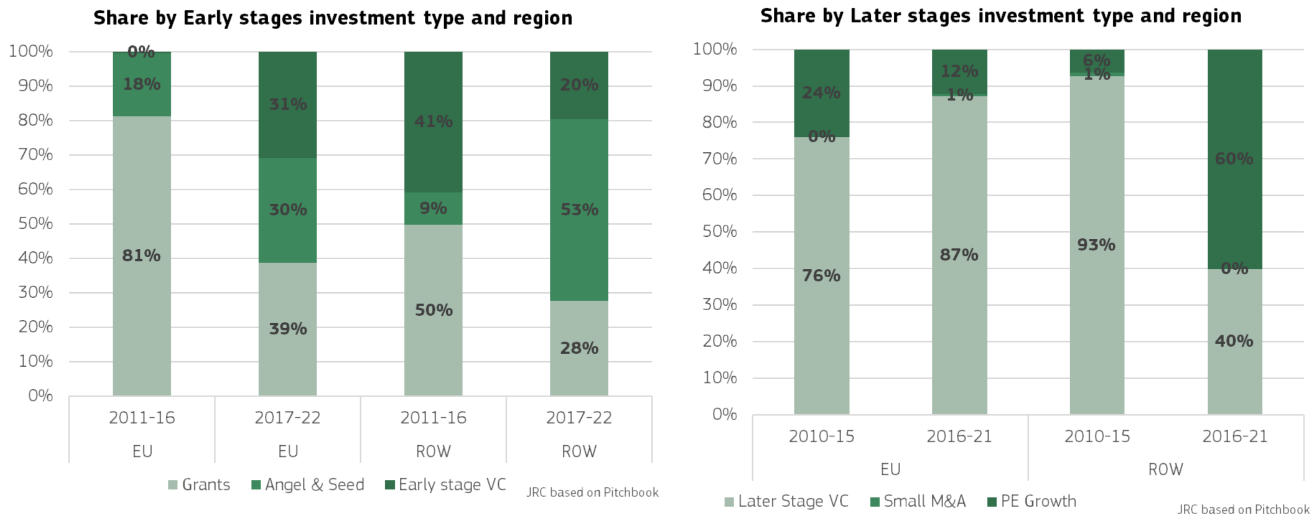
Figure 18. Early stage (left) and later stage (right) VC investment in the wind energy sector by region (2010-2022).



Source: JRC based on Pitchbook, 2023.

In terms of early stage investment, both in the EU and globally, there is less reliance on grants and an increase in private equity investment (Angel & Seed and early stage VC investment) (see **Figure 19**).

Figure 19. Share of early stage investment (left) and later stage investment (right) in the wind energy sector by type and region (2011-2022).



Source: JRC based on Pitchbook, 2023.

2.6 Patenting trends

The following sections provide information on patenting activity and the protection of international property rights in the wind sector. The leading countries and organisations active in patenting are analysed based on:

- **Number of inventions:** Patent families (inventions) include all documents relevant to a distinct invention (e.g. applications to multiple authorities).
- **International inventions:** Patent applications protected in a country other than the residence of the applicant are considered international.
- **High-value inventions:** High-value refers to patent families that include patent applications filed in more than one patent office. High-value inventions consider EU countries separately, while for international inventions, European countries are viewed as one macro category.

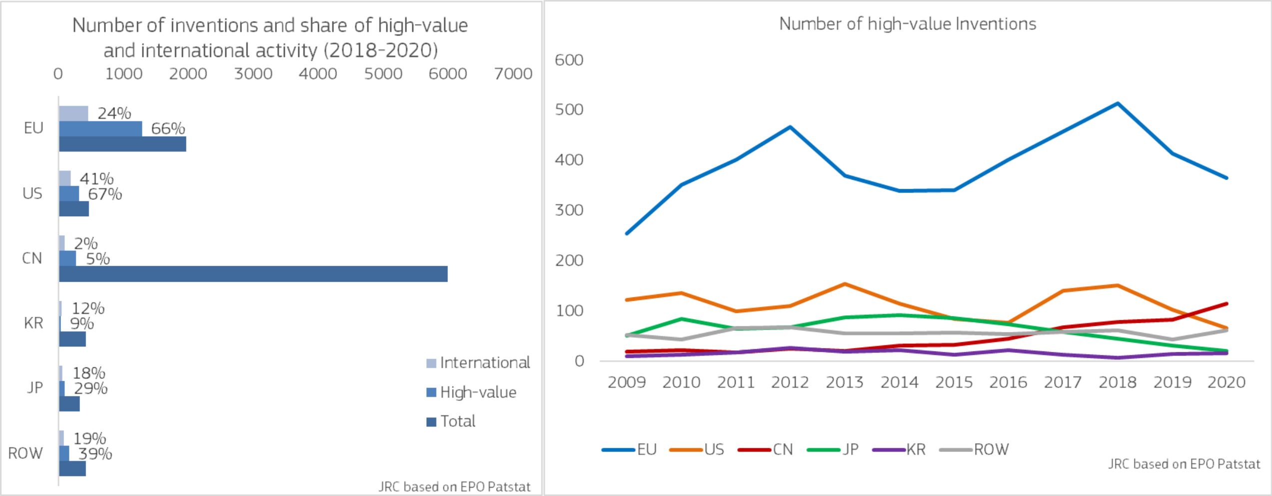
The Cooperative Patent Classification (CPC) codes considered for the evaluation of the patenting activity are: Y02B 10/30, Y02E 10/70, Y02E 10/72, Y02E 10/727, Y02E 10/728, Y02E 10/74 and Y02E 10/76. Data are incomplete for the year 2020, but are still an indication of the trend for the year.

China ranks first in wind energy inventions after overtaking the EU in 2009, which had been world leader since 2006. However, Chinese patenting activity focusses on its internal market with only 2% of patents being international (EU: 24%, US: 41%). In the period 2018-2020, only about 5% of the Chinese patenting inventions filed for wind energy technologies were high value, while high-value inventions account for about 66% of all European wind energy inventions filed. The share of high-value inventions in the US and Japan is 67% and 29% respectively, but both have significantly lower numbers in absolute terms (see **Figure 20**).

Globally, in the period 2018-2020, the EU's share of high-value inventions was 59%, followed by the US (15%), China (13%), Japan (4%) and Korea (2%) (see **Figure 20**).

At country level, Denmark leads on high-value inventions (596), closely followed by Germany (393) and the US (319). In total, five EU countries can be found within the top 10 (Denmark (596), Germany (393), Spain (110), France (51) and the Netherlands (42)). China and Japan rank fourth and fifth, filing 275 and 96 high-value patents in the period 2018-2020, respectively.

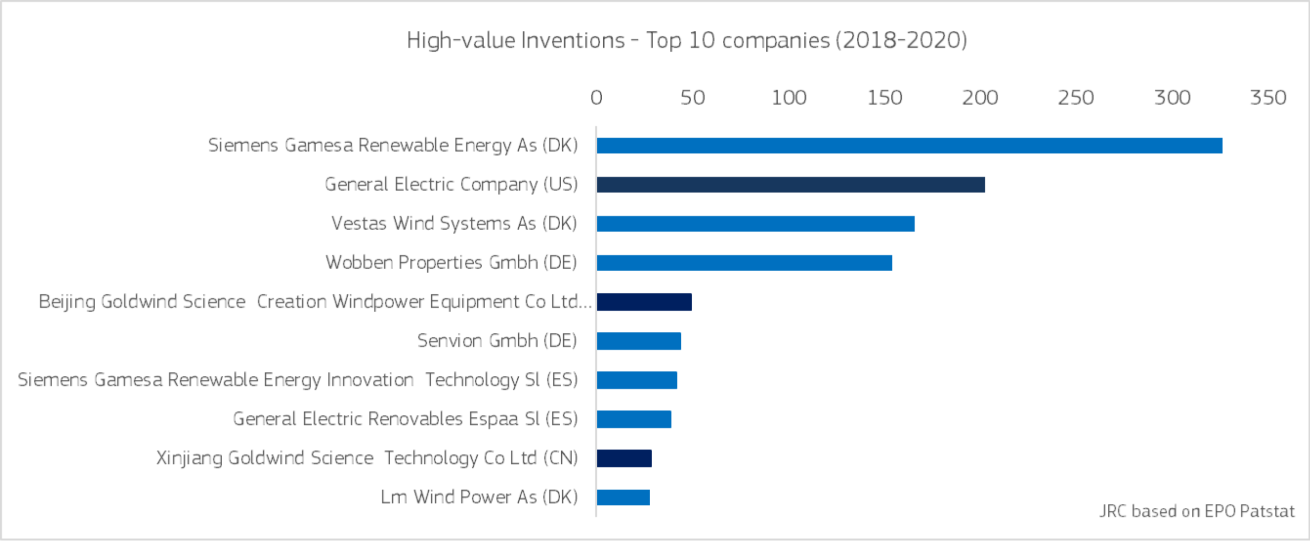
Figure 20. Number of wind energy inventions and share of high-value and international activity (2018-2020) (left) and development of high value inventions (2009 – 2020) (right)



Source: JRC based on Patstat, 2023.

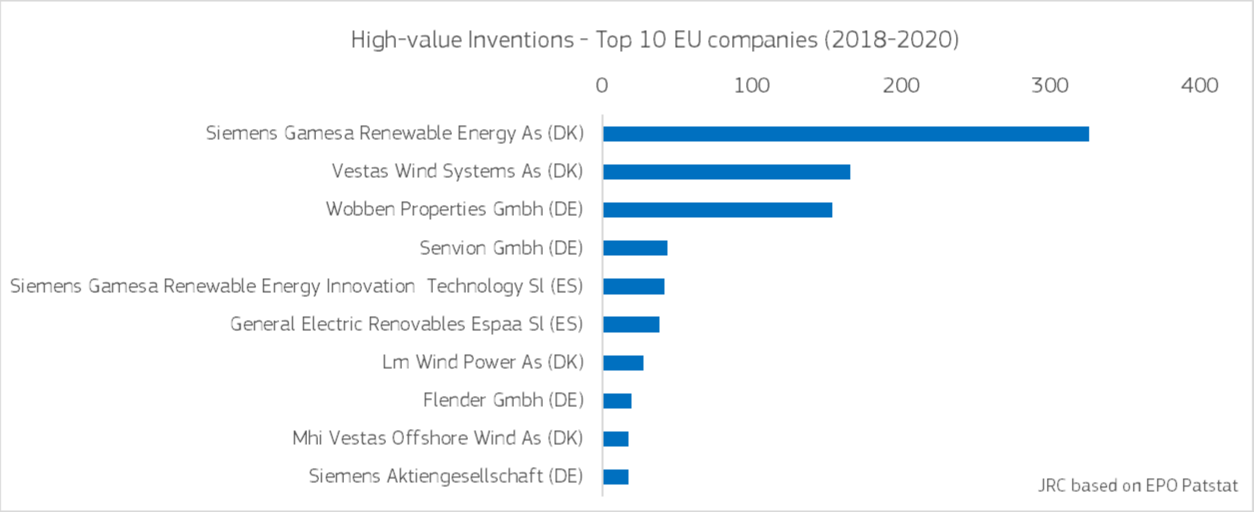
EU companies keep the lead in terms of high-value inventions filed in the period 2018-2020. EU-based original equipment manufacturers (OEMs) (e.g. SiemensGamesa, (first), Vestas (third), Enercon (Wobben Properties GmbH) (fourth) and Senvion (sixth)) hold a leading position in high-value patents, together with General Electric (US – second) and Goldwind (CN – fifth) (see **Figure 21**).

Figure 21. Top 10 organisations (global) - Number of inventions and share of high-value and international activity (2018-2020)



Source: JRC based on Patstat, 2023.

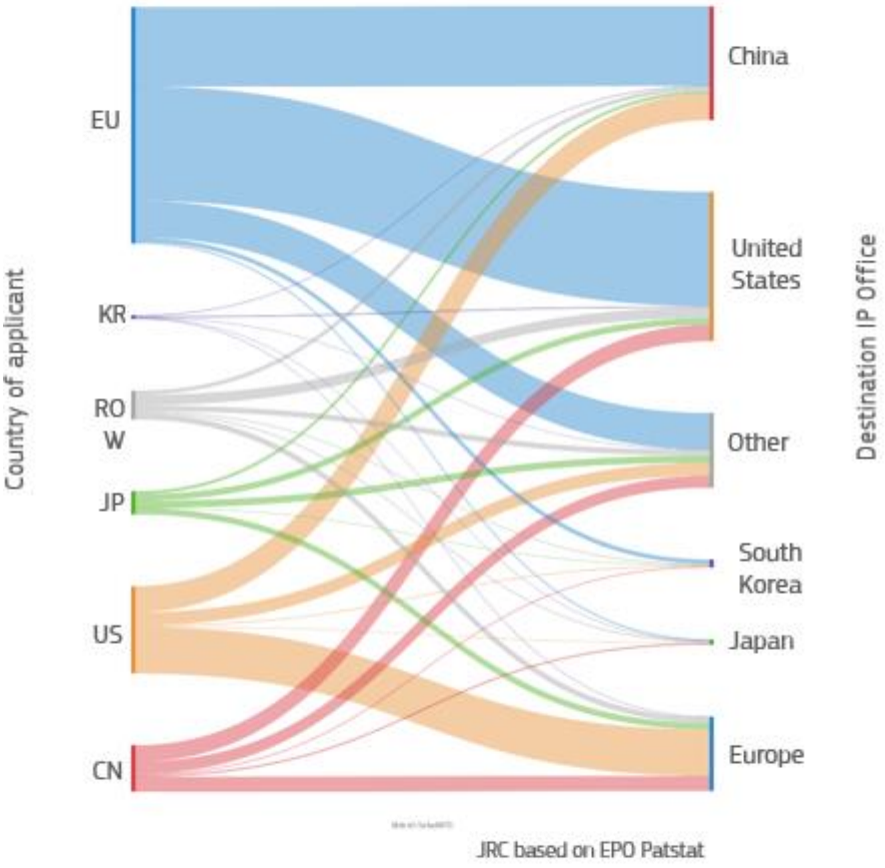
Figure 22. Top10 organisations (EU) - Number of inventions and share of high-value and international activity (2018-2020)



Source: JRC based on Patstat, 2023.

Figure 23 presents the flow of high-value inventions from the major economies to the main patent offices in the period 2018-2020. EU applicants show the highest share of inventions protected in the US (48%) and China (34%), whereas the US protect a substantial share of their inventions in Europe (53%) 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. International protection of high-value inventions (2018-2020)



Source: JRC based on Patstat, 2023.

2.7 Scientific publication trends

This chapter analyses bibliometric trends in the wind energy sector. Chapter 2.7.1 provides bibliometric indicators on the publications retrieved for the entire sector. This is followed by the analysis of subsets, based on bibliometric search queries clustered into the following thematic wind areas:

- Wind energy components
- Wind-Environmental impact
- Offshore wind
- Grid integration
- Airborne Wind Energy Systems
- Vertical Axis Wind Turbines
- Other

For all performed search queries this chapter provides information on:

- the number of peer-reviewed articles per year 2010-2022 (global and EU),
- the number of highly cited papers (top 10% cited, normalised per year and field),
- the FWCI[2] per country, measuring the citation impact of publications as compared to the global average of the research field

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[2] 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).

- h-index[3] per country, measuring both the productivity and citation impact of publications,
- the collaboration network among countries[4].

Publications in the wind sector are based on data from Scopus from 2010 to 2022. The overall number of wind energy publications grew continuously from 427 peer-reviewed articles in 2010 to 3 155 publications in 2022, an increase of 738%. In 2022, the number of articles is highest in China (32%), followed by the EU (17%), the US (8%) and the UK (7%). Within the EU, the leading countries in terms of deployment and first movers are matched by the highest publication activity. Since 2010, Germany (882) ranks first in the cumulative number of articles, followed by Denmark (613), Spain (585), Italy (479) and the Netherlands (366) (see **Figure 24**). Research activity in the wind sector has spread all over Europe, with all EU MSs recording publishing activity in the period 2010-2022 and 18 countries showing continuous publication activity (with more than 25 peer-reviewed articles in the same period).

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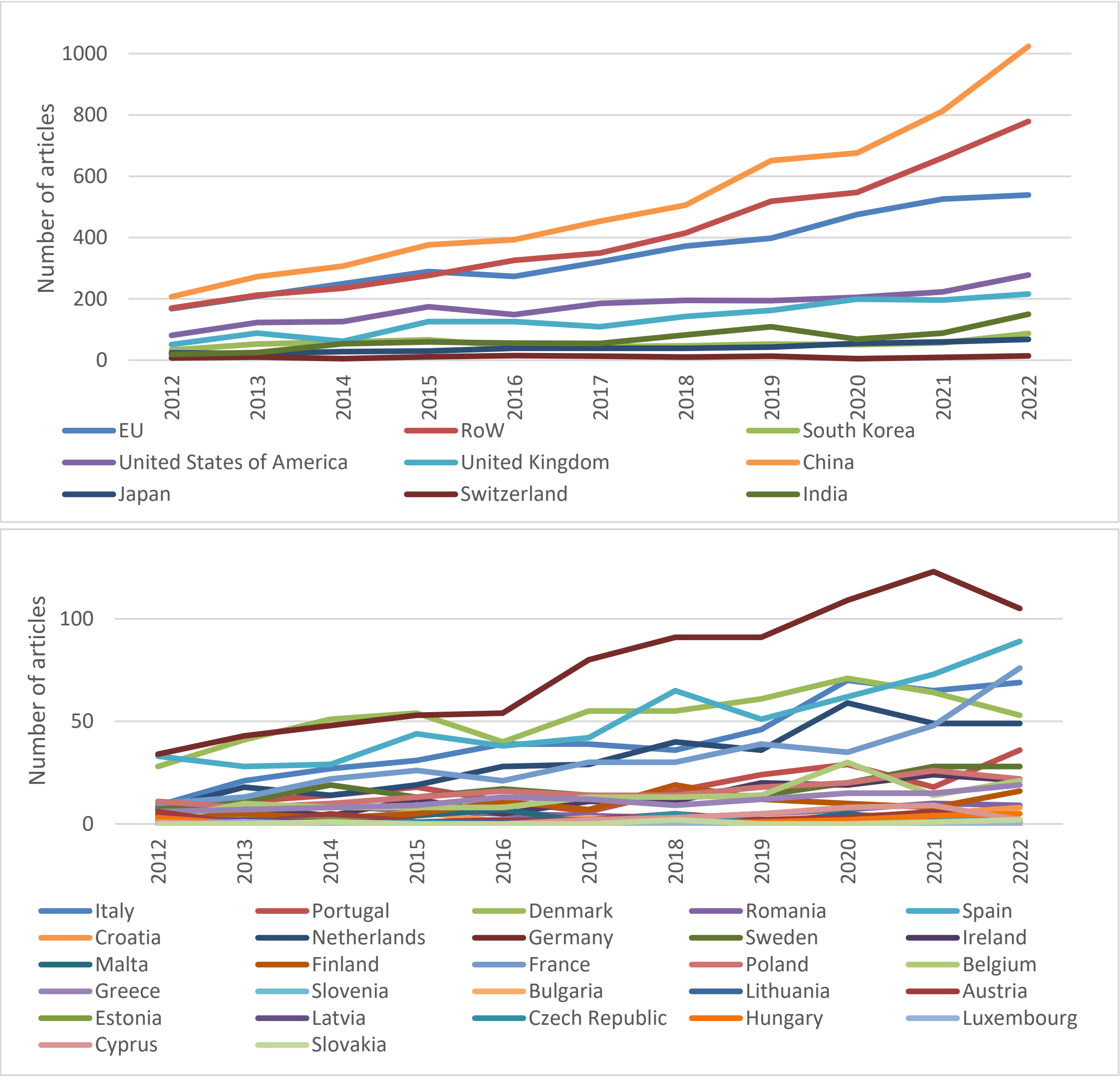
[3] The h-index (also Hirsch-Index) of a country is the largest number h such that at least h articles in that country for that topic were cited at least h times each (Hirsch, 2005).

[4] 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

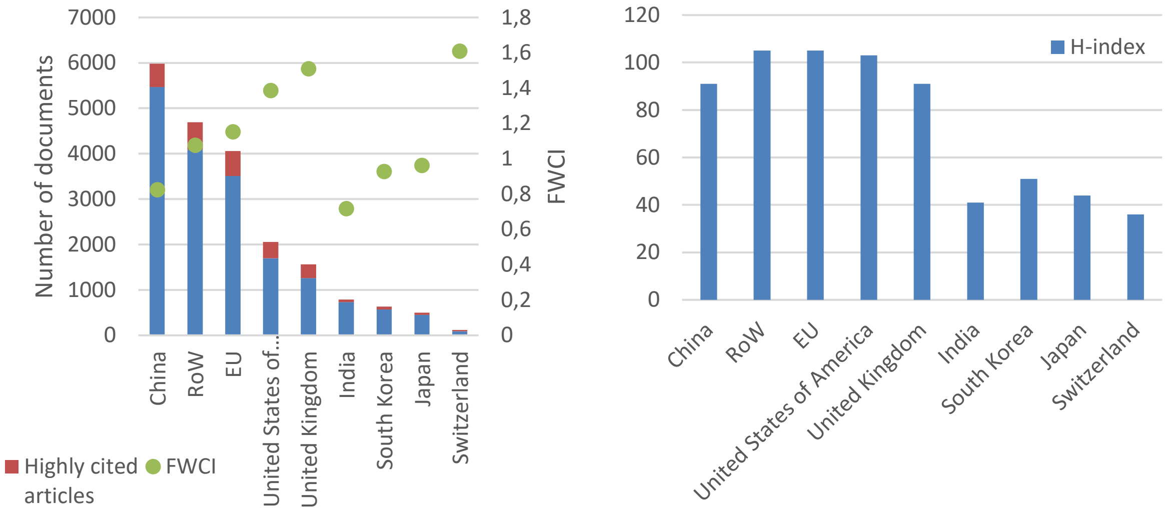
Figure 24. Wind energy - Number of peer-reviewed articles per year (2010-2022) globally (top) and in the top 10 EU MSs (bottom).



Source: JRC based on TIM, 2023.

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. The EU leads in highly cited articles (550), followed by China (514), the US (363) and the UK (299). The FWCI within the research field indicates that EU (1.15) performs above global average, ranking fourth behind Switzerland (1.6), the UK (1.5) and the US (1.3), all countries with significantly lower overall publication activity than the EU. Other competitors such as China (0.8), India (0.7), South Korea (0.9) and Japan (0.9) rank below the global average in FCWI (see **Figure 25** left). In terms of citation impact and productivity, measured by the H-index, the EU (105) leads, closely followed by the US (103), the UK (91) and China (91) (see **Figure 25** right).

Figure 25. Wind energy - Total number of peer-reviewed articles per year (2010-2022), FWCI (left) and H-index (right) of the EU and global competitors.

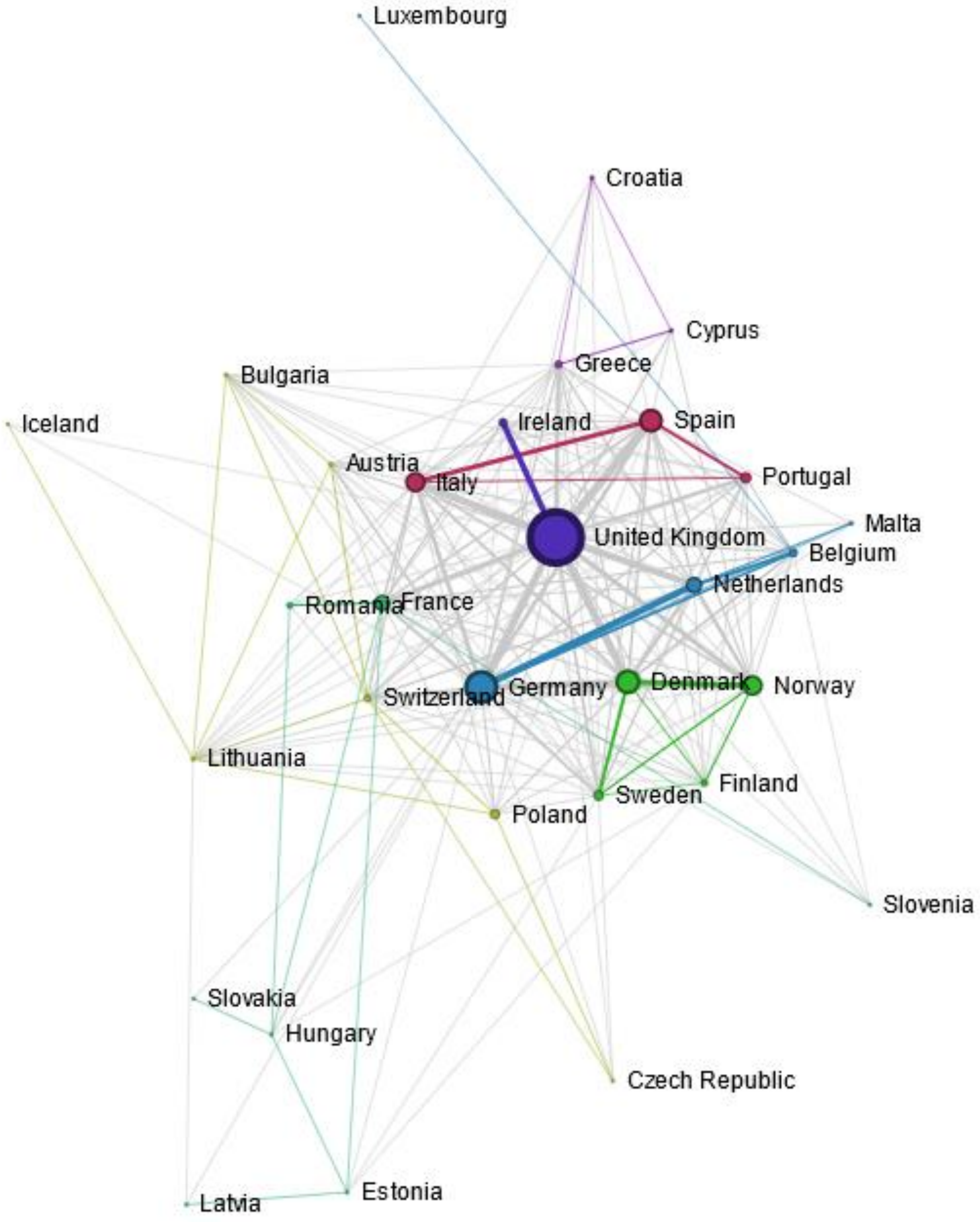


Source: JRC based on TIM, 2023.

In the period 2010-2022, 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 (see **Figure 27**).

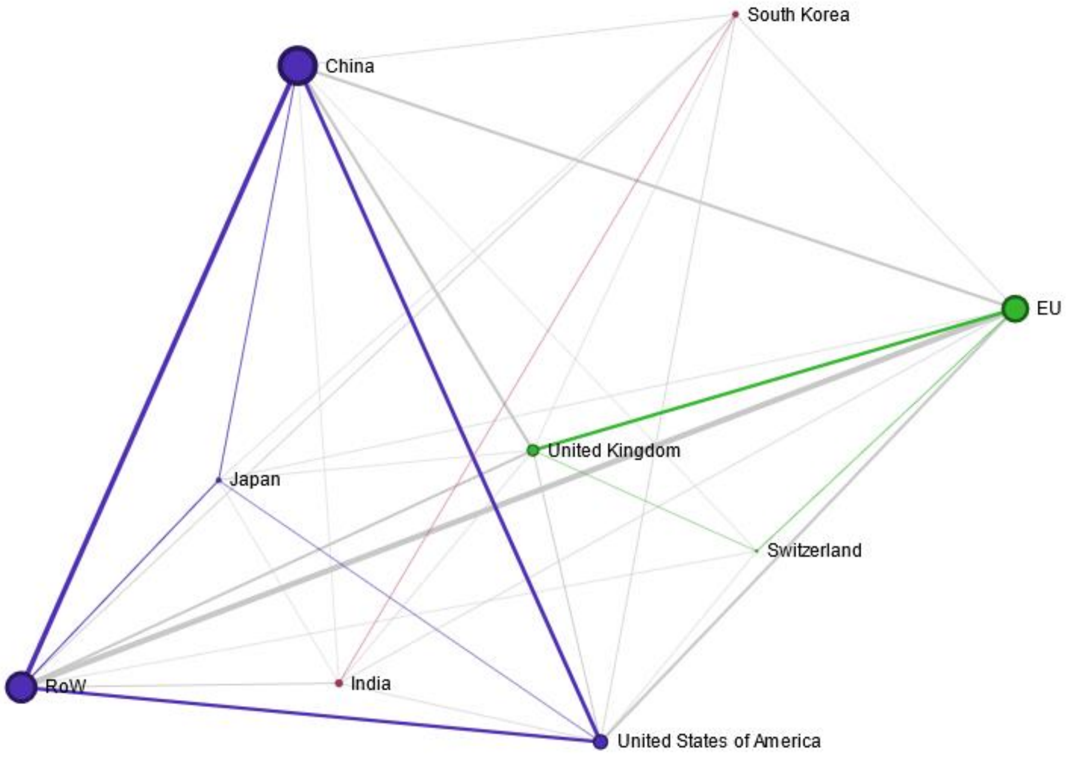
Within the EU, the strongest collaboration networks exist between Germany and the Netherlands, Germany and Denmark, Germany and Italy and the Netherlands and Denmark. Moreover, Spain, Denmark, Germany and the Netherlands show very strong publication ties with the UK (**Figure 26)**

Figure 26. Wind energy - Collaboration network between European countries based on peer-reviewed articles per year (2010-2022)



Source: JRC based on TIM, 2023.

Figure 27. Wind energy - Collaboration network of the EU and its competitors based on peer-reviewed articles per year (2010 – 2022)



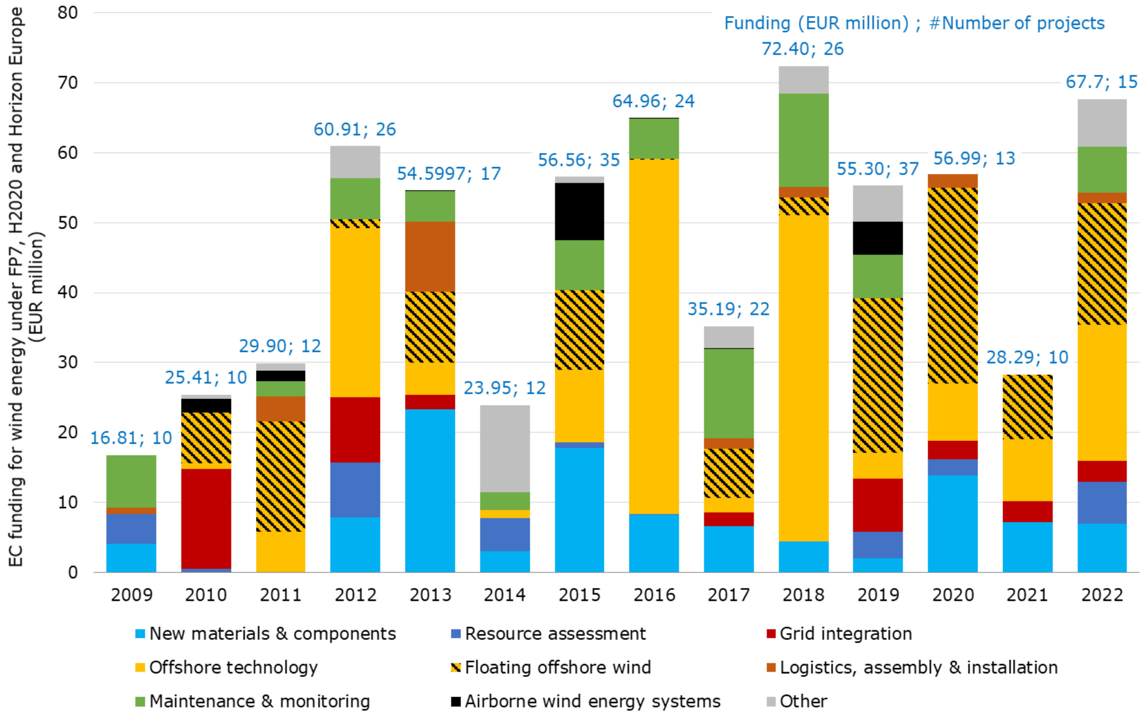
Source: JRC based on TIM, 2023.

2.8 Assessment of R&I project developments

Research funding in Europe's biggest research and innovation programme has showed continued support to wind energy in the last year. In 2022, as a result of the commencement of the Horizon Europe programme, funding increased both in terms of the number of projects funded as well as in financial support.**Figure 28**shows the development of R&I funding in the period 2009-2022 under Horizon Europe and its predecessors, FP7 and H2020.

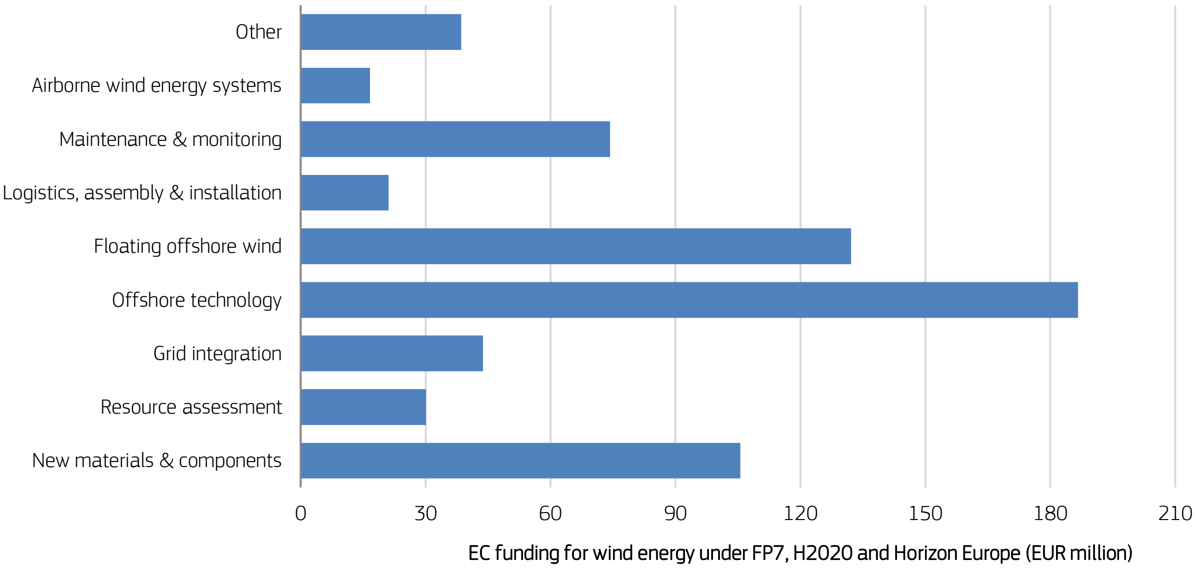
Since 2009, substantial funding has been allocated across all wind research R&I priorities, with projects on offshore wind technology (EUR 187 million), floating offshore wind (EUR 132 million) and research on new materials & components (EUR 106 million) accumulating most of the funds (see **Figure 29**).

Figure 28. Evolution of EU R&I funding categorised by R&I priorities for wind energy under FP7 (2009-2013), H2020 (2014-2021) and Horizon Europe (2022) programmes and the number of projects funded in the period 2009-2022. Projects specifically on wind energy and those with a significant wind energy component are accounted for. Note: the item 'Other' includes some projects exploring emerging technologies such as social acceptance and critical rare earth elements. Funds granted refer to the start year of the project.



Source: JRC based on Cordis, 2023.

Figure 29. EC funding on wind energy R&I priorities in the period 2009-2022 under FP7, H2020 and Horizon Europe.



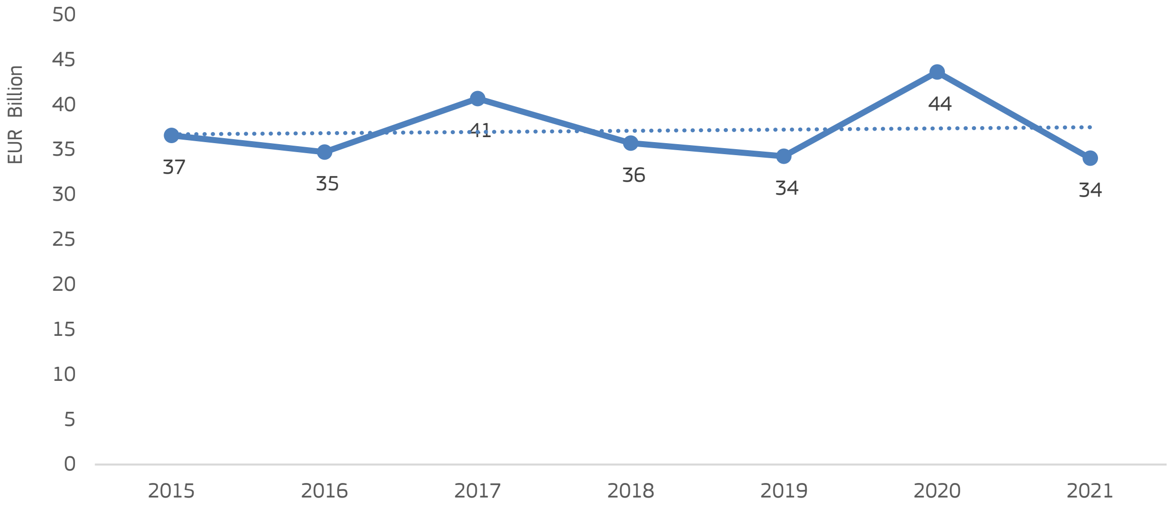
Source: JRC based on Cordis, 2023.

3. Value Chain Analysis

3.1 Turnover

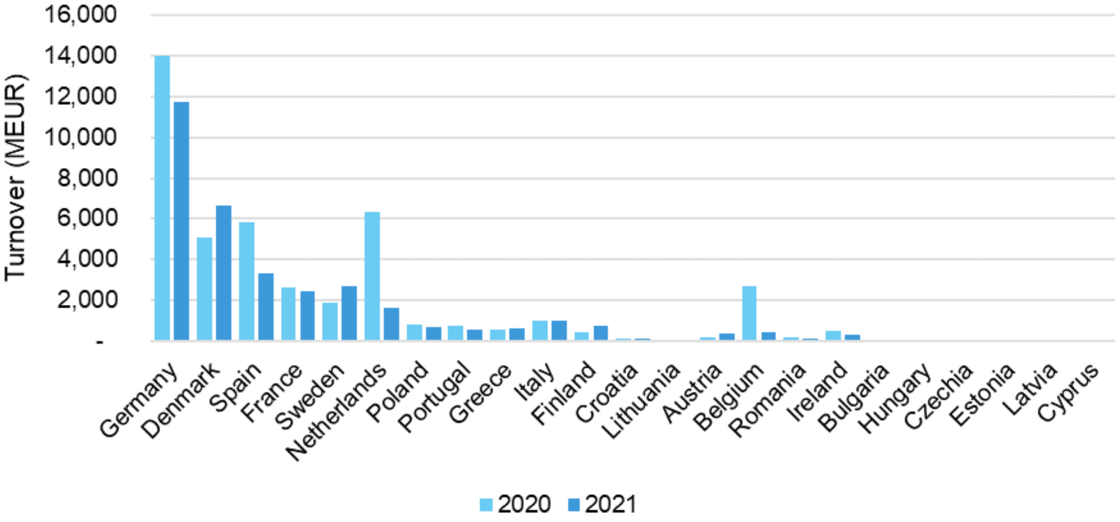
Turnover in the wind power sector accounted for between EUR 34 billion and EUR 44 billion in the period 2015-2021, with a stable trend (see **Figure 30**). Turnover values are calculated using an approach which is based on an evaluation of the economic activity of the wind sector. In order to allow a comparison between EU MSs, input-output tables are used and money flows from activities in the renewable energy value chain are considered. EurObserv'ER considers the following four activities: 1) investment in new installations, 2) Operation and maintenance activities for existing plants, including newly added plants, 3) Production and trade of renewable energy equipment and 4) Production and trade of biomass feedstock (EurObserv'ER, 2022)**.**

Figure 30. Turnover of the EU wind sector in the period 2015-2021.



Source: JRC based on EurObserv'ER, 2023.

Figure 31. Turnover of the wind sector in EU Member States in 2020 and 2021 for countries with more than 100M EUR turnover



Source: JRC based on EurObserv'ER, 2023.

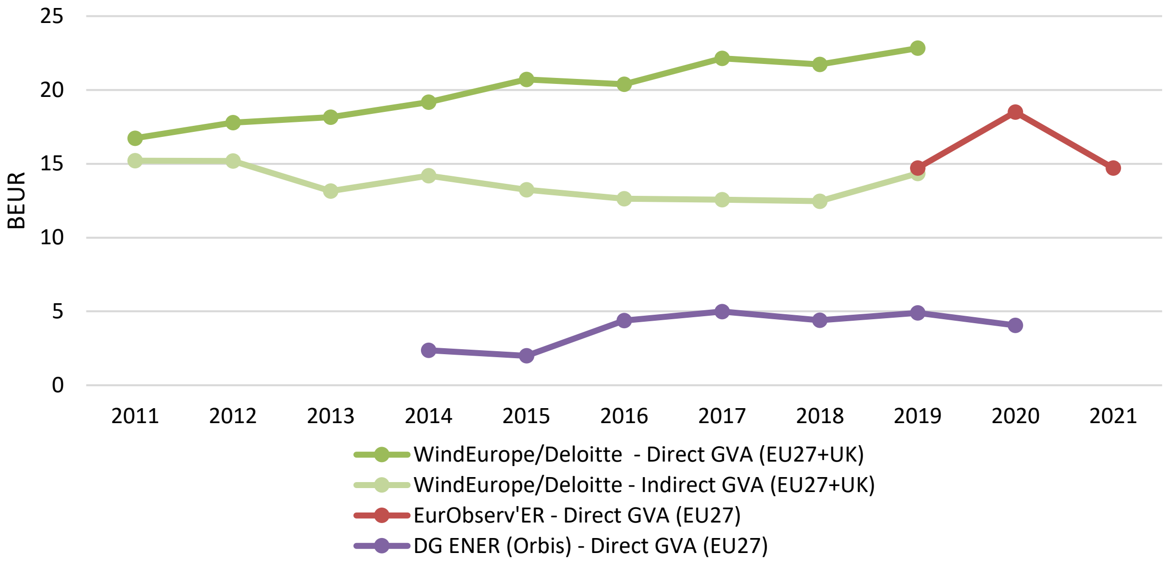
From 2020 to 2021, total turnover of EU companies decreased by about EUR 10 billion. At about EUR 11.8 billion, Germany leads on turnover, followed by Denmark, Spain and Sweden (see **Figure 31**). Denmark, Sweden, Poland and the Netherlands are the only countries that saw an increase in turnover from 2020 to 2021.

3.2 Gross value added

Estimates aiming to quantify the gross value added (GVA) of the EU wind sector show differences in the methodological approach and in geographical scope (**Figure 32**). EurObserv'ER (2022) derives the direct GVA from the sectoral turnover figures and value added/input factors per sector from Eurostat input-output tables. The direct GVA figure for one sector in a specific country describes the value of output minus the value of intermediate consumption. The geographical reference of the EurObserv'ER analysis is the EU27 (EurObserv'ER, 2022).

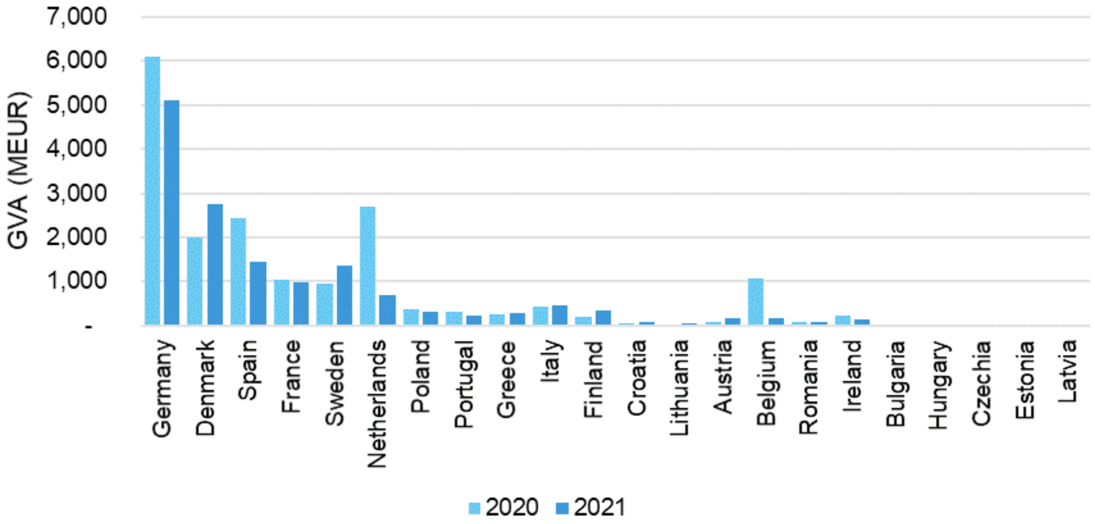
Direct GVA values calculated by EurObserv'ER (2022) decreased to 14.7 billion in 2021, a 26% decrease on the previous year's figure. With about EUR 5.5 billion, Germany leads in direct GVA, followed by Denmark (EUR 2.7 billion), Spain (EUR 1.4 billion) and Sweden (EUR 1.3 billion) (see **Figure 33**).

Figure 32. Gross Value Added (GVA) of the EU wind sector in the period 2011 to 2021.



Source: JRC based on EurObserv'ER and WindEurope, 2023.

Figure 33. Direct Gross Value Added (GVA) of the EU wind sector in 2020 and 2021.



Source: JRC based on EurObserv'ER, 2023.

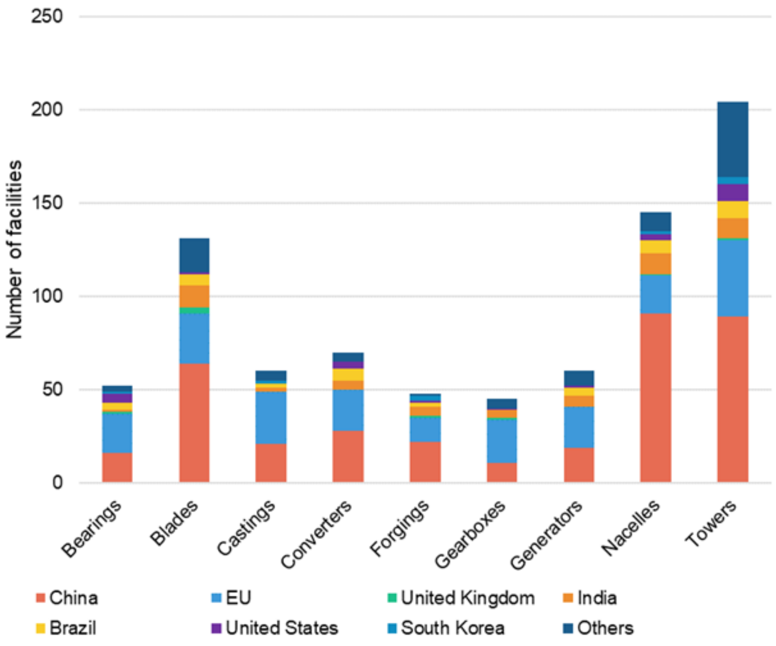
3.3 Role of EU Companies

The share of renewables in power generation is projected to further rise as the EU aims to achieve climate neutrality by 2050. The total installed wind capacity would need to more than double and reach 510 GW in 2030 according to REPowerEU. In order to achieve that, the annual deployment of wind technologies is projected to increase almost threefold (from 15 GW in 2022 to 42 GW in 2030). EU manufacturers need to consolidate their competitive edge and maintain or expand their current market shares throughout this decade, in line with the EU's REPowerEU technology deployment projections for its 2030 energy and climate targets. Since it is estimated that EU manufacturers currently produce around 85% of the EU's annual wind deployment needs, the Net-Zero Industry Act envisages the maintenance of these market shares throughout this decade.

Finally, the growth potential of EU manufacturing of net zero technologies is also being undermined by significant volatility in material prices and input costs, more expensive transportation and financing, and continued supply chain bottlenecks, though these factors have also made an impact, to some extent, on net-zero industries in other parts of the world. For example, according to industry data, the fall in investment in wind energy and in turbine orders in Europe (total orders for new wind turbines from EU manufacturers fell by almost 50% in 2022 relative to the previous year), partly due to inflation in commodity prices and other input costs, is reported to have compounded the problems faced by the EU's wind energy supply chain. The EU wind sector is one of the strongest players on world markets and is still led by domestic companies.

WindEurope/WoodMackenzie (2020) identifies about 800 wind energy manufacturing facilities (**Figure 34**), with the majority operating in China (45%) and Europe (31%), followed by India (7%), Brazil (5%) and North America (4.5%). In Europe, the leading markets, Germany, Spain, Italy, Denmark and France, host a substantial number of manufacturers (WindEurope/Wood Mackenzie, 2020)[5]. Looking more broadly at wind-related activities (e.g. R&D centres, operations, construction, services and ports), about 550 companies/entities are located in European countries.

Figure 34. Operational manufacturing facilities of wind energy components (global)



Source: WindEurope/WoodMackenzie, 2020

A detailed analysis of the onshore and offshore subcomponents supply chain is provided in the 2022 wind energy CETO report (Telsnig et al., 2022) .

The market shares for new installations in 2022, globally and in the EU, are presented in **Figure 35** and **Figure 36**.

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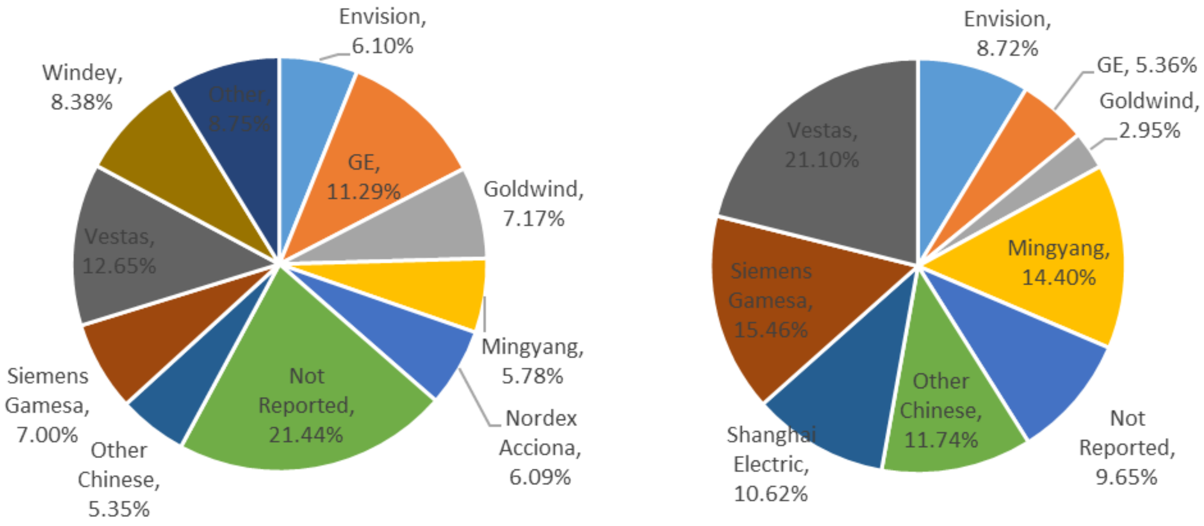
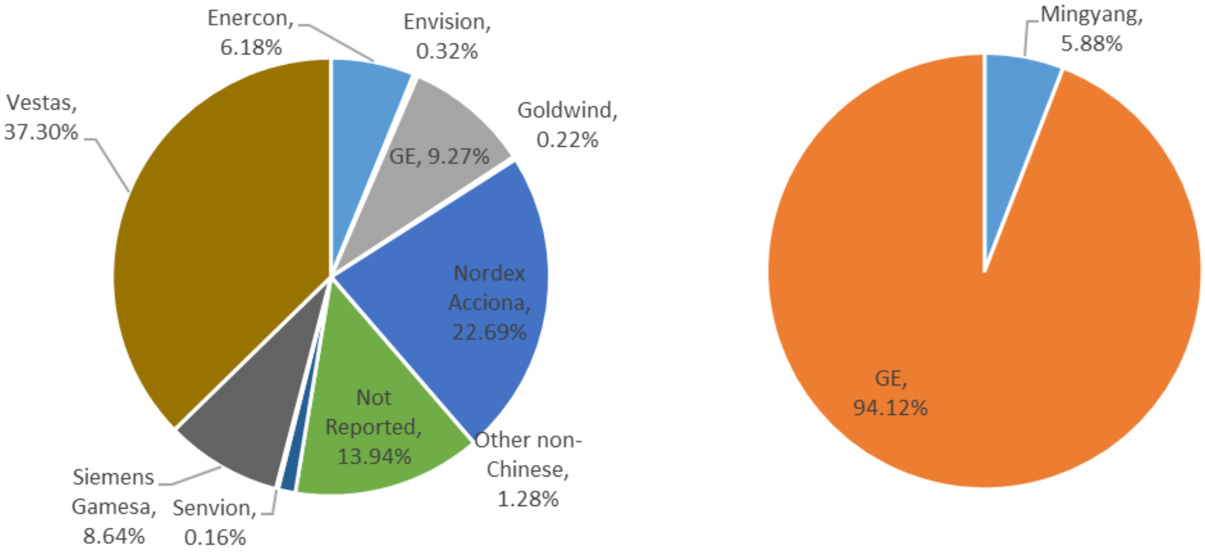
[5] The WindEurope/WoodMackenzie (2020) data set covers Tier1 and Tier2 component manufacturers of the following components: Nacelle, Bearings, Blades, Converters, Gearboxes, Generators, Castings, Forgings, Towers.

Figure 35. Global market share for 2022 onshore (left) and offshore (right) installations



Source: JRC based in GWEC, Wood MacKenzie, 2023

Figure 36. EU market share for 2022 onshore (left) and offshore (right) installations



Source: JRC based in GWEC, Wood MacKenzie, 2023

Table 4. Component sourcing strategy of GE and Vestas for selected offshore wind rotors
Note: Components manufactured in EU27 countries (highlighted in blue), in both EU27 and European countries (light blue) in European countries (grey) and non-European countries (red).

Turbine model	Haliade X-12MW	V164-9.5 MW
OEM	GE Renewable Energy	Vestas
Country (HQ) of OEM	US	DK
Main components (country of origin/country of manufacturing location)		
Blade	LM Wind Power (US/FR)	Vestas (DK/UK)
Blade bearing	Rollix (FR/FR)	Rollix (FR/FR)
		Liebherr (CH/DE)
Pitch System	Liebherr Components Biberach GmbH (CH/DE)	LJM (DK/DK)
		GLUAL (ES/ES)
Shaft	GE Renewable Energy (US/FR)	Vestas (DK/DK-UK)
Main bearing	Timken (US/RO)	Timken (US/RO)
Gearbox	n.a.	ZF (DE/DE)
Yaw System - Drive & Brake	Liebherr Components Biberach GmbH (CH/DE)	Lafert Group (Sumitomo) (JP/IT)
		Vestas (DK/UK)
Yaw System - Bearing	GE Renewable Energy (US/FR)	Vestas (DK/UK)
Yaw System - Gear type	Liebherr Components Biberach GmbH (CH/DE)	Comer Industries (IT/IT)
Generator	GE Renewable Energy (US/FR)	The Switch (Yakasawa) (JP/FI)
Converter	ABB (CH/PL)	Vestas (DK/DK)
Transformer	ABB (CH/FI)	Siemens (DE/DE-AT)
		ABB Oy Transformers (CH/FI)
Switchgear	GE Renewable Energy (US/FR)	ABB Distribution Solutions Distribution Automation (CH/NO)
		Siemens (DE/DE)
		Mitsubishi Electric (JP/JP-CN)

Source: JRC, IEC, 2022.

Table 5. Component sourcing strategy of SiemensGamesa RE for selected offshore wind rotors
Note: Components manufactured in EU27 countries (highlighted in blue), in both EU27 and European countries (light blue) in European countries (grey) and non-European countries (red).

Turbine model	SG 8.0-167 DD	SG 10-200 DD
OEM	SiemensGamesa RE	SiemensGamesa RE
Country (HQ) of OEM	DE-ES	DE-ES
Main components (country of origin/country of manufacturing location)		
Blade	SiemensGamesa RE (DE-ES/DE-UK)	SiemensGamesa RE A/S (DE-ES/**DK***-DE-UK)
Blade bearing	Rollix (FR/FR)	Thyssenkrupp Rothe Erde GmbH (DE/DE)
	Thyssenkrupp Rothe Erde GmbH (DE/DE)	TMB (Zhejiang Tianma Bearing Group Limited) (CN/CN)
	TMB (Zhejiang Tianma Bearing Group Limited) (CN/CN)	
Pitch System	SiemensGamesa RE (DE-ES)	
Shaft	SiemensGamesa RE (DE-ES/DE-DK-UK)	Jiangsu Bright Steel Fine Machinery Co.Ltd. (CN/CN)
		Jiangsu Hongde Special Parts Co.Ltd. (CN/CN)
		HegerFerrit GmbH (DE/DE)
Main bearing	Thyssenkrupp Rothe Erde GmbH (DE/DE)	Thyssenkrupp Rothe Erde GmbH (DE/DE)
	SKF (SE/AT-DE-FR-SE)	
Gearbox	n.a	n.a

Yaw System - Drive & Brake	SiemensGamesa RE (DE-ES/DE-DK-UK)	ABB Sp.z.o.o. (CH/PL)
Yaw System - Bearing	SiemensGamesa RE (DE-ES/DE-DK-UK)	Reducel S.L. (ES/ES)
		Niebuhr Gears (Tianjin) Co., Ltd. (CN/CN)
		Jiaxing Shimai Machinery Co., Ltd. (CN/CN)
Yaw System - Gear type	Comer Industries (IT/IT)	Bonfiglioli S.p.A. (IT/IT)
Generator	Siemens (DE/DE)	SiemensGamesa RE A/S (generator design) (DE-ES/DK-DE-UK)
Generator - Stator segments		Flender D.O.O. (SRB/SRB)
Generator - stator segments and rotor house		AVI Manufacturing Co. Ltd. (CN/CN)
Generator - electrical parts		KK Wind Solutions Polska Sp. z.o.o. (PL/PL)
Converter	Siemens (DE/DE)	KK Wind Solutions Polska Sp. z.o.o. (PL/PL)
Transformer	Siemens (DE/DE-AT)	Siemens Energy Austria GmbH (DE/AT)
Switchgear	Siemens (DE/DE)	

*Certificate mentions SiemensGamesa A/S in Denmark

Source: JRC, IEC, 2022.

Table 6 Component sourcing strategy of OEMs for selected onshore wind rotors
Note: Components manufactured in EU27 countries (highlighted in blue), in both EU27 and European countries (light blue), in European countries (grey) and non-European countries (red).

Turbine model	**V150-4.0 MW / V150-4.2 MW**	**E-126 EP3**	**SWT-DD-130 4.3MW**
OEM	Vestas	Enercon	SiemensGamesa RE
Country (HQ) of OEM	DK	DE	DE-ES
	Main components (country of origin/country of manufacturing location)		
Blade	Vestas Wind Systems A/S (DE-ES/DE-DK-ES-IT)	TPI Kompozit Kanat 2 (US/TR)	SiemensGamesa RE (DE-ES/DK)
Blade bearing	Vestas Wind Systems A/S (DK/DK)	Liebherr Components Biberach GmbH (CH/DE)	Thyssenkrupp Rothe Erde GmbH (DE/DE)
		Thyssenkrupp Rothe Erde GmbH (DE/DE) IMO GmbH & Co.KG (DE/DE)	TMB (Zhejiang Tianma Bearing Group Limited) (CN/CN) ZWZ (CN/CN)
Pitch System	LJM (DK/DK)	Emod (DE/DE)	Fjero A/S (DK/DK)
	Liebherr (CH/DE)	Ruckh (DE/DE)	Hydratec Industries N.V. (NL/NL)
	HINE Hydraulics (US/ES-BR-US-IN-CN) Hengli (US/US-DE-JP-CN)		
Shaft	Vestas (DK/DK)	Heger Group (DE/DE)	Siemens (DE/DE)
			Jiangsu Hongde Special Parts Co LTD (CN/CN)
Main bearing	FAG (Schaeffler Group) (DE/DE) SKF (SE/AT-DE-FR-SE)	PSL, a.s. (DE/SK) FAG (Schaeffler Group) (DE/DE)	Thyssenkrupp Rothe Erde GmbH (DE/DE) AB SKF (SE/SE)
	JTKET / KOYO (JP/JP-UK-DE-CZ-RO-CN-IN-PH)	SKF (SE/AT-DE-FR-SE)	
Gearbox	ZF (DE/DE)	n.a	n.a
	Winergy (DE/DE)		
Yaw System - Drive & Brake	Lafert Group (Sumitomo) (JP/IT)	Emod (DE/DE)	Siemens (DE/DE)
	ABB (CH/EU)	Ruckh (DE/DE)	
	Bonfiglioli (IT/IT)		

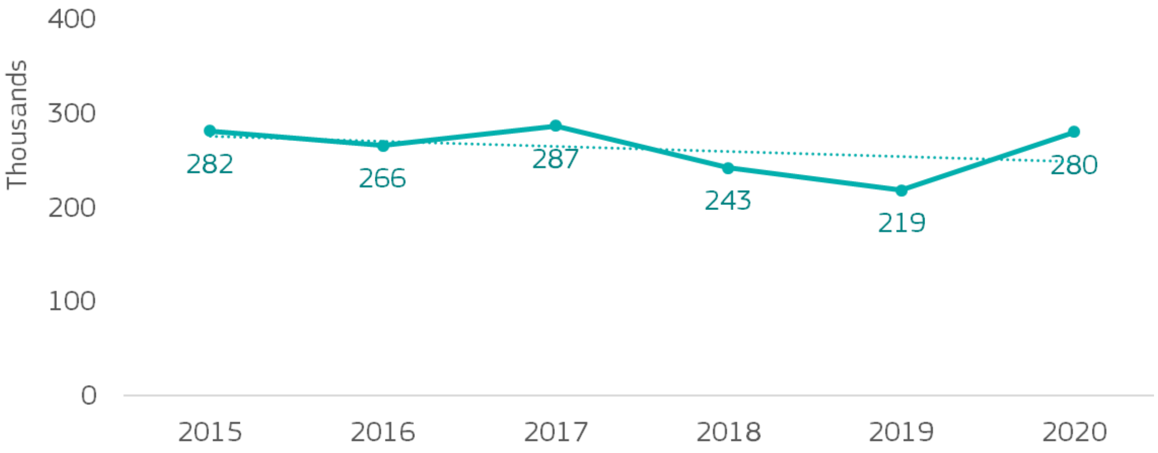
Yaw System - Bearing	Vestas Wind Systems A/S (DK/DK)	Liebherr Components Biberach GmbH (CH/DE)	SiemensGamesa RE (DE-ES/DK)
		Thyssenkrupp Rothe Erde GmbH (DE/DE)	
Yaw System - Gear type	Comer Industries (IT/IT)	Liebherr Components Biberach GmbH (CH/DE)	Comer Industries (IT/IT)
	Bonfiglioli (IT/IT)	Bonfiglioli (IT/IT)	Bonfiglioli (IT/IT)
			Siemens (DE/DE)
			ABB (CH/EU)
Generator	Vestas Nacelles Deutschland (DK/DE)	Windgeneratorenfertigung Magdeburg GmbH (DE/DE)	SiemensGamesa RE (DE-ES/DK)
Converter	Vestas Wind Systems A/S (DK/DK)	Elektric Schaltanlagenfertigung GmbH (Enercon) (DE/DE)	SiemensGamesa RE (DE-ES/DK)
Transformer	Siemens (DE/DE-AT)	J. Schneider Elektrotechnik GmbH (DE/DE)	SGB (DE/DE)
	SGB (DE/DE)		
Switchgear			Siemens (DE/DE)

Source: JRC, IEC, 2021.

3.4 Employment

Wind is a strategic industry for Europe. It is estimated that the sectors offers between 240 000 and 300 000 direct and indirect jobs[6], 77 000 of which relate to offshore wind. It is estimated that about 28% of EU direct jobs in the wind sector are located at turbine and component manufacturers, followed by about 15% working at service providers, 8% at developers and 3% at manufacturers of offshore substructures (WindEurope/Deloitte, 2020). The EU's total wind energy workforce forms about a quarter of the estimated global employment in the wind energy sector, with the largest proportion of all wind-related jobs located in China (44%) (IRENA/ILO, 2021). In 2020, Germany ranked first in terms of direct and indirect jobs, followed by Denmark and Spain (see **Figure 37** and **Figure 38**)

Figure 37. *Evolution of direct and indirect jobs in the wind energy sector in the period 2015-2020*



Source: JRC based on EurObserv'ER data.

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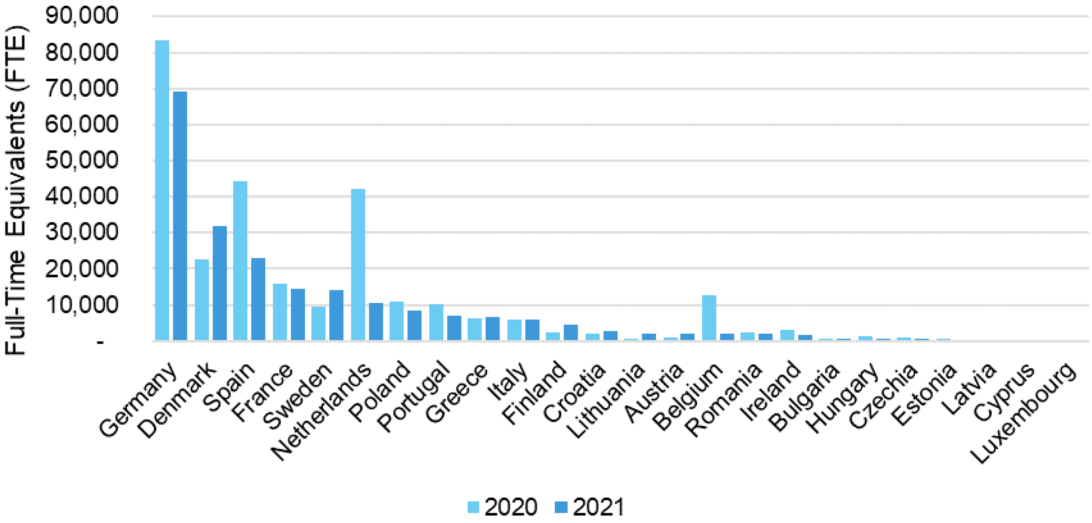
[6] These are estimates using different methods. WindEurope estimates the figure to be 300 000 (https://windeurope.org/about-wind/wind-energy-today/) while Eurobarometer estimates the figure to be 280 000 jobs in 2020.

Figure 38. Employment (direct and indirect jobs) in the wind sector in 2020 and 2021.
Note: Employment expressed in full-time equivalents (FTE).



Source: JRC based on EurObserv'ER, 2022.

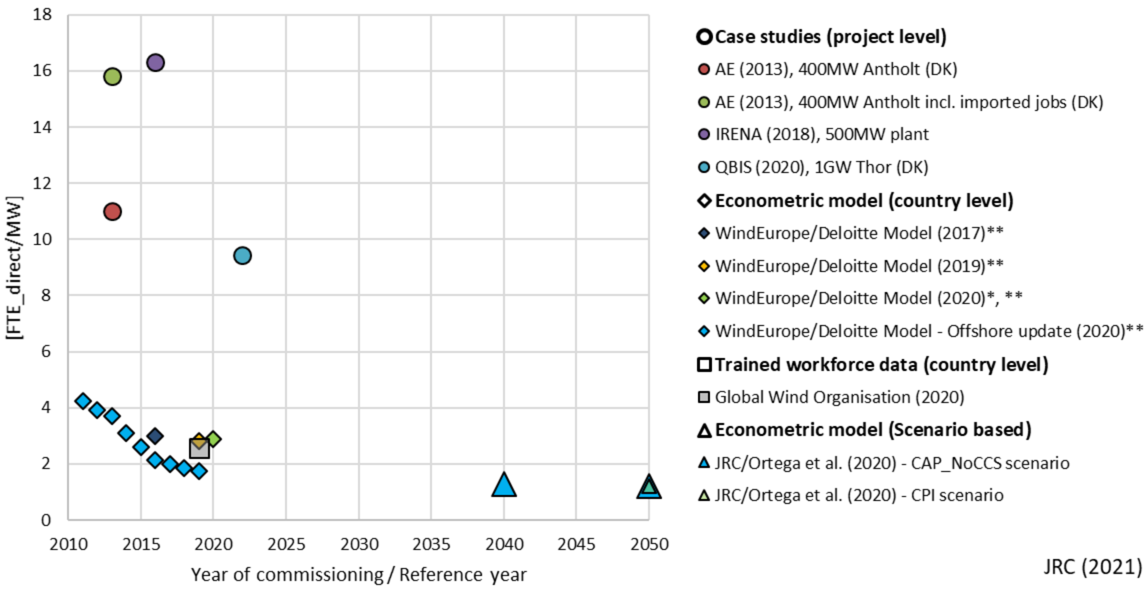
3.5 Energy intensity and labour productivity

3.5.1 Energy intensity

Labour productivity. Figures on labour productivity in the offshore wind sector, measured in direct full term 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 16.3-15.8 FTE/MW for projects in the period 2013-2016 (QBIS, 2020; IRENA, 2018). Due to productivity improvements, some studies estimate a further 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.

Figure 39. Estimated direct person years (FTE/MW) for offshore wind based on different case studies and modelling approaches.

Note: Employment 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.

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$_{\text{Installed}}$ in 2010 to a range of 1.8-2.9 FTE/MW$_{\text{Installed}}$ in 2020. When including indirect employment effects, 2.2 to 5.1 FTE/MW$_{\text{Installed}}$ 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$_{\text{Installed}}$ 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 1.7-3.0 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$_{\text{Installed}}$ with European estimates declining to about 0.7 FTE/MW$_{\text{Installed}}$ 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$_{\text{Installed}}$ (Ortega et al., 2020).

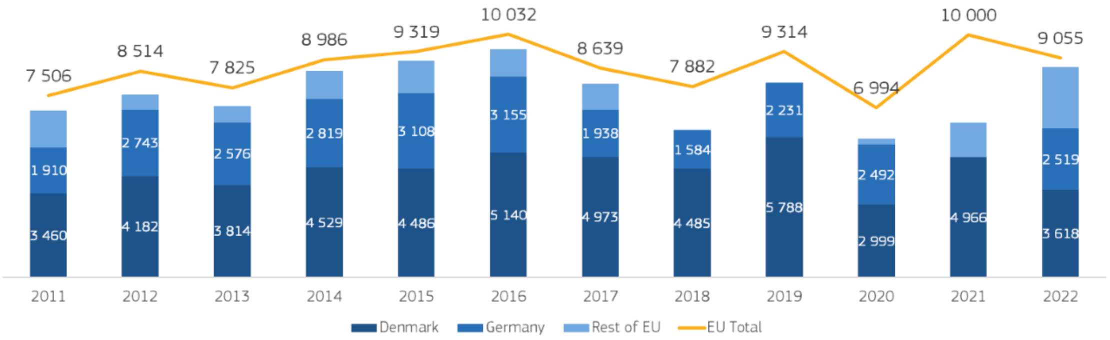
Energy intensity. The energy intensity is analysed based on the cumulative energy demand (CED) along the lifecycle of offshore wind. The majority of life cycle analyses find the cumulative energy demand to be between 0.1 and 0.19 MJ$_{\text{input}}$/kWh$_{\text{el}}$, a comparable order of magnitude when compared with the cumulative energy demand of current onshore wind turbines. Data points on floating offshore show higher values than bottom-fixed offshore wind in terms of cumulative energy demand. However, decisive factors influencing the CED, besides the life cycle inventory data used, are the chosen system boundary and assumed geographical reference (e.g. countries' electricity mix and wind resource; this becomes apparent in the outlier value of Wagner et al (2011) which also includes the connection of the Alpha Ventus wind farm to the electricity grid). Given the small amount of available LCA data in offshore wind, no clear trend in the CED can be observed, either in terms of evolution in time or with respect to the growth in turbine size. So far, no detailed LCA on the latest offshore wind turbines by Vestas, SiemensGamesa RE and GE has been found.

The energy intensity is analysed based on the cumulative energy demand (CED) along the lifecycle of 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 current levels, ranging from about 0.08 to 0.12 MJ_{input}/kWh_{el}.

3.6 EU Production Data

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. **Figure 40** shows the EU production of wind turbines in value. Over the past ten years (2013-2022), the production value has increased by 16% with an annual compound growth rate of 1% and an average value of EUR 8.8 billion. The EU wind manufacturing recovered after the pandemic with a 43% increase, yet in 2022, it decreased by nearly 10%, reaching EUR 9 billion. Denmark holds almost half of the EU production and Germany around one quarter (ten-year average). 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.

Figure 40. EU production value and top producers among the Member States disclosing data [EUR million]



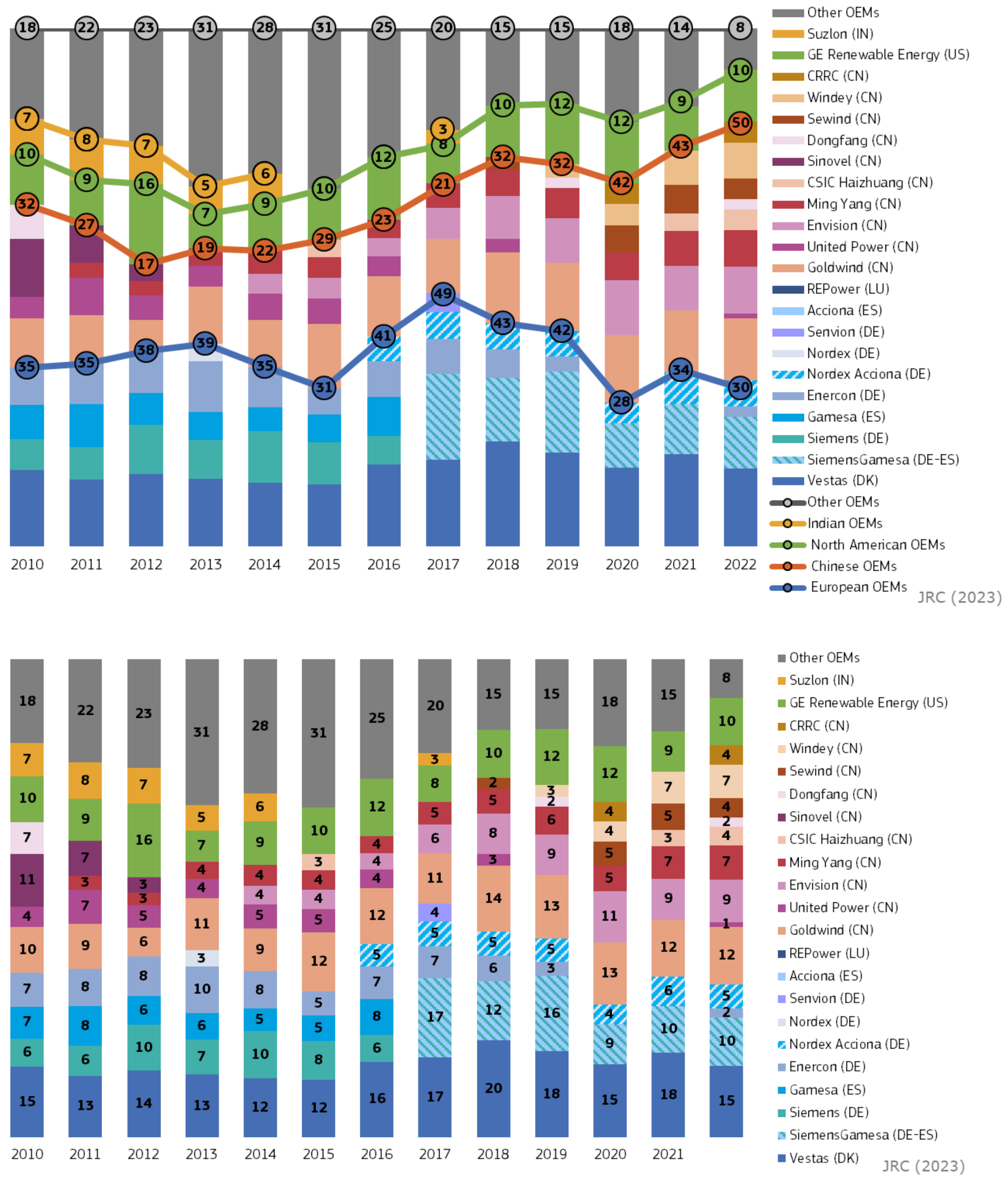
Source: JRC based on PRODCOM data, 2023

4. EU Market Position and Global Competitiveness

4.1 Global & EU market leaders

European original equipment manufacturers (OEMs) have held a leading position in the wind energy sector in the last few years. In 2021, they ranked second behind Chinese OEMs in terms of deployment market share. Among the top 10 OEMs in 2021, Chinese OEMs led with 43% of market share, followed by companies in Europe (34%) and North America (9%) (see **Figure 41**, top).

Figure 41 Market share (%) of the top 10 OEMs in wind energy (bottom) over the period 2010-2022 and their respective origin (top)
Note: Market shares include both onshore and offshore wind deployments

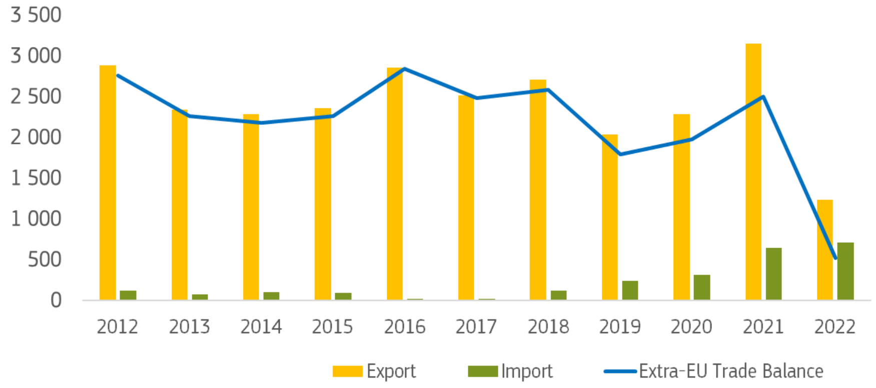


Source: JRC, 2023.

4.2 Trade (Import/export) and trade balance

The EU presence in the global market of wind generating sets is declining as, in 2022, exports decreased by 60%, and imports increased by 10% compared to the previous year (**Figure 42**). As a result, the extra-EU share in global exports in 2020-2022 shrunk to 54% from 73% in 2019-2021. For the same reference periods, the share of intra-EU imports dropped to 66% from 78%.

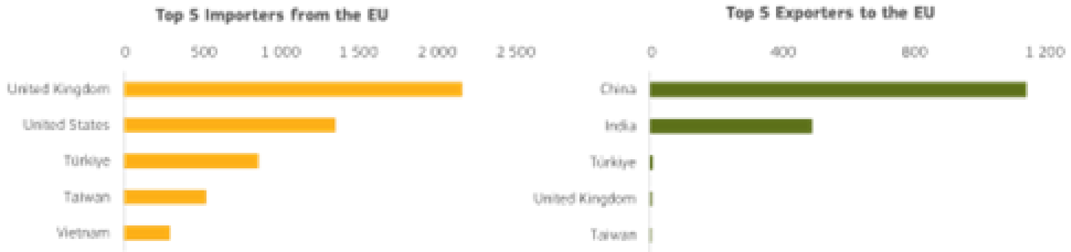
Figure 42. Extra-EU trade for wind generating sets [EUR million]



Source: JRC based on COMEXT data, 2023

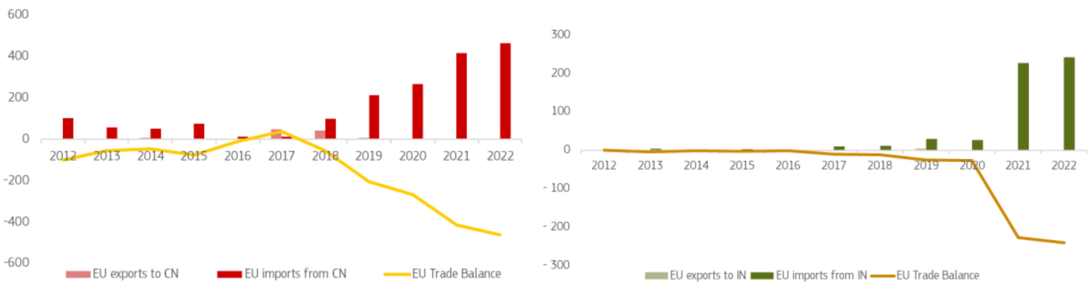
In 2022, to satisfy the needs for wind generating sets which the EU Single Market could not cover, Member States turned mainly to China and India for imports (**Figure 43)**. Trade with India boomed in 2021, and in 2022, the EU had a trade deficit of EUR 241 million (**Figure 44**). Trade with China started growing after 2019, and in 2022, the EU reached a negative trade balance of EUR 464 million. More specifically, 63% (2020-2022 average) of the extra-EU imports came from China, which is near the 65% limit set by NZIA. During 2020-2022, Sweden and Italy each imported more than EUR 170 million's worth of wind generating sets from China, which accounted for more than 86% of their importing flows.

Figure 43. Top countries importing from (left) and exporting to (right) the EU (2020-2022) [EUR million]



Source: JRC based on COMEXT data, 2023

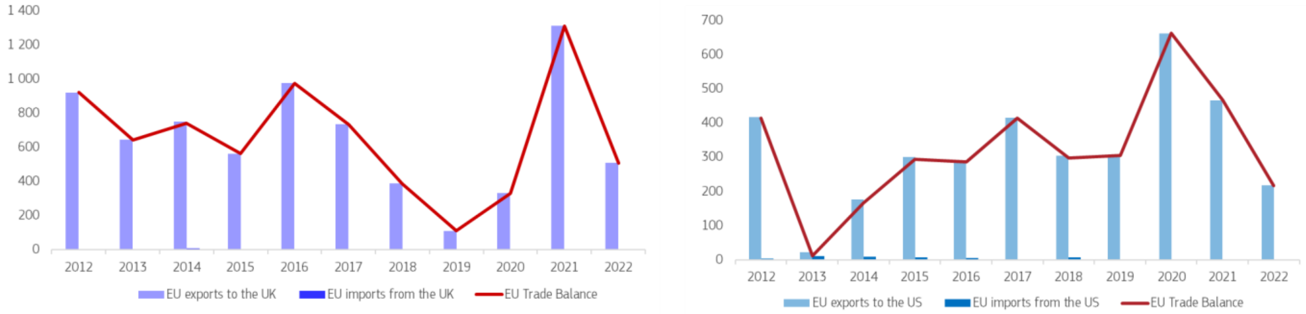
Figure 44. EU trade with China (left) and India (right) [EUR million]



Source: JRC based on COMEXT data, 2023

EU exports fell to EUR 1.2 billion in 2022 mainly due to the decrease of exports to its top importing partners (**Figure 45**). More specifically, the exported value to the UK, the US and Türkiye dropped by 61%, 53% and 84% respectively.

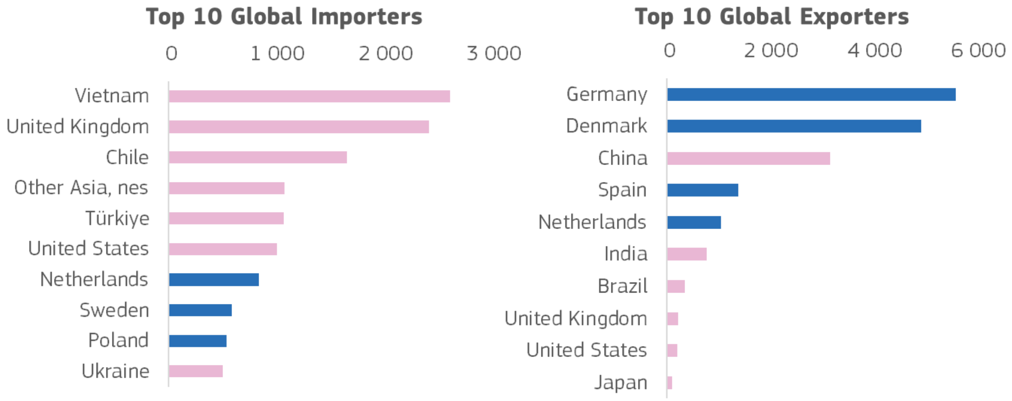
Figure 45. EU trade with the UK (left) and the US (right) [EUR million]



Source: JRC based on COMEXT data, 2023

The EU maintained its former position in the top 10 global exporters and its presence in the top 10 global importers (**Figure 46**), where the Netherlands fell three ranks, and Sweden and Poland replaced Belgium and Denmark. Vietnam, in its first appearance in the ranking list, was the top global importer.

Figure 46. Top global importers (left) and exporters (right) of wind generating sets (2020-2022) [EUR million]



Source: JRC based on COMEXT and COMTRADE data, 2023

The EU captured the import flows of most of the growing markets[3] (EU share greater than 40%) during 2019-2021[4], apart from Chile, Vietnam and Argentina (**Table 7**).

Table 7. Growing markets based on a 2-year average of net import change

Country	Total import (2019-2021) [EUR million]	% import from the EU	2-year average of net import change
United Kingdom	2 466	99%	2 964
Chile	1 327	22%	1 315
Other Asia,not elsewhere specified	1 219	85%	649
Türkiye	1 193	92%	597
Russia	396	77%	348
Kazakhstan	187	47%	305
Morocco	185	85%	170
Vietnam	2 689	17%	154
Argentina	125	12%	124

Source: JRC based on COMTRADE data, 2023

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 8***).

Table 8. 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

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).

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 9**. A more comprehensive analysis can be found in (Carrara et al., 2023; Telsnig et al., 2022).

Table 9. Material intensity estimates in kg/MW for wind turbines in general (ranges) and for the different turbine types (Carrara et al., 2020) and latest material data on wind turbines released in 2022 (Vestas, 2022). Note: Please see Annex 3 for the definition of the turbine types and their drive train configurations. For a comprehensive list of the materials in use and assumptions on the figures please refer to (Carrara et al., 2020)

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)
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	4600	4600	4600	4600	4600	3670 - 4430
Glass/carbon composites	7700 - 8400	8100	8100	8400	7700	7530 - 9350
Aluminium (Al)	500 - 1600	700	500	1600	1400	1660 - 1740
Boron (B)	0 - 6	0	6	1	0	0.3
Chromium (Cr)	470 - 580	525	525	580	470	560 - 675
Copper (Cu)	950 - 5000	5000	3000	950	1400	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	1266 - 1581
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)	5500	5500	5500	5500	5500	1191 - 1204

Source: JRC, 2022.

Other raw materials with a high supply risk are niobium (used for steel alloys in turbine towers) and boron (also used for permanent magnets). The latter is also a strategic material. Additional strategic materials relevant in the supply chain of wind turbines are aluminium, copper, manganese, nickel, and silicon metal. The EU production share in raw materials is only 2%, while China leads with 43%.

Blades are another crucial 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. Additionally, various composite materials such as glass fibre, carbon fibre, polymers, and plastics can also be employed.

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 2022. 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

Onshore wind and bottom-fixed offshore wind turbines have reached commercial readiness, but floating offshore wind and efficient transmission and interconnection technologies are key enablers for the large-scale deployment of offshore renewable energy technologies. Wind technologies at a lower technology readiness level will need continuous support to reach market readiness (e.g. AWES, VAWT and downwind rotors).

2022 marks another strong year in global wind energy deployment. In total, 77 GW of new capacity was installed globally, split between 68 GW onshore and 9 GW offshore. EU Member States (MSs) added another 15 GW of onshore wind capacity, making it the strongest year in onshore capacity additions since 2010. EU offshore annual deployments saw only 1.2 GW of offshore wind capacity deployed in 2022.

A total of 188.9 GW of onshore wind is installed in EU MSs, an increase of 6% on 2020 and more than double the 2010 figure (with an additional 141%). The total offshore wind capacity in EU MSs at the end of 2022 was about 16.2 GW, led by Germany (8 GW), the Netherlands (3 GW), Denmark (2.3 GW) and Belgium (2.3 GW).

Despite continuous deployment, EU electricity generation from wind energy decreased by 3% as compared to 2020 as a consequence of low wind. This trend is less pronounced for offshore wind as wind resources are steadier at current deployment locations. Nevertheless, wind electricity accounts for about 14% of the EU's total electricity generation in 2021.

Both onshore and offshore wind show a continuous reduction in costs, which are expected to further reduce towards 2050 as a consequence of scaling effects and technology development. Based on the main cost estimates and projections for onshore wind, the LCoE range spans from EUR 33 to EUR 74 per MWh in the period 2019-2022. However, commodity price inflation, increasing shipping costs and supply chain disruptions have led to increasing wind turbine prices since 2020. Moreover, financing costs vary considerably among EU countries.

In the last decade, the EU has led on investment in public R&D spending, followed by Japan and the US. In the last decade (2010-2021), Japan led at country level on public R&D investment in wind energy, followed by Germany, the US, Norway and South Korea. The Netherlands, Denmark, Spain and France were also amongst the top ten countries investing in wind energy. At about 42%, Germany leads in EU public R&D investment, followed by Denmark (15%) and the Netherlands (12%) in the period 2010-2021.

However, EU R&D funding in wind energy comes predominantly from the corporate sector. Since 2015, the share of private R&D funding ranged between 91% and 94% as compared to public funding (6% and 9%). EU companies are among the leading investors in R&D. Moreover, a strong representation of Chinese OEMs is observed among the Top 20 global R&D investors. These have been increasing their shares lately.

The EU hosts about 41% of all innovators, of which about 40% are venture capital companies and 60% are corporates. Five countries host almost 80% of identified innovators. The US (first) and the UK (fifth) have a very strong base of venture capital companies while most innovators in Germany (second), China (third) and Japan (fourth) are corporate innovators.

The number of research articles is highest in China (32%), followed by the EU (17%), US (8%) and UK (7%). Within the EU, the leading countries in terms of deployment and first movers are showing the highest publication activity. Since 2010, Germany has ranked first in the total number of articles followed by Denmark, Spain, Italy and the Netherlands. Bibliometric 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, leading in terms of highly cited articles and productivity indicators.

The EU provides constant R&D support to the wind sector via its major funding programmes. Since 2009, FP7, H2020 and Horizon Europe have allocated substantial funding across all wind research R&I priorities with projects on offshore wind technology (EUR 187 million), floating offshore wind (EUR 132 million) and research on new materials & components (EUR 106 million) securing most of the funds.

Value chain analysis

In 2021, turnover decreased by about EUR 10 billion as compared to 2020. With about EUR 11.8 billion, Germany leads in turnover, followed by Denmark, Spain and Sweden. Denmark, Sweden, Poland and the Netherlands are the only countries that increased their turnover in 2021.

Figures on labour productivity in the wind sector have been declining in recent years as the learning effect improves, with more capacity installed in the sector.

The energy intensity (based on the cumulative energy demand (CED)) along the lifecycle of wind power plants indicates a decrease in the CED driven by the continuous development of more powerful turbines which allow the generation of more electricity per input of primary energy than their predecessors.

Given the small amount of available LCA data in offshore wind, no clear trend in the CED can be observed, either in terms of evolution over time or with respect to the growth in turbine size. So far no detailed LCA on the latest offshore wind turbines by Vestas, SiemensGamesa RE and GE has been identified.

EU position and global competitiveness

The share of imports from the EU in the period 2019-2021 shows the leading position of EU products globally. More than 12 countries have import shares of above 50% stemming from the EU, including some of the leading wind energy markets.

Over the past ten years (2013-2022), the production value of wind rotors has increased by 16% with an annual compound growth rate of 1% and an average value of EUR 8.8 billion. EU wind manufacturing recovered after the pandemic with a 43% increase, yet in 2022, it decreased by nearly 10% to EUR 9 billion.

The EU presence in the global market of wind generating sets is declining as, in 2022, exports decreased by 60%, and imports increased by 10% on the previous year. As a result, the extra-EU share in global exports shrunk from 73% in 2019-2021 to 54% in 2020-2022. For the same reference periods, the share of intra-EU imports dropped from 78% to 66%.

Rare earth elements, used in the permanent magnets of turbine generators and within wind turbine towers, are identified as critical raw materials. Dysprosium, neodymium, praseodymium and terbium are subject to a high supply risk as EU material sourcing relies mainly on China. Moreover, high supply risks are identified for borate and niobium, used for iron-alloy metals in the main frame of the wind turbine, and both sourced from just one non-EU country.

With regard to processed materials, the supply risk is highest for balsa wood which is used in blades, NdFeB permanent magnets and polyurethane. Blade manufacturers are experiencing a strong resource dependency as most balsa wood is sourced from Ecuador. The literature estimates that Ecuador supplies between 75% and 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).

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List of abbreviations and definitions

AWES	Airborne wind Energy Systems
CAPEX	Capital Expenditure
CED	Cumulative Energy Demand
CETO	Clean Energy Technology Observatory
CfD	Contracts for Difference
CPC	Cooperative Patent Classification
CRM	Critical Raw Materials
CTP	Climate Target Plan
CWEA	Chinese Wind Energy Association
DC	Direct Current
DG	Directorate General
DOE	Department of Energy (US)
EBIT	Earnings Before Interest and Taxes
EBITDA	Earnings Before Interest, Taxes, Depreciation, and Amortisation
EC	European Commission
EDA	European Defence Agency
EIA	Environmental Impact Assessment
EMFAF	European Maritime, Fisheries and Aquaculture Fund
EoL	End-of-Life
EPBT	Energy Pay-Back Time
EU	European Union
FTE	Full-Time Equivalents (employment)
FWCI	Field Weighed Citation Impact
GE	General Electric
GVA	Gross Value Added
GW	Gigawatt
HAWT	Horizontal Axis Wind Turbines
HVDC	High-Voltage Direct Current

IEA	International Energy Agency
IPR	Intellectual Property Rights
IRR	Increased Range Resolution
ITC	International Trade Commission
kW	Kilowatt
LCA	Life Cycle Analysis
LCOE	Levelised Cost of Energy
LCR	Local Content Requirements
LTE	Long-Term Evolution
LTS generator	Low Temperature Superconducting generator
LVRT-technology	Low-Voltage Ride-Through technology
MHI	Mitsubishi Heavy Industries
MSP	Maritime Spatial Planning
MSs	Member States
MW	Megawatt
MWh	Megawatt hour
NdFeB	Neodymium Magnet
NDRC-China	National Development and Reform Commission-China
NECPs	National Energy Climate Plans
NID	Nature Inclusive Design
NNL	No Net Loss
NOWRDC	National Offshore Wind Research and Development Consortium
NSNG	North Sea Net Gain
O&M	Operation & Maintenance
OECD	Organisation for Economic Co-operation and Development
OEMs	Original Equipment Manufacturers
OPEX	Operational Expenditure
ORES	Offshore Renewable Energy Strategy
OW	Offshore Wind

OWF	Offshore Wind Farm
OWGP	Offshore Wind Growth Partnership
OWIC	Offshore Wind Industry Council
PET	Polyethylene Terephthalate
PSR	Primary Surveillance Radars
R&D	Research & Development
R&I	Research & Innovation
R&T	Research & Technology
RAM	Radar Absorbing Material
RAP	Recognised Air Picture
RD&D	Research, Development & Demonstration
RES	Renewable Energy Systems
RNS	Rich North Seas
SCD-technology	Super Compact Drive technology
SDG	Sustainable Development Goal
SET Plan	Strategic Energy Technology Plan
SGRE	SiemensGamesa Renewable Energy
TANC	Turbine Adaptive Nulling concept
TCP	Technology Collaboration Programme
TEM	Topical Experts Meetings
TLP	Tension-Leg Platform
TRL	Technology Readiness Level
TWh	Terawatt hour
VAWT	Vertical Axis Wind Turbines
VC	Venture Capital
VC	Value Chain
WACC	Weighted Average Cost of Capital
WETO	Wind Energy Technologies Office (US)
WT	Wind Turbine

ZVRT-technology	Zero-Voltage Ride Through technology

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Annex 1 Summary Table of Data Sources for the CETO Indicators

Table 10. Data sources

Theme	Indicator	Main data source
Technology maturity status, development and trends	Technology readiness level	JRC
	Installed capacity & energy production	JRC database, GWEC, 4COffshore
	Technology costs	JRC, BNEF, Beiter et al, 2021
	Public and private RD&I funding	JRC based on IEA
	Patenting trends	Patstat
	Scientific publication trends	CORDIS
	Assessment of R&I project developments	JRC based on Pitchbook
Value chain analysis	Turnover	EurObserv'ER
	Gross Value Added	EurObserv'ER and WindEurope
	Environmental and socio-economic sustainability	WindEurope/WoodMackenzie, BNEF
	EU companies and roles	JRC database
	Employment	EurObserv'ER
	Energy intensity and labour productivity	IRENA
	EU industrial production	PRODCOM
Global markets and EU positioning	Global market growth and relevant short-to-medium term projections	JRC, GWEC, BNEF
	EU market share vs third countries share, including EU market leaders and global market leaders	JRC, GWEC, BNEF
	EU trade (imports, exports) and trade balance	COMEXT
	Resource efficiency and dependencies (in relation EU competiveness)	JRC

Annex 2 Sustainability Assessment Framework

Table 11. 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)*:* *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 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)*:* ***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)*:* *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)*:* ***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 1.4.4 (on future deployments) and chapter3.4 (on the industrial value chain)*
Trade impacts	*Yes, see chapter 4.2 on trade*
Market demand	*Yes, see chapter 1.4.4 (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).
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 R&I projects funded under the Horizon Europe program

Table 12. R&I projects funded under the Horizon Europe program and started in 2022

Project Acronym	Start Year	Project DOI	EU Financial Contribution (EUR)	Wind share	Research area
ADOreD	01/10/2022	10.3030/101073554	4011944	100%	Offshore technology
TWEET-IE	01/11/2022	10.3030/101079125	1498250	100%	Other
FRONTIERS	01/09/2022	10.3030/101072360	2502993	100%	New turbine materials & components
Romain	01/09/2022	10.3030/101070320	1981831	100%	Maintenance & monitoring
MERIDIONAL	01/10/2022	10.3030/101084216	5996868	100%	Resource assessment
NEXTFLOAT	01/11/2022	10.3030/101084300	15995130,36	100%	Floating offshore wind
OPTIWISE	01/06/2022	10.3030/101056769	4660337	100%	Maintenance & monitoring
JustWind4All	01/11/2022	10.3030/101083936	2786907	100%	Other
WENDY	01/10/2022	10.3030/101084137	2999687	100%	Other
MARINEWIND	01/11/2022	10.3030/101075572	1380033	100%	Floating offshore wind
SETIPWind	01/09/2022	10.3030/101075499	996107	100%	Other
INFINITE	01/11/2022	10.3030/101084321	15455944	100%	Offshore technology
RESPONDENT	01/11/2022	10.3030/101082355	2147112	50%	Grid integration
SiC4GRID	01/10/2022	10.3030/101075496	3787065	50%	Grid integration
EuReComp	01/04/2022	10.3030/101058089	8903632	50%	New turbine materials & components

Source: JRC based on Cordis 2023

Annex 4 POTEnCIA and POLES-JRC Model overview

1.1 POTEnCIA Model overview

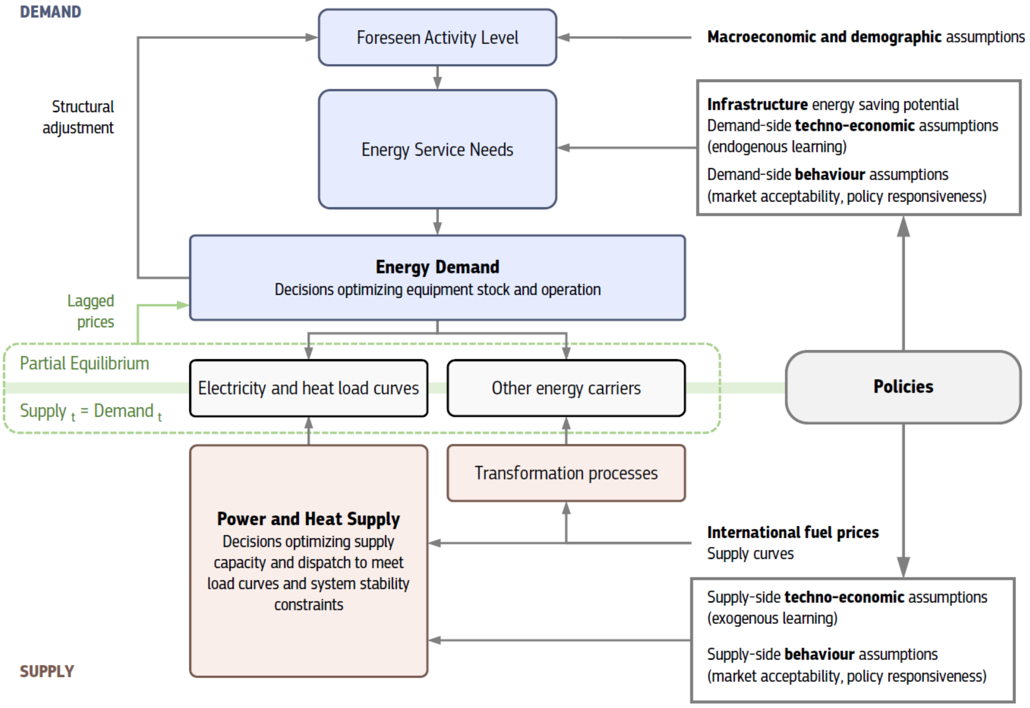
The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed 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 47; 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 maximise its benefit or minimise its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies. This core modelling approach is tailored to each sector, for instance to represent different planning horizons and expectations about future technologies under imperfect foresight. In particular, power dispatch modelling uses a high time resolution with full-year hourly dispatch to suitably depict the increasing need for flexibility from storage and demand response, and the changing role of thermal generation in a power system dominated by variable renewable energy sources. Within this sector modelling framework, investment decisions of the representative agents are simulated with discrete-choice modelling. The model then finds an overall equilibrium across different sectors using price signals for resources such as traditional and renewable energy carriers while accounting for efficiency and environmental costs.

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 CO2 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; Mantzos et al., 2018). Developed in parallel to POTEnCIA, an updated release of this database is planned by 2024 to ensure the transparency of POTEnCIA's base-year conditions and to support further research by external stakeholders.

Figure 47. The POTEnCIA model at a glance



Source: JRC adapted from Mantzos et al., 2019

1.2 POTEnCIA CETO Climate Neutrality Scenario overview

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 EU27 GHG emissions by 55% by 2030 versus 1990, and reaches the EU27´s climate neutrality by 2050 under general assumptions summarised in Table 13. To suitably model technology projections under these overarching GHG targets, the scenario includes a representation 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 deployment of bioenergy and renewable power generation technologies to 2030 is consistent with the EU's Renewable Energy Directive target (42.5% share of renewables in gross final energy consumption by 2030). Similarly, the adoption of alternative powertrains and fuels in transport is also promoted by a representation of updated CO_2 emission standards in road transport and by targets of the ReFuelEU Aviation and FuelEU Maritime proposals.

Table 13. General assumptions of the POTEnCIA CETO Climate Neutrality Scenario

General scenario assumptions	**Modelled scenario and policy assumptions**
GDP growth by Member State	GDP projections based on EU Reference Scenario 2020, with updates to 2024 from DG ECFIN Autumn Forecast 2022
Population by Member State	Population projections based on EU Reference Scenario 2020, with updates to 2032 from EUROPOP 2019
International energy markets	Natural gas import projections consistent with REPowerEU targets for supply diversification and demand reduction. International fuel price projections to 2050 aligned with REPowerEU

1.3 POLES-JRC 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. POLES-JRC is hosted at the JRC and is particularly adapted to assess climate and energy policies.
POLES covers the entire energy system, from primary supply (fossil fuels, renewables etc.) to transformation (power, biofuels, hydrogen) and final sectoral demand. International market and prices of energy fuels are simulated 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 2050 and is updated yearly with recent information.

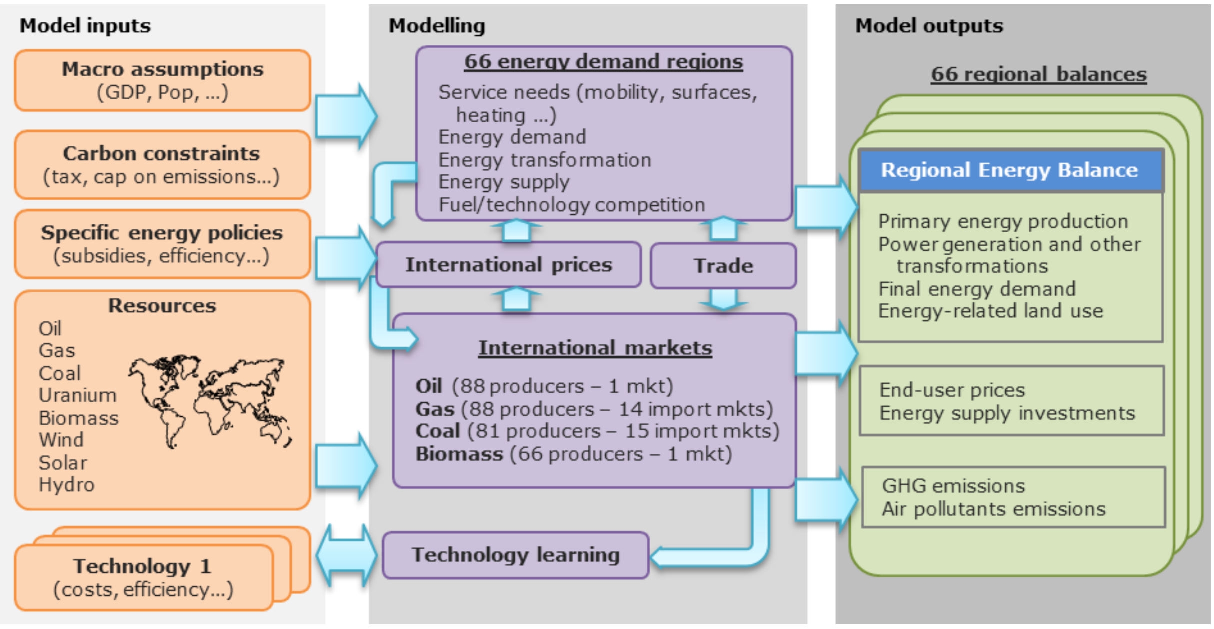
The POLES-JRC model is used to assess the impact of European and international energy and climate policies on energy markets and GHG emissions, by DG CLIMA in the context of international climate policy negotiations and by DG ENER in the context of the EU Energy Union.

POLES has also been applied for the analyses of various Impact Assessments in the field of climate change and energy, among them: the Proposal for a revised energy efficiency Directive (COM(2016)0761 final) and The Paris Protocol – A blueprint for tackling global climate change beyond 2020 (COM(2015) 81 final/2).
Moreover, POLES-JRC provided the global context to the EU Long-Term Strategy (COM(2018) 773) and formed the energy/GHG basis for the baseline to the CGE model JRC-GEM-E3.

POLES-JRC forms part of the Integrated Assessment Modelling Consortium (IAMC) and participates in inter-model comparison exercises with scenarios that feed into the IPCC Assessment Reports process.

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://ec.europa.eu/jrc/en/geco

Figure 48. Schematic representation of the POLES-JRC model architecture



1.4 POLES-JRC Model description

1.4.1 Power system

POLES-JRC considers 37 power generating technologies existing technologies as well as emerging technologies. Each technology is characterised by its installed capacity, cost parameters (overnight investment cost, variable & fixed operation and maintenance cost), learning rate and other techno-economic parameters (e.g. efficiencies). The cost evolution over time is taken into account by technology learning driven by accumulated capacity.

For renewable technologies maximum resource potentials are taken into account. Similarly, the deployment of CCS technologies is linked to region-specific geological storage potential.

In addition to these technical and economic characteristics, non-cost factors are applied to capture the historical relative attractiveness of each technology, in terms of investments and of operational dispatch.

With regard to the clean energy technologies covered by CETO, the model includes power generation using photovoltaics (utility and residential), Concentrated Solar Power (CSP), on-shore and off-shore wind , ocean energy, biomass gasification and steam turbines fuelled by biomass, geothermal energy as well as hydropower. CCS power technologies are considered as well. Moreover, electricity storage technologies such as pumped hydropower storage and batteries are also included.

Electricity demand

The total electricity demand is computed by adding the electricity demand from each sector (i. e. residential, services, transport, industry and agriculture). The evolution over time of the sectoral electricity demand is driven by the activity of each sector and competition between prices for electricity and fuels.

POLES uses a set of representative days with an hourly time-step in order to capture load variations as well as to take into account the intermittency of solar and wind generation. The usage of representative days also allows to capture hourly profiles by sector and end-uses.

With a view to CETO demand side technologies, the model includes heat pumps in the residential and service sector, batteries for electric vehicles and electrolysers.

Power system operation and planning

The power system operation assigns the generation by technology to each hour of each representative day. The supplying technologies and storage technologies must meet the overall demand, including grid imports and exports.

The capacity planning considers the existing structure of the power mix (vintage technology), the expected evolution of the load demand, the production cost of technologies.

1.4.2 Hydrogen

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

Hydrogen is used as fuel in all sectors. Moreover, hydrogen is used to produce fertilisers as well as to produce fuels used in the transport sector (i.e. gaseous and liquid synfuels and ammonia). POLES-JRC models global hydrogen trade and considers various means of hydrogen transport (pipeline, ship, truck, refuelling station).

1.4.3 Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM model[7]. This approach allows to model bioenergy demand and supply of biomass adequately

by taking into account biomass potential, production cost and carbon value. Moreover, the emissions from land use and forestry (CO2) as well as agriculture (CH4 and N2O) are derived from GLOBIOM.

Power generating technologies using biomass considered are biomass gasification (with and without CCS) and biomass fuelled steam turbines.

Hydrogen can be produced from biomass via gasification and pyrolysis. Moreover, the production of first and second generation of biofuels for gasoline and diesel is considered.

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[7] Global Biosphere Management Model (GLOBIOM) model description. International Institute for Applied Statistical Analysis, Laxenburg, Austria. http://www.globiom.org

1.4.4 Carbon Capture Utilisation and Storage (CCUS)

POLES-JRC uses CCUS technologies for:

- 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 coal and biomass pyrolysis.
- Direct air capture (DAC) where the CO2 is stored or used to produce synfuels (gaseous or liquid).

Model documentation and publications:

A detailed documentation of the POLES-JRC model and publications can be found at:
https://ec.europa.eu/jrc/en/poles

1.5 POLES JRC's Global *NDC-LTS CETO* Scenario

The global scenario data presented in the CETO technology reports refers to a NDC-LTS CETGO scenario modelled by the POLES-JRC model.

The *NDC-LTS CETO* scenario takes into account the latest emission pledges found in the Nationally Determined Contributions (NDCs) and Long-Term Strategies (LTSs) announced by the signatory countries of the Paris Agreement. The *NDC-LTS CETO* scenario considers the policies of NDCs in the medium term and the LTSs in the longer term.

This scenario assumes that the objectives in the NDCs (including conditional objectives) are reached in their relevant target year (2030 in most cases). To this end, carbon values and other regulatory instruments are put in place on top of existing, legislated measures. Beyond 2030, the objectives of the countries' LTS, where they exist, are pursued; if the country has not announced an LTS, it is assumed that no additional decarbonisation effort is made, and carbon values, if any, are kept constant to their 2030 level. This scenario includes the net zero targets announced by many countries. The *NDC-LTS CETO* scenario also considers decarbonisation proposals related to international aviation and maritime transportation sectors (international bunker fuels).

The *NDC-LTS CETO* scenario has been developed within the CETO project with a view to provide each technology report with specific scenario data. The scenario implemented up-to-date techno-economic parameters provided by authors of the CETO technology reports.

The *NDC-LTS CETO* scenario is very similar to the *NDC-LTS* scenario of *the Global Climate and Energy Outlook 2023*, which is currently under development.

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