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

Joint Research Centre

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Contents

Abstract

The aim of this report is to provide an update of the state of the art of wind energy technology. This includes onshore wind, offshore wind (both bottom-fixed and floating offshore wind) and when available selected findings on lower technological readiness level wind technologies (e.g. research and innovation information on e.g. airborne wind energy systems, vertical axis wind turbine, downwind rotors among others). It provide an analysis of research and development trends focussing particularly on the technology progress made in EU-funded research until end of 2021 in view of the SET-Plan targets. Moreover, this work provides an analysis on EU position and global competitiveness within the wind value chain and identifies potential bottlenecks and supply risks towards the targets formulated in the European Green Deal.

Foreword

This report is an output of the Clean Energy Technology Observatory (CETO). CETO's objective is to provide an evidence-based analysis feeding the policy making process and hence increasing the effectiveness of R&I policies for clean energy technologies and solutions. It monitors EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal; and assesses the competitiveness of the EU clean energy sector and its positioning in the global energy market.

CETO is being implemented by the Joint Research Centre for DG Research and Innovation, in coordination with DG Energy.

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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 the performance. Since 2020 EU waters host the first floating offshore wind farm employing a semi-submersible platform following continuous support in R&D (25 MW WindFloat Atlantic project in Portugal). As technology advances wind turbines both onshore and offshore are getting bigger. In 2021, an offshore turbine with 15 MW capacity and 115 m blade length has been installed at a test site in Denmark. Newest onshore wind turbines reach capacities of more than 6 MW.

2021 marks another record year in global wind energy deployments, with 72 GW of onshore wind deployment (2nd strongest year in onshore wind deployment) and an unprecedented record year for offshore wind with 21 GW. The surge in global offshore installations was mainly driven by China's expiring Feed-in-Tariff for offshore wind with the result of installing in 2021 the same amount of offshore installations as EU did in cumulative terms so far. In 2021, EU Member States (MSs) added another 10 GW of onshore wind capacity making it the second strongest year in onshore capacity additions since 2010. EU offshore annual deployments saw only 1 GW of offshore wind capacity deployed in 2021 in EU 27 countries. All European sea basins (including projects installed in the United Kingdom and Norway) host a cumulated capacity of 28.2 GW.

2021 showed a record high R&I investment in floating offshore wind development in order to harvest wind energy from deeper waters. Efficient transmission and interconnection technologies are key enablers for the large scale deployment of offshore renewable energy technologies and main developments in this area are focussed on high-voltage direct current (HVDC). Moreover, R&I priority actions in the offshore sector include wind turbine technology, system integration, industrialisation of the sector, Operation& Maintenance & Installation (e.g. the development of Digital Twins), social impact & human capital, and basic wind energy sciences. The sector still invests in alternative wind technologies (e.g. airborne wind energy systems (AWES), Vertical-axis wind turbines (VAWT), and downwind rotors among others) which are still at a lower technology readiness level, and this will need continuous support towards market readiness. Moreover, as the wind sector expands R&D is needed to address inter-sectoral themes (e.g. co-existence with other sectors, circularity in design, recycling, environmental impact, and life-time extension among others).

Both onshore and offshore wind show continuous decline in costs and are expected to further decline on the long term towards 2050 as a consequence of scaling effects and technology development. However, since the outbreak of the COVID-19 pandemic an increase in LCoE is observed as a consequence of commodity price inflation (further increased following Russia's invasion of the Ukraine in Spring 2022), increasing transportation costs and supply chain disruptions. Moreover, financing costs vary considerably among EU countries. A further decrease and convergence among countries in financing costs might be achieved by focussing on policies that implement support schemes decreasing the volatility of a projects cash flow (e.g. Contracts for Difference).

EU companies and research organisations are among the leading innovators in the wind energy sector. Protection of intellectual property rights (IPR) is an important issue among competitors and markets. IP infringement remains the leading reason for the reluctance of EU companies to take their innovative technologies to other markets (e.g. China), thus hampering technology diffusion through trade. IP litigation cases among major wind OEMs hold the potential to delay the delivery of wind energy projects posing a threat to the ambitious targets ahead.

The wind energy sector has evolved into a global industry with about 800 manufacturing facilities worldwide. The majority wind factories operate in China (45%) and Europe (31%), followed by India (7%), Brazil (5%) and North America (4.5%). The European manufacturing supply chain is builds mainly on companies from EU Member States. Current manufacturing capabilities in EU easily cover the current 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 regards 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 investments 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 investments in new vessels capable to install next generation wind turbines and substructures.

Among the top 10 OEMs in 2021, Chinese OEMs led with 43% of market share, followed by the European (34%) and North American (9%) companies. EU has a positive trade balance in wind related goods to countries outside the EU, however in the last decade some stagnation can be witnessed, due to a negative trade balance with China and India. Since China's restrictive wind market policy (local content requirements, import tariffs and VAT exemption to domestic manufacturers), the trade balance clearly leans towards China, with a record surplus (trade deficit for EU) of EUR 411 million for China in 2021. EU also showed a negative trade balance with India with imports from India surging to about EUR 227 million in 2021. This can be explained as a first reaction of major wind turbine manufacturers exploring the possibility to use India as a low-cost export hub of their components as they are facing increasing costs from the ongoing US-China trade tensions.

EU has a positive trade balance with the United Kingdom and the United States. However, latest policies in the United Kingdom granting support for renewable energy projects (and particularly offshore wind projects), introduced a local content scoring criteria favouring UK over imported content. As such, a shift in the UK-EU trade balance on wind energy related goods can be expected if the UK local content criteria prevails. Trade barriers such as local content requirements hold the potential to distort trade and cause unintended effects on investment across value chains. In the last decade, the United States remained reliant on imports from the EU as imports largely follow the annual deployment market shares of EU OEMs in the United States.

Both Russia and Ukraine have a negative trade balance with EU in wind energy related goods as both countries have a nascent wind energy supply chain. Following Russia's invasion of the Ukraine several major wind energy players announced that they will stop new investments in Russia or even withdrew their operations from Russia.

Potential bottlenecks and supply risks in the wind sector might arise from critical raw materials. Particularly rare earth elements used in the permanent magnets of the turbine generators and within wind turbine towers are identified as critical in terms of supply risk as they are sourced from just one non-EU country.

With regards to processed materials the supply risk is highest for balsa wood used in blades, NdFeB permanent magnets and polyurethane. Blade manufacturers experience a strong resource dependency as most balsa wood is sourced from Ecuador supplying 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 hybrid designs (OEMs). When analysing wind energy components the supply risk of manufactured NdFeB magnets is critical. It is estimated that China's manufacturing capacities of permanent magnets are at the same scale as for the respective alloys, reaching 94% of global production of permanent magnets. Particularly in offshore wind, permanent magnets replace conventional rotor windings in generators at a much faster pace as they allow a higher power density, reduced size and weight.

Table 1 Analysis of strengths, weaknesses, opportunities and threats ('SWOT analysis') of the EU wind energy sector.

Strengths	**Weaknesses**
• Onshore wind and offshore wind reached commercial readiness with EU players at the forefront of R&I • Cost competitiveness of 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 strong overall market share contributing to a positive trade balance	• Stronger emphasis on MSP and coexistence among sectors needed • Emphasizing circularity in design, environmental impact and human capital agenda among others • Varying financing costs among MSs • Negative trade balance with major competitors (China and India) • Potential bottlenecks and supply risks from critical raw materials (REE) and processed materials (e.g. NdFeB magnets, balsa wood among others)
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 among others • Niche wind technologies (VAWT, downwind rotors, AWES, small scale wind) • Investment in manufacturing capabilities at EU ports and new vessels	• Administrative barriers (e.g. organisation and duration of the permit-granting process) • COVID-19 and Russia's invasion of the Ukraine causing LCoE increase (commodity price inflation, increased transportation costs, supply chain risk) • Protection of intellectual property rights (IPR) and major IP litigation cases causing delays and limiting technology diffusion • Potential EU supply chain bottleneck towards ambitious targets ahead • China's restrictive market policy • India's rise to a low-cost export hub putting EU based manufacturing and jobs at risk • Trade barriers and local content requirements (e.g. China, UK (AR4), Taiwan) • Geopolitical risks in new markets (e.g. Taiwan)

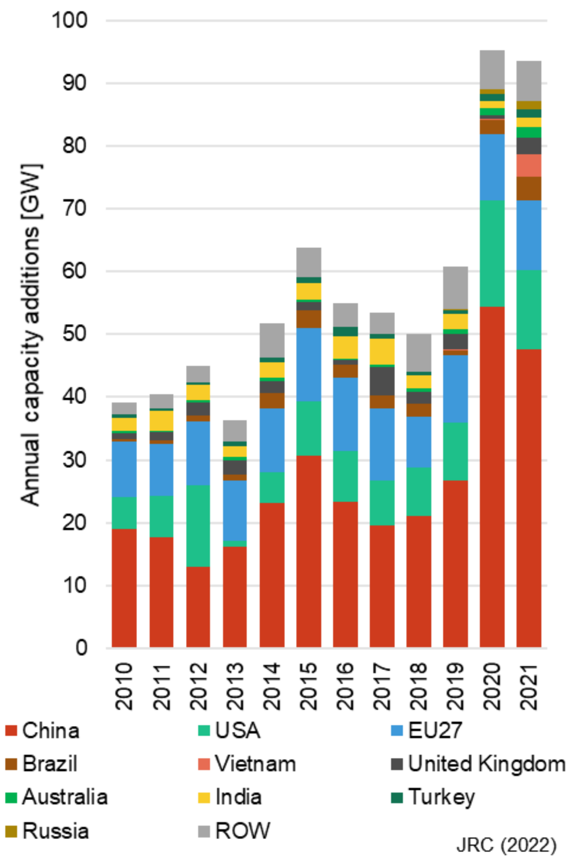
Source: JRC, 2022.

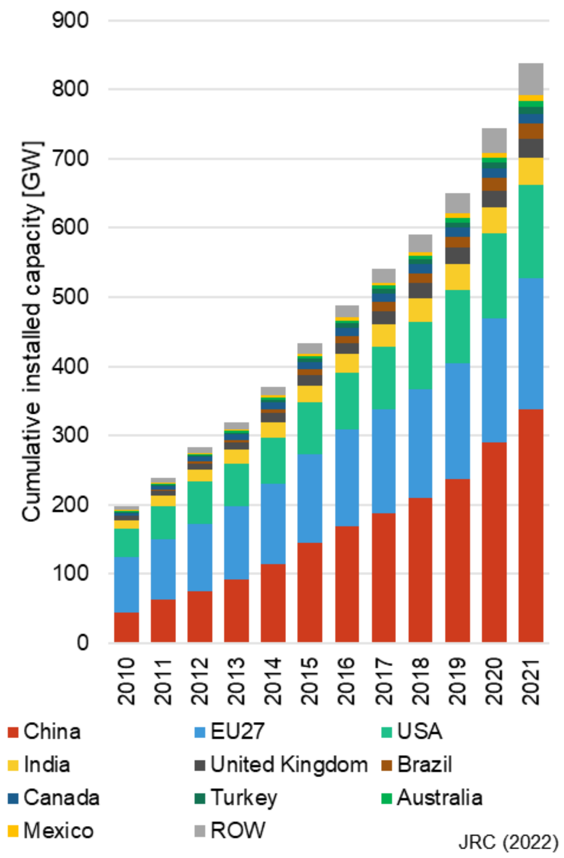
1 Introduction

The aim of this report is to provide an update of the state of the art of wind energy technology. This includes onshore wind, offshore wind (both bottom-fixed and floating offshore wind) and when available selected findings on lower TRL wind technologies (e.g. R&I information on e.g. AWES, VAWT, downwind rotors among others). It provides an analysis of R&D development trends focussing particularly on the technology progress made in EU-funded research until end of 2021 in view of the SET-Plan targets. Moreover, this work provides an analysis on EU position and global competitiveness within the wind value chain and identifies potential bottlenecks and supply risks towards the targets formulated in 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 main indicators deployment and electricity generation providing a detailed analysis on wind energy reaching a global cumulative installed capacity of about 838 GW in 2021 (see **Figure 1**). Moreover, this chapter outlines modelling projections of the current 2030 Climate Target Plan and the targets as expressed in the REPowerEU Plan in response of the global energy market disruption caused by Russia's invasion of the Ukraine. Chapter 2.2.5 provides an outlook towards European and global offshore wind capacity targets and estimated installed capacities towards 2030 and 2035. Chapter 2.3 analyses the present and future cost development in wind energy by analysing latest estimates on LCoE, CAPEX, OPEX and WACC. Competitiveness indicators measuring public & private R&D funding, patenting trends, trends scientific publications are given in chapters 2.4 to 2.7, followed by an analysis of the impact and trends of EU-supported research and innovation.

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





Source: JRC based on GWEC, 2022.

Chapter 3 focuses on the wind energy value chain and includes an analysis of macroeconomic indicators (turnover, Gross Value Added (GVA), employment, production data) and a mapping of indicators on environmental and socio-economic sustainability. It provides an in-depth assessment of the role of EU companies in the wind sector elaborating 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 the analysis of the UK-EU supply chain dependencies.

Chapter 4 gives an insight into EU's global position and competitiveness by assessing the market shares of the Top EU and global market leaders in onshore and offshore wind. Moreover, this chapter analyses the trade balance between EU and its main competitors. Starting from analysing the type and quantities of the main raw materials and processed materials used in wind power plants chapter 4.3 investigates the supply risks and critical dependencies along the supply chain.

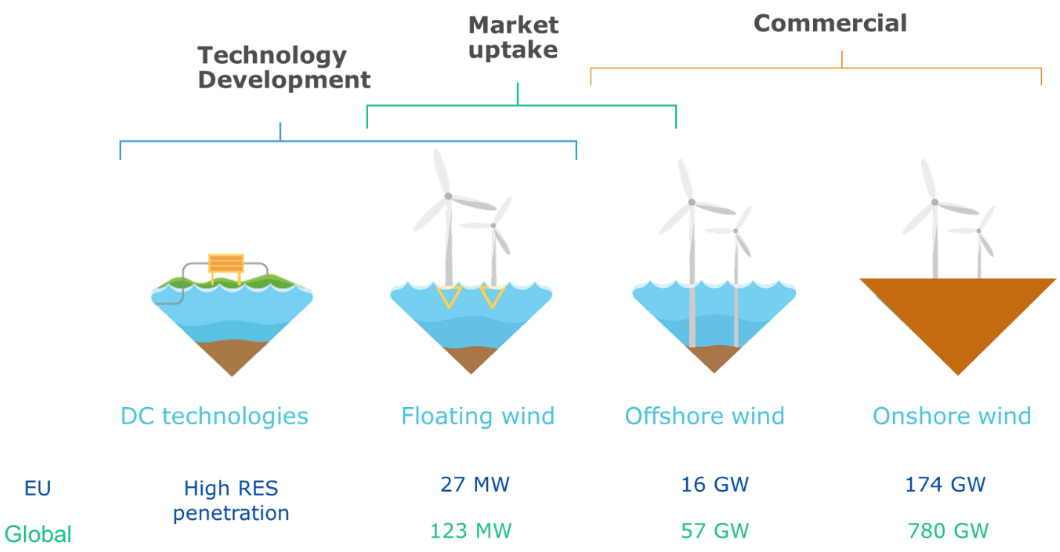
2 Technology State of the art and future developments and trends

2.1 Technology readiness level (TRL)

Current large scale wind turbines for onshore and offshore locations are horizontal axis, three-bladed turbines. These wind turbines have reached commercial readiness 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). Moreover, offshore wind turbines that 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 renewable energy. Floating applications seem to become a viable option for EU countries and regions with deep waters (depths between 50-1000 metres) and could open up new markets such as the Atlantic Ocean, the Mediterranean Sea and potentially the Black Sea. At the end of 2021, EU MSs deployed 27 MW of floating offshore wind in EU sea basins whereas the global cumulative installed capacity is at about 123 MW. The main distinctive criterion in multiple floating designs is the substructure used to provide the buoyancy and thus the stability to the plant (typologies include Spar-buoy, Semi-Submersible, Tension-leg platform (TLP), Barge or Multi-Platforms substructures). As the technology is still on the way to full commercialisation, no concept has yet prevailed over the others; however, notably 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, being the first semi-submersible floating wind farm).

Figure 2 Technology readiness level of the main technologies in wind energy and EU and global installed capacities in 2021 of the wind energy generation technologies.
Note: Direct current (DC) technologies are mentioned as they are a key enabler for high offshore RES penetration rates



Source: JRC, 2022.

A key enabler for the large scale deployment of offshore renewable energy technologies concerns the efficient transmission and interconnection of the generated electricity. For long distance transmission of the electric power generated, high-voltage direct current (HVDC) can be an efficient and economical alternative to alternate-current transmission. However offshore deployment of HVDC systems at large scale will require additional technology development in order to overcome high cost, grid connection requirements and existing challenges in operation among operators. The EC aims for the installation of the first multi-vendor multi-terminal HVDC system in Europe by 2030 [EC 2020a].

In March 2022, the 2nd SET Plan Implementation Plan for offshore wind addressed the need for targeted R&I in order to achieve EU ambitions in offshore wind[1]. The Implementation Plan formulates the following cost and capacity targets for offshore wind:

- Annual installed offshore wind capacity: from 3.8 GW/year (in 2020-2023), and 8.1 GW/year (in 2024-2027) towards 8.7 GW/year (in 2028-2030)
- Annual grid capacity: from 12.1 GW/year (in 2020-2023), and 20.0 GW/year (in 2024-2027) towards 21.4 GW/year (in 2028-2030)
- Generating costs of bottom-fixed offshore wind EUR 38-60 per MWh (in 2030), and EUR 28-48 per MWh (in 2050)
- Generating costs of floating offshore wind EUR 103-135 per MWh (in 2030), and EUR 53-76 per MWh (in 2030)

In order to follow this pathway, the Implementation Plan proposes to support the R&I priority actions on a) Wind Turbine Technology, b) Offshore Wind Farms & System Transformation, c) Floating Offshore Wind & Wind Energy Industrialisation. d) Wind Energy Operation, Maintenance & Installation, e) Ecosystem, Social Impact & Human Capital Agenda and f) Basic Wind Energy Sciences [EC 2022a].

Other wind energy technologies generating electricity are at a lower technology readiness level.

Airborne wind energy systems (AWES) convert wind energy into electricity using autonomous kites or unmanned aircrafts, linked to the ground by one or more tethers. So far, individual AWES on a kW-scale have been tested. As compared to conventional wind energy concepts AWES offer the possibility to harness stronger and steadier winds by flying at higher altitudes. Moreover, research in that field claims that AWES offers a resource efficient low cost alternative. At this stage both fundamental academic research and long-term investments are needed towards commercialisation [Watson et al. 2019, IEA 2022a].

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

Downwind rotors hold the potential to be an emerging technology as conventional (upwind) wind turbines continue to grow aggressively in size and might reach limits in terms of maximum allowable blade-tip deflections to avoid tower strike, which is less a concern for downwind wind turbines. Yet research challenges for downwind rotors remain, particularly concerning noise, fatigue loads, advanced controls, highly tilted rotors, higher fidelity aerodynamic models and integration in floating offshore wind [Bortolotti et al. 2022, IEA 2022b].

Small scale wind turbines (up to a 100 kW size) represent a niche technology but have reached the commercial stage with significant numbers of turbines installed in multiple countries (e.g. Denmark (1977-2020): 611 MW, Germany (until 2020): 36 MW, Italy (until 2020)[2]: 190 MW, United Kingdom (until 2019): 142 MW, United States (2013-2020): 1.53 MW, China (2007-2020): 611 MW [Orrell 2021, McCabe et al. 2022].

[1] The updated SET-Plan Implementation Plan targets includes the required annual installed capacity of wind power and grids towards 2030 to achieve the upper target of 450 GW offshore wind by 2050. The range in the cost reduction targets for bottom fixed and floating offshore wind reflects the effect of high and low installation scenarios.

[2] Up to a 250 kW size

2.2 Installed energy Capacity, Generation/Production

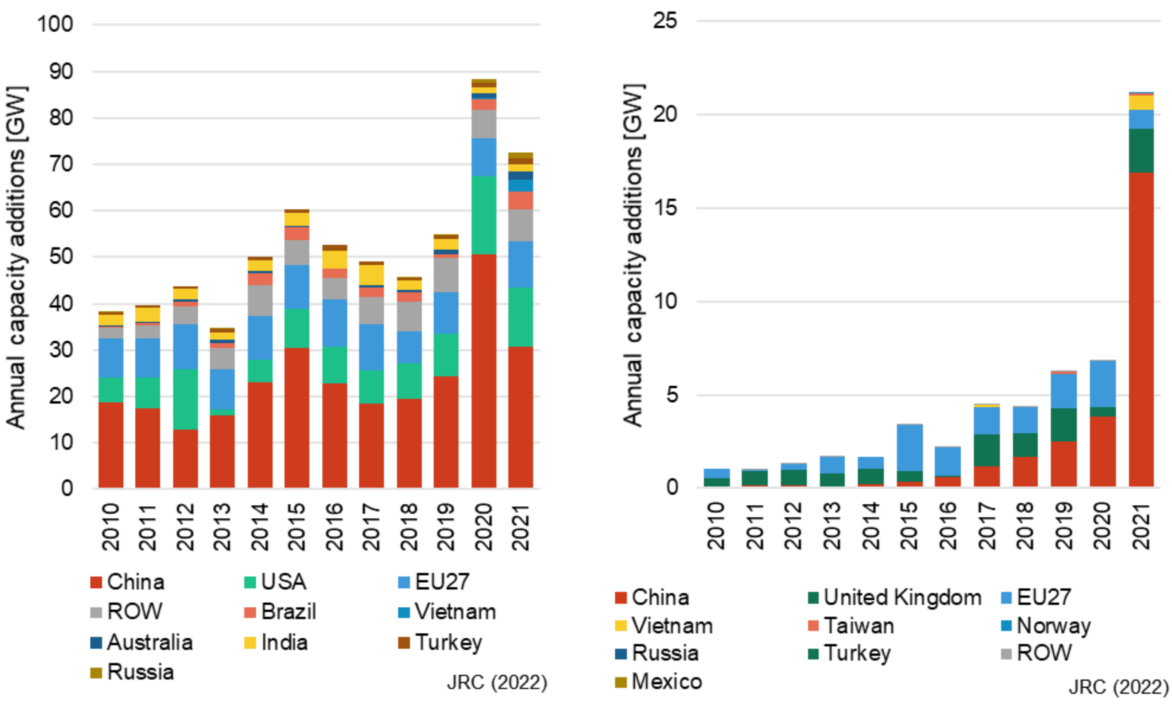
2.2.1 Global deployment

2021 marks another record year in global wind energy deployments. Although new onshore wind capacity decreased by 18% from the record year 2020, 72 GW mark the second strongest year in onshore wind deployment and almost a doubling of capacity additions as compared to 2010-levels. Offshore wind saw an unprecedented record year with 21 GW of new capacity installed, a more than threefold increase after a record year in 2020.

For both, onshore and offshore wind China is leading in newly added capacity with 30.6 GW and 16.9 GW, respectively. With 12.7 GW the US rank second in onshore wind additions closely followed by the EU with 10 GW. Behind China, the UK is the second strongest offshore wind market adding 2.3 GW followed by EU deploying 1 GW in European waters.

The latest surge in Chinese wind deployment in 2020 and 2021 can be explained through a set of new policies targeting renewable energy integration and a shift from Feed-in-Tariffs towards a tender-based support scheme. Since May 2018, the National Development and Reform Commission (NDRC) requires wind energy projects to participate in tenders. Aiming for 'subsidy-free' onshore wind, only projects approved before 2018 and grid-connected by the end of 2020 will receive the Feed-in-Tariff (0.40– 0.59 RMB/kWh (0.05 – 0.07 EUR/kWh))[3] [Xia et al. 2020].

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



Source: JRC based on GWEC, 2022.

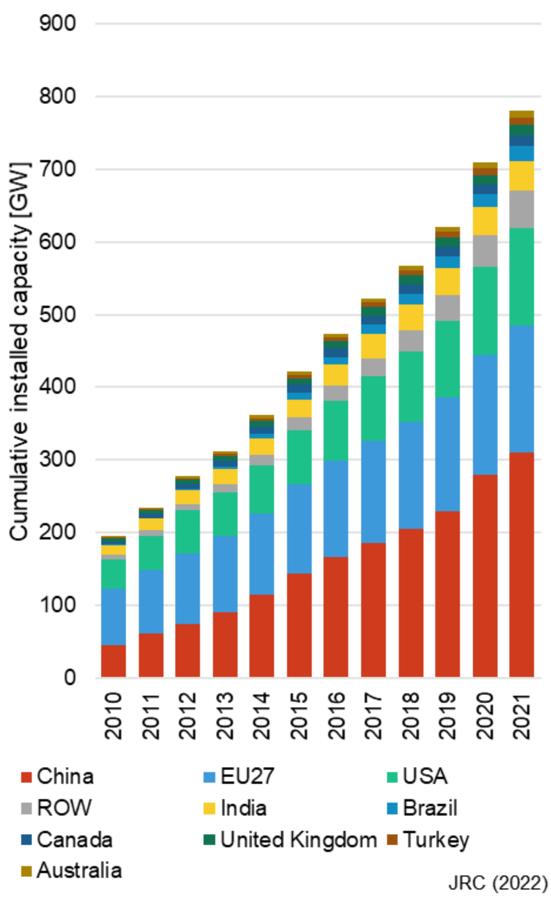
Similarly, offshore wind projects approved before 2018 and grid connected by end of 2021 still receive a Feed-in-Tariff of 0.85 RMB/kWh (0.11 EUR/kWh), whereas auctions in the following two years will implement a price cap of 0.80 RMB/kWh and 0.75 RMB/kWh, respectively. In the US onshore wind deployments are mainly

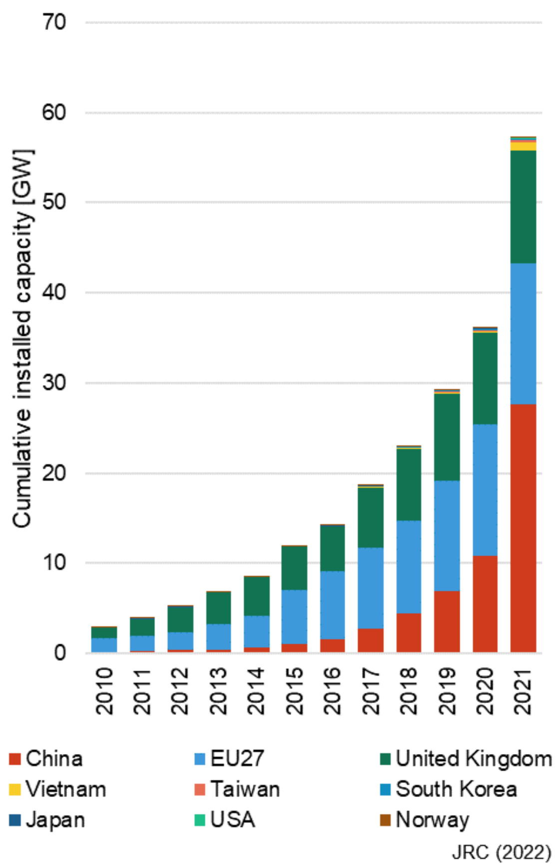
3 Four categories of FiT exist which are distinguished based on the geographical distribution of wind resources, project engineering related factors and provincial coal power price. FiT rates for onshore wind were introduced in 2009 and stepwise reduced to the following values in 2018: Category I (best wind resource): 0.40 RMB/kWh; Category II: 0.45 RMB/kWh; Category III: 0.57 RMB/kWh; Category IV: 0.59 RMB/kWh.

driven by the U.S. production tax credit (PTC). The PTC is a per-kilowatthour (kWh) credit for the first 10 years of electricity generation for utility-scale wind[4] [EIA 2021].

Cumulative global capacity (onshore/offshore). As a consequence of China's strong deployment rates, the country is now leading for the first time in cumulative offshore wind deployment with 27.7 GW, followed by the EU (15.6 GW) and the United Kingdom (12.5 GW). Since 2015 China leads in cumulative wind onshore deployment and has further strengthened its lead since then, from about 34% in 2015 to 40% in 2021 (310.6 GW). The European onshore wind market represented 22% (173.7 GW) of the global market in terms of cumulative installed capacity, followed by the US with 17% (134.3 GW) (see **Figure 4**).

Figure 4 Global cumulative installed capacity of onshore wind (left) and offshore wind (right).





Source: JRC based on GWEC, 2022.

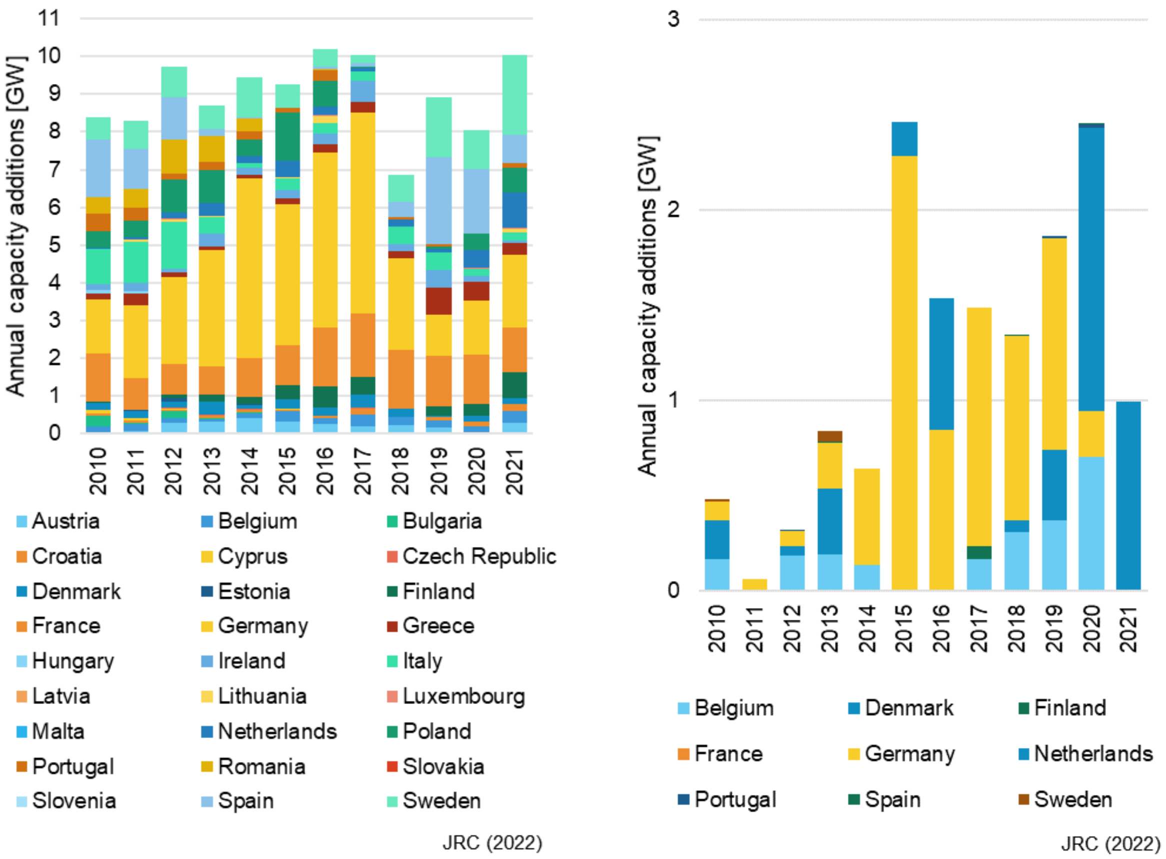
2.2.2 EU 27 deployment

In 2021, EU Member States (MSs) added another 10 GW of onshore wind capacity making it the second strongest year in onshore capacity additions since 2010. In total 18 countries added new capacity with Sweden in the lead (2.1 GW), followed by Germany (1.9 GW), France (1.2 GW) and the Netherlands (1 GW). Projects added in Sweden and the Netherlands have an average project size of about 66 MW and 31 MW respectively, whereas the German (12 MW) and French (15 MW) projects are of smaller size. With 1.3 GW (13%) a significant amount of projects in EU MSs deployed large scale onshore wind turbines with a nameplate capacity above 5 MW.

4 At the end of December 2020, Congress extended the PTC at 60% of the full credit amount, or USD 0.018 per kWh (USD 18 per megawatthour), for another year through December 31, 2021.

After 2020 which marked the second strongest year in EU offshore annual deployments, 2021 saw only 1 GW of offshore wind capacity deployed in EU 27 countries. Only two EU MSs added additional offshore projects. The Netherlands led in capacity additions with 0.6 GW, followed by Denmark adding 0.4 GW of new offshore capacity.

Figure 5 Annual capacity additions of onshore wind (left) and offshore wind (right) in the EU.



Source: JRC based on GWEC, 2022.

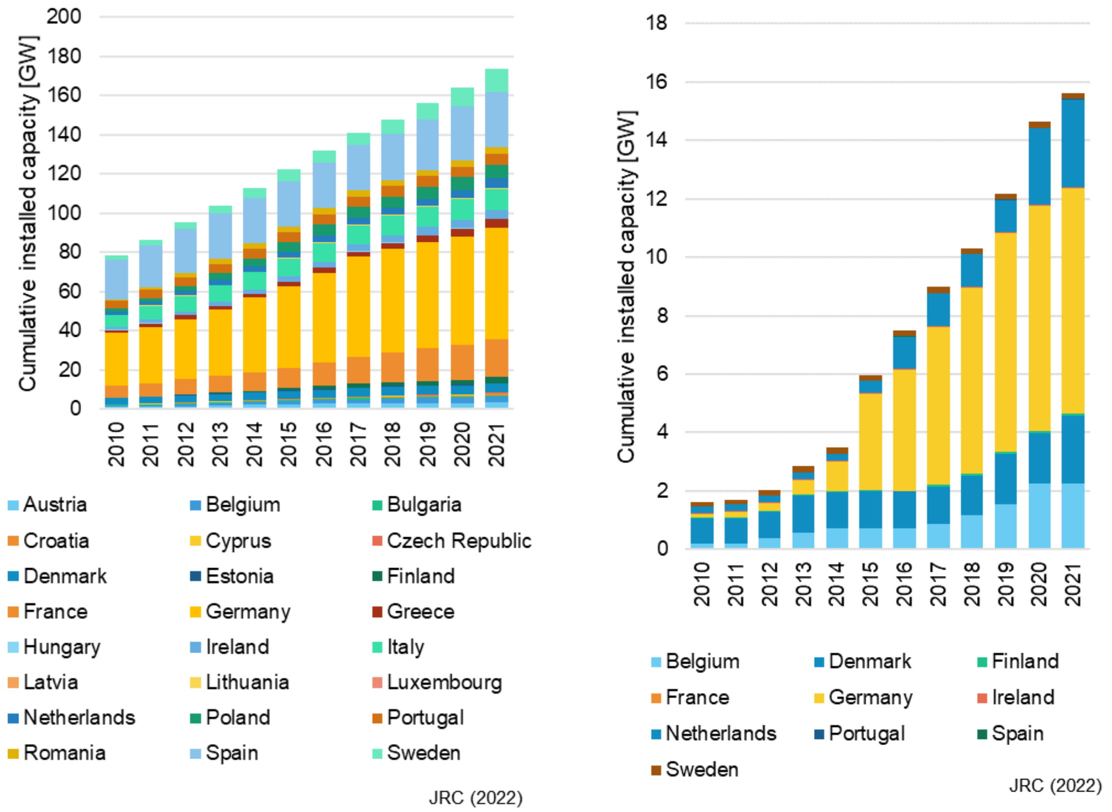
173 GW of onshore wind is installed in EU MSs cumulatively, an increase by 6% as compared to 2020 and more than a doubling (+122%) as compared to 2010. Among the top countries, Germany leads cumulative onshore wind deployment with 56.8 GW, followed by Spain (28.3 GW), France (19.1 GW), Sweden (11.9 GW) and Italy (10.8 GW). So far only Malta has no wind energy capacity installed, moreover Slovenia (3MW) and Slovakia (3MW) have an insignificant amount of wind capacity by means of single demonstrator projects.

Cumulative offshore wind capacity in EU MSs at the end of 2021 is at about 15.6 GW, with Germany (7.7 GW), the Netherlands (3.0 GW), Denmark (2.3 GW) and Belgium (2.3 GW) as the leading countries.

In 2021, all European sea basins (including projects installed in the United Kingdom and Norway) hosted a cumulated capacity of 28.2 GW.

Floating offshore wind. Floating offshore wind is a growing sector that is strengthening Europe's leadership in renewable energy. Floating applications seem to become a viable option for EU countries and regions with deep waters (depths between 50-1000 metres) and could open up new markets such as the Atlantic Ocean, the Mediterranean Sea and potentially the Black Sea. At the end of 2021, EU MSs deployed 27 MW of floating offshore wind in EU sea basins whereas cumulative installed capacity in the United Kingdom and Norway is at 80 MW and 6 MW, respectively.

Figure 6 Cumulative installed capacity of onshore wind (left) and offshore wind (right) in the EU.



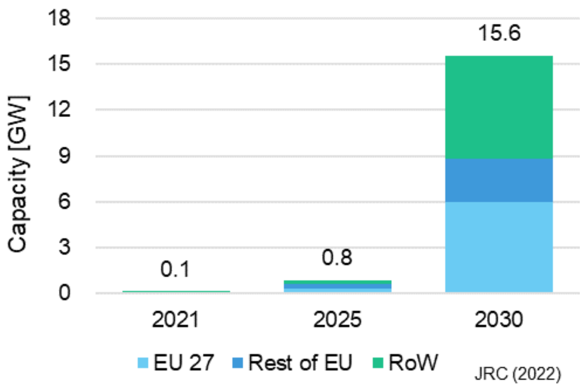
Source: JRC based on GWEC, 2022.

The first multi-turbine floating project was Hywind Scotland with a capacity of 30 MW (five 6 MW turbines on a spar buoy substructure), commissioned in 2017 by Equinor, followed by the Floatgen project in France and the WindFloat Atlantic in Portugal. In 2021 the Kincardine project was fully commissioned in Scotland (UK) after being delayed due to supply chain issues caused by the Covid-19 pandemic. With 48 MW the project is currently the world's largest floating offshore wind farm [Principle Power 2021]. Moreover, the commissioning of the 3.6 MW TetraSpar demonstrator was completed at the METCentre test site in Norway at the end of 2021. The concept uses a tetrahedral structure assembled from tubular steel components aiming for an industrialised and lean production of offshore foundations [Stiesdal 2021]. At the same location (MET-Centre) the H2020-funded FLAGSHIP ('FLoAtinG offSHore wInd oPtimization for commercialization) project aims to install by the end of 2022 a cost-effective 10 MW floating offshore wind turbine by using a floating semi-submersible concrete substructure. There is a pipeline of projects that will lead to the installation of 530 MW of floating capacity in European waters by 2025 (of which 247 MW are deployed in EU MSs), which would need to accelerate afterwards [JRC 2020a, EC 2022b]. A higher level of ambition and clarity is needed to reach a market size sufficient to yield cost reductions: there is potential to reach an LCoE of less than EUR 100/MWh in 2030 if large capacity is deployed. Moreover, the EU wind industry targets 150 GW of floating offshore by 2050 in order to become climate-neutral [ETIPWind 2020].

The global market for floating offshore wind represents a considerable market opportunity for EU companies. Latest announcements of national floating offshore wind targets (particularly in Europe and Asia) suggest a substantial increase in the deployed capacity in the mid-term. In total about 12.2 GW to 15.6 GW of floating offshore wind energy is expected by 2030, with significant capacities in some Asian countries (South Korea and Japan) besides the European markets (France, Norway, Italy, Greece, Spain, the United Kingdom) (Figure 7). The current leadership of European countries in deployment of floating offshore wind is expected to change in the second half of the decade with South Korea, Japan joining the established European markets (Norway, the United Kingdom and France). Thus, the market share of European countries (including the United

Kingdom and Norway) in floating offshore wind is expected to decrease from 71% in the period 2021-2025 to about 44% in the period 2026-2030. By then by Asia (37%) and North America (19%) are expected to hold significant shares of the market. Due to good wind resources in shallow waters, no significant floating offshore capacity is expected in China in the mid-term[5] [GWEC 2020a].

Figure 7 Global capacity outlook until 2030 on floating offshore wind.



Source: JRC based on 4COffshore, 2022.

The main distinctive criterion in multiple floating designs is the substructure used to provide the buoyancy and thus the stability to the plant, such as Spar-buoy, Semi-Submersible, Tension-leg platform (TLP), Barge or Multi-Platforms substructures. So far, no concept has prevailed over the others; however, Equinor's spar-buoy concept (Hywind project) has already been deployed in a pre-commercial project (see **Table 2**). Given the variety of concepts estimates are that the TRL of offshore floating wind concepts range between 4 and 9 [Moro et al. 2019]. Spar-buoy and semi-submersible concepts have already reached TRL 8-9 as they are being built and tested at large scale. Based on estimates on the current global project pipeline until 2030 semi-submersible floaters will hold the highest share in floating offshore wind projects with about 64% followed by spar-buoy (13%), barge (10%), TLP (7%) and semi-spar (4%) [GWEC 2021a]. With a 2 MW floating prototype in France (Floatgen Project, generating 6 GWh in 2019 [WPM 2020a]) Ideol aims to demonstrate the capabilities of a concrete barge-type substructure ('Damping Pool' floating foundation) in a deep water setting. To date TLP designs have not yet reached this level of maturity [Watson et al. 2019].

With 88 MW (11 8 MW SGRE-turbines), the next significant up-scaled project (Hywind Tampen) will be deployed close to the Gullfaks and Snorre fields to meet approximately 35% of the annual power requirement of five oil and gas platforms. This would also mean an increase in the design of the spar-buoy platforms (weight, draught and catenary length of the concrete floater) as compared to the initial Hywind Scotland design as the project will be located 140 km from shore at a water depth of about 260-300 m. Moreover, it is first time an offshore wind farm is directly connected to O&G platforms [JRC 2020a, Equinor 2022]

In early 2022, Netherlands-based Seawind Ocean Technology signed a Memorandum of Understanding (MOU) with Petrofac (UK), a leading international service provider to the energy industry. Petrofac will support design verification as well as project management and EPC service to the SeaWind concept. The company claims that this will enable the deployment of a first 6.2 MW demonstrator in European waters by 2024 [Seawind 2022a]. Moreover, Seawind announced its cooperation with Japanese majors JGC Japan Corporation (JGC) (JP) and Mitsui O.S.K. Lines (MOL) (JP) which will support the delivery of a first demonstrator [Seawind 2022b].

Floating hybrid energy platforms are still at a lower TRL (1-5), though the announced Katanes Floating Energy Park – Pilot (based on the P80 wind-wave energy platform) comprising a 3.4 MW wave converter and an 8 MW wind turbine could lift this system to TRL 6-7 by 2022.

[5] JRC analysis based on 4COffshore Offshore Wind Database

Table 2 EU and other European floating offshore wind farms and demonstrators and the respective floating substructure concept used (announced and operational). R&D projects taking place outside of the EU are listed in blue font in the bottom half of the table.

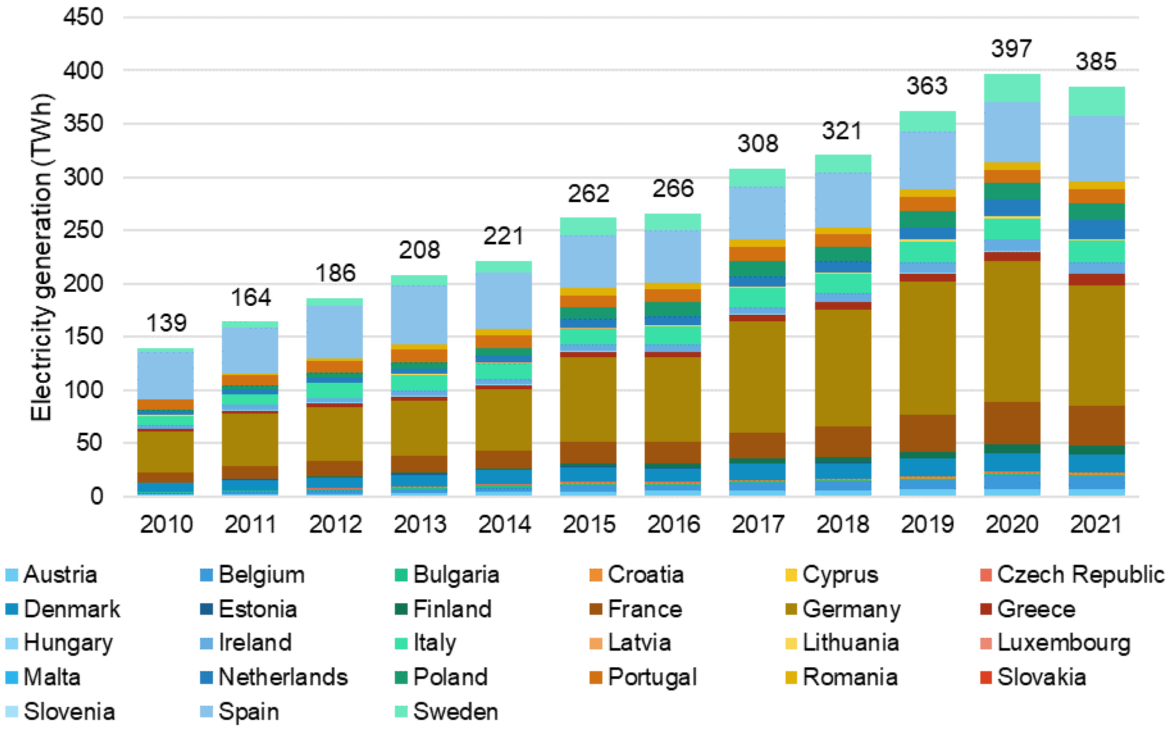
Project	Country	First Power	Capacity [MW]	# of turbines	Floating concept
SeaTwirl S1	Sweden	2015 (operational)	0.03	1	Spar-buoy
Floatgen Project [1]	France	2018 (operational)	2	1	Barge
WindFloat Atlantic (WFA) [2]	Portugal	2020 (operational)	25	3	Semi-Submersible
PivotBuoy - PLOCAN	Spain	2022	0.225	1	Semi-Submersible
DemoSATH - BIMEP[1]	Spain	2022	2	1	Barge
Floating Power Plant - PLOCAN	Spain	2023	5	1	Semi-Submersible
EOLINK 5 MW Demonstrator	France	2023	30	3	Barge
Provence Grand Large[2]	France	2023	30	3	Semi-Submersible
Golfe du Lion	France	2023	28.5	3	Semi-Submersible
Groix & Belle-Île	France	2023	25	5	Spar-buoy
EolMed [4]	France	2024	25.2	3	Tension-leg platform
SeaWind Demonstrator	Not decided	2024	6.2	1	Semi-Submersible
FLOCAN 5[2]	Spain	2024	50	4	Semi-Submersible
GOFIO	Spain	2025	8	1	Semi-Submersible
MULTIPLAT2	Spain	2026	10	2	Semi-Submersible
UNITECH Zefyros by Hywind Technology	Norway	2009 (operational)	2.3	1	Spar-buoy
Hywind Scotland Pilot Park**	United Kingdom	2017 (operational)	30	5	Spar-buoy
Kincardine - phase 1**	United Kingdom	2018 (operational)	2	1	Semi-Submersible
Kincardine - phase 2**	United Kingdom	2021 (operational)	48	5	Semi-Submersible
TetraSpar Demonstrator - Metcentre	Norway	2021 (operational)	3.6	1	Spar-buoy
Hywind Tampen	Norway	2022	88	11	Spar-buoy
FLAGSHIP - Metcentre [1]	Norway	2022	10	1	Semi-Submersible
SeaTwirl S2[3] (VAWT)	Norway	2024	1	1	Spar-buoy
Blyth Offshore Demonstrator - phase 2**	United Kingdom	2025	58.4	5	Semi-Submersible
TwinHub**	United Kingdom	2025	40	4	Semi-Submersible
Erebus**	United Kingdom	2027	96	10	Semi-Submersible
Dolphyn Project - pre-commercial**	United Kingdom	2027	10	1	Semi-Submersible

[1] Funded by the EC's FP7 or H2020 programme
[2] Funded by the EC's NER300 programme
[3] Received a €2.48 million grant from the European Innovation Council's SME instrument
[4] Co-financed by the European Investment Bank
[5] Combined wind-wave generator. Project will be further developed to 47MW
** UK projects are listed because of the role in R&D of floating wind technology.
Source: JRC, 2022.

2.2.3 European and global electricity generation

In 2021, about 385 TWh was generated from wind energy in EU MSs (see **Figure 8**). Despite an additional 11GW (+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 8 Wind energy electricity generation of EU MSs in 2021.



Source: JRC based on EurObserv'ER, 2022.

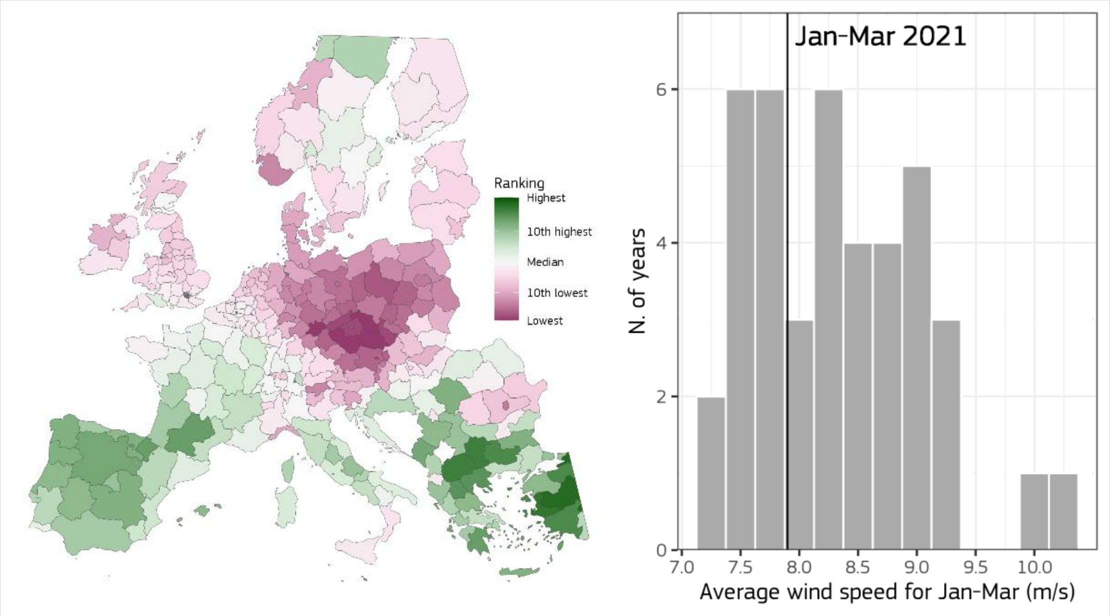
This can be explained by a moderate wind year in 2021 (see information in **Box 1**) having particularly a strong effect on wind power plants in Germany (-14% in electricity generation from wind as compared to 2020 despite a 1.7GW of new capacity). A similar effect can be witnessed for Ireland (-16%), Lithuania (-12%), France (-8%), Luxembourg (-7%) and Belgium (-7%) with all of them experiencing decreased wind electricity generation at growing cumulative capacity.

Box 1. Classification of low-wind speed events and the impact of an extended EU offshore wind fleet in 2030

In 2021, low wind speed periods occurred in the first quarter (January to March). This affected particularly Northern and Central European countries whereas Southern European countries benefitted from higher wind resource, when compared with data from the period 1980-2021 [EC 2021a].

With 7.9 m/s Q1 2021 values ranks only the 15th lowest year in terms of average wind speed in the last 42 years.

Figure 9 Ranking of the wind resource on NUTS2 level in Q1 2021 in comparison to first quarter values in the period 1980 -2021 (left) and ranking of the average wind speed on the current offshore wind fleet of Q1 2021 as compared first quarter values in the period 1980 -2021



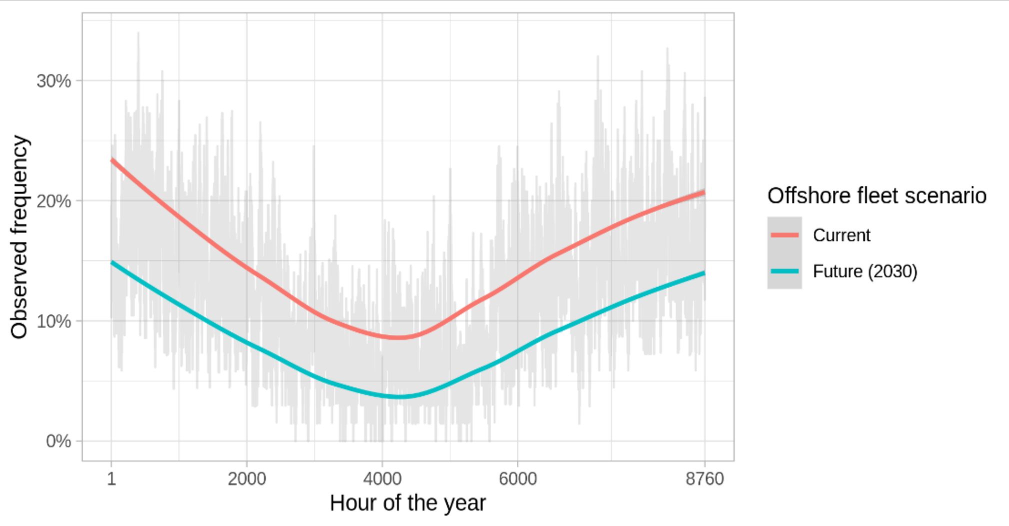
Source: JRC, 2022.

Accelerated offshore wind deployments in EU waters hold the potential to reduce the occurrence of low wind speed events (defined here as low-wind for 48 hours consecutively). We assume that current cumulated offshore wind capacity (25 GW in 2020) increases to more than 120 GW in European waters by 2030.

Results show that the median duration of a low-wind event affecting 50% of the capacity is about 17 hours with a maximum of 170 hours, taking wind resource data from the period 1950 to 2020 as a basis. If we consider the planned 2030 offshore fleet instead, the numbers are slightly lower: 14 hours the median duration of low-wind speed events and 144 hours the maximum.

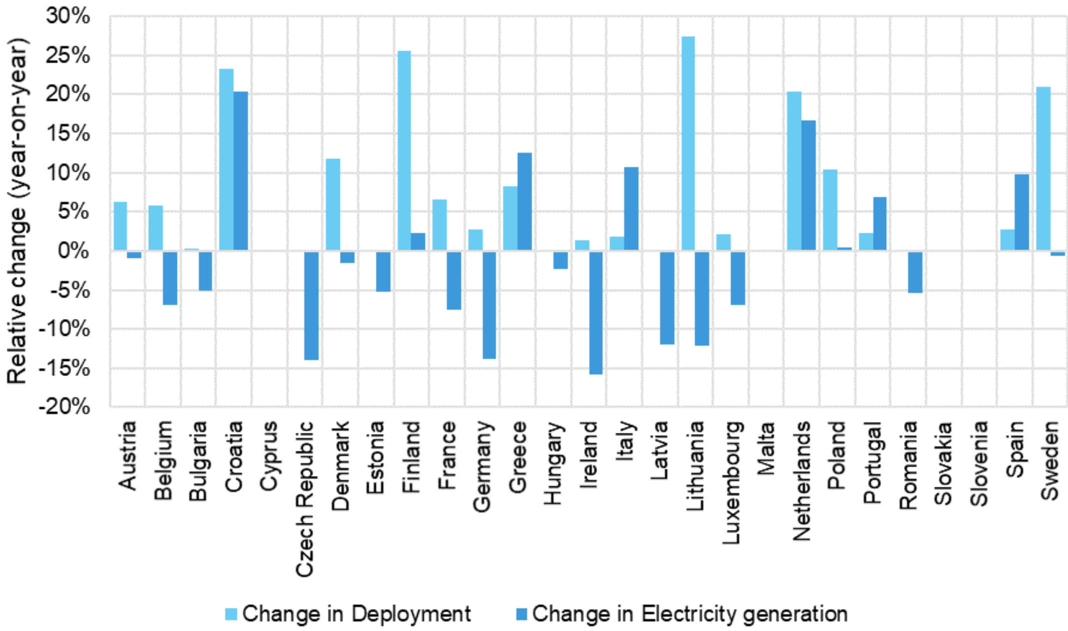
The hourly frequency of low-wind events – defined as the number of events observed in the 1950-2020 period out of the total number of years – is shown in **Figure 10**, both considering the current and the future (2030) offshore fleet.

Figure 10 Comparison of the frequency of low wind speed events of the current and 2030 offshore wind fleet in EU waters



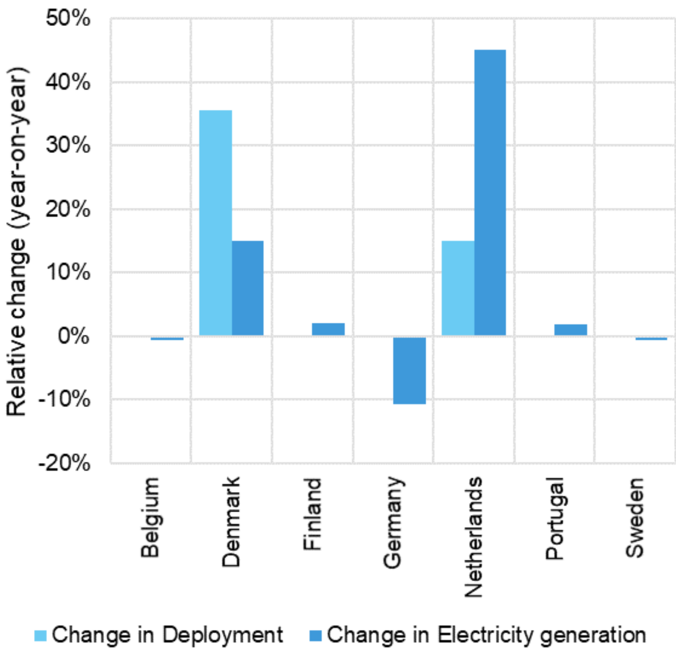
Source: JRC, 2022.

Figure 11 Relative change (year-on-year (2020 to 2021)) in cumulative wind energy deployment and wind energy electricity generation of EU MSs.



Source: JRC based on EurObserv'ER, 2022.

Figure 12 Relative change (year-on-year (2020 to 2021)) in cumulative offshore wind energy deployment and offshore wind energy electricity generation of EU MSs.



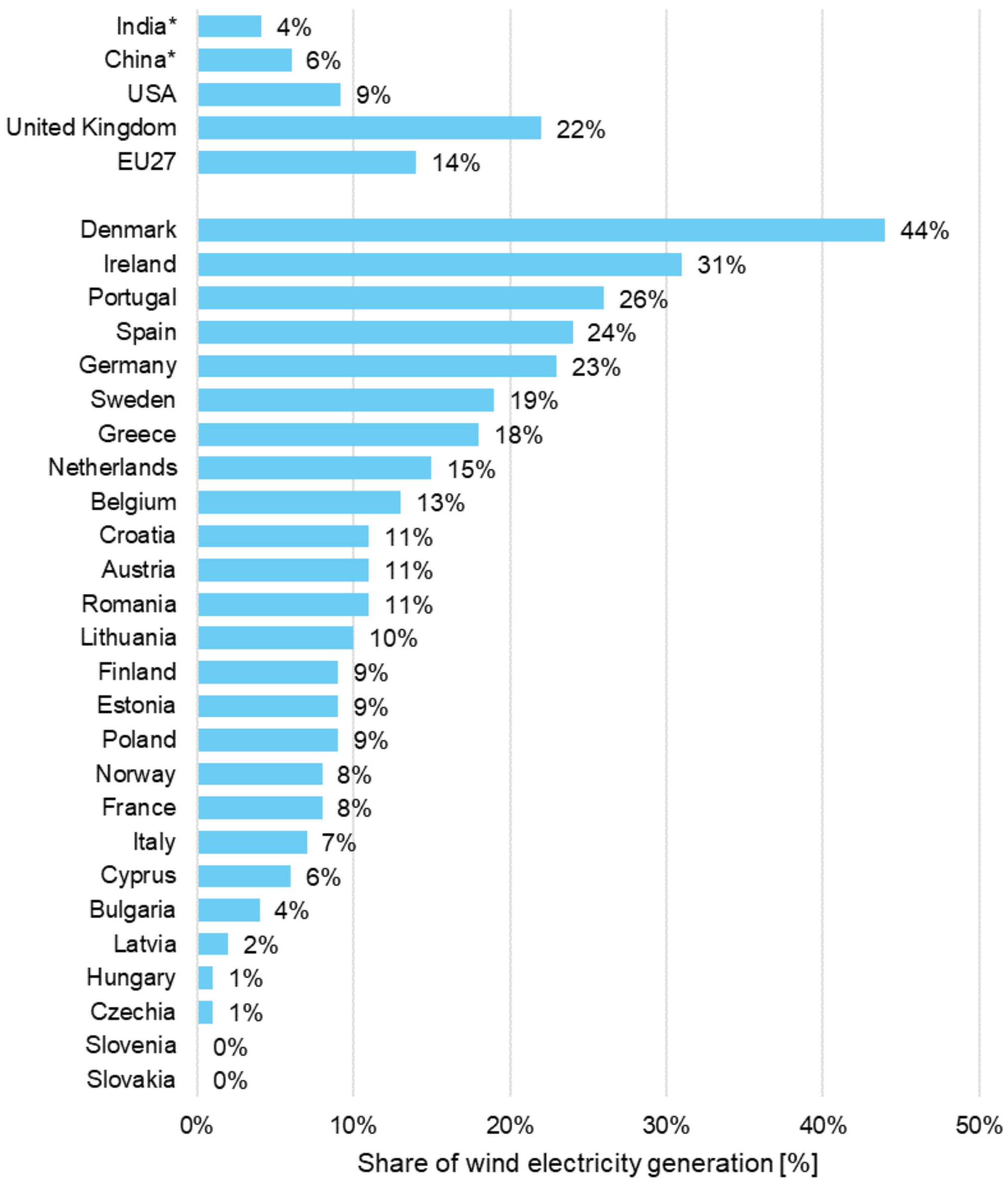
Source: JRC based on EurObserv'ER, 2022.

EU wind electricity accounts for about 14% of the total electricity generation in 2021. Denmark (44%) shows the highest wind electricity share in its electricity mix followed by Ireland (31%), Portugal (26%), Spain (24%)

and Germany (23%). Most eastern EU countries show lower wind shares, as a consequence of lower deployment rates.

Among EU's global competitors, the United Kingdom and the United States show the highest wind electricity shares with 22% and 9%, respectively. Latest available data on the share of wind electricity generation of China and India indicate lower values as compared to EU, however increasing at a fast pace as deployment rates are surging (see **Figure 13**).

Figure 13 Share of wind generation in EU and globally as % of the total electricity generation in 2021.
* Data for India and China represent 2020 values



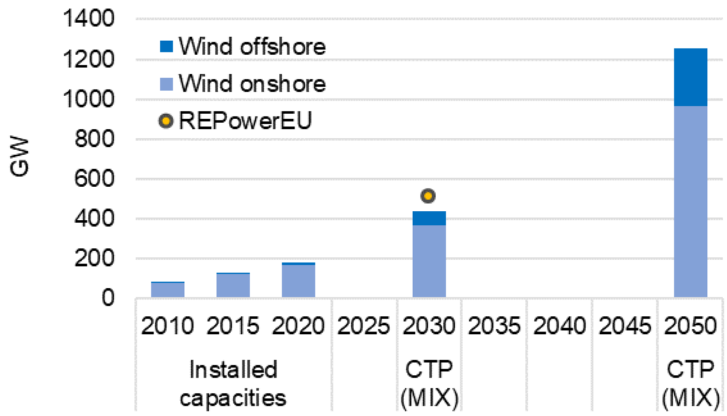
Source: JRC based on WindEurope, IEA, EIA, 2022.

2.2.4 EU 27 modelling projections

Results of the scenario modelling of the 2030 Climate Target Plan (CTP-MIX scenario) show onshore wind deployments surging to 366 GW and 963 GW in 2030 and 2050, respectively. An even stronger relative increase is calculated for offshore wind deployments with 73 GW in 2030 and 290 GW by 2050 (see **Figure 14)**. Based on these deployments the share of onshore wind in EU electricity mix will rise from 14% (2021) to 27.3% (847 TWh) in 2030 and 32.9% (2259 TWh) in 2050. Current EU offshore wind electricity generation accounts for about 2% (2021) of the EU electricity mix and increases to 7.4% in 2030 and 16.8% in 2050 in the CTP-MIX scenario (see **Figure 15**) [EC 2020b].

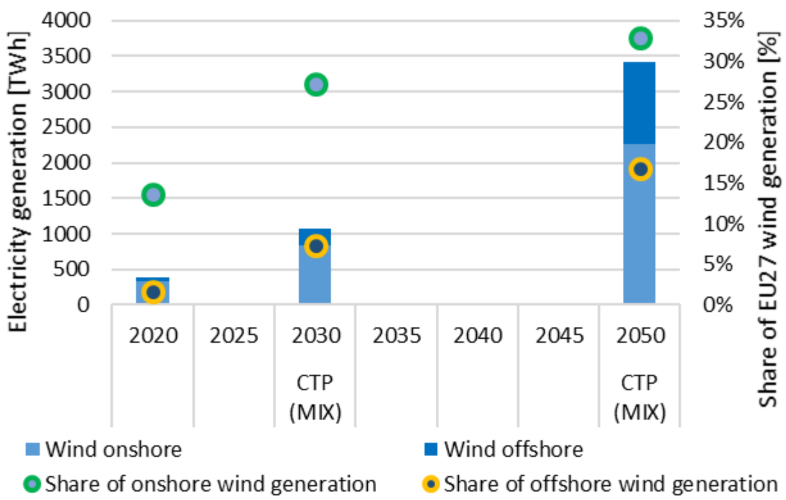
In May 2022, the EC presented the REPowerEU Plan in response of the global energy market disruption caused by Russia's invasion of the Ukraine. Among other measures the plan foresees an accelerated rollout of renewables increasing the target for renewables from 40% to 45% by 2030. With respect to wind energy the REPowerEU Plan proposes an installed capacity of 510 GW by 2030, an increase by 16% as compared to CTP-MIX scenario [EC 2022c].

Figure 14 Installed wind capacities and wind capacity targets in the EC CTP-MIX scenario and comparison with the installed wind capacity in the REPowerEU Plan.



Source: JRC based on 2030 Climate Target Plan Impact Assessment, 2022.

Figure 15 Current and future electricity generation from onshore and offshore wind and its share in total electricity generation of the EU.



Source: JRC based on 2030 Climate Target Plan, BEIS and WindEurope, 2022.

Figure 16 tracks the remaining gap of EU MS towards their wind energy targets or estimated targets in 2030 as expressed in their National Energy and Climate Plans [EC 2022d]. In terms of the absolute needed capacity France shows the largest capacity gap with 26 GW followed by Germany (25.2 GW), Spain (22.1 GW), Poland

(15.7 GW) and the Netherlands (12.3 GW). In total EU MSs fall about 151 GW short towards the 2030 target, not taking into account the updated REPowerEU targets.

Figure 16 Installed wind capacities, wind capacity targets and remaining gap towards NECP target of EU MS. Note: For countries not expressing a dedicated wind capacity target in their NECP the capacity estimate from the WindEurope NECP scenario was used. Numbers do not take into account the REPowerEU targets.

Source: JRC based on EC and WindEurope, 2022.

2.2.5 European and global offshore wind outlook

The EU Strategy on Offshore Renewable Energy (ORES) proposes to increase Europe's offshore wind capacity from its current level (14.6 GW in 2020) to at least 60 GW by 2030 (and to 300 GW by 2050) [EC 2020a]. Following current national targets as expressed in the MSs National Energy Climate Plans (NECPs) suggest that the ORES target for 2030 can be achieved. Multiple NECPs do not differentiate between onshore and offshore wind, however limiting to those countries that formulated a specific offshore wind target for 2030 would lead to a cumulated offshore wind capacity of 62.5 GW. With 20 GW in 2030, Germany is the country with the highest NECP offshore wind target followed by the Netherlands, Denmark, France, Ireland, Belgium and Poland. Offshore wind targets at limited scale were formulated by Portugal, Lithuania and Italy. Even though not explicitly mentioned in their NECPs, a set of MSs is expected to deploy substantial offshore wind capacities until 2030.

Latest commitments to offshore wind suggest an even more accelerated deployment path. In May 2022, Belgium, Denmark, Germany, and the Netherlands pledged in the Esbjerg declaration to deploy at least 65 GW of offshore wind by 2030 and 150 GW by 2050 to speed up the phase-out of fossil fuels and to minimise reliance on energy imports from Russia. The declaration sees the North Sea as a Green Power Plant of Europa consisting of multiple connected offshore energy projects and hubs and capable to produce a combined 20 GW of green hydrogen [KEFM 2022].

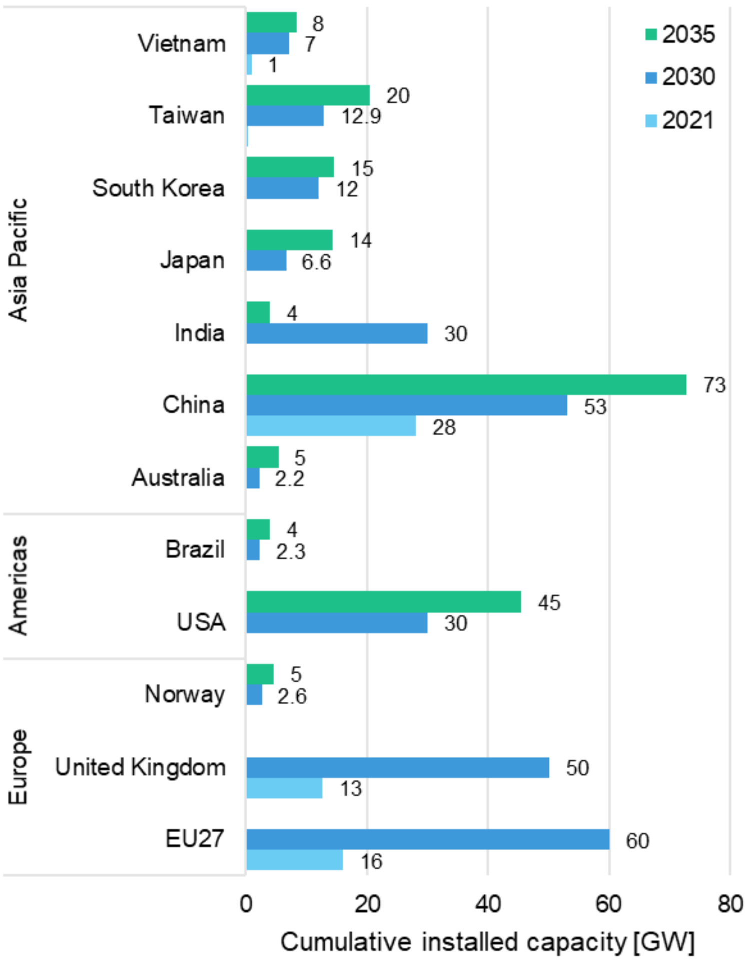
Estimates suggest that the United Kingdom requires 65-125 GW of offshore wind towards its 2050 decarbonisation target. The government has ambitions for 40 GW+ by 2030 including 1 GW of floating wind. In early 2022, the UK government reinforced its commitment to offshore wind through the announcement of increasing the offshore wind capacity target to 50 GW until 2030 (of which 5 GW are envisaged as floating offshore) as well as the introduction of a local content criteria in the application process of the latest UK renewable energy allocation round (AR4). The new target comes in response to rising global energy prices as a consequence of surging demand after the COVID-19 pandemic and Russia's invasion of the Ukraine [OW 2022e].

Norway has not formulated a legally binding target so far yet the government announced in May 2022 to allocate sites capable of supporting 30 GW of offshore wind by 2040. Until 2035, the development of Utsira Nord site and the Sørlige Nordsjø II might lead to the construction of about 4.5 GW [WPM 2020b, WPM 2022a].

In 2021, the US government announced its goal to deploy 30 GW of offshore wind in the United States by 2030, with the ambition to reach 110GW by 2050 [WH 2021]. The targets formulated at state level and accelerated leasing and consenting activities suggest that by end of 2035 a potential offshore wind capacity of up to 46 GW might be installed in US waters. In Brazil first auctions for offshore wind could take place in 2023, in the mid-term capacities up to 4GW can be expected [4COffshore 2022].

In Australia the state of Victoria became the first to formulate offshore wind targets of least 2 GW by 2032, estimates suggest about 5 GW offshore by 2035. After a record breaking 2021 cumulative deployment in China stands at 26 GW. Following the phase out of the offshore wind Feed-in-Tariff deployment rates are expected to slow down. Yet it is estimated that offshore wind in China will grow towards 53 GW by 2030 and 73 GW by 2035. However, local Chinese governments of the coastal provinces formulated more ambitious targets aiming for 58.5 GW to be installed in the period 2021-2025, resulting in a cumulative offshore capacity of about 85 GW by 2025. On the longer term Chinese local authorities are reported to aim for 150 GW of offshore wind. India set an offshore target of 30 GW by 2030, however it is unlikely that this will be achieved as delays occurred due to lack of funding and the legal and political framework in place. The first offshore wind farm is expected in Gujarat and about 4 GW of offshore wind are expected in the mid-term. Japan targets 10 GW of offshore wind capacity to be auctioned by 2030 with 5.7 GW being operational upon that stage. Based on the current project pipeline about 14 GW are expected by 2035. The government in South Korea targets an ambitious 12 GW of offshore wind capacity by 2030. So far, Taiwan awarded about 5.5 GW of offshore capacity in its waters. The country aims for decarbonisation until 2050 and formulated an offshore target of 15 GW by 2026-2030. Moreover, Taiwan targets 40 GW to 55 GW of offshore wind by 2050. Vietnam is currently close to approve an offshore wind target of 7 GW by 2030 [4COffshore 2022, Energy Iceberg 2022, MNRE 2022].

Figure 17 European and global offshore wind capacity targets, ambitions and estimated installed capacities towards 2030 and 2035.



Source: JRC, 2022.

2.3 Technology Cost – Present and Potential Future Trends

Onshore. Based on the main cost estimates and projections on onshore wind, **Figure 18** identifies an LCoE range spanning from EUR 34 per MWh to EUR 74 per MWh in the period 2019 - 2021 which is expected to further decline on the long term to values between EUR 19 per MWh to EUR 33 per MWh in 2050.

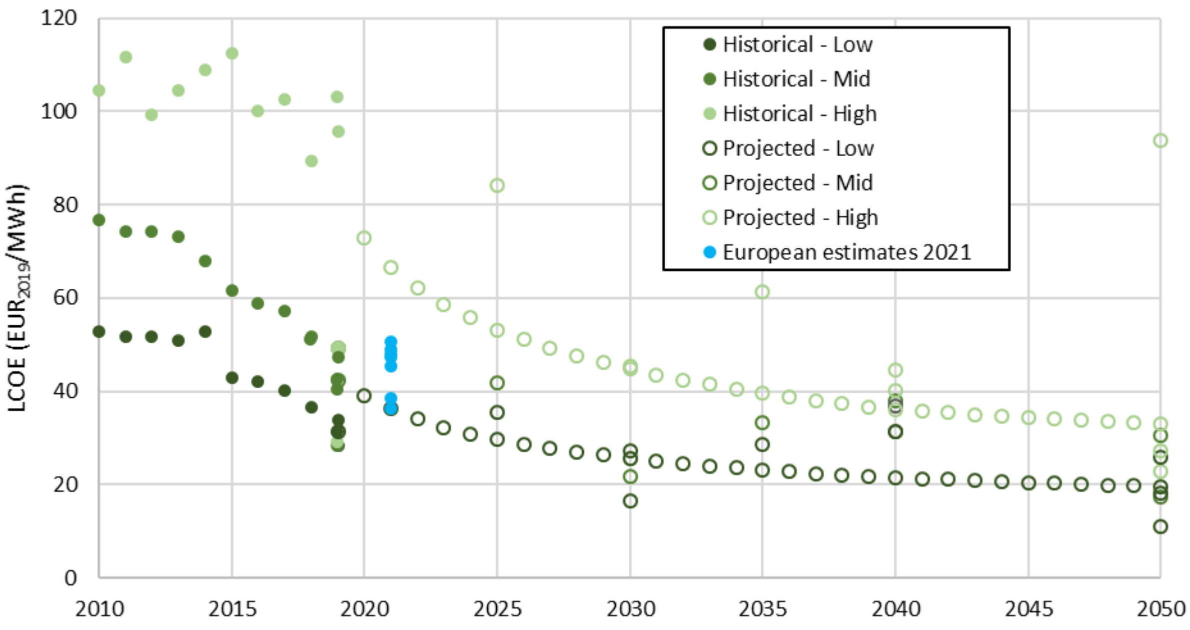
Yet since the beginning of the COVID-19 pandemic LCoE estimates in the main EU markets increased by 2% to 12%. Commodity price inflation, increasing shipping costs and supply chain disruptions have led to increasing wind turbine prices since 2020. In early 2022, BNEF (2022) reports global average turbine prices increasing by 18% as compared to pre-pandemic levels. As a consequence of cost inflation pressure and declining margins OEMs increase turbine prices, implement cost-cutting programmes and incorporate cost inflation clauses into its contracts (e.g. SiemensGamesa including commodity indexation clauses (mainly to tower steel), reopeners and exit clauses, which began to be incorporated into bids made in the second half of 2021). In early 2022, commodity price inflation further increased following Russia's invasion of the Ukraine with commodity prices surging (particularly for steel used for towers: +80%). Moreover, prices of materials for key wind turbine components remain at very high levels as compared to pre-pandemic levels, e.g. neodymium (+300%), epoxide resins (+200%) and copper (+30%) [SGRE 2021, BNEF 2022a].

According to WindEurope data, the LCoE of onshore wind will decrease from EUR 40 per MWh in 2019, to EUR 26 per MWh in 2030, to EUR 19 per MWh in 2050. BNEF estimates the LCoE of onshore wind in EU countries between EUR 36 and 51 EUR/MWh in 2021, depending on for example location and financing conditions [BNEF 2022b].

CAPEX for onshore wind projects range in the established European markets between EUR 1060/kW and EUR 1425/kW. Current projections see onshore wind CAPEX decreasing by 8% and 18% until 2030 and 2050, respectively. Within this time period an even stronger decrease is expected for OPEX which range currently at about EUR 18 per MWh to EUR 36 per MWh, decreasing by 14% by 2030 and up to 30% in the long term (2050) [BNEF 2022b].

Although a decrease in the cost of finance (weighted average cost of capital (WACC)) of onshore wind projects can be observed in the last years this indicator varies considerably among EU countries. Whereas many central EU countries benefit from low WACC (1.3%-4.3%), less developed markets such as Greece, Romania and the Baltic States show a WACC range of about 7% to 10%. This spread can to some extent be explained by diverging interest rates and country risks faced by investors. Evidence suggests that a further decrease (and convergence among countries) in WACC could be achieved by focussing on de-risking debt financing of wind energy projects by policies that implement support schemes decreasing the volatility of a projects cash flow (e.g. Contracts for Difference) [AURES 2021].

Figure 18 Range of historical, current (European estimates 2021) and projected onshore wind LCoE estimates.

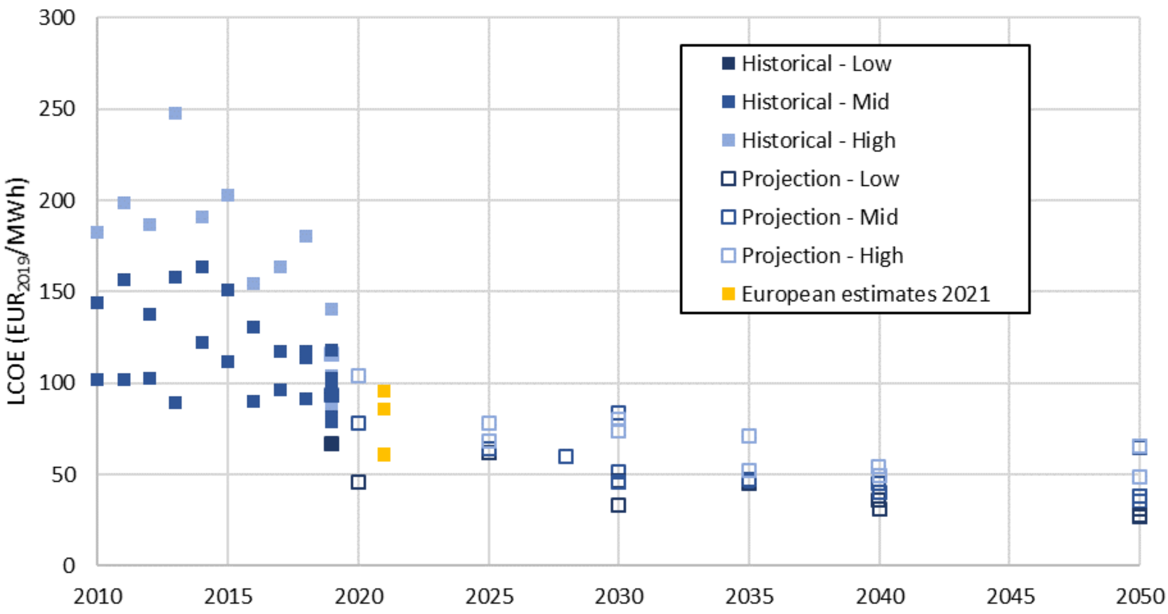


Source: JRC, BNEF, Beiter et al, 2021 (chart reproduced from Beiter et al.), 2022.

Offshore. Estimates on bottom-fixed offshore wind LCoE declined rapidly to today's values ranging from EUR 61 per MWh to EUR 140 per MWh (see 2019-2021 range in **Figure 19**). Latest estimates on EU offshore LCoE suggest a range of EUR 61 per MWh to EUR 96 per MWh. Particularly since 2014 an upscaling in project and turbine size can be observed in order to capitalise on the decrease of the unit costs (economies of size). Following current projections on the future costs of bottom-fixed offshore wind LCoE levels in the range of EUR 30 per MWh to EUR 60 per MWh can be expected by 2050. The cost of offshore wind installations is therewith reaching similar levels as the one of onshore installations.

As for all other capital intensive RES technologies the cost of finance (weighted average cost of capital (WACC)) impacts LCoE considerably. The WACC is mainly influenced by country risks and interest rates. Although there is not much data on offshore wind WACC, a recent study finds generally higher values for offshore wind (ranging from 3.5% to 9%) than for onshore wind as the technology is at an earlier stage of development thus having a higher risk profile. Evidence suggests that a further decrease (and convergence among countries) in WACC could be achieved by focussing on de-risking debt financing of wind energy projects by policies that implement support schemes decreasing the volatility of a projects cash flow (e.g. a sliding feed-in premium scheme (Contract for Difference)) [JRC 2019, AURES 2021].

Figure 19 Range of historical, current (European estimates 2021) and projected offshore wind LCoE estimates.



Source: JRC, BNEF, Beiter et al, 2021 (chart reproduced from Beiter et al.), 2022.

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

CAPEX for offshore wind projects declined until the outbreak of the pandemic. At the end of 2021, CAPEX increased in the main offshore markets at an average of about 29% as compared to pre-pandemic levels. Depend on the rated turbine capacity, depth of the site (and the foundation technology pursued) and the size of a project CAPEX estimates range in the established European markets between EUR 2900/kW and EUR 3750/kW [BNEF 2022b].

Floating offshore wind. 4COffshore estimates future floating offshore wind to be in the range of bottom-fixed offshore by the end of the decade. CAPEX estimates of current Equinor projects (pre-commercial projects) are in the range of EUR 5000 - 7300/kW [4COffshore 2021]. A recent expert elicitation expects LCoE for floating offshore to decrease substantially in the mid to long term (on average decreasing by 17% in 2030 and 40% by 2050 as compared to a 2019 bottom-fixed reference plant) given the nascent state of floating offshore wind. Moreover experts expect the gap between fixed-bottom and floating offshore costs to narrow within this period [Wiser et al. 2021]. In the context of the UK's offshore expansion significant cost reduction estimates for floating offshore wind are expected. ORE Catapult assumes two scenarios until 2040 which foresee 8 GW to 10 GW of floating offshore in UK waters. Under these assumptions CAPEX for floating offshore wind are expected to decrease by about 65% in the period 2027 – 2040. OPEX reductions are expected to be in the range of about 32-36% [ORE Catapult 2021]. For floating offshore wind, ETIPWind/WindEurope estimates LCoE reductions of about 65% in 2030 and 78% in 2050 as compared against a EUR 184 per MWh baseline (assuming a capacity factor of 47-55%, a technical lifetime of 25-30 years and a WACC of 7-8%). Strongest drivers of cost reduction are seen in the industrialisation of floating technology, the knowledge transfer form established offshore industries and scaling effects in the operation and maintenance of large floating offshore projects [ETIPWind/WindEurope 2021].

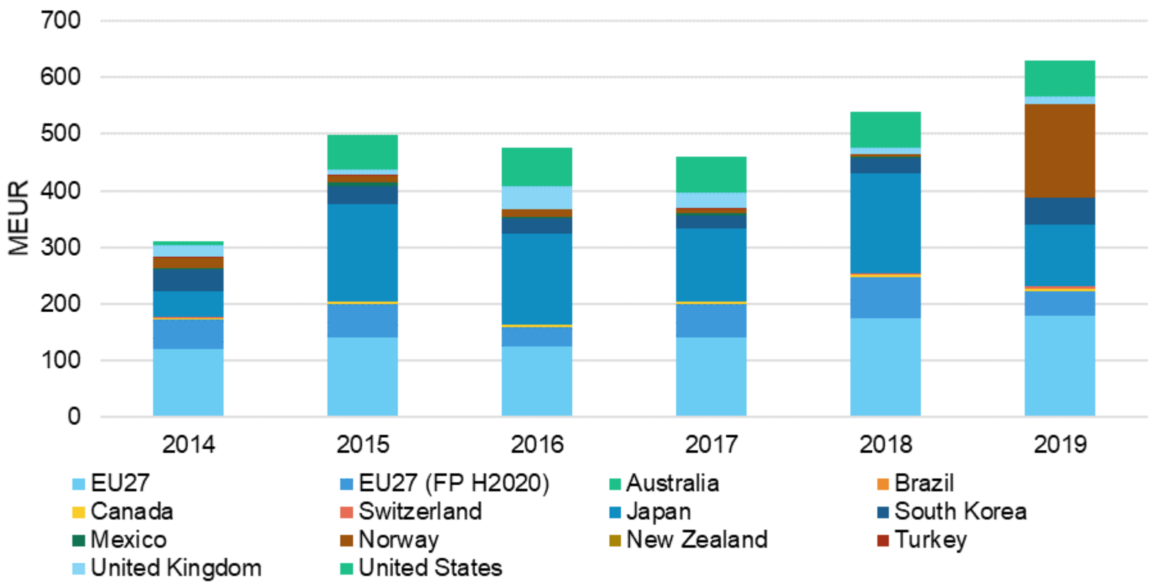
2.4 Public R&D funding

Public R&D investments are analysed based on the IEA energy technology RD&D budget and includes data from national investments in EU and the main OECD non EU countries[6]. Moreover, since 2014 EU funding from the EU H2020 framework programme (see EC FP) is included [IEA 2021]. In addition to that, Chapter 2.8.1 provides a detailed assessment of the evolution of EU R&I funding categorised by R&I priorities for wind energy under FP7 (2009-2013) and H2020 (2014-2021) programmes.

Since 2014 EU leads on investment in public R&D spending EUR 883 million followed by Japan (EUR 790 million) and the United States (EUR 330 million) (see **Figure 20** and **Figure 21**).

In the last years (period 2017-2019), Japan led at country level on public R&D investment in wind energy, with about EUR 415 million spent, followed by Germany, the United States, Norway and South Korea. The Netherlands, Denmark, Spain and France were also amongst the top ten countries investing in wind energy. However, taking the EU Member States together, their combined public R&D investment spend on wind energy was EUR 496 million, surpassing that of Japan in the same period.

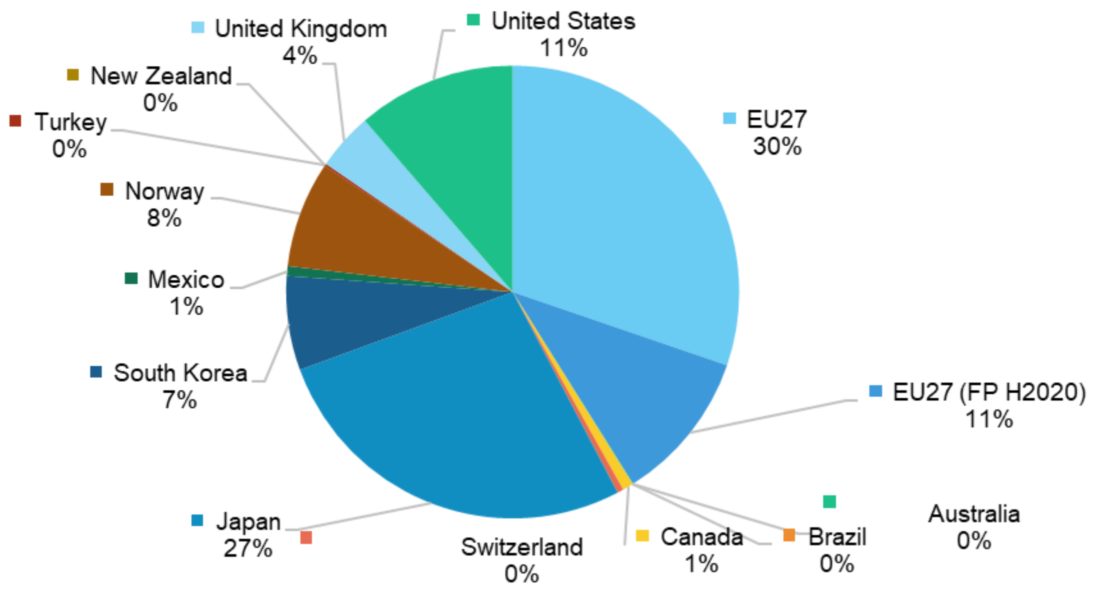
Figure 20 Evolution of public R&I investments in wind energy in EU and major OECD countries the period 2014 - 2019.



Source: JRC based on IEA, 2022.

6 This 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

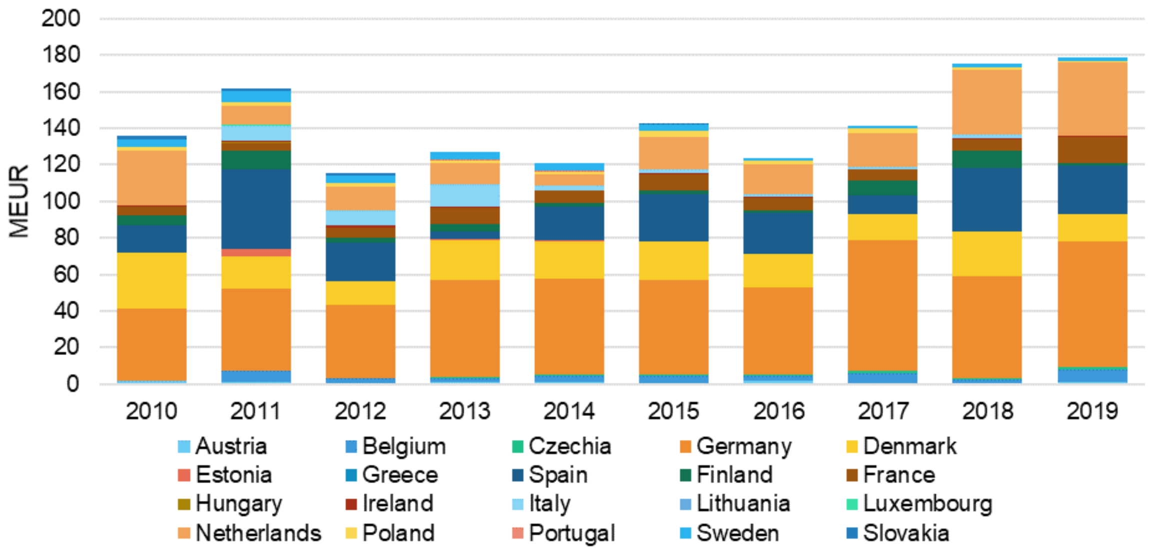
Figure 21 Public R&I investments (shares) in wind energy in EU and major OECD countries the period 2014 - 2019.



Source: JRC based on IEA, 2022.

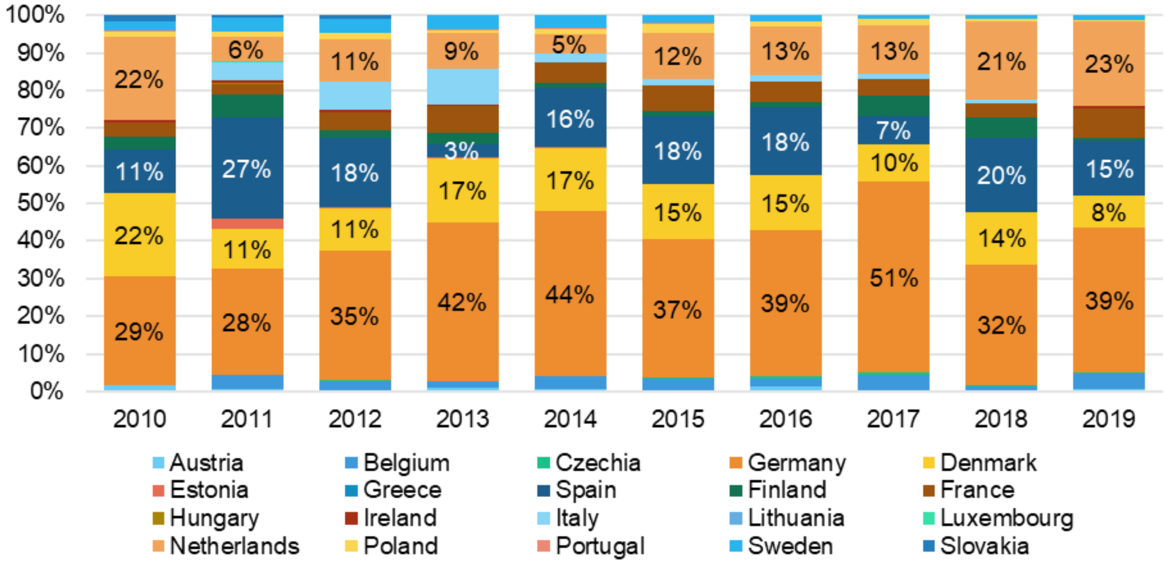
Since 2010 EU MSs spent about EUR 1.42 billion in public R&I in wind energy. Public R&D investment in EU MSs remained roughly constant between 2012 and 2016, at around EUR 120 to EUR 145 million. The trend subsequently increased, reaching EUR 179 million by 2019. This equates to a 32% increase in public R&D investment since 2010. Preliminary numbers for selected EU Member States in 2020 indicate that this increase in public investment is continuing (**Figure 22**). With about 37%, Germany leads in EU public R&D investment followed by Spain (16%), the Netherlands (14%) and Denmark (14%) in the period 2010 -2019. Analysing the evolution of annual shares in public R&I investments unveils that the Netherlands continuously increased their spending since 2014, with record years in 2018 and 2019. Germany, Spain and Denmark show no clear trend with values alternating around their 2010-2019 average. (**Figure 23**).

Figure 22 Evolution of public R&I investments in wind energy in the EU in the period 2010 - 2019.



Source: JRC based on IEA, 2022.

Figure 23 Public R&I investments (shares) in wind energy in the EU in the period 2010 - 2019.



Source: JRC based on IEA, 2022.

2.5 Private R&D funding

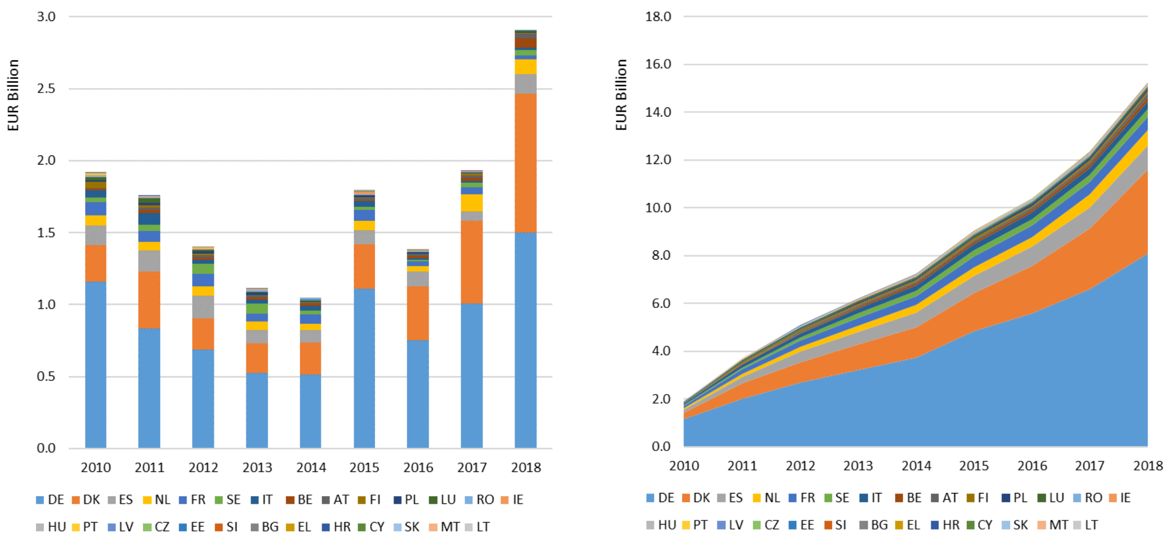
2.5.1 Aggregated private R&D funding on MSs, EU and global level

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

In 2018, the private R&D investment from these two MS reached 85% and 80% of EU corporate and total R&D funding respectively. In relative terms, their private R&D investment has remained relatively constant in the last years averaging at about 75% and 69% of EU corporate and total R&D funding annually over the period 2010-2018. German companies generated 53% of EU private R&D investment over the period 20010-2018, followed by corporations from Denmark (23%) and Spain (7%).

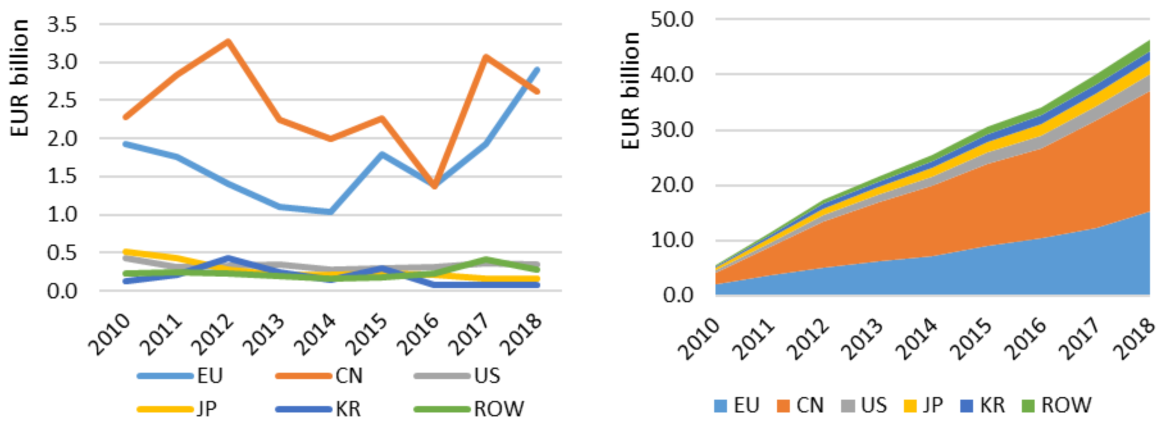
Figure 24 EU private R&D investment in the wind energy sector. Annual investment (left) and cumulative investment (right) per EU MSs.



Source: JRC SETIS [Fiorini et al. 2017, Pasimeni et al. 2019, Mountraki et al. 2022], 2022.

Regarding the international competitors, EU is at the forefront in private R&D investments in wind energy closely followed by China. In cumulative terms China is estimated to lead private R&D investments with about 47% of the total private R&D funding in the period 2010 – 2018, followed by EU (33%) and the United States (6%).

Figure 25 Global private R&D investment in the wind energy sector. Annual investment (left) and cumulative investment (right).



Source: JRC SETIS [Fiorini et al. 2017, Pasimeni et al. 2019, Mountraki et al. 2022], 2022.

EU companies are among the leading investors in R&D. In the period 2015 – 2018 four EU companies were among the Top5 global R&D investors in the wind energy sector (see **Table 3**). However, Senvion the leading company in this indicator 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 2019a]. Moreover, a strong representation of Chinese OEMs is observed among the Top20 global R&D investors increasing their shares lately when compared to their position since 2010. Other competitors include General Electric (US) ranking in 6th position and with Hitachi, Mitsubishi and NTN Corporation three companies from Japan.

Table 3 EU Leading companies (and their origin) in private R&D investment in the period 2015-2018 and comparison with their ranking in the period 2010 – 2018.
Note: Leading company Senvion went into insolvency at the end of 2019

Position (2015-2018)	Company		Position (2010-2018)	Change in position
1	SENVION GMBH	DE	2	1
2	GUODIAN UNITED POWER TECHNOLOGY CO LTD	CN	1	-1
3	Siemens Gamesa Renewable Energy AS	DK	6	3
4	VESTAS WIND SYSTEMS AS	DK	3	-1
5	WOBBEN PROPERTIES GMBH	DE	5	0
6	GENERAL ELECTRIC COMPANY	US	4	-2
7	STATE GRID CORPORATION OF CHINA	CN	8	1
8	BEIJING GOLDWIND SCIENCE CREATION WINDPOWER EQUIPMENT CO LTD	CN	10	2
9	SIEMENS AKTIENGESELLSCHAFT	DE	7	-2
10	Zhejiang Windey Co Ltd	CN	19	9
11	Nordex Energy GmbH	DE	14	3
12	MING YANG SMART ENERGY GROUP LTD	CN	-	-
13	SAMSUNG HEAVY IND CO LTD	KR	9	-4
14	XINJIANG GOLDWIND SCIENCE TECHNOLOGY CO LTD	CN	-	-
15	CHINA ELECTRIC POWER RESEARCH INSTITUTE CO LTD	CN	16	1
16	HITACHI LTD	JP	-	-
17	MITSUBISHI HEAVY INDUSTRIES LTD	JP	11	-6
18	NTN CORPORATION	JP	-	-
19	ENVISION ENERGY JIANGSU CO LTD	CN	-	-
20	JIANGSU JINFENG SCIENCE & TECHNOLOGY CO., LTD.	CN	-	-

Source: JRC, 2022.

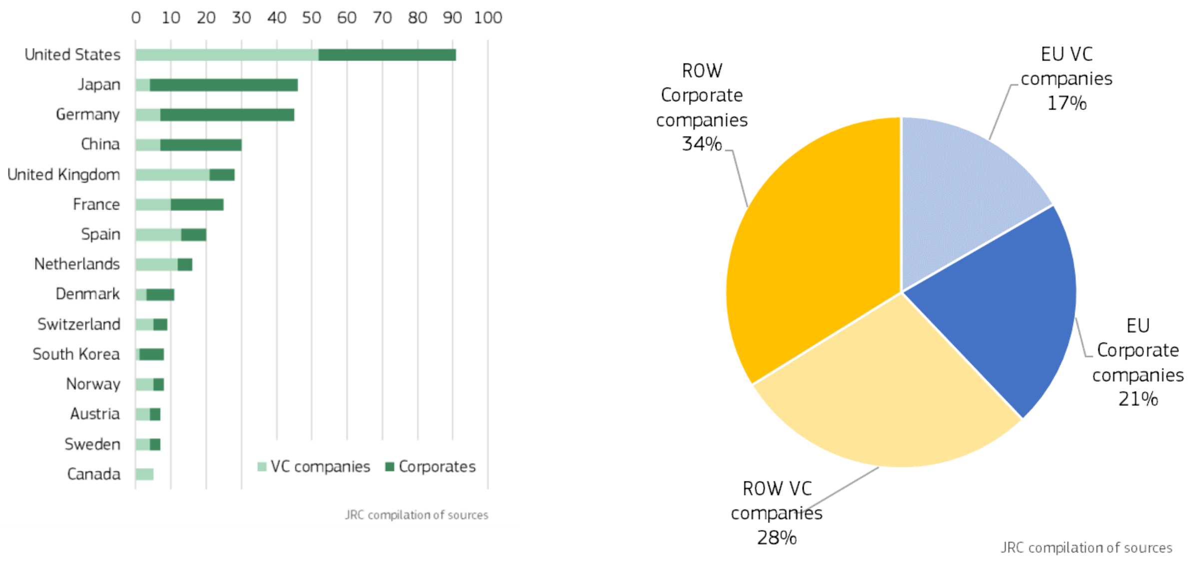
2.5.2 Early stage and later stage private investments

Analysing early stage and later stage venture capital (VC) investments[7] in wind energy related innovations identifies about 400 companies that can be divided into corporates and venture capital companies. The EU hosts about 38% of all innovators, of which about 44% are venture capital companies and 56% are corporates, in similar proportions to the rest of the world (46% and 54% respectively). Countries showing a significantly higher number of venture capital companies active in the wind sector are the United States (57% of all innovating companies are venture capital companies), the United Kingdom (75%), Spain (65%), the Netherlands (75%), Norway (63%) and Canada (100%) (see **Figure 26**).

Five countries host almost 80 % of identified innovators. The US (1st) and the UK (5th) have a very strong base of venture capital companies while most of innovators in Japan (2nd), Germany (3th) and China (4th) are corporate innovators. To that extent, it is worth noting that the essential of later stages investments realised in China only benefited two firms (Clobotics, provider of cloud-based data analytics services and Aeolon, manufacturer of wind turbine blades). Within Europe (hosting 38 % of identified companies), several countries also report a strong share of venture capital companies (France, Spain, The Netherlands).

[7] 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 reflect 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 26 Number of innovating companies in the wind energy sector (2016-2021) by country of origin (left) and by innovator type (right).



Source: JRC, 2022.

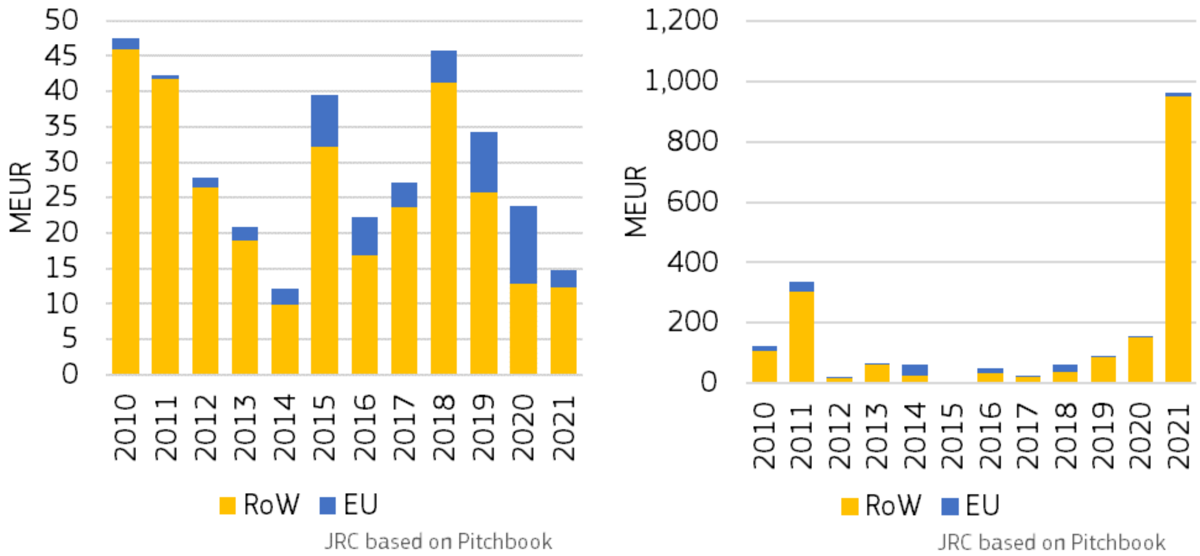
Onshore wind venture capital investments. In the period 2016-2021 global early stage VC investments in the onshore wind sector represented only 11% of all VC investments and declined from about EUR 45 million in 2018 to EUR 15 million in 2021, their lowest levels since 2014.

United States received by far most of investments in early ventures (52%) over the 2016-2021 period, followed by China (8 %) and the United Kingdom (7%). Investments in the EU are rather distributed over several countries Latvia, Spain, Sweden Netherlands and France.

Later stage VC investments dominate in this period largely because of a single deal by a consortium in 2021. In this case, GIC Pte Ltd (a Singapore based sovereign wealth fund), Sequoia Capital (an US private equity firm) and Primavera (a Chinese private equity firm) invested EUR 860 million of Private Equity (PE) growth capital in the Chinese wind OEM Envision [GIC 2021]. This investment alone outweighs global early and later stages VC investments in onshore wind technology developers realised since 2016. Still, if this deal is excluded from the analysis, later stage VC investments are a fourfold of early stage investments in the period 2016-2021.

Excluding outlying Envision deal, global later stages investments peaked in 2020, putting an end to a growth initiated in 2017 and sustained by investments in China and the US. Chinese firms attracted most of investments (41%) in the period 2016-2021, overtaking the US (30%) where investment decreased as compared to 2015-2020. Despite a rebound in 2021, investments in EU firms have decreased (-27% as compared to 2015-2020), amounting to EUR 66 million and accounting for 14% of global investments.

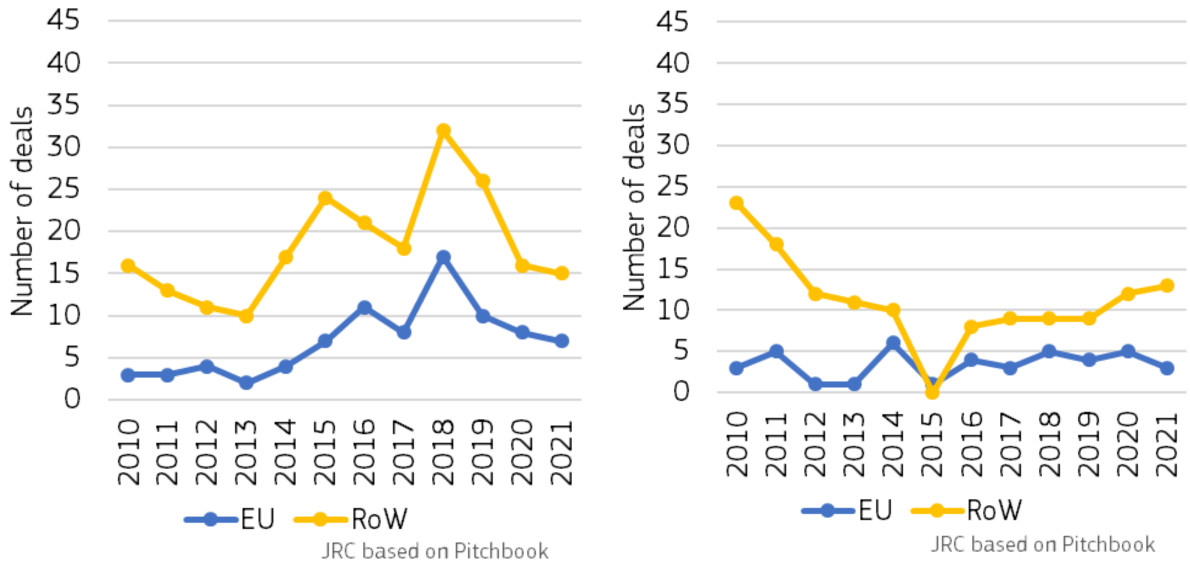
Figure 27 Early stage (left) and later stage (right) VC investments in the onshore wind energy sector by region (2010-2021).



Source: JRC based on Pitchbook, 2022.

Apart from the Envision deal, the number of VC deals follows the investments in the period 2016-2021 (see **Figure 28**) as the average deal size remains in the same range. In the period 2016-2021, early stage VC investments showed an average deal size ranging from EUR 0.3 million to EUR 1.3 million, with EU investments at the lower scale of this range. In the same period the average deal size for later stage investments (excluding the Envision deal) ranged from EUR 0.5 million to EUR 12.5 million. As compared to the first half of the 2010-decade, average deal sizes decreased by 37% and 10% for early stage and later stage VC deals, respectively.

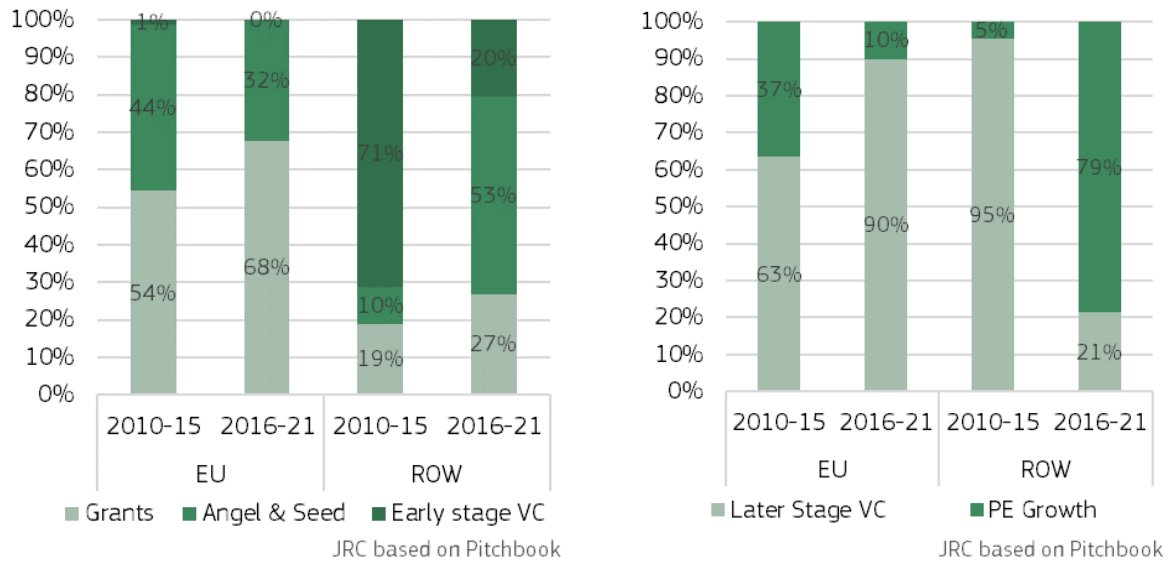
Figure 28 Number of early stage deals (left) and later stage deals (right) in the onshore wind energy sector by region (2010-2021).



Source: JRC based on Pitchbook, 2022.

Despite a sharp drop in 2021, investments in early EU ventures have grown since 2017 and are more than twice higher than over 2010-15 (+ 138 %). They however essentially rely on grants (68% in the period 2016-2021) rather than private equity investments (32% Angel & Seed investments in the period 2016-2021) (see **Figure 29**). EU growth investments at a later stage include to a vast majority (90%) later stage VC and to a lesser extent Private Equity Growth/Expansion (10%). EU companies raising later stage VC since 2016 are active in the field of airborne wind energy systems (e.g. Kitepower (NL)), wind turbine components and installation (Lagerwey (NL), Nabrawind (ES), Fersa Bearings (ES)), autonomous O&M software (Morphosense (FR), Green Eagle Solutions (ES)) and hardware (Aerones (LV)).

Figure 29 Share of early stage investment (left) and later stage investment (right) in the onshore wind energy sector by type and region (2010-2021).

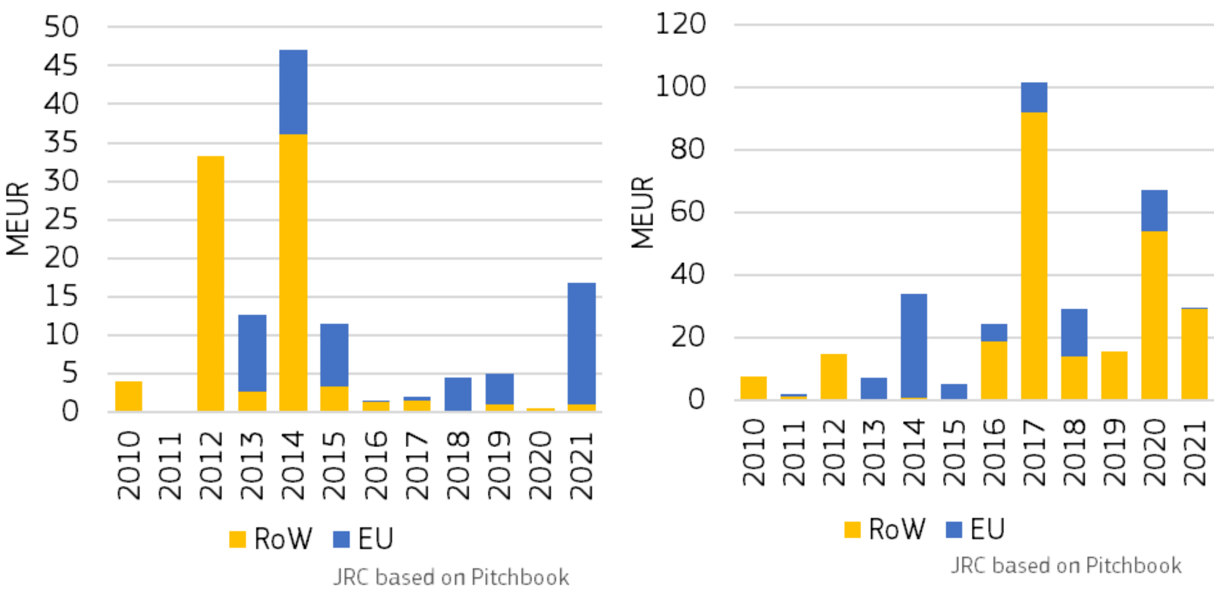


Source: JRC based on Pitchbook, 2022.

Offshore wind venture capital investments. In the Offshore wind sector, there are only a few identified venture capital companies (several of which are also providing solutions to other industries, including the Onshore Wind sector) and venture capital investments in those technology developers do not display clear discernible trends. In total only 55 deals have been identified of which 22 deals were taking place in EU.

In the period 2016-2021 global early stage VC investments in the offshore wind sector represented only 10% of all offshore wind related VC investments. Early stage VC investments remained at a relatively modest level ranging between EUR 0.5 million and EUR 5 million in the period 2016-2020. In 2021, early stage VC investments increased again to about EUR 16.7 million mainly through transactions taking place in EU (e.g. Gazelle Wind Power (IE), X1 Wind (ES) and Rope Robotics (DK)) (see **Figure 30**).

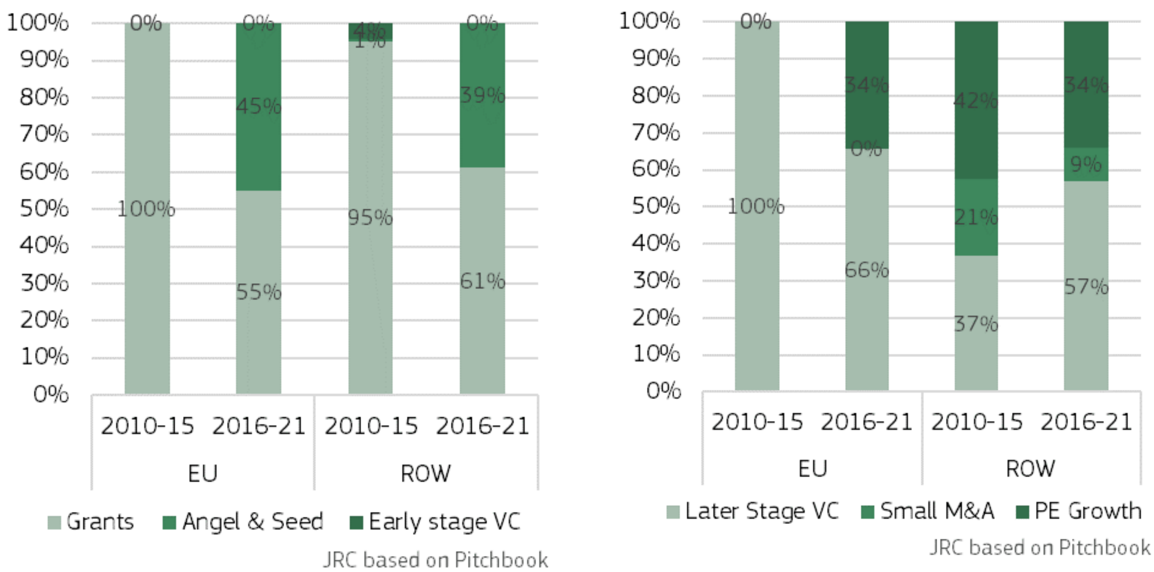
Figure 30 Early stage (left) and later stage (right) VC investments in the offshore wind energy sector by region (2010-2021).



Source: JRC based on Pitchbook, 2022.

Early stage investments almost entirely consist of grants (see **Figure 31**) and the EU accounts for 83 % of early stages investments, amounting to EUR 24.7 million in the period 2016-2021, mostly benefiting to companies in Ireland, Spain and Denmark. As compared to the previous period, investments in early ventures sharply dropped in countries like the United States, France and to a lesser extent, the United Kingdom. As companies from these countries are scaling-up, later stage investments increased substantially in those countries since 2016.

Figure 31 Share of early stage investment (left) and later stage investment (right) in the offshore wind energy sector by type and region (2010-2021).



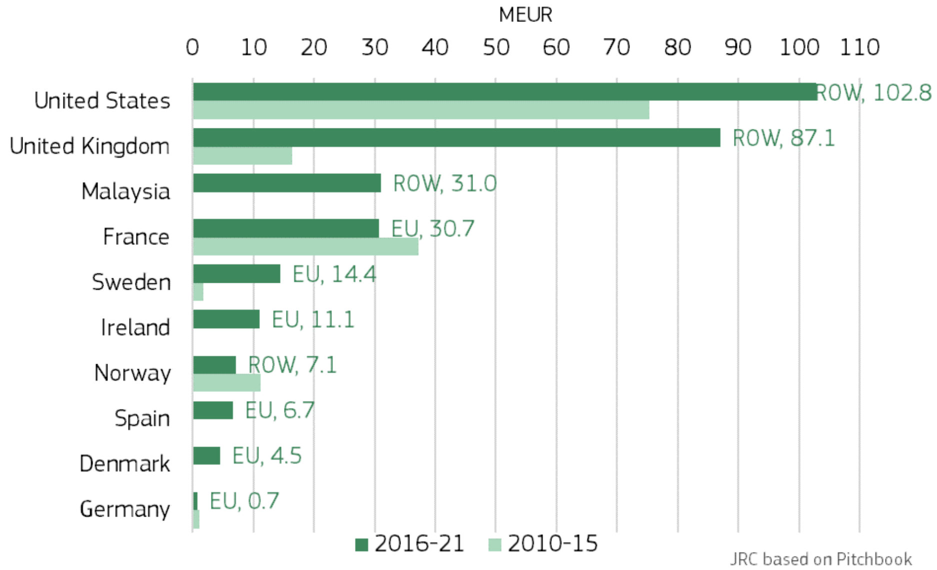
Source: JRC based on Pitchbook, 2022.

Therefore, EU accounts for only 16.5% of global later stages investments (EUR 43.8 million in the period 2016-2021) trailing behind the US (38%) and the UK (32%). Since 2016, later stage investments in EU and

RoW mainly stem from later stage VC investments (66% and 57%, respectively) and Private Equity Growth/Expansion (34%).

Mainly driven by later stage investments the United States, the United Kingdom and Malaysia (two deals by Malaysia-based Aerodyne, a provider of drone technology solutions) lead in terms of total VC investments in the period 2016-2021 (see **Figure 32**). Since 2016, five later stage VC investments took place in EU limited to two companies from Sweden and France active in the area of floating offshore wind (Hexicon (SE) and BWIdeol (FR)). Companies from Ireland, Spain, France and Denmark show some activity with regards to earlier stage VC investments raising funds for innovations in the area of floating offshore wind and automated O&M techniques.

Figure 32 Top countries in total (early and later stage) investments in the offshore wind sector (2010-2021).



Source: JRC based on Pitchbook, 2022.

2.6 Patenting trends

The following sections provide information on the 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 different to the residence of the applicant are considered as 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

In 2020, a major revision of the Cooperative Patent Classification (CPC) took place. A substantial number classification tags (Y-tags) has been removed, regrouped, and reviewed and patent families have been reclassified according to the new scheme[8]. Due to changes in the scope and the 2020 reclassification of the CPC scheme, the selection of CPC codes has changed[9] as compared to previous JRC-analysis (e.g. LCEO [JRC

8 EPO, 2020. Project RP0678, https://www.uspto.gov/web/patents/classification/cpc/pdf/CPCNOC935RP0678various.pdf

9 CETO includes seven codes (Y02B 10/30, Y02E 10/70, 10/72, 10/727, 10/728, 10/74, 10/76)

2020a]). Overall, the number of inventions selected for CETO is greater than LCEO. Annex 4 summarises the changes due to this reclassification and selection of CPC codes.

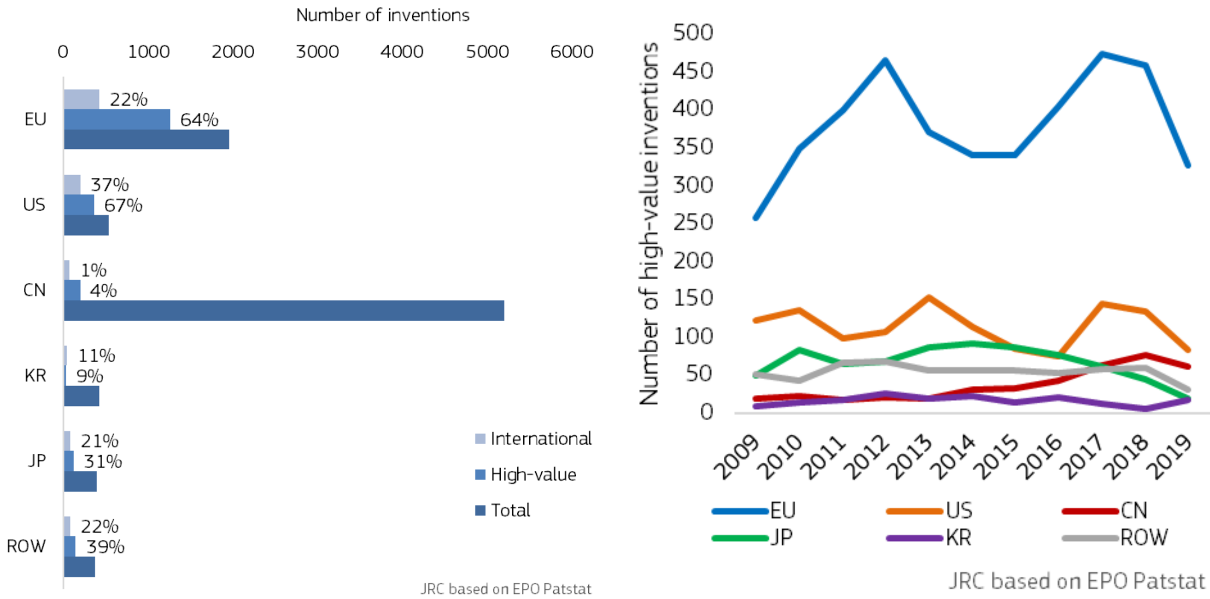
2.6.1 Leading countries and organisations in patenting

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 1% of patents being international (EU: 22%, US: 37%). In the period 2017-2019, only about 4% of the Chinese patenting inventions filed on wind energy technologies were high value, while high-value inventions account for about 64% of all European wind energy inventions filed. The share of high-value inventions in the United States and Japan is 67% and 31% respectively, but both have significantly lower numbers in absolute terms (see **Figure 33**).

Globally, in the period 2017-2019, the EU's share of high-value inventions was 59%, followed by the US (17%), China (9%), Japan (6%) and Korea (2%) (see **Figure 33**). This means a decrease of 5 percentage points when compared to the EU share of high-value patents in the period 2016-2018.

On a country level, Denmark leads in the high-value inventions (542 inventions) closely followed by Germany (469 inventions) and the United States (363 inventions). In total 5 EU countries can be found within the Top10 (Denmark, Germany, Spain (66), France (50) and the Netherlands (43)). China and Japan rank 4th and 5th positon filing 202 and 124 high-value patents in the period 2017-2019, respectively.

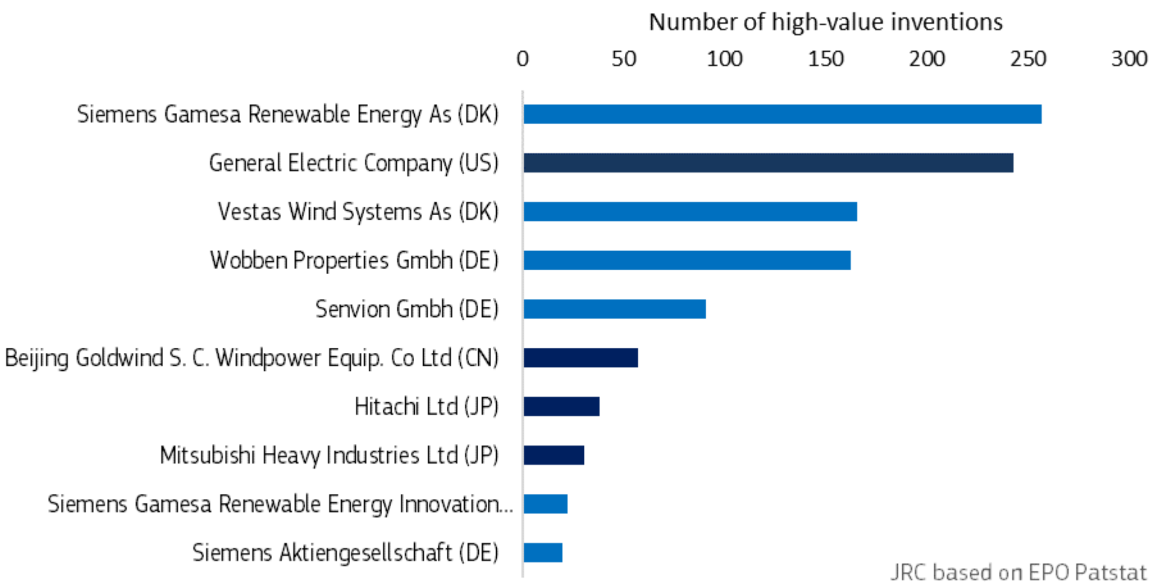
Figure 33 Number of wind energy inventions and share of high-value and international activity (2017-2019) (left) and development of high value inventions (2009 – 2019) (right)



Source: JRC based on Patstat, 2022.

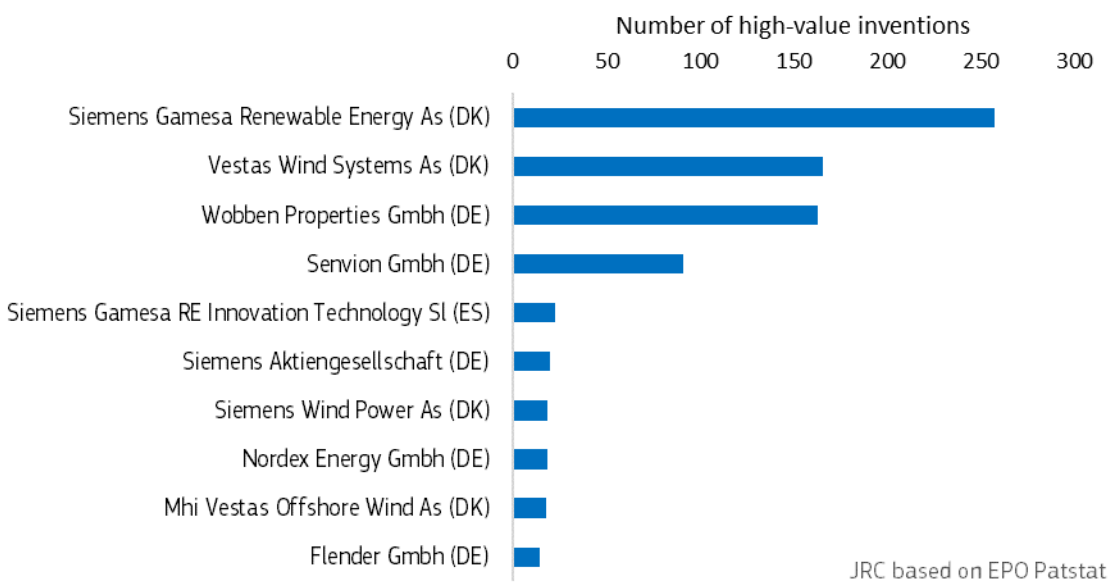
EU companies keep the lead in terms of high-value inventions filed in the period 2017-2019. EU-based original equipment manufacturers (OEMs) (e.g. Enercon (Wobben Properties GmbH), Senvion, Vestas and SiemensGamesa) hold a leading position in high-value patents, followed by General Electric (US), Goldwind (CN), Hitachi (JP) and Mitsubishi Heavy Industries (JP) (see **Figure 34**). Moreover, Nordex (DE) and Flender (DE) are among the Top10 EU companies in terms of high-value inventions.

Figure 34 Top10 organisations (global) - Number of inventions and share of high-value and international activity (2017-2019)



Source: JRC based on Patstat, 2022.

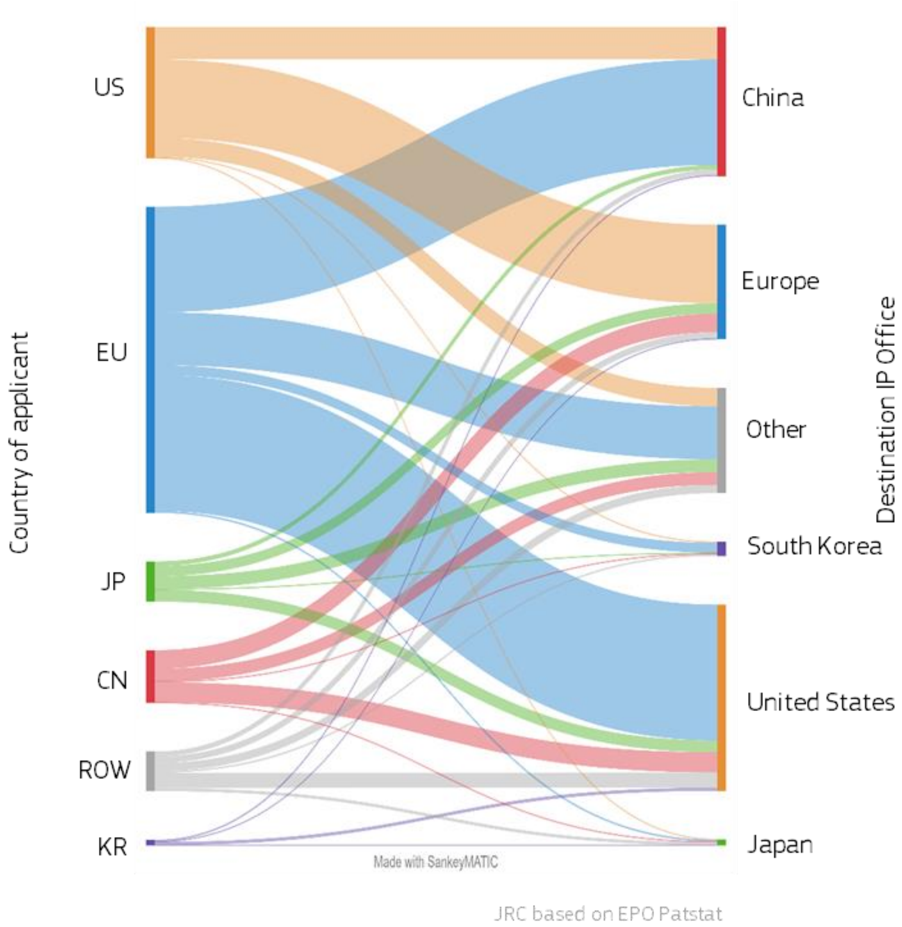
Figure 35 Top10 organisations (EU) - Number of inventions and share of high-value and international activity (2017-2019)



Source: JRC based on Patstat, 2022.

Figure 36 shows the flow of high-value inventions from the major economies to the main patent offices in the period 2017-2019. EU applicants show the highest share of inventions protected in United States (44%) and China (34%), whereas the United States protect a substantial share of their inventions in Europe (60%) and China (25%). China, Japan and South Korea protect a significant lower number high-value patents, yet Europe and the United States are again the main destinations of IP protection.

Figure 36 International protection of high-value inventions (2017-2019)



Source: JRC based on Patstat, 2022.

2.6.2 Intellectual property rights (IPR) in the wind energy sector

A patent is a legal title granting its holder the right, in a specific country and for a limited time, to prevent others from exploiting an invention for commercial purposes without authorisation [Pasimeni & Georgakaki 2020]. In order to acquire the relevant knowledge and overcome the technological gap, companies build on technology cooperation, licensing or even strategic purchases of selected foreign wind firms [Watson et al. 2015].

Comparing high-value inventions of the leading wind OEMs since 2010 shows that EU, US and JP companies are ahead in the major patent offices (EPO, USPTO, SINO). Only Envision Energy ApS, the Danish subsidiary of Envision, can be found within the Top 10 companies filing high-value inventions, with the remaining Chinese OEMs trailing behind.

In recent years, targeted wind technology areas crucial for Chinese OEMs catching up to European manufacturers in the offshore and grid integration sector have included the drive train (**permanent magnet direct drive technology** (e.g. 2008: Goldwind (CN) acquiring Vensys (DE); 2009: XEMC (CN) acquiring Darwin (NL)), **super compact drive (SCD) technology** for offshore wind (e.g. 2015: MingYang (CN) acquiring Aerodyn (DE)) and electronic control components (**low-voltage ride-through (LVRT) technology** (e.g. Sinovel using AMSC Windtec (US) LVRT components; 2012: Sinovel acquiring IPR from Mita-Teknik (DK)). Knowledge transfer also takes place directly in Europe, as many Chinese OEMs established their R&D centres in European countries (Envision Energy ApS, Goldwind or Ming Yang in DK, XEMC Darwin in NL) in order to generate international patents through their European subsidiaries filed by European inventors [Lam et al. 2017].

Protection of IPR is an important issue among competitors and markets. IP infringement remains the leading reason in 2020 for the reluctance of EU companies to take their innovative technologies to China [EU Chamber of Commerce in China 2020]. Moreover, IP litigations between major OEMs are used to secure a competitive advantage in certain markets but hold the risk of higher project development costs on the consumer side, project delays and less innovation. It is estimated that the wind energy industry lost up to EUR 4.6 billion (USD 5.3 billion) to avoidable IP infringements and trade secrets theft (in legal losses, blocking of product sales, denial of market access and loss of revenue) [Totaro 2019]. Recent patent infringement cases around the low-voltage ride-through (LVRT) or zero-voltage ride-through (ZVRT)[10] exemplify an OEM's strategy to either close the technological gap or protect its home market.

In China, Sinovel's long-term, market-leading position was based on a production license (for 1.5 MW turbines) acquired from Fuhrländer (DE) in 2004. Upgraded products in the following years also relied heavily on electronic control components from Windtec (AT-based subsidiary of AMSC (US)) providing low-voltage ride-through (LVRT) capabilities enabling optimised grid integration. In 2013, AMSC accused Sinovel of stealing intellectual property from AMSC in 2011 in order to produce its own turbines. In 2018, Sinovel was fined by a US court followed by a settlement agreement between the two companies[11]. In 2012, Sinovel went into a strategic partnership with Mita-Teknik (DK), purchasing the intellectual property rights on software and source code for electrical control systems [Sinovel 2016, US DoJ 2018].

In the US, General Electric (GE) has enforced its IP rights since 2003 after acquiring Enron Wind (and their patents on wind control systems; '705 patent' on zero-voltage ride-through (ZVRT)). By 2005, most European OEMs (Nordex, Acciona and Senvion) signed license agreements in order to prevent IP litigations in the US market. An exception was the refusal to license of Mitsubishi Heavy Industries (MHI), followed by an IP litigation with GE in 2008, which was settled with a cross-licensing agreement in 2013. However, within this five-year period, the case added substantial IP infringement cost risk to potential MHI asset owners, which resulted in MHI being driven out of the US onshore wind market. Similarly, GE and Vestas made claims against each other in 2017 over the breach of multiple patents (including the ZVRT patent), a litigation that was finally settled with the cross-licensing of patents in 2019[12] [Vestas 2019]. In 2020, GE sued SiemensGamesa RE (SGRE) of infringing the LVRT and ZVRT patents with the US International Trade Commission (ITC), confirming the complaint in 2021 for the LVRT, followed by a final ITO decision confirming the LVRT infringement in January 2022 [S&P Global 2022]. The complaint with regards to the ZVRT patent was rejected. In response, SGRE filed a litigation in 2020 against GE, claiming that GE's Haliade X turbines infringe the IPR of SGRE's offshore direct drive technology[13]. The ongoing patent dispute also expanded to other markets in 2021 when GE sued SGRE in the UK of infringing its ZVRT patent, a case that holds the potential to delay the delivery of major offshore wind projects in the UK for which SGRE will supply wind turbines (1.4 GW East Anglia 3 and 1.4 GW Hornsea Project 2) [MHI 2013, RN 2020, WPM 2021a, WPM 2021b]. In June 2022, a federal US court ruled that GE must pay royalty fees amounting to USD 30000/MW if its Haliade X turbines use SGRE's offshore direct drive technology. First estimates value the potential loss for GE at about USD 24 million at the Vineyard Wind 1 project (where GE hold a supply chain contract for its Haliade X turbines) and USD 225 million if GE captures one third of the market share of the 25-27 GW of offshore wind projects so far approved [WPM 2022b]. Furthermore, the same court ruled that US patent law applies to offshore wind technology even when projects are located beyond US territorial waters but within 200 nautical miles (370 km) off the coast. This means that the current US offshore wind project pipeline (60 GW) will be affected by the ruling. Aside from the ruling that GE has to pay royalty fees, potential consequence of these kind of litigation cases are delays of commercial commissioning and OEMs being exposed to liquidation damages of

[10] Low-voltage ride-through (LVRT) or zero-voltage ride-through (ZVRT) technology enable wind turbines to maximise power capture in fluctuating wind speeds and to cope with fluctuating grid voltage

[11] It is estimated that AMSC lost $1 billion in shareholder equity and almost 700 jobs because of this IPR infringement.

[12] U.S. Patents No. 7,629,705, No. 6,921,985, No. 7,102,247 and No. 7,859,125

[13] US patent no 9,279,413

the lost income of a project, holding the potential to outweigh IP litigation costs by far. In order to prevent this, expectable turbine design changes add an additional cost, thus giving a competitive advantage to OEMs not involved in this case (e.g. Vestas) [WPM 2022c].

2.7 Bibliometric trends/Level of scientific publications

This chapter analyses bibliometric trends of the wind energy sector. Section 2.7.1 provides bibliometric indicators on the publications retrieved for the entire sector. This is followed by the analysis of subsets of the dataset analysed in section 2.7.1, 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 (see Annex 5) 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[14] per country, measuring the citation impact of publications as compared to the global average of the research field
- h-index[15] per country, measuring both the productivity and citation impact of publications,
- the collaboration network among countries[16].

A detailed list of the Top10 organisations for each of the performed searches and thematic wind areas can be found in Annex 5)

2.7.1 Publication trends – Overall wind energy sector

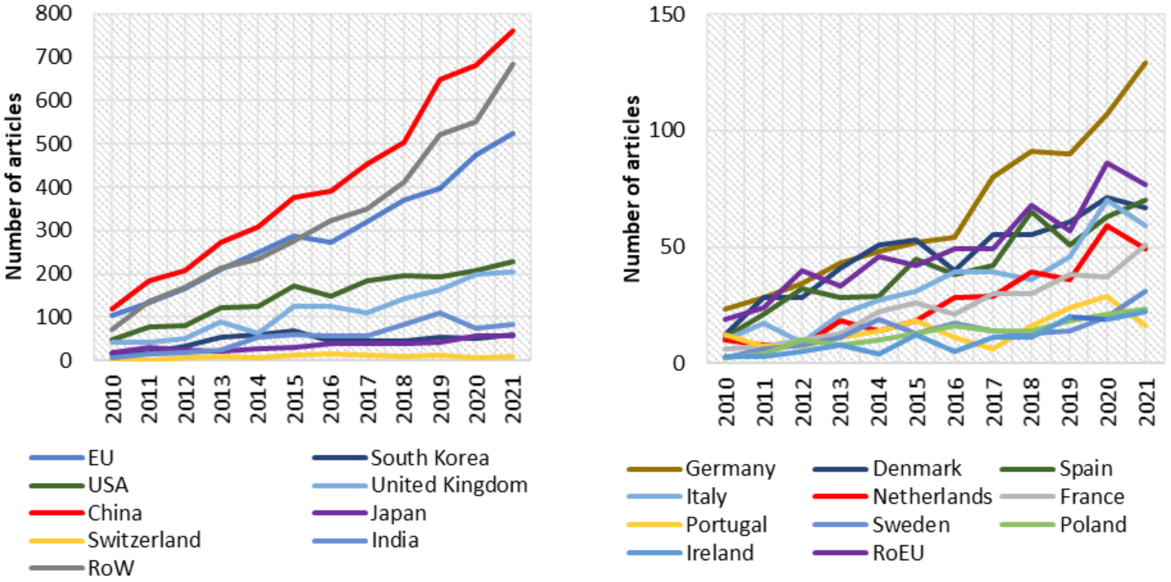
Publications in the wind sector are based on data from Scopus in the period 2010 to 2021. The overall number of wind energy publications continuously grew from 427 peer-reviewed articles in 2010 to 2607 publications in 2021, a more than fivefold increase (+511%). In 2021, the number of articles is highest in China (29%), followed by EU (20%), the United States (9%) and the United Kingdom (8%). Within EU, the leading countries in terms of deployment and first movers are showing the highest publication activity. Since 2010 Germany (779) ranks first in cumulative number of articles followed by Denmark (562), Spain (495), Italy (404) and the Netherlands (315) (see **Figure 37**). Moreover, research activity in the wind sector has spread all over Europe with all EU MSs showing publishing activity in the period 2010 – 2021 and 18 countries showing continuous publication activity (with more than 25 peer-reviewed articles in the same period).

[14] 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].

[15] 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].

[16] 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 37 Wind energy - Number of peer-reviewed articles per year (2010 – 2021) globally (left) and in the Top10 EU MSs (right).



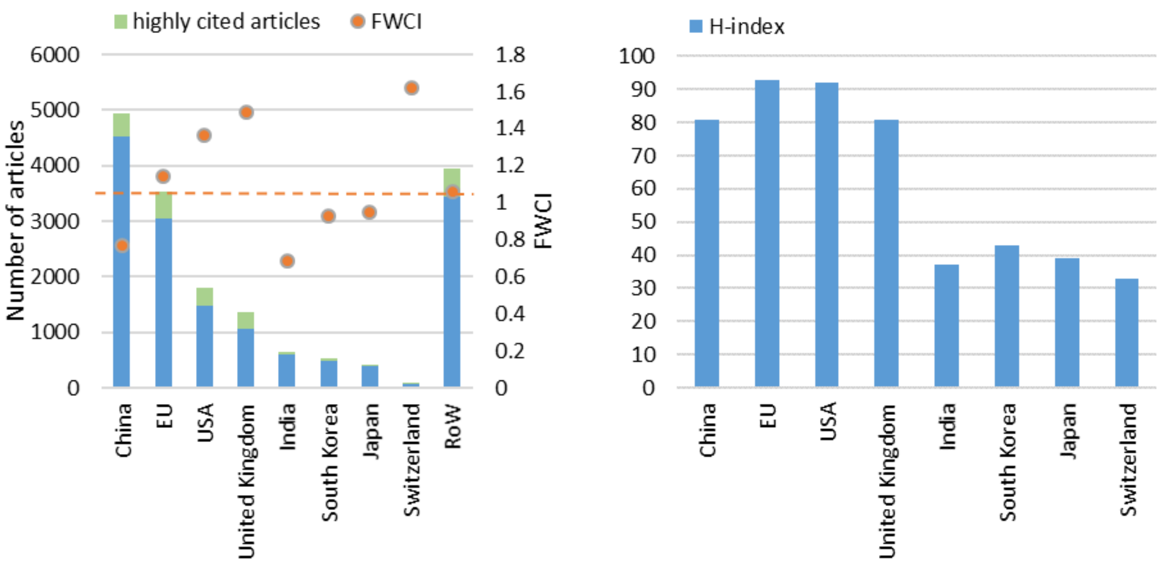
Source: JRC based on TIM, 2022.

Indicators measuring the impact and productivity of peer reviewed articles in the area of wind energy confirm that EU can compete with its international counterparts. EU leads in highly cited articles (487), followed by China (413), the United States (322) and the United Kingdom (289). The FWCI within the research field indicates that EU (1.2) performs above global average, ranking fourth behind Switzerland (1.6), United Kingdom (1.5) and the United States (1.4), all countries with significant lower overall publication activity than EU. Other competitors such as China (0.8), India (0.7), South Korea (0.9) and Japan (0.9) rank below global average in FCWI (see **Figure 38**, left). In terms of citation impact and productivity, measured by the H-index, EU (93) leads closely followed by the United States (92), the United Kingdom (81) and China (81) (see **Figure 38**, right).

Multiple EU Member States are recognised as having a high impact with their publication activity, with 13 Member States scoring above the average FWCI and 11 countries accounting for more than 10 highly cited articles in the period 2010 – 2021. Among the Top EU countries publishing in the area of wind energy Germany (89), Spain (83) and Denmark (78) show the highest number of highly cited articles, whereas the highest FWCI is found for Hungary (1.8, yet only 10 articles published in the period 2010-2021), Ireland (1.7, 126 articles) and Portugal (1.6, 172 articles). In terms of impact and productivity again Spain (51), Denmark (50), and Germany (50) show the highest H-index (see Annex 5, **Table 30**).

The leading organisations in terms of number of highly cited articles are Norwegian University of Science and Technology (NO), University of Strathclyde (UK) and the North China Electric Power University (CN). Three EU organisations can be found among the Top10 entities, namely Aalborg University (DK, ranking 5th), Delft University of Technology (NL, 7th) and Technical University of Denmark (DK, 9th), while 5 organisation in Top10 stem from China (see Annex 5, **Table 31**).

Figure 38 Wind energy - Total number of peer-reviewed articles per year (2010 – 2021), FWCI (left) and H-index (right) of the EU and global competitors.
Note: See Annex 5, ***Table 30*** for the EU MSs subset



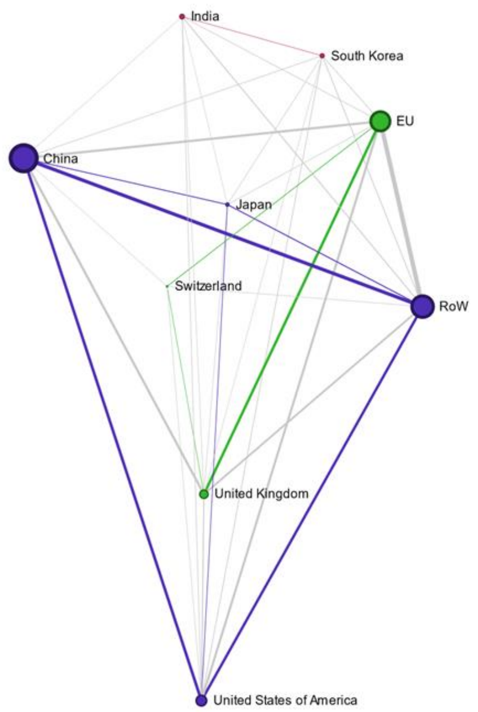
Source: JRC based on TIM, 2022.

In the period 2010 – 2021, EU organisations show the strongest collaboration ties in publishing peer reviewed articles with organisations from the United Kingdom (323 co-occurrences), China (270) and the United States (266). Similarly strong co-publication activity is observed between China and the United States (348) as well as between China and the United Kingdom (280) (see **Figure 39**).

Within EU the strongest collaboration networks exist between Germany and the Netherlands (47), Germany and Denmark (40), Germany and Italy (28) and the Netherlands and Denmark (26). Moreover, Spain, Denmark, Germany and the Netherlands show very strong publication ties towards the United Kingdom with 57, 53, 46 and 42 co-publications, respectively (see Annex 5, **Figure 122**).

Figure 39 Wind energy - Collaboration network of the EU and its competitors based on peer-reviewed articles per year (2010 – 2021)

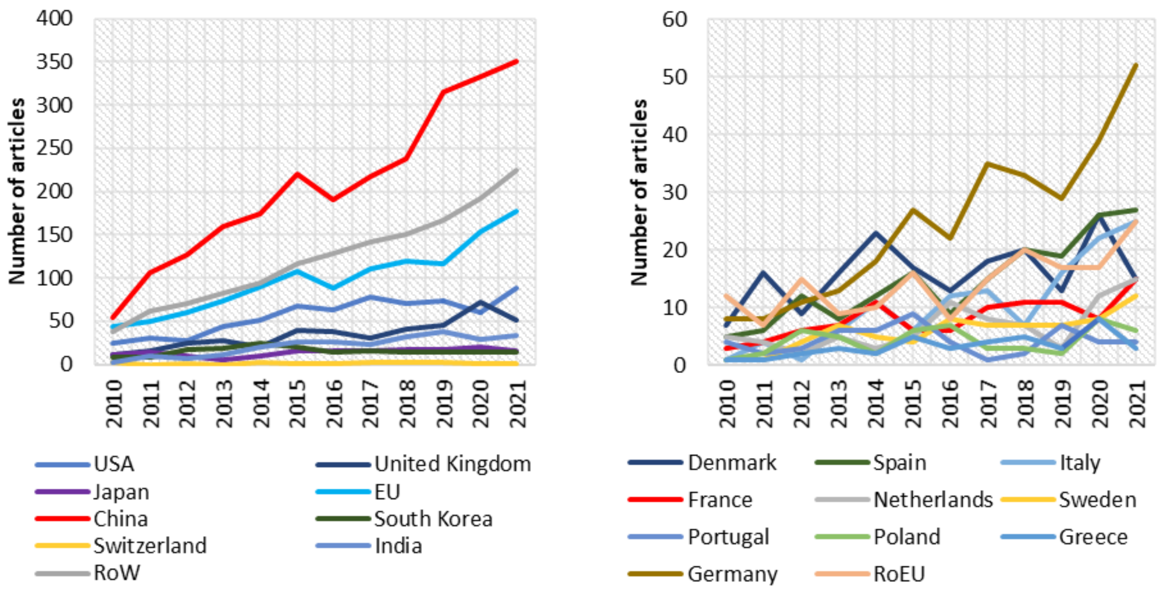
Note: See footnote 16 in chapter 2.7 for interpretation of network graphs and Annex 5, **Figure 122** for the EU MSs subset



Source: JRC based on TIM, 2022.

2.7.2 Publications trends - Wind energy sector – Topical subsets

Figure 40 Wind energy components - Number of peer-reviewed articles per year (2010 – 2021) globally (left) and in EU MSs (right).



Source: JRC based on TIM, 2022.

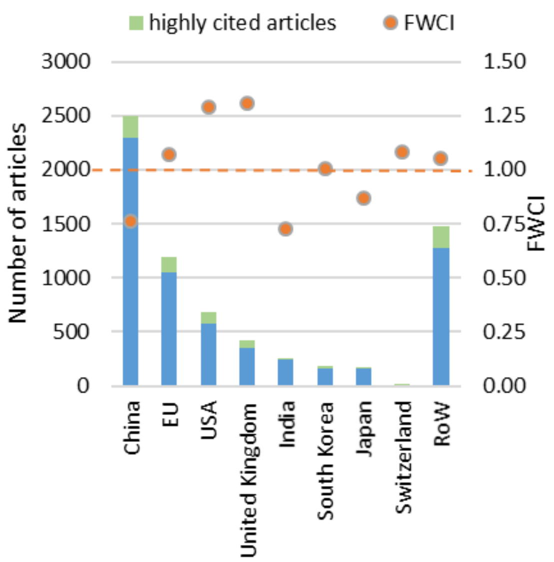
Wind energy components. The overall number of publications focussing on wind energy components shows a similar evolution as the entire wind sector. Publications grew from 199 peer-reviewed articles in 2010 to 958 publications in 2021 (+381%). In 2021, the number of articles is highest in China (37%), followed by EU (18%), the United States (9%) and the United Kingdom (5%). Within EU, Germany (295) ranks first in cumulative number of articles since 2010 followed by Denmark (193), Spain (175), Italy (124) and France (98) (see **Figure 40**). 25 countries showing publishing activity in the period 2010 – 2021 and 13 countries showing continuous publication activity (with more than 25 peer-reviewed articles in the same period).

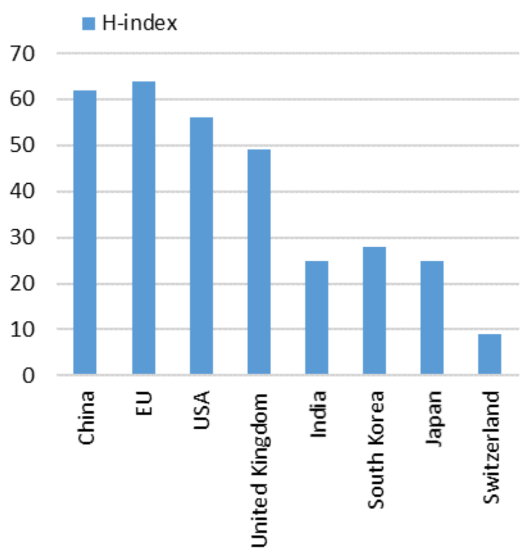
China leads in highly cited articles on wind energy components (194), followed by EU (152), the United States (113) and the United Kingdom (75). The FWCI within the research field indicates that EU (1.1) performs slightly above global average, ranking fourth behind the United Kingdom (1.3) the United States (1.3) and Switzerland (1.1). Other competitors such as China (0.8), Japan (0.9) and India (0.7) rank below global average in FCWI (see **Figure 41**, left). In terms of citation impact and productivity, measured by the H-index, EU (64) leads closely followed by China (62), the United States (56) and the United Kingdom (49) (see **Figure 41**, right).

Germany, Italy, Denmark, Spain and France show the highest number of highly cited articles, whereas high FWCI for countries with a significant number publications is found for France, Italy and Ireland. Denmark, Germany and France are the Top3 in terms of highest H-index (see Annex 5, **Table 33**).

The leading organisations in terms of number of highly cited articles addressing wind energy components are all stemming from China (North China Electric Power University, Xi'an Jiaotong University and Tsinghua University). Moreover, China has five organisations within the Top10, whereas with Technical University of Denmark (DK, 7th), Delft University of Technology (NL, 9th) and Aalborg University (DK, ranking 10th) only three are originating from EU (see Annex 5, **Table 34**)

Figure 41 Wind energy components- Total number of peer-reviewed articles per year (2010 – 2021), FWCI (left) and H-index (right) of the EU and global competitors.
Note: See Annex 5, ***Table 33*** for the EU MSs subset



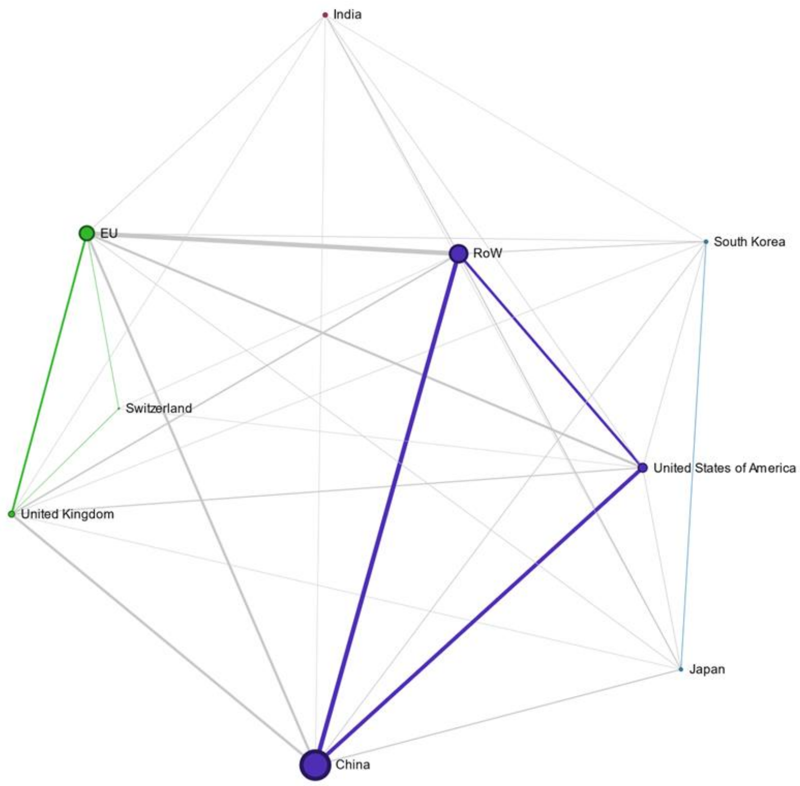


Source: JRC based on TIM, 2022.

In the period 2010 – 2021, EU organisations active in the area of wind component research show the strongest collaboration ties in publishing peer reviewed articles with organisations from the China (99 co-occurrences), the United States (91) and the United Kingdom (78). Increased co-publication activity is observed between China and the United States (165) as well as between China and the United Kingdom (103) (see **Figure 42**).

Within EU the strongest collaboration networks exist between Germany and Denmark (13), Germany and the Netherlands (12), Germany and Italy (12) and the Netherlands and Denmark (10). Moreover, Denmark, Germany and Italy show strong publication ties towards the United Kingdom (see Annex 5, **Figure 123**).

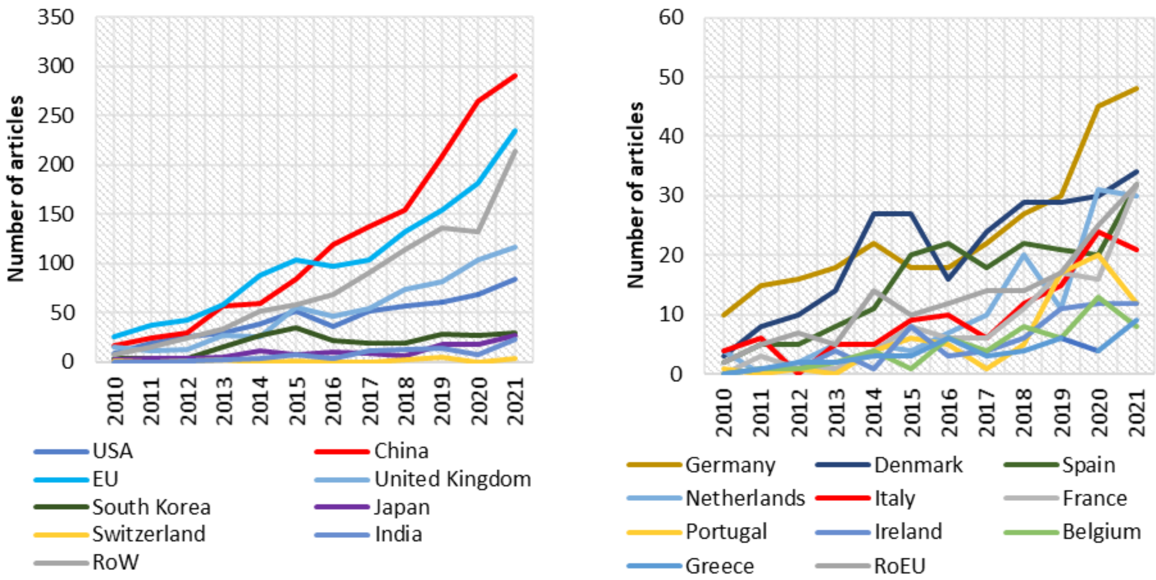
Figure 42 Wind energy components - Collaboration network of the EU and its competitors based on peer-reviewed articles per year (2010 – 2021)
Note: See Annex 5, **Figure 123** for the EU MSs subset



Source: JRC based on TIM, 2022.

Offshore wind energy. The overall number of publications focussing on offshore wind energy is strongly surging since 2010. Publications grew from 78 peer-reviewed articles in 2010 to 1023 publications in 2021 (+1212%). In 2021, the number of articles is highest in China (28%), followed by EU (23%), the United Kingdom (11%) and the United States (8%). Within EU, Germany (289) ranks first in cumulative number of articles since 2010 followed by Denmark (251), Spain (186), the Netherlands (129) and Italy (117) (see **Figure 43**). 22 countries showing publishing activity in the period 2010 – 2021 and 12 countries showing continuous publication activity (with more than 25 peer-reviewed articles in the same period).

Figure 43 Offshore wind energy - Number of peer-reviewed articles per year (2010 – 2021) globally (left) and in EU MSs (right).



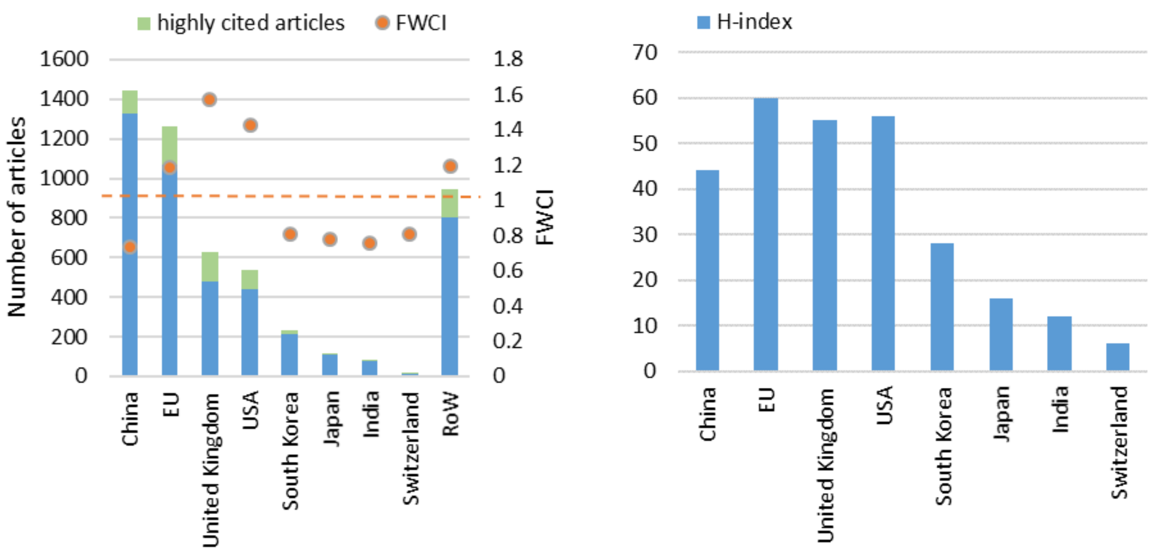
Source: JRC based on TIM, 2022.

EU leads in highly cited articles on offshore wind energy (190), followed by the United Kingdom (148), China (118) and the United States (98). The FWCI within the research field indicates that EU (1.2) performs above global average, ranking third behind the United Kingdom (1.6) and the United States (1.4). Other competitors show low FWCI values of about 0.8 (see **Figure 44**, left). In terms of citation impact and productivity, measured by the H-index, EU (60) leads closely followed by the United States (56) and the United Kingdom (55) (see **Figure 44**, right).

On EU level, Denmark, Spain, the Netherlands, Germany, Ireland, and Portugal show the highest number of highly cited articles, whereas high FWCI for countries with a significant number publications is found for Ireland, Belgium, Finland and Portugal. Denmark, Spain and Germany are the Top3 in terms of highest H-index in the field (see Annex 5, **Table 36**).

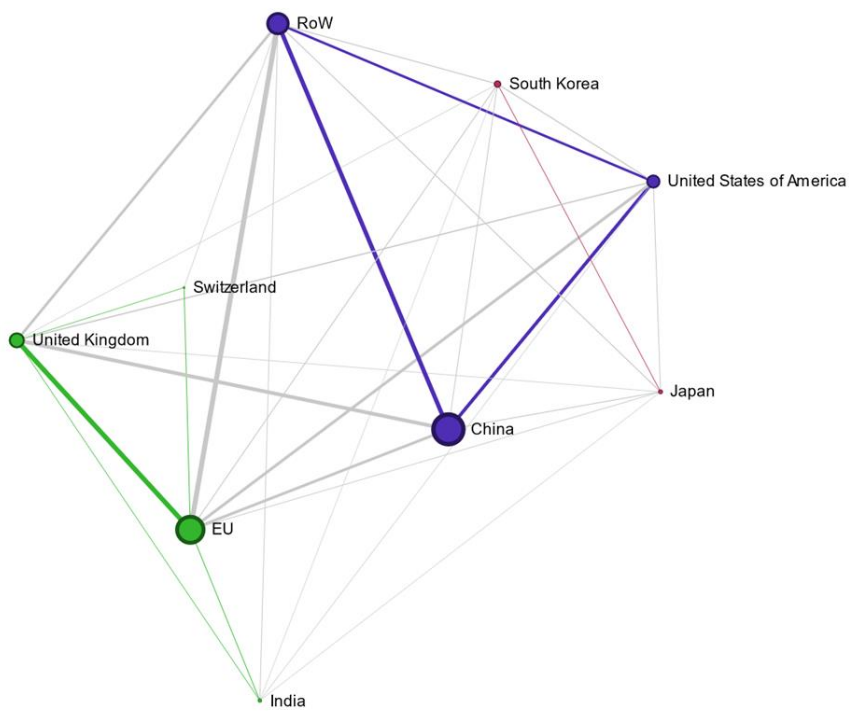
The leading organisations in terms of number of highly cited articles are Norwegian University of Science and Technology (NO), University of Strathclyde (UK) and Aalborg University (DK). With Delft University of Technology (NL, 6th), Technical University of Denmark (DK, 8th) and Universidade de Lisboa (PT, 10th) three additional EU organisations can be found among the Top10 entities. Moreover four UK based entities are among the Top10 publishing in the area of offshore wind energy (University of Strathclyde (UK), Cranfield University (UK), University of Bristol (UK) and University of Oxford (UK)) (see Annex 5, **Table 37**).

Figure 44 Offshore wind energy - Total number of peer-reviewed articles per year (2010 – 2021), FWCI (left) and H-index (right) of the EU and global competitors.
Note: See Annex 5, ***Table 36*** for the EU MSs subset



Source: JRC based on TIM, 2022.

Figure 45 Offshore wind energy - Collaboration network of the EU and its competitors based on peer-reviewed articles per year (2010 – 2021)
Note: See Annex 5, **Figure 124** for the EU MSs subset

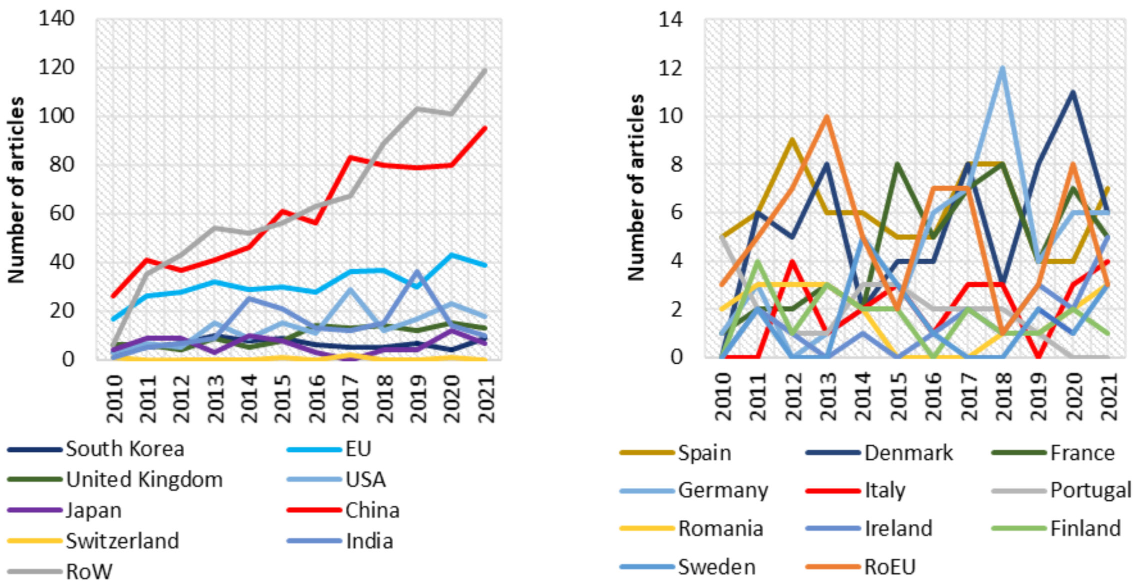


Source: JRC based on TIM, 2022.

In the period 2010 – 2021, EU organisations active in the area of offshore wind energy research show the strongest collaboration ties in publishing peer reviewed articles with organisations from the the United Kingdom (176 co-occurrences), the United States (99) and China (95). Increased co-publication activity is observed between China and the United Kingdom (132) as well as between China and the United States (119) (see **Figure 45**). Within EU the strongest collaboration networks exist between Germany and the Netherlands (23) and Germany and Denmark (22). Clearly the strongest ties of EU offshore wind research is observed towards the United Kingdom with Spain (37), Denmark (30) and the Netherlands (25) showing the most pronounced collaboration network with the United Kingdom (see Annex 5, **Figure 124**).

Wind energy & Grid integration. The overall number of publications focussing on wind energy & grid integration is increasing since 2010. Publications grew from 67 peer-reviewed articles in 2010 to 310 publications in 2021 (+363%). In 2021, the number of articles is highest in China (31%), followed by EU (13%) and the United States (6%). Within EU, Spain (73) ranks first in cumulative number of articles since 2010 followed by Denmark (65), France (55) and Germany (50) and Italy (117) (see **Figure 46**). 24 EU countries showing publishing activity in the period 2010 – 2021 and 4 countries showing continuous publication activity (with more than 25 peer-reviewed articles in the same period).

Figure 46 Grid integration - Number of peer-reviewed articles per year (2010 – 2021) globally (left) and in EU MSs (right).



Source: JRC based on TIM, 2022.

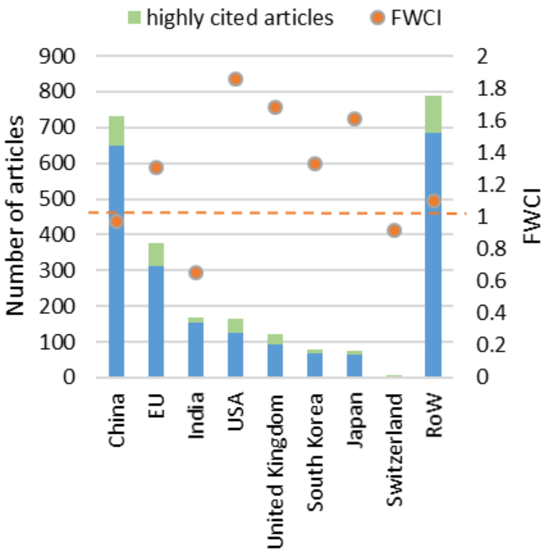
China leads in highly cited articles on wind energy & grid integration (82), followed by EU (66), the United States (38) and the United Kingdom (30). A significant share of highly cited articles comes from RoW (105), particularly from Canada, Egypt, Iran, Saudia Arabia and Chile. The FWCI within the research field indicates that EU (1.3) performs above global average, ranking fifth behind the United States (1.9), United Kingdom (1.7), Japan (1.6) and South Korea (1.3). Other competitors show average (e.g. China) or low FWCI values (e.g. India and Switzerland) (see **Figure 47**, left). In terms of citation impact and productivity, measured by the H-index, EU (60) leads closely followed by the United States (56) and the United Kingdom (55) (see **Figure 47**, right).

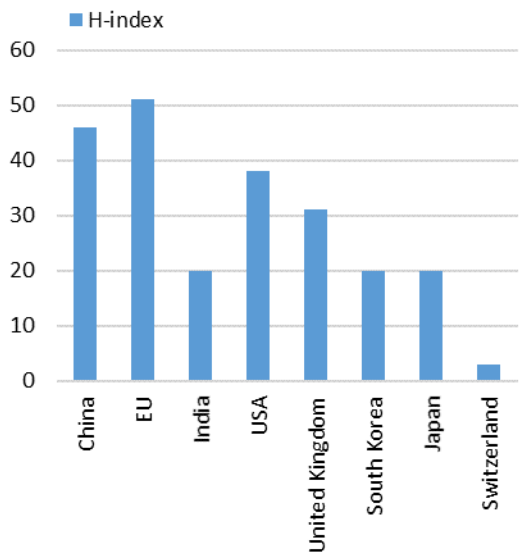
On EU level, Germany, Spain and Denmark show the highest number of highly cited articles, whereas high FWCI for countries with a significant number publications is found for Portugal, Germany and Sweden. Spain, Germany and Denmark are the Top3 in terms of highest H-index in the field (see Annex 5, **Table 39)**.

The leading organisations in terms of number of highly cited articles are Huazhong University of Science and Technology (CN), North China Electric Power University (CN) and Ain-Shams University (EG). With Aalborg University (DK, 7th) and Technical University of Munich (DE, 9th) two EU organisations can be found among the Top10 entities in the wind energy & grid integration topic. (see Annex 5,

Table *40*).

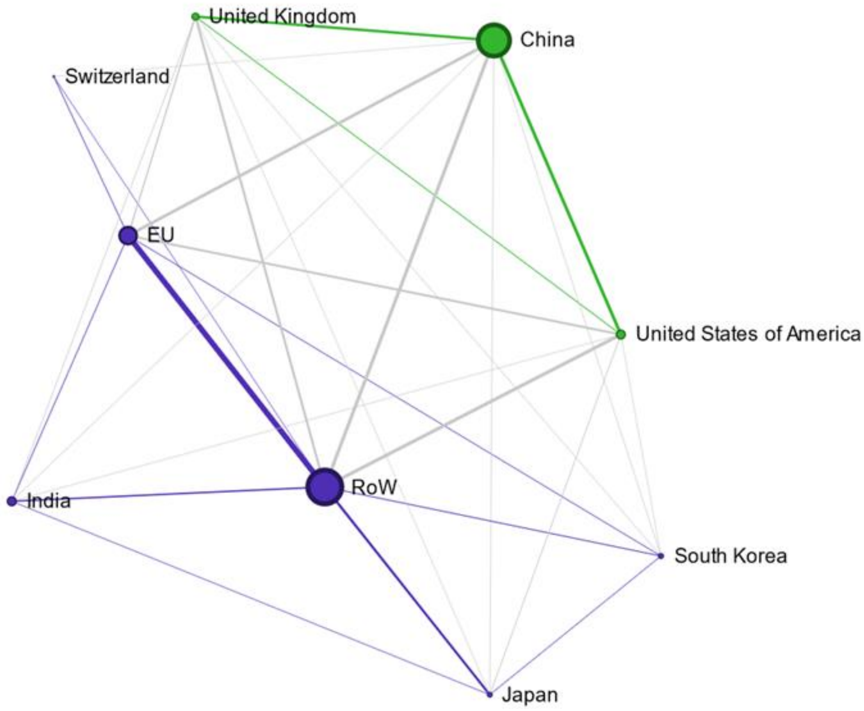
Figure 47 Grid integration - Total number of peer-reviewed articles per year (2010 – 2021), FWCI (left) and H-index (right) of the EU and global competitors.
Note: See Annex 5, ***Table 39*** for the EU MSs subset





Source: JRC based on TIM, 2022.

Figure 48 Grid integration - Collaboration network of the EU and its competitors based on peer-reviewed articles per year (2010 – 2021)
Note: See Annex 5 for the EU MSs subset



Source: JRC based on TIM, 2022.

In the period 2010 – 2021, EU organisations active in the area of wind energy & grid integration research show the strongest collaboration ties in publishing peer reviewed articles with organisations from China (49 co-occurrences), the United States (32) and the United Kingdom (16). Increased co-publication activity is observed between China and the United States (50) as well as between China and the United Kingdom (40) (see **Figure 48**). Within EU collaboration networks are rather weak with Denmark and Spain forming the strongest ties with 5 co-publications in the period 2010 – 2021 (see Annex 5, **Figure 125**).

Other wind energy topics (Vertical Axis Wind Turbines, Wind energy & environmental impact, Airborne Wind Energy Systems, Other wind energy related publications[17]).

Bibliometric searches on the research areas of vertical axis wind turbines, wind energy & environmental impact, airborne wind energy systems and other wind related topics retrieved a smaller number of articles than the searches performed earlier in this section and therefore allow only limited analysis of possible trends.

All investigated areas show growth since 2010 with research on wind energy & environmental impact (274%), vertical axis wind turbines (+773%) and Other (+338%) showing continued increase particularly in the second half of the last decade. Publications on airborne wind energy systems are still rare ranging between 15 to 25 articles/year in the last five years. EU leads in publication counts in all of the mentioned research areas except on vertical axis wind turbines trailing second behind China.

Among EU MS, Germany and Italy hold a leading position in all mentioned wind energy topics. Moreover Spain is among the leading countries addressing the wind energy & environmental impact topic, whereas Polish organisations are among the leading authors with regards to vertical axis wind turbines. Some publication activity on airborne wind energy systems is also observed from Dutch entities (see **Figure 49**).

[17] Other includes research areas that could not be allocated to the other searches performed (e.g. repowering, downwind rotor, multirotor)

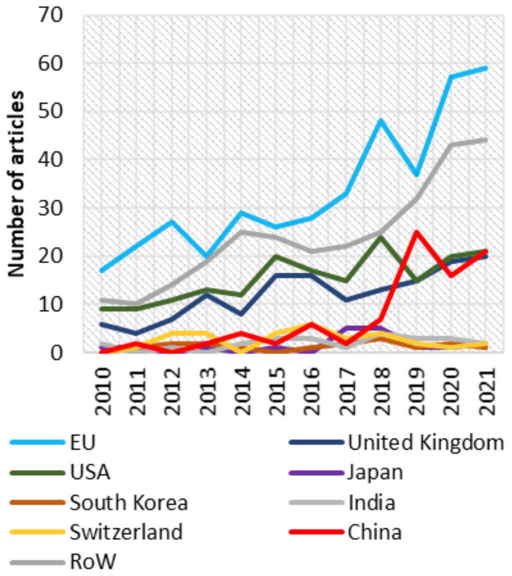
EU is among the top players in publishing highly cited articles in all four research areas and performs above global average in terms of FWCI in the areas of wind energy & environmental impact and vertical axis wind turbines. However, EU underperforms in the area of airborne wind energy systems as compared to competitors from Switzerland, South Kora and the United States. Chinese research articles are most impactful in wind energy & environmental impact but far below the average in the other topics. Both, the United States and the United Kingdom show high impact publications in the areas of wind energy & environmental impact, vertical axis wind turbines and other wind energy related research (see **Figure 50**).

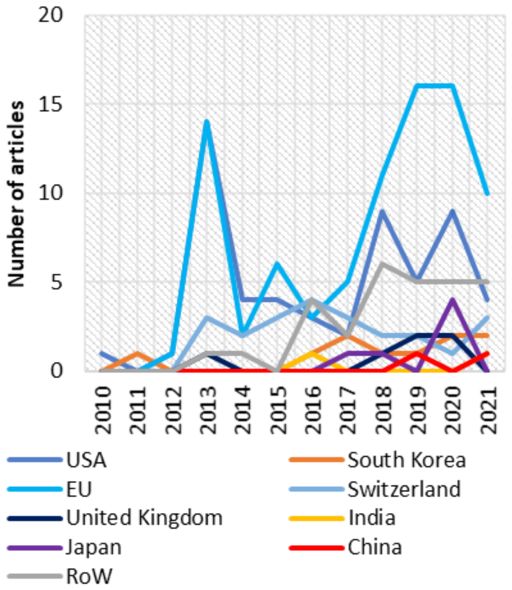
The leading organisations terms of citation impact and productivity in the area of wind energy & environmental impact stem mainly from the United Kingdom (British Trust for Ornithology, University of the Highlands and Islands, University of Exeter, University of Glasgow, RSPB Centre for Conservation Science) and Norway (Norwegian Institute for Nature Research, Norwegian University of Science and Technology). Furthermore among the Top10 organisations addressing this topic two EU organisations can be found, namely Aarhus University (DK) and Technical University of Denmark (DK) (see Annex 5, **Table 42**).

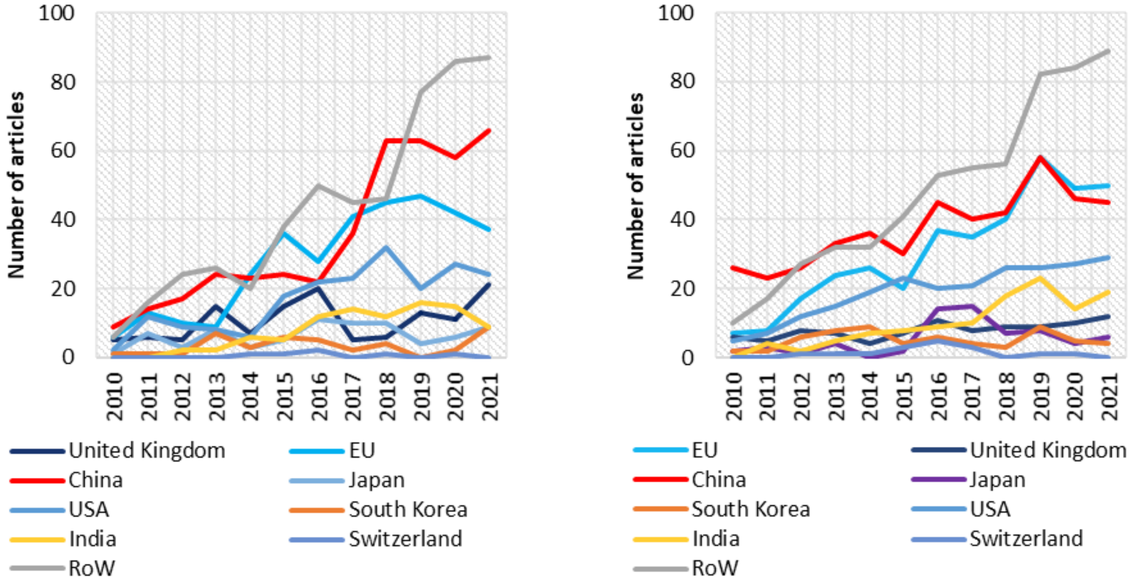
The most impactful research articles focussing on airborne wind energy systems are published by organisations from EU (Delft University of Technology (NL), University of Freiburg (DE), SkySails GmbH (DE), University of Limerick(IE)), Switzerland (ETH Zurich, ABB Switzerland Ltd.) and the United States (University of Kansas, University of North Carolina at Charlotte, University of California) (see Annex 5, **Table 44**).

High impact research in vertical axis wind turbines is particularly performed in EU (CNR (IT), Eindhoven University of Technology (NL), University of Florence (IT)). Moreover, among the top 10 in terms of highly cited articles organisations from the United States (University of Kansas, California Institute of Technology), China (University of Shanghai for Science and Technology, Shanghai Jiao Tong University), United Kingdom (University of Sheffield), Egypt (Helwan University) and Malaysia (University of Malaya) can be found (see Annex 5, **Table 46**).

Figure 49 Number of peer-reviewed articles per year (2010 – 2021) globally on environmental impact (top left), airborne wind energy systems (top right), vertical axis wind turbines (bottom left) and other wind related research (bottom right).



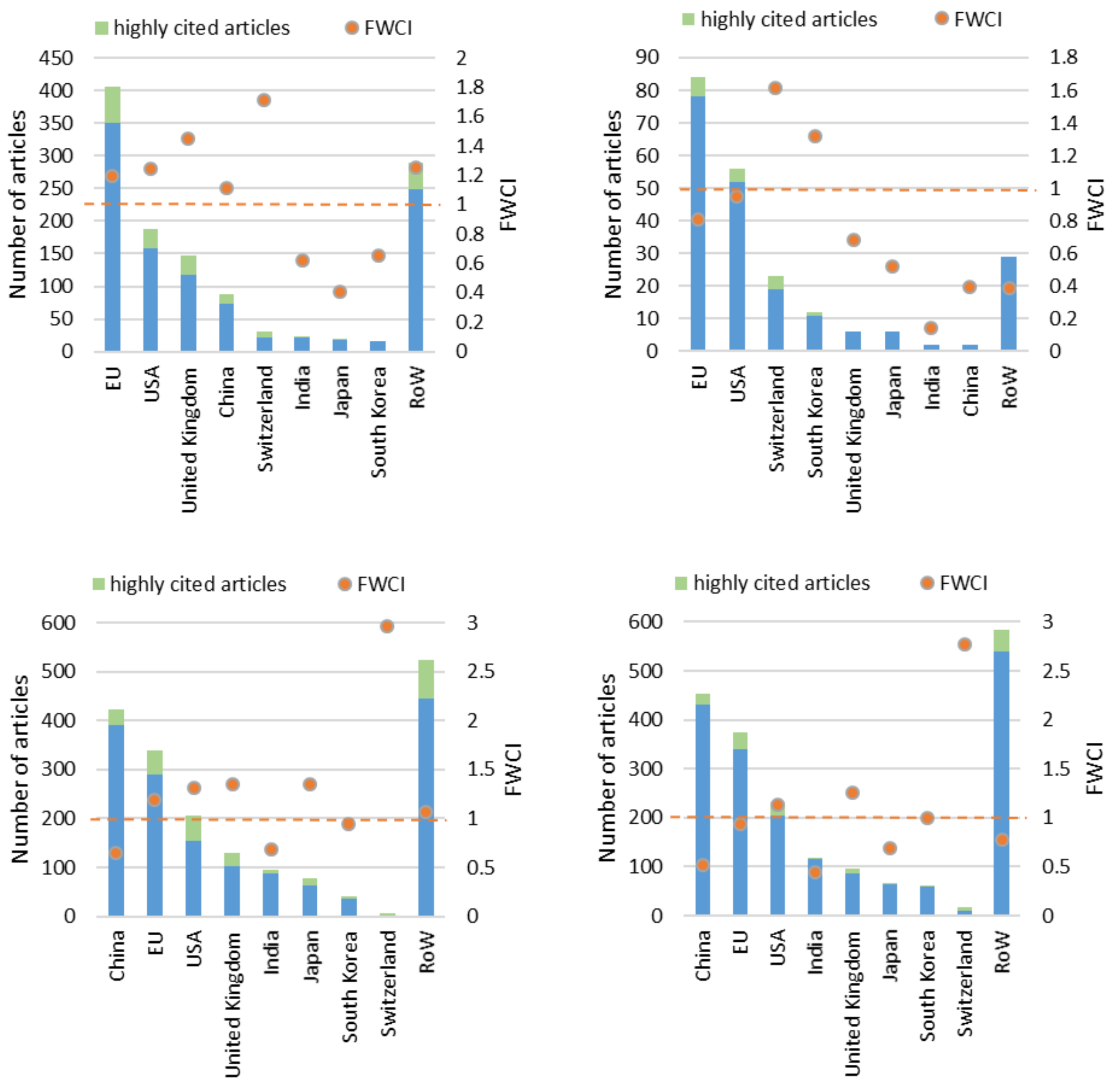




Source: JRC based on TIM, 2022.

Leading organisations in publishing highly cited articles in other wind related research are stemming from China (Shanghai Jiao Tong University), Switzerland (Ecole Polytechnique Federale de Lausanne EPFL) and EU (Delft University of Technology). Moreover another three EU organisations (University of Florence (IT), CNR (IT), Eindhoven University of Technology (NL)) are among the Top10 (see Annex 5, **Table 48**).

Figure 50 Total number of peer-reviewed articles per year (2010 – 2021), highly cited articles and FWCI of the EU and global competitors in the area of environmental impact (top left), airborne wind energy systems (top right), vertical axis wind turbines (bottom left) and other wind related research (bottom right).

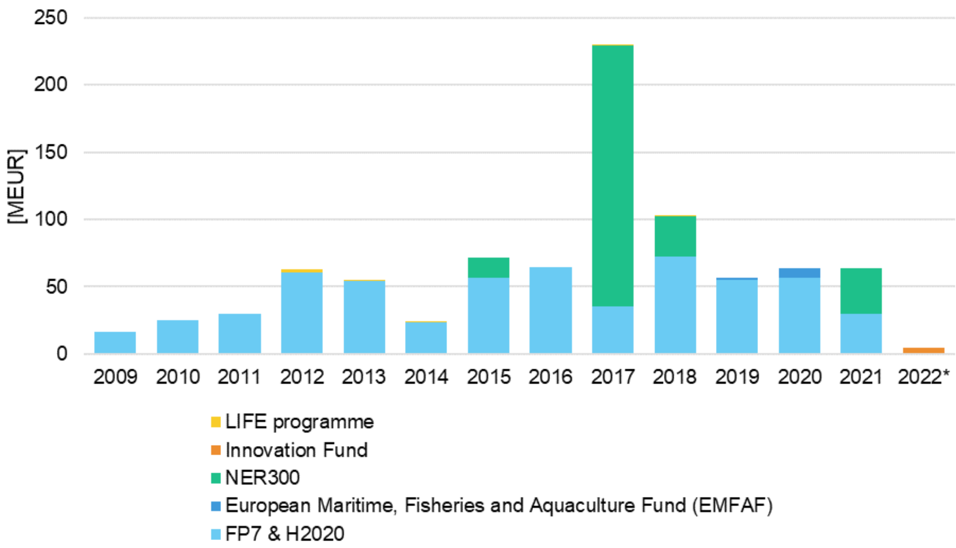


Source: JRC based on TIM, 2022.

2.8 Impact and Trends of EU-supported Research and Innovation

This section gives an overview of the main R&D initiatives in the wind sector with a special emphasis on EU-funded research. The analysis monitors the R&D activities and investments in wind energy within the European FP7/H2020 programme, the European Maritime, Fisheries and Aquaculture Fund (EMFAF), the LIFE programme, the NER300 programme and its successor the Innovation Fund. In total, this analysis identifies EUR 874 million of wind energy related funding by these major EU programmes in the period 2009 – 2021 (see **Figure 51**). This is complemented by the latest information on R&D in the area of circularity in design and R&D trends enabling the co-existence of offshore wind and defence activities, two areas of particular interest within the European Green Deal as formulated in the EU's Circular Economy Action Plan and the EU Offshore Renewable Energy Strategy.

Figure 51. Evolution of EU R&I funding by funding programme in the period 2009-2021.
Note: Funds granted refer to the start year of the project. *Data on 2022 refers to Innovation Fund only.



Source: JRC, 2022.

2.8.1 Development and priorities of R&D investment in H2020

Research funding in Europe's biggest Research and Innovation programme showed continued support to wind energy in the last year. However, funding decreased both in terms of number of projects funded as well as in financial support as a consequence of the end of the H2020 programme (and the Horizon Europe programme not yet started). The number of wind energy projects decreased from 13 to 11 in 2021, cumulated investment granted to European wind energy projects decreased by about 47% (30.0 million EUR) as compared to 2020 (57.0 million EUR) (see **Table 4**).

Table 4. Wind energy specific funding under Horizon 2020 granted to projects starting in 2021.

H2020-funded projects	Total project cost Million EUR (Million USD)	EU contribution Million EUR (Million USD)	Number of projects
Wind-specific projects	19.7 (22.1)	16.4 (18.3)	7
Non-wind specific projects	17.4 (19.5)	13.6 (15.3)	4
Total funding for wind energy	37.1 (41.6)	30.0 (33.6)	11

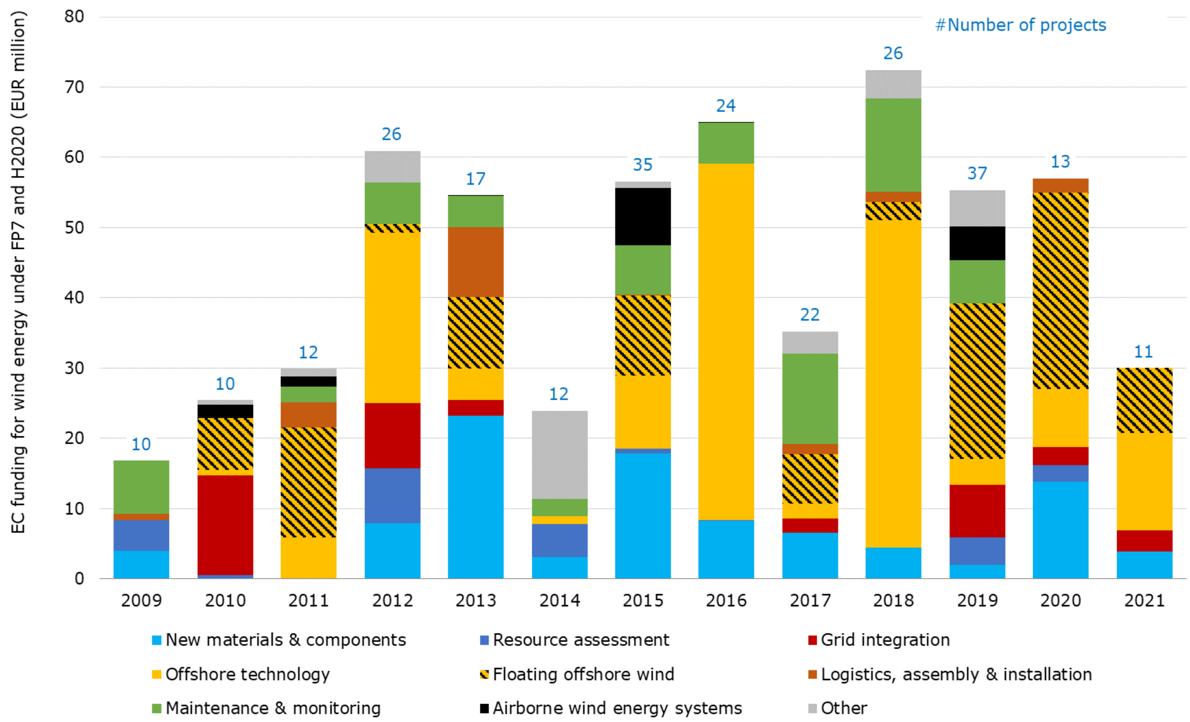
** In 2021, non-wind specific projects include the following project with limited wind energy share: FIBREMACH, OYSTER, FIBREGY, EU-SCORES.*

Source: JRC analysis, 2022.

Figure 52 shows the development of R&I funding in the period 2009 – 2021 under H2020 funding programme and its predecessor FP7. With 46% of EC funding (13.9 million EUR (15.5 million USD)) granted to wind energy projects starting in 2021 focused on offshore wind technology research, followed by floating offshore (31%) and New materials & components (13%) [JRC 2022]

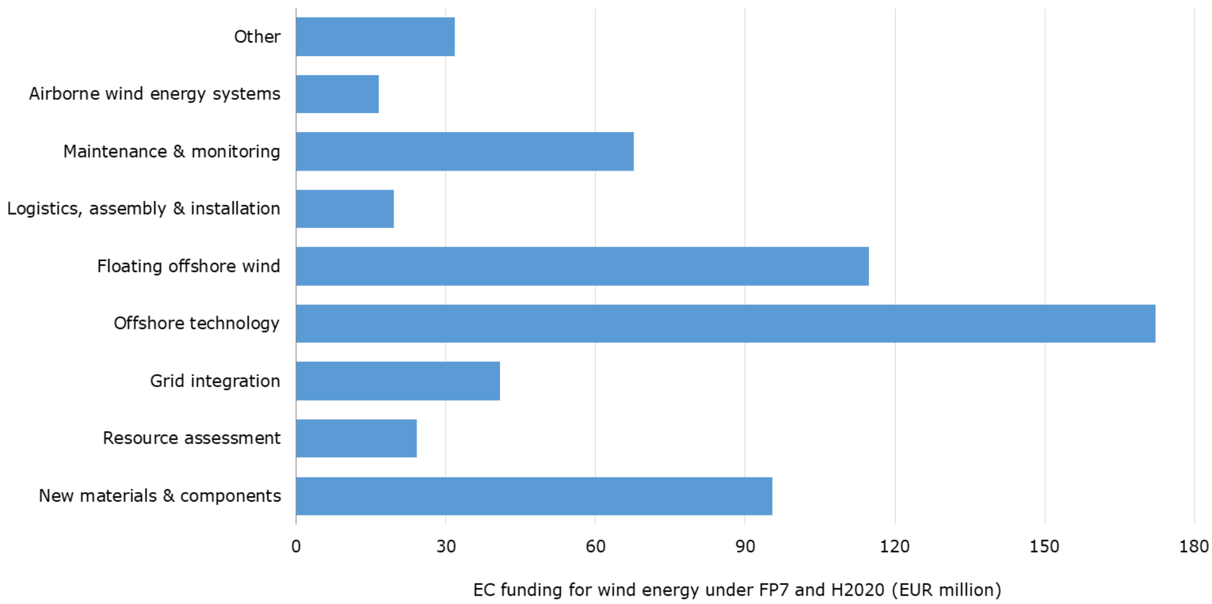
Since 2009 FP7 and H2020 have allocated substantial funding across all wind research R&I priorities with projects on offshore wind technology (172 million EUR), floating offshore wind (115 million EUR) and research on new materials & components (95 million EUR) accumulating most of the funds (see **Figure 53**).

Figure 52. Evolution of EU R&I funding categorised by R&I priorities for wind energy under FP7 (2009-2013) and H2020 (2014-2021) programmes and the number of projects funded in the period 2009-2021. Project specifically on wind energy and those with a significant wind energy component are accounted for (see **Table *4***). Note: the item other includes some projects exploring emerging technologies such as social acceptance and critical rare earth elements among others. Funds granted refer to the start year of the project.



Source: JRC, 2022.

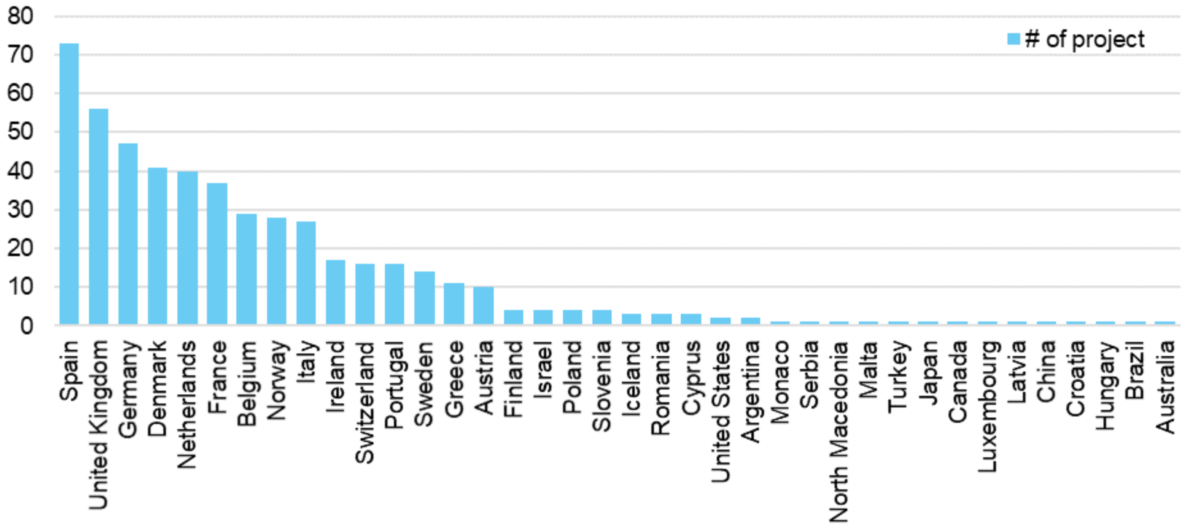
Figure 53. EC funding on wind energy R&I priorities in the period 2009 -2021 under FP7 and H2020.



Source: JRC, 2022.

Organisations from Spain, the United Kingdom, Germany, Denmark, the Netherlands and France showed the highest number of participation in wind energy related H2020 projects. In total, 38 countries were at least once part of a H2020 project (see **Figure 54**).

Figure 54. Beneficiary countries (in terms of number of participated projects) of wind energy H2020 projects in the period 2015 -2021.



Source: JRC based on TIM, 2022.

2.8.2 H2020 projects starting in 2021

New turbine materials & components. With FIBREGY, FIBREMACH and PARTIMPACT three projects started in 2021 addressing the material and components dimension of wind energy related R&D. With about 6.5 million EUR (7.3 million USD) the FIBREGY project received the highest EU funding among wind-related H2020 projects starting in 2021. It aims for the extensive use of Fibre Reinforced Polymers (FRP) materials in the structure of the next generation of large Renewable Energy Offshore Platforms in order to replace steel which is more prone to degradation in offshore environments [EC 2021b]. The project includes testing of different prototypes and the building of a real scale demonstrator. With respect to offshore wind FIBREGY's activities are focused on the Enerocean's W2Power twin wind turbine platform [FIBREGY 2022]. The PARTIMPACT project (Marie Skłodowska-Curie Actions) proposes to accurately model the damage caused to wind turbine blades by solid and liquid particles. The approach should increase understanding of the erosion impact of incident particles such as hailstones or rain droplets [EC 2021b]. FIBREMACH is identified within this analysis as a non-wind specific project, however it can be assumed that project results impact the supply chain for composites and thus the wind sector. The FIBREMACH project consortium will develop cleaner processes in composite manufacturing and increase the competitiveness of the EU industry by proposing a robotic system (including an internal dust suction system for improved health and safety conditions). Moreover, the project aims for reduced energy consumption and increased performance [EC 2021c].

Offshore technology. The OYSTER project aims for the development and demonstration of a compact electrolyser solution designed for the integration at offshore wind turbines. PEM electrolyser manufacturers, ITM Power together with offshore wind developer Ørsted and turbine manufacturer Siemens Gamesa Renewable Energy will develop and test a shore-side pilot MW-scale electrolyser at Grimsby (UK). Project partners aim for hydrogen being produced from offshore wind at a cost that is competitive with natural gas (with a realistic carbon tax), thus unlocking bulk markets for green hydrogen [EC 2021d, OYSTER 2022]. With XROTOR, a second project focusses on the offshore technology dimension proposing a disruptive new offshore wind turbine concept. The projects aims to take its X-shaped offshore wind concept from current technology readiness level of TRL 1 to TRL 3 and claims a potential LCoE reduction of 20-30% [XROTOR 2021, EC 2022e]. EU-SCORES project (NL) aims to demonstrate multi-source offshore parks across different European sea basins. The project will develop two demonstrators: an offshore solar PV system combined with a bottom-fixed offshore wind plant in Belgium and a wave energy array in Portugal co-located with a floating offshore wind farm. The project envisages an increased performance with respect to electricity generation, costs and reduced marine space [EC 2021e].

Floating offshore wind. Four projects starting in 2021 address the floating offshore wind R&D sector. FLOATECH aims to increase the technical maturity and the cost competitiveness of floating offshore wind energy. The project will develop a fully-coupled, aero-hydro-servo-elastic design and simulation environment (named QBlade-Ocean) in order to reduce of the uncertainties in the design process and improved cost competitiveness. Moreover, the project will develop innovative control techniques, namely the Active Wave-based feed-forward Control and the Active Wake Mixing, which will lead to an increase of the actual energy yield of floating wind farms [EC 2021f]. X1 ACCELERATOR project is developing a disruptive floating system for deep water locations claiming that the developed platform benefits from reduced weight and low installation and operating costs. The project aims to design and certificate the so-called X90 platform, capable to support offshore wind turbines in 6MW range [EC 2021g, X1 Wind 2022]. The ARCHIME3 project proposes a concrete-based floating platform (Beridi platform) for the installation of wind turbines in the 15-20MW class. The main objectives of the ARCHIME3 project include modelling, certification of the platform, the installation of a first prototype and the validation of performance in real operating conditions [EC 2021h, Beridi Maritime 2022]. The SEAFLOWER project (Marie Skłodowska-Curie Actions) proposes strategies to exploit the knowledge anchor foundations gained from the offshore oil and gas industry and transfer it to the floating offshore wind sector. Based on a Finite Element (FE) study aims to define a numerical procedure that can store past experience on anchor foundations and make it available to the needs of the floating offshore wind market [UNIBO, EC 2021i].

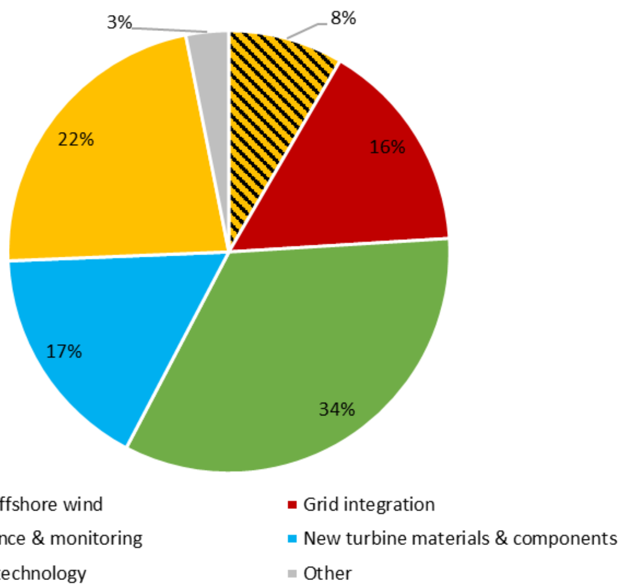
Grid integration. The FASTAP project aims to bring the wind turbine application of a very fast on-load tap changer transformer technology from TRL6 to TRL8. The technology allows to choose the optimum voltage at which the WTG operates in, not only in steady-state conditions but also for dynamic and transient events. As such it enables the electric capabilities of a turbine in weak grid conditions and increase its Low and High Voltage Ride Through (LVRT/HVRT) capabilities [EC 2021j].

2.8.3 Impact assessment of H2020 projects ending in 2021

In 2021, 17 projects ended (with a cumulated EC investment of EUR 24.7 million (USD 27.7 million)) with 34% of EC funding addressing Maintenance & monitoring followed by Offshore technology (22%), New turbine materials & components (17%) and Grid integration (16%) (see **Figure 55**).

Maintenance & monitoring. 6 out of the 17 projects ending in 2021 proposed solutions on challenges in the wind sector with maintenance and monitoring aspects. The WindTRRo (DK) project develops a robot performing all the phases of wind turbine blade leading edge maintenance and repair, which might be an economic alternative for manual repair. First customers of the first fleet of robots are the leading wind OEMs SiemensGamesa RE and Vestas [Rope Robotics, EC 2020c]. As a result, the project lead Rope Robotics unveiled the BR-8 robot capable to document and repair blade damage by performing repair processes such as sanding, cleaning and applying a new coating [EC 2022f]. The WINDMIL (CH) project developed the WINDMIL Suite: a long-term monitoring solution that uses low-cost sensors to provide real-time cradle-to-grave feedback on the condition of the wind turbine. The project claims that the solution provides important structural information such as on damage, fatigue and deterioration allowing to optimise operation and maintenance planning and extend turbine lifetime [EC 2022g, ETH 2022].

Figure 55. Share of wind energy funding under H2020 granted to projects completed in 2021 categorised by research area for wind energy.



Source: JRC, 2022.

Within the NOTUS (ES) project the company das-Nano (ES) has developed a contact-less tool, based on terahertz technology[18], specifically designed for wind turbine inspection. The tool allows deep characterization of individual coating layers of both metallic and dielectric materials, such as coating and paints in wind blades and aero structures. This includes detection of defects on individual layers, gaps between layers, surface erosion, surface roughness and anticipation of possible defects by quantifying inter-layer adherence. The project claims a potential annual economic saving of 10 % of operating and maintenance costs for wind farm operators [EC 2021k]. BladeInsight SA (PT) developed in the WINDRONE ZENITH project a drone solution capable of inspecting all three blades on both onshore and offshore turbines in a single operation. The drone is capable to fly autonomously and gather high-resolution images helping to identify cracks in the structure (see **Figure 56**). The project claims that the solution reduces inspection downtime by a factor of 6, with direct blade inspection costs reduced by over 50%, resulting in average annual OPEX of EUR 2800 per onshore turbine and EUR 8850 per offshore turbine. Moreover, a distinction criteria to other concepts is that the solution uses an external inspection device (drone) combined with an internal one (crawler robot) to complement the inspections of wind turbine blades [EC 2021l]. The EOLOGIX (AT) project developed the first condition-based monitoring system (eolACC) mounted on blades that combines three features: blade crack detection, pitch angle measurements and blade icing detection. The developers claim that the solution will save wind turbine owners up to EUR 2.9 million throughout the lifetime of the turbine [EC 2022h]. The WEGOOI (ES) project has developed an autonomous wind turbine inspection drone (EgoiZ) for both onshore and offshore platforms. The projects claims a reduction of operation and maintenance costs by up to 80% with respect to traditional methods, and at least 50% with respect to other remotely piloted aircraft systems [EC 2021m].

Offshore technology. The NEXUS (FR) project investigated vessel concepts and designed and tested two Service Operation Vessel (SOV) demonstrators (TRL 5) with the overall aim to reduce the marine logistics cost of offshore wind turbine maintenance by 20% compared to current practices and to reduce CO2 emission by 30%. As a result a baseline SOV design concept proposed by the project included a double-ended monohull, a

[18] Terahertz time-domain spectroscopy (THz-TDS) is a spectroscopic technique in which the properties of matter are probed with short pulses of terahertz radiation.

customised gangway system, a boat transfer system and a battery biased power system allowing offshore charging (16 hours operation/6 hours charging) [NEXUS 2021, EC 2022i].

Figure 56. BladeInsight inspection drone.

Source: BladeInsight, 2022.

To improve the collection of wind resource data the FloatMastBlue (EL) project developed a floating Tension Leg Platform (TLP) which is anchored to the sea bed via wire ropes. The concept integrates a met mast and a Lidar remote sensing device in a stable floating foundation [EC 2021n]. The OFFSHORE TALL TOWER (UK) project provides a novel methodology to study offshore wind towers under waves and winds in order to optimise offshore wind tower manufacturing. The project involved the modelling and experimental testing of small scale offshore towers which could serve as a basis to explore the critical mechanical characteristics of the offshore wind turbine tower structure [EC 2021o].

New turbine materials & components. The NBTECH (ES) project develops an innovative and cost competitive steel frame tower using its patented self-erecting system based on a hydraulic lifting mechanism. The technology allows transporting parts separately and assemble on-site. At the end of 2021, Nabrawind (ES) received the Design certification by DNV for its self-erecting tower followed by the installation of a 144m high wind tower in Morocco [EC 2021p, NABRAWIND 2021, NABRAWIND 2022]. Moreover, the FiberEUse (IT) project aimed for large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fibre reinforced composites. With respect to wind energy, the project proposes to use EoL wind turbine blades in one of its use cases, namely 'Use case 1: mechanical recycling of short GFRP and re-use in added-value customized applications'[EC 2021q].

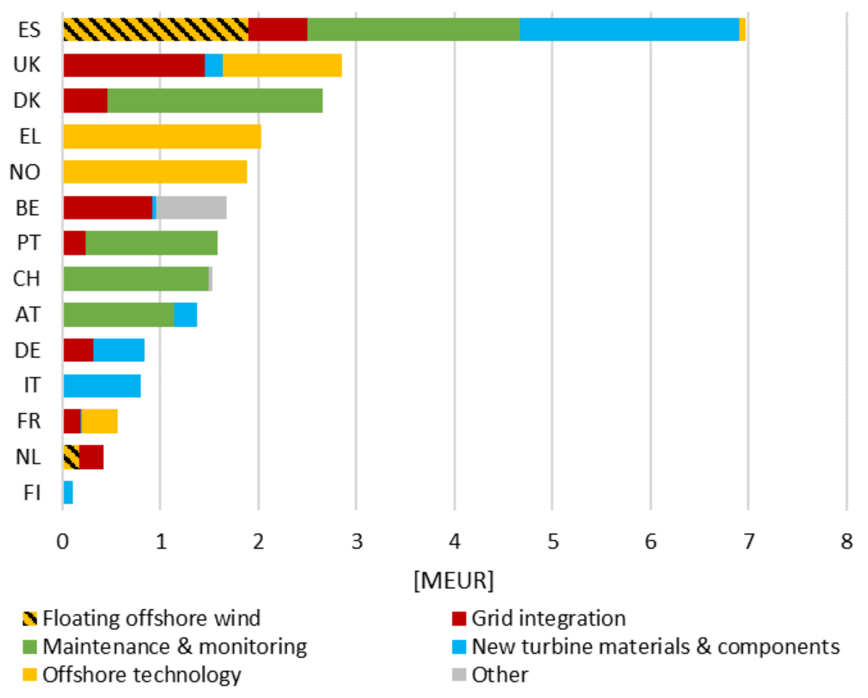
Floating offshore wind. The SATH (ES) project is the demonstration in real conditions of a floating structure for offshore wind, which will allow a reduction in LCoE over the current floating technology. Within this project the SATH (Swinging Around Twin Hull) 1:6-scale prototype of a 10 MW wind turbine will be built and deployed for a 24-month offshore testing programme to de-risk a 2 MW demonstrator, known as DemoSATH/BlueSATH. The prototype, constructed in Santander (Spain), is to be installed on the Basque Marine Energy Platform (BIMEP) in 2022. The SATH design is based on a joined pair of cylindrical pre-stressed concrete hulls anchored to the seabed via a single-point mooring system that allows the unit to swing like a weathervane to face the wind. The concept has previously been put through an extensive part-scale testing campaign in wave tanks at the University of Cantabria's Instituto de Hidráulica Ambiental and lately the manufacturing and handling operation of the floater prototype [Saitec 2019a, Saitec 2019b, EC 2022j, Saitec 2022]. The EDOWE (NL) project (Marie Skłodowska-Curie Actions) investigated the control and monitoring strategies of floating offshore wind turbines with the aim of delivering a novel distributed multi-scale control and monitoring system. The project developed a fully data-driven control (subspace predictive repetitive control) for load reductions and fault-tolerant control on a floating offshore wind turbine. Simulations show that the control is very effective at load reduction and fault-tolerance. The solution is complemented by a fault diagnosis system to increase the safety and reliability of the floating offshore wind turbine [EC 2021r].

Grid integration. The InnoDC (UK) project focuses on the models and methods for integrating offshore wind turbines, VSC HVDC converters and long AC cables into the existing power-system. The project aimed training 15 early stage researchers and their capabilities of converting their new knowledge of offshore wind power and DC grids into future products and services. are working with experts to tackle key issues, such as how to adapt new devices that behave differently to traditional power-systems [EC 2022k]. The HPCWE project addresses crucial computational challenges faced by wind energy industries in Europe and Brazil. These include the efficient use of computational resources in wind turbine simulations, accurate integration of meso- and micro-scale simulations, and optimisation [EC 2022l].

Other projects ending in 2021 include the European Technology & Innovation Platform on Wind Energy (ETIPWind) providing a public platform to identify research priorities and foster innovations and the GiFlex (CH) project striving for effective and increased integration of renewable generation [EC 2022m, EC 2022n].

With about EUR 7 million (28% of total funding) Spain received a significant amount of the H2020 funds for wind related H2020 ending in 2021. Moreover, grants to recipients from Spain addressed all research areas. The research area 'Maintenance & monitoring' accumulated most of the R&D funds with applicants from multiple European countries, namely Spain, Denmark, Portugal, Switzerland and Austria. A significant share of H2020 funding addressed the research areas 'Floating offshore wind' and 'Offshore technology' with recipients stemming from both established (United Kingdom, the Netherlands) and emerging offshore wind markets (Spain, Greece, Norway, France) (see **Figure 57**).

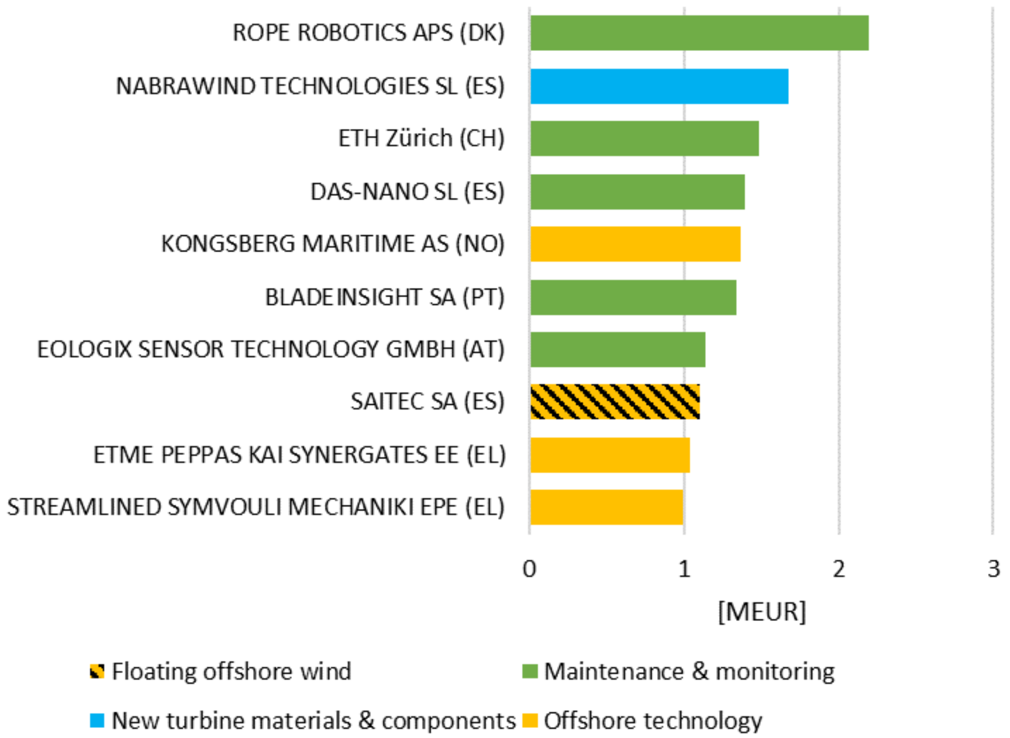
Figure 57. Wind energy related EC funding in H2020 projects completed in 2021 by beneficiary country.



Source: JRC, 2022.

Consequently, also 9 of the top 10 recipients of these funds address the research categories 'Maintenance & monitoring' and 'Offshore technology' stemming 7 different European countries (see **Figure 58**).

Figure 58. Top10 organisations in terms of received wind energy related EC funding by H2020 projects completed in 2021.



Source: JRC, 2022.

H2020 projects ending in 2021 show a strong emphasis on bringing innovations to market readiness (>TRL 6) by developing demonstrators or by testing new concepts in real-world conditions. Consequently, the predominant funding instrument used was the 'Innovation in Small and Medium Enterprises – Phase 2' (SME) with eight out of 17 identified wind-related H2020 projects (see **Table 5**).

Table 5. Overview of selected impacts of H2020 projects completed in 2021 (based on publicly available information).

Project Acronym (Type of instrument)	Research area	# peer reviewed papers	Other major impacts reported
FiberEUse (IA)	New turbine materials & components	2 (10)*	- **Demonstration of de-manufacturing processes** using wind blades samples, at the "Demanufacturing pilot plant" at ITIA-CNR in Milan (Italy) - Realisation of a physical and a virtual library of rGFRP and rCFRP FiberEUse parts
InnoDC (MSCA)	Grid integration	28	Training of 15 early stage researchers
NEXUS (SME)	Offshore technology	4	Basic design concept for a medium size SOV including Vessel simulation, testing and demonstration.
WindTRRo (SME)	Maintenance & monitoring	0	**Demonstrated blade maintenance robot** (market introduction BR-8 robot)

FloatMastBlue (SME)	Offshore technology	0	The **demonstrator** deployed off the coast of Makronisos island in the Aegean, Greece; Project issued **FloatMast patent**; Certified wind measurements and technical feasibility as it completed a full 12-months campaign in operational conditions. Project completed the main goal of TRL 7 and **reached TRL 8**
HPCWE (RIA)	Grid integration	4	EU-Brazil wind energy network
SATH (SME)	Floating offshore wind	0	- **Demonstration of the SATH platform** (scale 1:6) in real conditions - Extensive part-scale testing campaign in wave tanks - Manufacturing and handling operation of large scale floater prototype
NBTECH (SME)	New turbine materials & components	0	- Nabrawind (ES) received the **Design certification by DNV** for its self-erecting tower; - **Installation** of a 144m high wind tower in Morocco
WINDMIL (ERC-STG)	Maintenance & monitoring	23	Development of a long-term maintenance monitoring solution
NOTUS (SME)	Maintenance & monitoring	1 (5)*	- Social impact: New **83 jobs will be created** in das-Nano in five years thanks to NOTUS expansion in the market - Obtained certificates: ISO 27001 (Information Security Management) and ISO 9001 (Quality management) - Market introduction: One system sold to car industry
Windrone Zenith (SME)	Maintenance & monitoring	0	- Field test done in 2020 at Parque Eólico do Vergão 2 (PT) - Proof of Concept on the navigation strategy chosen, as well as to test various photographic sensors - Selection of drone (DJI M300 RTK) capable to carry the new payload
EOLOGIX (SME)	Maintenance & monitoring	1	- Certification of the new platform as a condition monitoring system - First systems sold to end customers - **Solution implemented** in onshore wind projects in AT, DE, UK
WEGOOI (SME)	Maintenance & monitoring	0	- **Demonstration** flights performed at Canary Islands Navigation and analytics software update, Hardware platform update, Onshore and Offshore field tests; **- European patent granted approval** **- Patent extended to 20 countries.** - Registered trademark in EU and US - S09001:2015 continuation and implementation
OFFSHORE TALL TOWER (MSCA)	Offshore technology	2	Proposal of an advanced finite element model for the efficient study of the structural response of the tower model during erection under current, wave and wind interaction.
EDOWE (MSCA)	Floating offshore wind	9	Developed a fully data-driven control (subspace predictive repetitive control) for load reductions and fault-tolerant control

** In brackets: Number of papers reported by project applying the method to other sectors or are of broader scope not directly connected with the funded project.*
Note on type of instrument: IA (Innovation Action); RIA (Research Innovation Action); ERC-SG (ERC Starting Grant); MSCA (Marie Skłodowska-Curie Actions); SME (Innovation in Small and Medium Enterprises).
Projects (ETIPWind (CSA) and GiFlex (MSCA)) allocated to research area 'Other' not included in table.

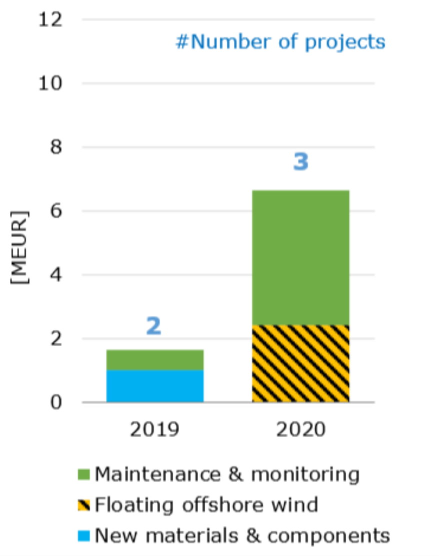
Source: JRC, 2022.

2.8.4 Development and priorities of R&D investment in EMFAF

The European Maritime, Fisheries and Aquaculture Fund (EMFAF) supports the EU Green Deal and a sustainable blue economy by implementing actions in the field of the Union's Maritime Policy, the Common

Fisheries Policy and the EU international ocean governance agenda. Since 2019, five projects addressed wind related topics (in the research areas: 'Maintenance & monitoring', 'Floating offshore wind' and 'New materials & components') with a cumulated EC investment of 8.3 million EUR (see **Figure 59**).

Figure 59. EU R&I funding categorised by R&I priorities for wind energy under EMFAF. Note: Funds granted refer to the start year of the project.



Source: JRC, 2022.

Two projects started in 2019. The LEAPWind project develops a novel leading-edge wind-blade component that prevents blade erosion by employing advanced composite materials. The solution proposed s incorporated into the manufacturing stage of the blade. The project claims a potential maintenance cost reduction for offshore blades of up to 20% [EIRE Composites 2019, EC 2021s]. The DOCC-OFF project aims for a condition monitoring strategy reducing the impact of hydraulic pitch system failures modes on the wind turbine's design load cases. The project validated the concept in the lab in early 2021, and began test bench during the first months of 2021. The solution enables preventive detection of failures avoiding downtime and reducing operation and maintenance costs [EC 2021t].

In 2020, two projects started addressing the 'Maintenance & monitoring' research area and one project focused on floating offshore wind. The ATOMS project targets the reduction of Operation & Maintenance (O&M) costs for offshore wind farms by launching and testing a new technology for Large Corrective Maintenance (LCM) operations. The technology includes a mid-size floating twin hull barge, a conventional onshore crane and a coupling ring structure (CRS). As compared to conventional solutions (e.g. use of jack-up vessels) the project claims a CO2 emission reduction of 51% and a reduction of O&M costs of up to 25% [EC 2022o, Esteyco 2022]. The Aerones project (LV) develops a prototype for a remotely-operated robotic offshore wind turbine maintenance system. The project estimates a 3 to 6 times faster O&M service as compared to current solutions and significant reduction in CO2 emissions, marine litter and rotor blade waste [Aerones 2019, EC 2022p]. SATHScale (ES) is the successor of the H2020 DemoSATH project and aims for the commercialisation of the SATH (Swinging Around Twin Hull) floating offshore technology. The project develops an industrialized fabrication system for mass production and gathers data on its DemoSATH demonstrator in open-sea conditions at BiMEP (Biscay Marine Energy Platform) in Biscay (Spain) in order to optimise the system. The project defined a LCoE target at about 50 - 55 EUR/kWh [EC 2022q, SATHScale 2022].

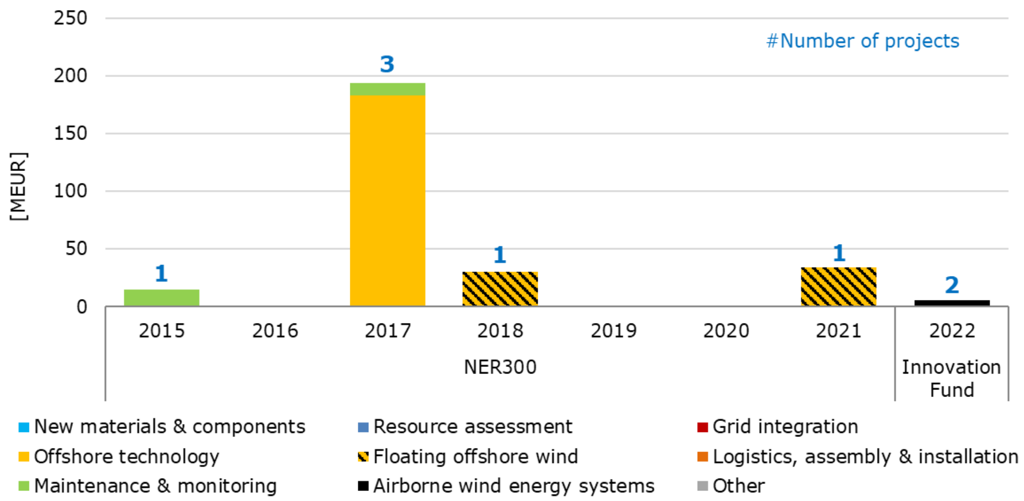
2.8.5 Development and priorities of R&D investment in the Innovation Fund programme

The Innovation Fund programme (the successor of the NER300 programme) funds demonstration of innovative low-carbon technologies. The programme sources its funding from the EU Emission Trading System by auctioning 450 million allowances in the period 2020 to 2030. The scheme is divided into calls for small-scale and large-scale projects with funding needs below and above EUR 7.5 million, respectively.

The first small-scale project call of the Innovation Fund saw two out of 30 projects addressing wind related demonstration projects with both of them in the R&I area of airborne wind energy systems (AWES). The EUR 3.4 million NAWEP (Norse Airborne Wind Energy Project) project (NO) proposes to build and operate an onshore array of at least twelve 100kW AWES devices generating a combined 1.2 MW. The developers aim for 50% lower costs than conventional HAWT and an 80% reduction in carbon footprint. The Aquilon project (DE) is a demonstrator for both airborne wind energy production at 160 kW scale and an integrated renewable energy and storage (RES) solution (Funding: EUR 2.0 million). No wind energy project secured grants in the first large - scale project call of the Innovation Fund [EC 2022r]. The NER 300 programme[19], the predecessor of the Innovation Fund, granted about EUR 273.2 million to wind energy projects since 2015 putting a strong emphasis on demonstrators and innovations in the 'offshore technology', 'floating offshore wind' and 'maintenance & monitoring' domains (see Figure 60).

In July 2022, the second large scale call of the Innovation Fund pre-selected 17 innovative projects for grant agreement preparation including the Nordsee Two Offshore Windfarm Innovation Project (N2OWF), a 450 MW offshore wind farm aiming to introduce several innovations in foundation design (single piece monopiles, secondary steel concept, vibratory piling and green steel usage) and integration of a hydrogen concept (integration of a 4 MW electrolyser on the offshore substation producing 337.5 t/year of green hydrogen for the service operation vessels and for the emergency power of the offshore substation) [EC 2022s, EC 2022t].

Figure 60. NER300 and Innovation Fund funding categorised by R&I priorities for wind energy. Note: Funds granted refer to the start year of the project.



Source: JRC, 2022.

2.8.6 Wind energy related R&D investment in the LIFE programme

The EU LIFE programme is a funding instrument for the environment and climate action. With respect to wind energy five projects have been identified since 2010 addressing the research areas 'New materials & components', 'Logistics, assembly and installation' and 'Other'.

[19] Please find a detailed description of NER300 projects in [JRC 2020a]

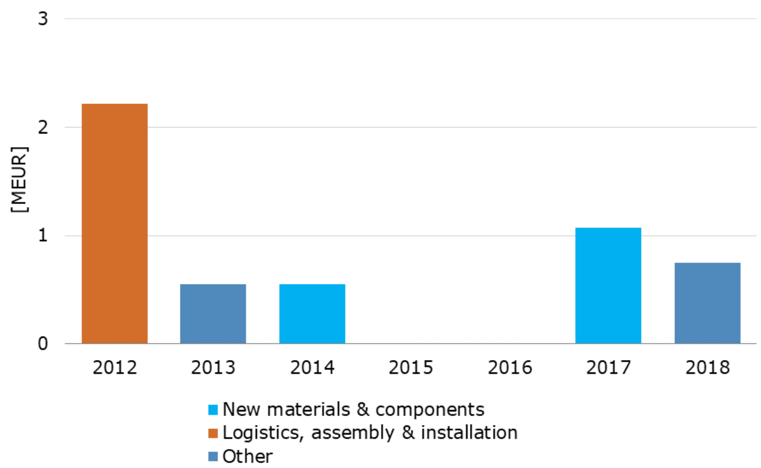
In 2012 the BIAS project aimed for implementing standards and tools for the management of underwater noise in accordance with the Maritime Strategy Framework Directive (MSFD) in the marine region of the Baltic Sea. Within this context the project identifies offshore wind farm installation as one of the major sound sources besides shipping, seismic surveys for oil and gas exploration, marine, military and mapping sonars, offshore industrial activities such as dredging, drilling and the use of explosives, and the use of acoustic deterrent devices. The project developed standards on continuous noise measurement and on signal processing. Moreover soundscape maps were developed allowing to track substantial changes in the soundscape of the Baltic Sea [FOI 2016, EC 2022u].

With LIFE-BRIO and LIFE REFIBRE two projects addressed the 'New materials & components' domain. LIFE-BRIO aimed for recovering fibres to use them in cement-based products and as cores in functionalised multilayer structures. The process involves the dismantling of the rotor blades at the Coal Clough wind farm in the UK, the recycling process for material resources recovery, and their incorporation in the new products. The obtained prototypes were inspected, tested and installed in real life conditions and results showed that the use of the fibres slightly reduces the use of other materials (cement and aggregates). Moreover the fibres recovered from wind turbine blades recycling can improve the performance of precast concrete products [EC 2022v]. LIFE REFIBRE produced a prototype plant for the mechanical recycling of dismantled wind turbine blades. Twelve blades were collected and treated to obtain their glass fibres. This recycled material was used in bituminous mixtures to construct a demonstration road section. The project claims positive results after performing a one year performance test of the road section comparing it with conventional asphalt [EC 2022w].

Other LIFE projects included the LIFE WINDFARMS & WILDLIFE aiming for the demonstration of cutting-edge technologies for preventing and mitigating impact of wind farm installations on biodiversity, such as collisions with wild birds and bats. The project testes several methods such as video surveillance, a range of radars, bat detectors and early warning systems in Greece. Early warning systems, which were installed at two wind farm sites (CRES Demonstration Wind Farm – PENA Keratea and Derveni, Thrace), showed effective ways of preventing birds from colliding with wind turbines [EC 2022x]. Moreover, the LIFE-UrbanWind.PL project aims to build and test a prototype of the Urban Wind Power Station (UWPS), based on a modular cylindrical wind turbine with a self-propulsion. The technology should demonstrate the potential of air streams created by human activity in urban spaces as a new renewable energy source for producing low-emission and cost efficient electricity [EC 2022y].

Several project funded by the LIFE programme use wind energy as a source to decrease the CO2 emissions of their solutions proposed. Examples are the LIFE-RENEWAT (demonstrating the use of sustainable technologies for reducing the energy demand of WWTP), the LIFE REGS II (constructing a dedicated wind energy plant to provide electricity for a sustainable feldspar production) and the LIFE UPHS project (sourcing wind energy for a demonstrator for large-scale underground energy storage, which utilises abandoned or inactive mines).

Figure 61. LIFE programme funding categorised by R&I priorities for wind energy.
Note: Funds granted refer to the start year of the project.



Source: JRC, 2022.

2.8.7 R&D trends and investments addressing circularity in design in the wind sector

As part of the European Green Deal, the EU's Circular Economy Action Plan stresses the need to scale up the circular economy in order to achieve climate neutrality by 2050 and decouple economic growth from resource use. The plan proposes a transition towards a regenerative growth model that strives in the coming decade for a reduction in the EU's consumption footprint and a doubling of its circular material use rate [EC 2020d].

According to EC decarbonisation scenarios, wind energy will become a core component of the European energy sector with up to 1300 GW of wind capacity installed by 2050 [EC 2020e]. Although 80-95% of the total mass of a wind turbine can be recycled some components, such as blades, pose a challenge. Given the ageing wind fleet and the substantial share of wind turbines reaching their end of life, recycling and the transition to a circular economy will become key.

WindEurope (2020) estimates that by 2023 about 14 000 blades (or up to 60 000 tonnes) will be decommissioned and that composite waste from wind turbine blades will amount to about 400 000 by 2040 [WindEurope 2020a]. Moreover, the wind industry called for a Europe-wide landfill ban on decommissioned wind turbine blades by 2025. Within the wind energy industry several companies and original equipment manufacturers have announced ambitious targets with respect to recycling and circularity approaches. In 2020, Vestas announced its intention to become carbon neutral by 2030 and to eliminate non-recyclable waste from the manufacturing, operation and decommissioning of its wind turbines by 2040. This was followed in October 2021 by the announcement of a roadmap that further increases the company's ambitions by adding commitments to increase material efficiency by 90%, achieve 100% rotor recyclability and reduce supply chain waste by 50%, all by 2030. Vestas also announced the reduction of light rare earth elements content from their most recent EnVentus turbines, while eliminating the use of heavy rare earth elements in this specific model. Moreover, Vestas commits to the 55% utilisation of refurbished components by 2030, reaching 75% by 2040, in large part by creating new repair loops for minor components. The company's waste stream leading to landfill will be reduced to below 1%, ensuring a recycling rate of all manufacturing materials of more than 94% [Vestas, WindEurope, WPM 2020c, Vestas 2022a].

Beyond the current approaches to keep composite waste from wind turbine blades out of landfill, this section maps innovations and measures for circular economy strategies in other wind turbine components e.g. components such as the tower, mooring, nacelle housing and grid integration technologies) (see **Table 6**). Notably, almost all of them address circular economy strategies at the material level by using alternative materials or by eliminating waste from production through design (waste prevention).

Table 6. Current collaborations and initiatives addressing circularity in design in the wind energy sector (see Annex 6 for full information on budget volume and R&D funding at national and EU level)
Note: Intiatives receiving EU R&D funding are in blue font, initiatives receiving other types of investment (private or by national programmes) are in black font. A detailed analysis of each of collaborations can be found in [Telsnig 2022]

Component	Collaboration/Initiative	Type of process/innovation	Estimated TRL
Wind turbine blades	ZEBRA (Zero wastE Blade ReseArch)	New recycleable materials	n.a. (TRL 7 by 2024)
	CETEC project (Circular Economy for Thermosets Epoxy Composites)	Chemical (ChemCycling)	n.a.
	AIOLOS project (Affordable and Innovative Manufacturing of Large Composites)	Manufacturing (Automatisation/Digitalisation)	n.a.
	AKER – University of Strathclyde collaboration (Affordable and Innovative Manufacturing of Large Composites)	Thermal (fluidised bed)	3
	DecomBlades (Affordable and Innovative Manufacturing of Large Composites)	Manufacturing (Automatisation/Digitalisation)	n.a.
	SiemensGamesa RecycleBlades	Chemcial (Solvolysis)	6 to 8
	FibreEUse (Pyrolysis and Re-use)	Thermal (Pyrolysis)	8 to 9
	GE RE – Veolia (US) (Co-processing – Cement production)	Mechanical (Co-processing)	9
	GE RE – LaFargeHolcim and Neowa (EU) (Co-processing – Cement production)	Mechanical (Co-processing)	9
	BCIRCULAR (R3Fiber process)	Thermal (Pyrolysis & Gasification)	5 to 6
	HiPerDiF project (High Performance Discontinuous Fibre Composites)	Mechanical (Hydrodynamic alignment)	4 to 5
	Hohenstein Institute (Biotechnological recovery of fibers)	Biotechnological	1 to 2
	SusWIND initiative (Accelerating sustainable composite materials and technology for wind turbine blades)	Unknown	n.a.
	Colorado State University consortium (US) (Additive Manufacture of Fiber Reinforced Composites)	Additive manufacturing/ Recyclable materials	2 to 6
	GE Research – AMERICA project (US) (Additive and Modular Enabled Rotor Blades)	Additive manufacturing/ Recyclable materials	4 to 6
	NREL consortium (US) (Additive Manufactured Wind Blade Core Structure)	Additive manufacturing/ Recyclable materials	4 to 6
	ORNL/UMaine/Orbital Composites (US) (On-Site, High-Throughput Additive Manufacturing)	Additive manufacturing/ Recyclable materials	2 to 6
	SANDIA consortium (US) (Additive manufacturing)	Additive manufacturing/ Recyclable materials	n.a.
	UMaine consortium – MEGAPRINT (US) (Additive Manufacturing for large modular blade moulds)	Additive manufacturing/ Recyclable materials	3 to 6
	UMichigan consortium (US) (Robot-Based Additive Manufacturing of modular moulds)	Additive manufacturing/ Recyclable materials	3 to 5
	Blade repurposing (multiple initiatives)	Reprocessing	7 to 9
Tower	GE RE – LaFargeHolcim (CH) and Cobod (DK) (3d-printing/co-processed cement)	Additive manufacturing	6
	Modvion (Modular wooden towers)	New recyclable materials	7
Mooring (Floating)	TFI (Load reducing polymer spring)	New component	5
Nacelle housing (Offshore wind turbine)	Greenboats – Sicomin (NFC offshore nacelle)	New recyclable materials	6 to 7
	GE/Fraunhofer/Voxeljet (Advance Casting Cell (ACC) 3D printer)	Additive manufacturing	4 to 6 (TRL 9 by 2025)
Drivetrain/Generator	ECOSwing (Superconducting Wind Generator)	New component	7 to 8

	GreenSpur (UK) (Rare Earth Free Permanent Magnet Generator)	New component	5
	GE (US) (High-efficiency ultra-light low temperature superconducting (LTS) generator)	New component	5
	VALOMAG (Upscale of Permanent Magnet Dismantling and Recycling)	Manufacturing (H2 Decrepitiation/HDDR or Hydrometallurgy)	2 to 4
	SUSMAGPRO (Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy)	Manufacturing (Sintering, HDDR, Sintering-debinding-shaping (SDS), recasting)	3 to 5
Grid integration - High voltage transmission	LIFEGRID (SF6-free High Voltage Circuit Breakers (HVCB))	New component	5
	SuperNode (MVDC transmission system based on superconducting cable technology)	New component	3
Grid integration - Hydrogen transport	SoluForce (Flexible Composite Pipes)	New component	8 to 9
Other / Collaborations addressing multiple components	MAREWIND (Material innovations for offshore wind life extension)	Multiple new components	n.a.

Source: JRC, 2021.

With respect to the types of organisation active in the various initiatives, a strong participation of industry players is observed. In total, the identified collaborations count 124 participations by industry players as compared to 50 by research institutions. Moreover, wind energy OEMs, developers and energy utilities such as LM Wind (US), Vestas (US), SiemensGamesa (DE/ES), GE RE (US), Aker Offshore Wind (UK), Vattenfall (SE) and Ørsted (DK) are leading some of the most recent collaborations on circularity strategies in the blade component, confirming their commitment to their ambitious targets in pursuance of carbon neutrality and the elimination of non-recyclable waste.

For 24 out of 34 initiatives dedicated information on R&D funding at national or EU level was identified. EU funding through various programmes (H2020, EIC accelerator, LIFE programme) accounts for EUR 49.3 million, followed by US initiatives (EUR 34.6 million), funded through the DOE on Advanced Manufacturing and the development of an ultra-light low temperature superconducting (LTS) generator as well as through the US National Offshore Wind Research and Development Consortium (NOWRDC) to develop innovative mooring for floating offshore wind. It can be observed that the national R&D funding for addressing circularity identified in EU member states (EUR 12.45 million) happens mainly in Denmark, through its Innovation Fund Denmark programme, and addresses the wind blade component in particular. Moreover, two projects in the UK, funded by EPSRC and the Innovate UK programme aimed for hydrodynamic alignment of discontinuous fibres and Rare Earth Free Permanent Magnet Generators (EUR 2.6 million). The remainder of current initiatives are privately funded R&D collaborations for which there was no information on the overall budget.

2.8.8 R&D trends enabling the co-existence of offshore wind and other marine activities

Current and future uses of the sea include offshore renewable energy, aquaculture, shipping, ports, sand extraction, nature conservation, fisheries, military, research, munition storage site, coastal protection, cables and pipelines, tourism, measuring poles and radars among others. This asks for coordinated planning approach. The EU Maritime Spatial Planning (MSP) Directive defines MSP as a process by which authorities analyse and organise human activities in marine areas to achieve ecological, economic and social objectives. The Directive sets out several minimum requirements for maritime spatial plans (e.g. land-sea interactions, the ecosystem-based approach, coherence between MSP and other processes such as integrated coastal management, the involvement of stakeholders, the use of best available data, transboundary cooperation between Member States, and cooperation with third countries) and encourages MSs to address in their MSP the sustainable development of all relevant sectors[20]. Moreover, the MSP framework required MSs to develop a national maritime spatial plan by March 2021, with the first progress implementation revision in 2022 unveiling good progress of a first wave of national plans particularly in countries of the North Sea and Baltic Sea. The EC supports the implementation of the MSP by a Member States expert group, the EU MSP Platform and dedicated project funding (e.g. H2020, Interreg, European Maritime and Fisheries Fund (EMFF)) [EC 2014, EC 2022z].

Fisheries and aquaculture. Offshore wind farms can lead to increased co-existence of the space available for fishing and aquaculture activities. The main conflicts between offshore wind and fisheries are circulating around accidental damage (including to subsea cables), disturbance of species, socio-cultural conflicts and ecological & economic consequences of spatial exclusion [EC 2022aa]. Van Hoey et al. (2021) shows that the installation and operation of offshore wind structures might lead to changes in the seafloor ecosystem. These can be negative effects during construction (such as sediment displacement or underwater noise because of piling activity) or potentially positive or mixed effects during the operational phase (e.g. foundations providing habitats for fouling species and by attracting various fish and crustacean species (artificial reef effect); offshore wind farm area as a refuge and recovery area for fish due to limited fishing activity). Yet these changes in biodiversity are not well understood as only limited knowledge is available on the change in ecosystem functions and processes. Co-location of fisheries in offshore wind farms poses a challenge mainly because of safety risks such as collision risk (limited distance between turbines) and cable damaging asking for a management process within MSP. Offshore aquaculture show co-location potential yet it is still at an early stage of development requiring incentives to prove its economic viability. Socio-economic effects of offshore wind farms on fisheries and aquacultures need more research, in order to assess threats and benefits and develop a better understanding of potential incentives and compensation needs [Van Hoey et al. 2021]. The EU MSP Platform currently lists 6 ongoing EU funded projects on MSP and fisheries, namely ARGOS, BSVKC, COMPASS, EcoScope, EMODNet and MPA Networks with a focus on governance, knowledge sharing information platforms, and marine observational & data management capacity. Moreover, the 'The Rich North Sea' project in the Netherlands is building artificial reefs for oysters, tube worms, and Northern horse mussels at 7 locations in Dutch offshore wind farms and test sites since 2019 [EC 2019a]. Some completed MSP projects addressed the co-existence of offshore wind farms with fisheries and aquacultures. The EDULIS project (completed in 2019) showed the feasibility of a mussel culture in offshore wind farms in Belgian waters (C-Power and Belwind wind farms). The project managed to deliver equivalent mussel yields as conventional mussel cultures and stressed the need for robust systems due to harsh North Sea conditions and optimisation needs to become a competitive concept [EDULIS 2019]. The MARMONI project (completed in 2015) developed concepts for assessing the conservation status of marine biodiversity including a guideline for environmental impact studies on marine biodiversity for offshore wind farm projects in the Baltic Sea Region [EC 2016]. The aim of the SustainBaltic project (completed in 2019) was to integrate current human activities, land use and nature and environmental management data by GIS derive tools. In 4 case studies the project produced Integrated Coastal Zone Management plans including one for Estonia which included wind energy as one of its themes [EC 2019b].

Multi-use. The MUSES project builds on existing knowledge to explore the real opportunities for Multi-Use in European Sea basins. The project identifies the scope for innovation and Blue Growth potentials and presents practical solutions on how to overcome existing barriers and minimise risks associated with multi-use development. MUSES (completed in 2018) encompasses five EU sea basins (Baltic Sea, North Sea, Mediterranean Sea, Black Sea and Eastern Atlantic) and investigates five multi-use combinations for offshore wind, namely with tourism, fisheries, aquaculture and marine renewable energy [EC 2018]. The Space@Sea project (completed in 2020) aims to develop multi-use platforms with the objective to develop safe and cost efficient deck space at sea. The standardised floaters will form artificial islands and serve as housing, renewable energy hub, aquafarming (seaweed, algae and fish farms) and infrastructure for logistics

[20] For a full list of MSP sectors and associated conflicts, please see: https://maritime-spatial-planning.ec.europa.eu/sectors

equipment. The project elaborated three different case studies: an energy hub in the North Sea, an aquaculture in the Mediterranean and a floating logistics hub in the Black Sea. In 2021, the project published a Development and Deployment Roadmap highlighting the remaining technical issues need to be resolved as well as issues regarding regulations, legislation, and marine spatial planning [EC 2020f, Flikkema et al. 2021]. The Blue Growth Farm project (completed in 2022) aims to develop an offshore multipurpose floating platform, including a central protected pool to host an automated aquaculture system, capable of producing high quality fish, as well as a large storage and deck areas to host a commercial 10 MW wind turbine and a number of wave energy converters. The project delivered a 1:40 physical wave tank prototype (Hydrodynamics and Ocean Engineering Tank (HOET) at Centrale Nantes in France) and a 1:15 physical open sea prototype at NOEL testing facility in Reggio Calabria (Italy) [EC 2022ab]. The MUSICA project develops a smart multi-usage of space (MUS) platform for the concurrent use of three types of renewable energy (wind, PV and wave), providing a decarbonising one-stop shop for small islands. The project aims for a pilot demonstrator at Inousses Island (EL) to test and demonstrate the validity of the concept in a real operating environment [EC 2022ac].

Tourism. Conflicting elements of offshore wind farms and tourism originate from the fear of the visual impact of wind turbines and the loss of attractiveness of a coast site and recreational activities (e.g. blocking of sailing routes). Moreover, property owners might fear that a nearby offshore wind farm leads to a loss of value of their houses. EC (2022) provides a set of preventive and adaptive mitigation options to address potential conflicts in relation to offshore wind development and tourism. Preventive solutions include the zoning of wind farms farther away from the coast to minimise the visual impact of offshore wind farms. Moreover, sensitive siting of offshore wind farms to minimise socio-cultural impacts can be applied by considering using the concept of culturally significant areas (CSA) in the development of a maritime spatial plan. Most MSP lack data on recreation and tourism activities in coastal waters. Thus, setting up a database on important recreation areas can help to build a solid knowledge base at the beginning of a MSP process. Developers should also include dedicated Tourist Impact Statements in EIA. Mitigation options include allowing recreational vessels access to offshore wind farms (as in the case of the UK, the Netherlands, Denmark and Poland) with some countries introducing additional rules for this case. Conflicts might also be mitigated by early involvement of tourism through providing multi-use combinations such as establishing facilities for recreational boating or including offshore wind farms into guided tourist boat tours. Moreover, the MSP process can be used to ensure offshore wind farm development benefits local communities (e.g. by the use of cooperative models), to stimulate new innovations that decrease the conflict potential with tourism and to communicate clear and transparent on the visibility of a project and provide alternatives and mitigation measures [EC 2022ad].

Defence. With respect to defence related activities and offshore wind, the EU Offshore Renewable Energy Strategy (ORES) indicates that the EC and European Defence Agency (EDA) will set up a joint action to identify barriers of co-existence between offshore renewable energy deployments and defence activities. The ORES aims for a substantial increase in offshore renewable energy with offshore wind accounting for at least 60 GW in 2030 and 300 GW in 2050, respectively. Although technical potentials for offshore wind are vast in EU sea basins, this surge in offshore wind deployment asks for an intensified exchange with the users of the sea. As such, Maritime Spatial Planning (MSP) is key for a balanced coexistence of the offshore wind sector and defence activities. Offshore wind farms and its associated activities (e.g. construction and O&M vessels) can conflict with military infrastructure (radar, underwater cables), naval training zones or storage sites [EC 2020a].

The negative impact of offshore wind on air defence (AD) detection capabilities can be seen as a major barrier for the coexistence of offshore wind and defence activities. Offshore wind farms affect the data of long range Primary Surveillance Radars (PSR), which results in a reduced response time in producing the Recognised Air Picture (RAP). The interference (complex clutter) caused by wind turbines results in radar detections either being not displayed or even discarded. This could be exploited by objects flying under the radar entering the wind farm area or by objects starting in the wind farm area (e.g. helicopters) [BEIS 2021a].

A set of mitigation options exists, yet there is no single solution that fits all cases. Off-the shelf mitigation techniques include the use of infill 2D/3D radars located either onshore or offshore-based at wind turbines or transformer stations. Capabilities (and the respective costs) of these infills range from 2D Air Traffic Radars to Modern Active Electronically Scanned Array 3D Long Range radars. Moreover, electro optical trackers could serve as an infill alternative to radars [BOEM 2020, DOE 2020a].

Current R&D proposes upgrades that use new algorithms and signal processing techniques. This includes the Turbine Adaptive Nulling concept (TANC) which combines low and high beams in order to place a null on the wind turbine at low elevation angles. Increased Range Resolution (IRR) is another technique detecting targets within the wind farm by transmitting and receiving high bandwidth waveforms. In case of overlapping radars, the concept of “radar fusion” is discussed among researchers as promising solution [FSSC 2016]. On the longer term, R&D efforts should focus on the development of next generation radar systems resistant to wind turbine interference.

When exploring mitigation options at the wind turbine level, the reduction of the wind turbines reflectivity might be considered. This can be achieved via the use of radar absorbing material (RAM, such as iron ball paint, including carbonyl iron or ferrite) (e.g. used by Vestas for the wind turbine blades in a French wind farm (Eolien Catalan project)) or innovative lighting protection cables designs (segmented cables; reactively loaded cables) [Vestas 2014, Karlson 2020].

Over-the-horizon radars (High Frequency Surface Wave Radar like ROTHR (US), NOSTRADAMUS (FR), STRADIVARIUS (FR), PLUTO (CY)) using refraction via ionosphere to detect objects represent a special case in relation to how they are affected by interference from wind farms. Wind farms in close proximity can cause interference issues (causing attenuation of ground clutter patch). This asks for accurate modelling data on planned wind farms (technical indicators of wind turbines) and exchange with developers in order to recalibrate models in use [DOE 2020b].

Another barrier of concern for the coexistence of offshore wind and defence activities is the impact of OWF on navigational safety. Offshore wind farms affect the performance of electronic navigation systems of vessels as structures produce radio interference (e.g. shadowing, false echoes and increased propagation of turbine signals as WT covers a large vertical area). This interference and the presence of more objects in the water could result in ship collision. Mitigation options currently under consideration include the upgrade of vessels with new Pulse Compression Radars and the implementation of marine monitoring and traffic management systems at ports (Vessel Traffic Service). This is in line with putting a stronger emphasis on synergies arising in ports between the offshore wind and defence sector. Exemplarily green hydrogen production in ports fed by offshore wind electricity could serve industry and defence applications. Moreover, synergies at offshore wind farms might exist, such as the potential recharging points for unmanned military vessels (e.g. mine-sweepers) [Detweiler 2020, NATO 2021a, NATO 2022].

Certain elements of the offshore wind infrastructure show a high vulnerability that could be exploited by attacks. This concerns undersea power cables used for interconnectors, offshore wind subsea cables (inter-array and grid connectors), communication and network technologies in the offshore energy infrastructure. With respect to interconnectors certain EU areas are more exposed than others, with a high reliance on few links to other MSs and single (future) offshore wind farms contributing to a higher extent to the energy security. As an example, Baltic States made significant investments in new power interconnectors with Central and Northern Europe (EstLink-1&2, NordBalt, Harmony Link) completing the **desyncronisation from Russia and Belarus** [NATO 2021b, NATO 2021a]. Moreover, Estonia and Latvia are collaborating on a joint 1 GW offshore wind farm that will contribute significantly to the total electricity generation of the Baltics. Vulnerability of (offshore) wind communication and network technology can be exploited by cyber-attacks manipulating the satellite-based remote control of wind farms. Exemplary, an **allegedly Russian cyber-attack in February 2022 caused the cut of about 6000 Enercon wind turbines** from their satellite-based remote control. In order to restore the communication link Enercon refitted large parts of their fleet with LTE mobile communication (Long-Term Evolution (LTE) is a fourth-generation (4G) wireless standard) [Enercon 2022a, RC 2022].

Harmonisation of wind energy safety rules can be seen as a barrier among MSs that might affect airborne and navigational safety and hence the military sector. To prevent this, policies should aim for harmonisation of paint markings and aircraft detection light systems [NATO 2021b, NATO 2021a].

Looking ahead, defence activities might comply with stricter environmental legislations necessitating an even stronger exchange and integrated approach when it comes to MSP. Moreover, with new offshore wind technologies moving further offshore (floating offshore wind) new defence and security aspects may arise in vicinity of offshore wind farms.

Latest defence related calls in Horizon Europe (Cluster 3) include topics on cyber-security and disruptive technologies, which are relevant to for the entire (offshore) wind sector, confirmed by latest cyber-attacks on the satellite remote controls of Enercon turbines in March 2022. Another focus area addressed in the calls of Horizon Europe (Cluster 5) concerns the vulnerability of (offshore) electricity grids.

Moreover, the European Defence Agency (EDA) has established a number of specific Capability Technology groups ('CapTechs') to undertake research & technology (R&T) activities in response to agreed defence capability needs. In order to address energy and environmental challenges within the EU Armed Forces the Energy and Environment CapTech was established with Wind Energy identified as one of 10 relevant research and technology priorities (Technology Building Blocks - TBB08 - Wind energy) [EDA 2022].

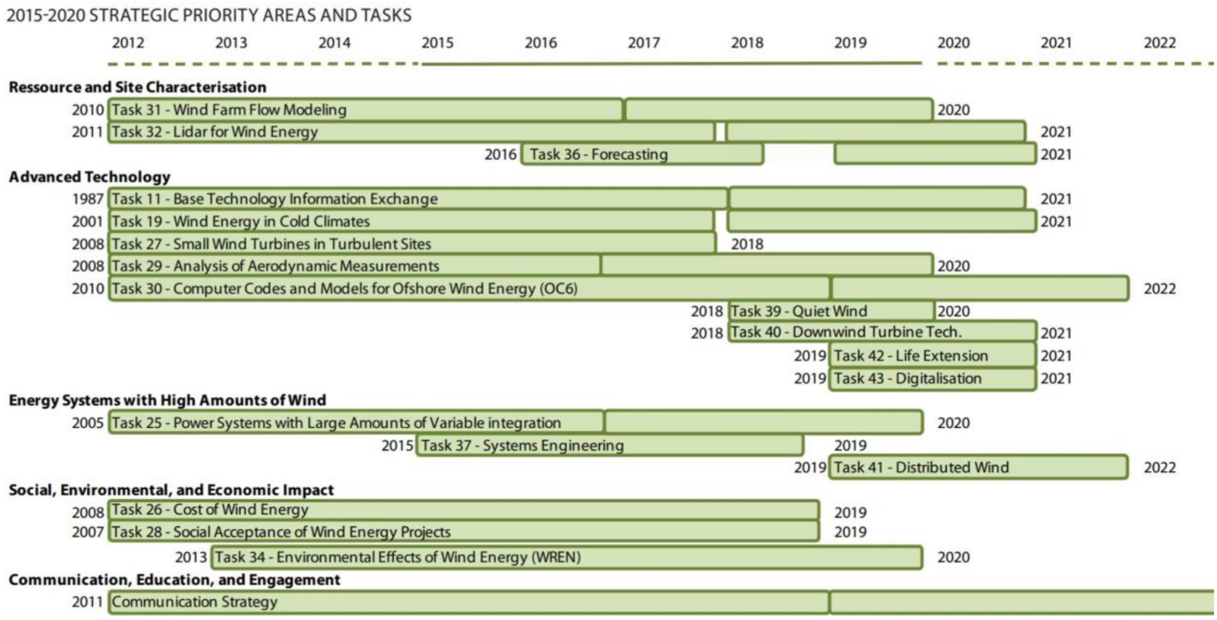
2.8.9 IEA Technology Cooperation programme on wind energy systems (IEA TCP Wind) and R&D focus of selected non-EU countries

The IEA Technology Cooperation programme on wind energy systems (IEA TCP Wind) is to stimulate co-operation on wind energy research, development, and deployment (RD&D). The 2019-2024 Strategic Work Plan helps to guide the IEA Wind activities for the next five-year term along the following strategic objectives:

- Maximise the value of wind energy in energy systems and markets
- Lower the cost of land-based and offshore wind energy
- Facilitate wind energy deployment through social support and environmental compatibility
- Foster collaborative research and the exchange of best practices and data

The revised Research Priorities 2019-2024 aim to reduce wind energy costs by addressing research in five strategic areas (see **Figure 62** for sub tasks and strategic priority areas: a) Resource and Site Characterization, b) Advanced Technology, c) Energy Systems with High Amounts of Wind Energy d) Social, Environmental, and Economic Impacts, e) Communication, Education, and Engagement) [IEAWind 2021].

Figure 62. Strategic priority and research tasks in the IEA Wind TCP in 2020



Source: IEAWind TCP, 2021.

Table 7 lists the different research task in each of the main research priority actions of the IEA TCP and gives an update on the high-level actions, activities and topical experts meetings (TEM).

In 2020 the **United States** funded wind energy related research with about USD 104 million (EUR 85 million) and increase of USD 12 million (EUR 9.8 million). R&D priorities in 2020 included offshore wind (including USD 21 million (EUR 17 million) for three projects on offshore wind demonstration and resource characterisation), land-based wind, distributed wind and system integration [IEAWind 2021].

Table 7. IEA Wind 2019–2024 Research Priority Areas, High Level Actions and completed and active activities

Research Priority Areas	High-Level Actions	2021-2022 Activities (completed & active)
Resource, Site Characterisation and External Conditions		
Better understand, measure, and predict the physics of wind energy systems (including the atmosphere, land, and ocean) to assess wind resources, wake behavior, local climate, and extreme conditions.	• Characterise normal and extreme environmental conditions for both land-based and offshore wind plants • Improve design and analysis tools through formal verification, validation, and uncertainty quantification • Develop low-cost, high-resolution site assessment techniques to inform siting and plant design	• Topical Expert Meetings (TEMs) (Task 11) (active) • Cold Climates (Task 19) (completed) • Aerodynamics (Task 29) (completed) • Offshore (Task 30) (active) • Flow Modeling (Task 31) • Lidar (Task 32) (completed) • Forecasting (Task 36) (completed) • Quiet Wind (Task 39) (active)
Advanced Technology		
Support pre-competitive and incremental technological development to overcome design, manufacturing, and operational challenges (including upscaling and disruptive innovations). Impact: Reduce the costs of design, installation, and maintenance; increase production; and expand market to new locations	• Advance and establish best practices for design, digitalisation and optimisation techniques for wind turbines and plants • Investigate advanced technologies to address specific site conditions (taller towers, logistics, offshore support structure design, advanced airfoils and strategies to increase flexibility, reliability, etc.) • Advance best practices and technologies for repowering and end-of-life processes	• TEMs (Task 11) (active) • Cold Climates (Task 19) (completed) • Cost of Wind (Task 26) (completed) • Small Wind (Task 27) • Aerodynamics (Task 29) (completed) • Offshore (Task 30) (active) • Life Extension (Task 42) (active) • Digitalisation (Task 43)) • Lidar (Task 32) (completed) • Systems Engineering (Task 37) (active) • Quiet Wind (Task 39) (active) • Downwind (Task 40) (active)
Energy Systems with High Amounts of Wind		
Research power system operations, forecasting, and grid and market integration of high amounts of wind generation. Impact: Develop the 21st century electrical system to support high levels of wind energy and to maximise the system value of wind energy in a broad range of applications	• Study flexibility in both production and demand to achieve 100% renewable energy systems in the future • Identify best practices to increase the system value of wind, which includes capacity value, grid support (e.g., ancillary services value), and opportunities for flexible demand and sector coupling • Investigate improved wind power forecasts and increase the value of existing forecasts for users	• TEMs (Task11) • System Integration (Task 25) (active) • Forecasting (Task 36) (completed) • Distributed Energy Future (Task 41) (active)
Social, Environmental, and Economic Impacts		
Identify acceptance needs and develop solutions for social, environmental, and economic impacts over the plant's lifecycle to increase the social support for and environmental compatibility of wind energy projects; maximise socio-economic benefits; and enable large-scale deployment of wind power. Impact: Directly inform regulatory authorities, helping to make informed decisions on wind deployment, permitting, and safety	• Document, develop, and advance best practices, planning approaches, and other tools to build social support for wind energy projects and mitigate social acceptance issues • Better understand and address wildlife conflicts and develop sensing, deterrent, mitigation, and minimisation technology • Expand technical knowledge and best practices for aeroacoustic design of wind turbine components	• TEMs (Task 11) (active) • Cost of Wind (Task 26) (completed) • Social Acceptance (Task 28) (active) • Aerodynamics (Task 29) • Environmental Assessment and Monitoring for Wind Energy Systems (Task 34) (active) • Quiet Wind (Task 39) (active) • Forecasting (Task 51) (active) • Wind Energy Economics (Task 53) (active)
Communication, Education, and Engagement		
Establish the IEA Wind as the definitive source for wind R&D expertise, best practices, and data (including deployment statistics and national R&D programs). Impact: Affect the cost, performance, and deployment of wind energy systems by distributing key results and information	• Develop and distribute an easy access platform to promote discussion and information sharing with wind energy and other experts on key results and information from IEA Wind • Expand network of experts and researchers and communicate findings between IEA and TCPs to increase synergy • Promote a new integrated discipline of wind energy science and engineering to achieve the full potential of low cost/high value wind energy	• The IEA Wind Secretariat and all research Tasks support this priority area

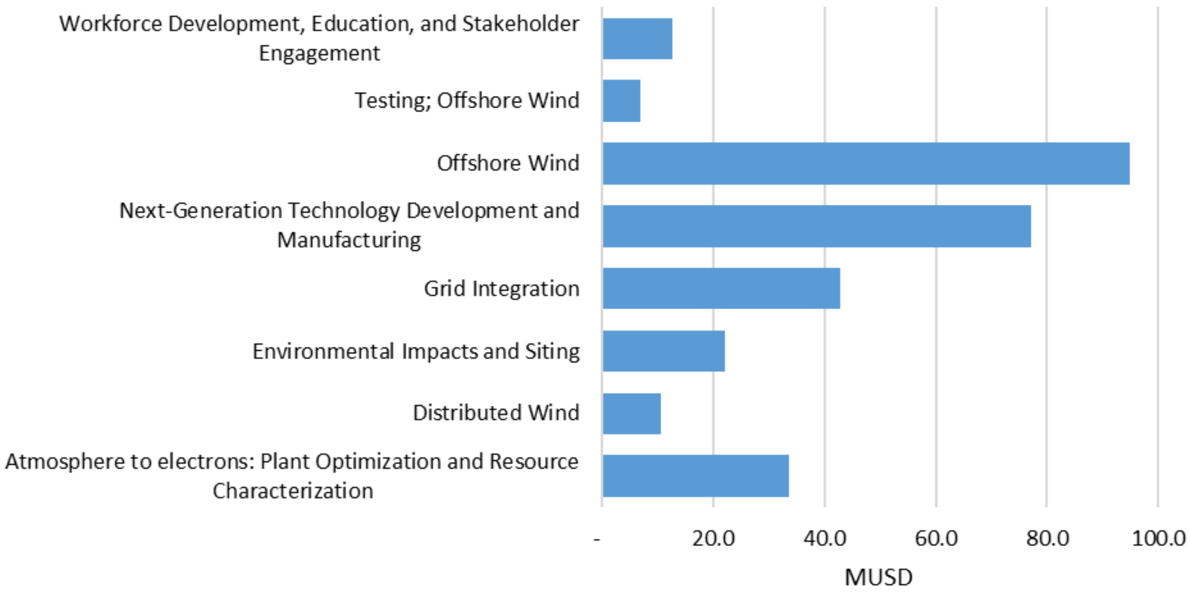
Source: JRC based on IEAWind TCP, 2021.

The U.S. Department of Energy's (DOE)) Wind Energy Technologies Office (WETO) further details specific focus areas into the following programme areas:

- **Offshore Wind:** Funding research to develop and demonstrate effective turbine technologies and overcome key barriers to deployment along U.S. coastlines.
- **Distributed Wind:** Addressing the cost, performance, and engineering challenges associated with small and medium wind turbines by focusing on design optimization, testing, certification, and manufacturing.
- **Atmosphere to Electrons:** Optimizing wind plant design, siting, and operation through an improved understanding of the complex physics governing wind flow into and through wind plants.
- **Resource Assessment and Characterization:** Supporting efforts to accurately define, measure, and forecast the United States' land-based and offshore wind resources.
- **Next-Generation Wind Technology:** Increasing the performance and reliability of next-generation wind technologies with industry partners through prototype, component, and utility-scale turbine research and development.
- **Grid Integration:** Working with electric grid operators, utilities, regulators, and industry to incorporate increasing amounts of wind energy into the power system while maintaining economic and reliable operation of the grid.
- **Environmental Impacts and Siting of Wind Projects:** Reducing barriers to wind power deployment and increasing the acceptance of wind power technologies by addressing siting and environmental issues.
- **Workforce Development and Education:** Addressing the wind industry's workforce needs through targeted investments to ensure that qualified workers and skilled scientists and engineers will support continued growth in the U.S. wind industry.
- **Testing and Certification:** Developing and using testing facilities to support research and certification of wind turbine technologies at the component, turbine, and wind plant levels.
- **Wind Manufacturing and Supply Chain:** Collaborating with wind technology suppliers to increase reliability while lowering production costs, and to promote an industry that can meet all domestic demands while competing in the global market.

Based on WETO the overall direction of US wind research funding can be analysed based on the currently active projects. In total about 111 active funded projects have been identified (see Annex 7 for the full list of active projects including beneficiaries) with about USD 95 million addressing the Offshore Wind domain followed by Next-Generation Technology Development and Manufacturing (USD 77 million) and Grid Integration (USD 43 million) (see **Figure 63**) [DOE 2022].

Figure 63. Wind energy related R&D funding by the US Department of Energy's Wind Energy Technologies Office, active projects in 2022.



Source: JRC based on DOE, 2022.

ORE Catapult reports the following wind energy related R&D priority areas for the **United Kingdom**:

- **Next Gen turbines:** Supersizing and light weighting; Sustainability in design and end of life; Greater use of composites and advanced manufacturing
- **UK supply chain acceleration:** Work to identify Supply Chain pinch points as we plan for 4GW+pa.; Enhanced focus on new entrants from other sectors.
- **Smart O&M:** Translation of robotics, data and digital technologies to offshore wind; ROV/robotics at sea demo zones; Simulation and visualisation environments; Focus on the decarbonisation of offshore operations.
- **Floating wind:** Understanding the impact of floating platform on turbine. Dynamic cable systems, mooring systems, substructure design and technology digitisation and simulation; Floating wind demonstrations to aid the de-risking of key technologies.
- **Project pipeline:** Accelerate site development using existing data sets in new ways. Innovative technologies to capture new data, to allow faster decision making and swifter site licencing.
- **Future energy System**: Work with industry to head off the major offshore grid issue; Power to X solutions.

Since 2017 several R&D funds were launched highlighting the UK Government's will to support renewables including wind sector as part of a wider UK industrial strategy and its Clean Growth Plan. In the period 2017 - 2021 annual R&D funding in offshore wind ranged between GBP 14 million and GBP 31 million with IUK, EPSRC and BEIS being the top UK enabling bodies for R&D projects [ORECatapult 2022].

In 2022, the Chinese Wind Energy Association (CWEA) reports mainly R&D targets in relation to offshore wind and floating offshore wind. Planned offshore wind R&D targets include the development of a 10 MW floating wind turbine and (bottom-fixed) offshore wind models in the 15-20 MW range. Current developments suggest that **China** is showing strong progress towards these targets. CWEA reports a first operational 5.5 MW floating wind project, accomplished test of large scale wind turbine blades (e.g. a 103m blade finished the static test in the National Offshore Wind Power Equipment Quality Supervision and Inspection Center), certification of a 16 MW offshore wind turbine and the construction of a 6.2 MW floating offshore wind turbine [CWEA 2022].

2.8.10 Joint Industry Programmes

The main Joint Industry Programmes mapped in this section include projects from the Dutch GROW programme, the programmes of the UK's Carbon Trust (UK) and DNV GL's Joint Industry Projects (JIP) on Wind Energy. ***Table 8*** to ***Table 11*** provide an overview of the most recent projects within these programmes, the consortium members, area of research, estimated TRL level and budgets.

The Dutch GROW programme (Growth through Research, development & demonstration in Offshore Wind) aims to accelerate innovations in the offshore wind sector with most of its active projects targeting a TRL 3-6. Current projects focus in the research domains 'Installation', 'Environment', 'End-of-life' and 'Foundation' and more recently as well on in the areas of 'Energy system', 'Turbine' and 'Wind farm optimisation' (see ***Table 8***) [GROW 2022].

Table 8. Current projects of the GROW joint industry research programme

Project (Description)	Consortium	Research Area / TRL estimate / Funding
Bubbles JIP – contributes to a more efficient and effective designs of bubble curtains to reduce noise during offshore installation. This project researches the current practice of bubble curtain generation. It will also research the sound propagation of piling noise through water and soil and the physical mechanism of noise attenuation by air bubbles. (04/2020 – 09/2022)	Boskalis, IHC, Marin, Seaway 7, TNO, TU Delft, Van Oord, Heerema, Wageningen University	Installation, Environment TRL 4-6 0.9 MEUR
Corrosion Fatigue Life Optimisation (C-FLO) – develops an advanced corrosion-fatigue model for the service life prediction of monopile foundations. The project evaluates the existing knowledge on corrosion and fatigue of representative offshore wind monopiles, including the effects of environmental conditions and countermeasures. (06/2019 – 05/2023)	DNV Netherlands B.V., Eneco Wind B.V., Orsted Wind Power, Posco, PPG Coatings Europe B.V., RWE Offshore Wind Netherlands B.V., Shell Global Solutions International B.V., Sif Netherlands B.V., Stichting Deltares, Techn. Universiteit Delft, TNO, Van Oord Offshore Wind B.V., Vattenfall N.V.	Foundation TRL 4-6 1.4 MEUR
DOT3000 Power Train System (DOT3000 PTS): develops an operational hydraulic drive train system and an efficient auxiliary hydraulic support system to provide water to the main pump and to generate power from the pressurised outlet flow. (10/2019 – 09/2023)	Delft Offshore Turbine B.V., TU Delft	Turbine TRL 5-7 4.8 MEUR
Dynamic Wind Farm Flow Control: aims to take the crucial next step in the effort to minimize wake effects for modern wind farms. The project will further develop and implement closed-loop active wake steering (based on yaw control) in combination with the novel HELIX active wake mixing technology. (05/2021 – 12/2028)	Eneco, Shell, TU Delft, Crosswind, SGRE	O&M, Wind Farm Optimisation TRL 3-7 n.a.
Flexible Offshore Wind Hydrogen Power Plant Module (FlexH2): designs a novel offshore wind-onshore hydrogen production concept. The project aims to achieve higher efficiency and greater flexibility of the power system. (04/2022 – 03/2026)	DNV, Shell, TNO, TU Delft, Van Oord, ABB, GE, TKF, TU Eindhoven, Vonk	Energy system, Turbine Wind farm optimisation, Other TRL 3-6 n.a.
Gentle Driving of Piles (GDP): aims to develop and test a novel pile installation method based on simultaneous application of low-frequency and high-frequency vibrators exciting two different modes of motion on the monopiles.	Baggermaatschappij Boskalis B.V., Delft Offshore Turbine B.V., Eneco Wind B.V., Energieonderzoek Centrum Nederland, IQIP B.V., Shell Global Solutions International B.V., SHL Offshore Contractors B.V., Sif Netherlands B.V., Stichting Deltares, Stichting GROW, Techn. Universiteit Delft, TNO, Van Oord Offshore Wind B.V.	Installation, Environment, Foundation TRL 3-5 2.8 MEUR
Gentle Driving of Piles 1.2 (GDP1.2): aims for a solid and comprehensive proof-of-concept of the GDP technique to demonstrate	Construction and Piling Equipment Holland B.V., Delft Offshore Turbine	Installation, Environment, Foundation

that the pile penetration rate also remains uncompromised for clay containing soil (06/2021 – 09/2023)	B.V., Eneco Wind B.V., IQIP B.V., RWE Offshore Wind Netherlands B.V., Shell Global Solutions International B.V., SHL Offshore Contractors B.V., Stichting Deltares, Techn. Universiteit Delft, Van Oord Offshore Wind B.V.	TRL 3-5 0.9 MEUR
Hydraulic Pile Extraction Scale Tests 1.2 (HyPE-ST 1.2): Hydraulic Pile Extraction Scale Tests for testing the removal of piles from the soil at the end of their operational life (08/2021 – 03/2023)	Delft Offshore Turbine B.V., IQIP B.V., RWE Offshore Wind Netherlands B.V., Sif Netherlands B.V., Stichting Deltares, TNO	End-of-life, Foundation TRL 3-5 0.9 MEUR
Monopile Improved Design through Advanced cyclic Soil modelling (MIDAS): targets deeper fundamental understanding of monopile-soil interaction under cyclic loading. The project focuses on sandy soils, especially relevant to the North Sea. (05/2020 – 10/2023)	Eneco Wind B.V., IHC Offshore Technology Institute, RWE Offshore Wind Netherlands B.V., Shell Global Solutions International B.V., Siemens Gamesa Renewable Energy, Stichting Deltares, Techn. Universiteit Delft, Van Oord Offshore Wind B.V.	Foundation TRL 5-7 1.0 MEUR
PRecipitation atlas for Offshore Wind blade Erosion Support System (PROWESS): measure and monitor the characteristics of the precipitation at different sites in the Dutch North Sea and coast in detail and correlate the precipitation accurately with other weather data. (09/2021 – 08/2024)	Eneco, Shell, TNO, Equinor, Whiffle	Energy system, Turbine, Wind farm optimisation, Other TRL 6-7 1.1 MEUR
Roadmap for technological advancements for Symbiosis-Inclusive Design in Offshore Wind (Road2SID): assess the integration potential of various functions, such as active nature-inclusive design, aquaculture, and floating solar energy, while considering spatial requirements, technological readiness and potential risks and opportunities. (01/2022 – 07/2023)	Boskalis Offshore Contracting B.V., Marin, RWE Offshore Wind Netherlands B.V., Seaway Vessels B.V., SHELL International B.V., Stichting Deltares, Stichting GROW, TenneT TSO B.V., TNO Van Oord Offshore Wind B.V.	Environment TRL 2-4 0.2 MEUR
Sensor Assisted Wind farm Optimisation (SAWOP): improved power performance monitoring using spinner anemometers and nacelle LiDAR systems (02/2021 – 03/2023)	Shell, TNO, Vattenfall. ROMO Wind A/S, NoordzeeWind B.V.	Turbine Wind farm optimisation TRL 7-9 1.3 MEUR
Silent Installation of MonoPiLEs IIB (SIMPLE IIB): design, construct and test Vibrojet® prototypes (05/2022 – 06/2023	Deltares, Eneco, Shell, Cape, DEME, GBM	Installation, Environment, Foundation TRL 5-6 n.a.
Sustainable Installation of XXL Monopiles (SIMOX): Development and practical implementation of one or more innovative technologies for the installation of XXL monopiles, as an alternative to conventional impact hammering (06/2021 – 03/2024))	Boskalis Offshore Contracting B.V., Construction and Piling Equipment Holland B.V., Delft Offshore Turbine B.V., GBM Works B.V., IQIP B.V., RWE Offshore Wind Netherlands B.V., Shell Global Solutions International B.V., SHL Offshore Contractors B.V., Siemens Gamesa Renewable Energy, ,Sif Netherlands B.V., Stichting Deltares, Techn. Universiteit Delft, Van Oord Offshore Wind B.V.	Installation, Environment, Foundation, End-of-life TRL 5-7 4.0 MEUR
Wrapped Composite Joints for Next Generation Offshore wind support structures - Phase 1 (WrapNode-I) Investigating composite joint for jacket foundations to significantly reduce cost due to lighter structures and shorter manufacturing time. (05/2021 – 09/2023)	Enersea, HSM B.V., Shell, SGRE, Smulders, TU Delft	Foundation TRL 4-6 2.9 MEUR

Source: JRC, 2022.

The Danish Energy Technology Development and Demonstration Programme (EUDP) funds joint industry research projects focussing on wind energy demonstration. Since 2021 the programme funded projects with more than EUR 16 million focussing particularly on innovative concepts in installation techniques, blade optimisation, AI and O&M. Other major ongoing projects include RELIABLADE (EUR 11 million; ending in 2022) developing a Digital Twin for each individual wind turbine blade and MADEBLADES (EUR 7 million; ending in 2023) demonstrating a disruptive design (fibre preform materials) and manufacturing solution for large offshore wind turbine blades [EUDP 2022].

Table 9. Current projects funded by the EUDP research programme (projects starting in 2021 and 2022)

Project (Description)	Consortium	Research Area / TRL estimate / Funding
AI-powered Lean Wind Turbine Installation – develop and improve the existing monitoring system so that it covers the specific needs that apply to the installation of turbines on land. The project will develop and integrate new hardware (new types of sensors etc.) and carry out two test trials on larger SGRE land turbine installations and aims for a **cost reduction of 16% for the installation of onshore wind turbines**. (2022 – 2024)	Claviate, SiemensGamesa RE	Installation, AI TRL 8-9 1.3 MEUR
AMtip - Advanced blade tips enabled by additive manufacturing and jointed blades – the project develops blade technologies to fully utilise the design potential in jointed blades and specifically make use of additive manufacturing techniques to enable design of advanced aeroelastically tailored blade tips. This might enable **increased rotor sizes by up to 20%** and to lead to **5-15% increase in AEP compared to conventional blades and a targeted 4% decrease in LCOE** (2022 – 2024)	DTU, LM Wind Power, Blade Dynamics	Blades - 1.3 MEUR
EWIS - ENABL Vindmølle Installationssystem – the project develops and demonstrates a solution for installing large components on offshore wind turbines. The EWIS system will be an effective component lifting and stabilization solution for the installation and service of offshore wind turbines and **will increase the operating period by a minimum of 15-25 days** and reduce the operating time during the installation process (2022 – 2024)	ENABL A/S, Syddansk University	Installation TRL 8-9 1.1 MEUR
AQUADA-GO - the project will develop a methodology for an automated, non-contact, almost real-time wing damage detection and risk evaluation in a single step using thermography and computer vision. This without stopping the wind turbines' normal operation. The project will take the AQUADA technology – developed in DTU Wind Energy's laboratory – and apply it to operational offshore wind turbines. The solution is expected to **reduce CO2 emissions by 30-50% per turbine inspection** (2022 – 2025)	Energy Cluster Denmark, DTU, Quali Drone ApS, RWE	O&M, Wind Farm Optimisation TRL 7-8 1.0 MEUR
Fleksibel Offshore Drone – the project will introduce new service technologies within the offshore wind industry. This includes fully autonomous wind turbine inspections and package delivery using a drone from a fixed charging station on offshore service vessels (2022 – 2024)	Esvagt A/S, SiemensGamesa RE Syddansk University, Energy Cluster Denmark	O&M, Wind Farm Optimisation - 1.3 MEUR
Predictive Automatic Corrosion Management (PACMAN) - involves the development and maturation of an automatic corrosion detection and prediction program. Via AI and machine learning, the program must be able to perform autonomous corrosion predictions based on numerous inputs, both in the form of images and sensor technology. (2022 – 2024)	SEMCO Maritime, IPU, Aalborg University, MMSURVEY ApS, Energy Cluster DenmarkTREFOR El-net	O&M, AI, Wind Farm Optimisation TRL 7-9 1.3 MEUR
BLATIGUE-2 - develops a suite of software, tools and methods to enable significantly faster, realistic and more efficient fatigue testing methods for large wind turbine blades. The combined solutions will increase the quality of blade testing to reduce unplanned blade repairs by an estimated 10% and reduce the time to market for new blade designs significantly. The project estimates to increase the combined annual turnover of the involved companies by EUR 47 million and **create >150 new jobs by 5-7 years after project completion**. (2021 – 2025)	DTU, R&D Yesy Systmes A/S, LM Wind Power, Blade Test Centre A/S, Juel&Kroyer A/S, Bruel&Kjaer Sound & Vibration Measurement A/S, Siemens Industry Software NV, Det Norske Veritas Danmark A/S, Olsen Wings A/S Orsted Wind Power A//S	Blades, Turbine TRL 7-9 4.4 MEUR
CORTIR - fase II: the project aims to increase the reliability of blades during operation by installing the Root Transition Zone Solution. In addition, using the new inspection guidelines to achieve higher cost efficiency and higher AEP for wind turbine owners. (2021 – 2023)	Bladena ApS, DTU, BUILD, Engineering Consulting Corporation, Global Wind Service A/S, Kirt Thomsen ApS	Blades, O&M - 1.5 MEUR
Enabling the use of fiber rope in crane solutions for tall wind turbines – the project will enable the use of fiber ropes in crane solutions for tall wind turbines, which is a much lighter alternative to traditional steel wires. This will enable to operate at full capacity on wind turbines **over 200 meters.** (2022 – 2025)	LIFTRA ApS, Dynamica Ropes ApS, Aalborg University	Installation TRL 7-9 1.3 MEUR
LERCat - Categorization of Leading Edge Roughness – the project will establish an **open industry standard** for categorizing the	DTU, Vestas, Siemens Gamesa RE, LM Wind Power A/S, Suzlon, Power	Blades, O&M, Wind farm optimisation

performance loss (aerodynamic and acoustic) for wind turbines due to Leading Edge Roughness, which inevitably occurs during operation. (2022 – 2025)	Curve ApS	- 1.6 MEUR
IDEA - Integrated Design of Floating Wind Turbine Arrays – the project will establish reference data for wind, wave and current conditions as well as reference designs for floating wind farms. The project follows the international IEA project on the design of floating wind farms. (2022 – 2025)	DTU, DHI A/S	Floating offshore, Other - 0.2 MEUR

Source: JRC, 2022.

In the UK, the Carbon Trust provides large-scale collaborative research, development and deployment in five offshore wind programmes targeting the reduction of costs for offshore wind, development of industry best practice and standards, acceleration of floating offshore wind, reduction of impact of offshore wind farms in the marine environment, system integration and R&D in industry-wide challenges [Carbon Trust 2022] (see ***Table 10***). No information was available on the overall size of funds of the Carbon Trust research programmes.

Table 10. Current projects of the Carbon Trust joint industry research programme

Project/Research Area (Description)	Consortium	Research Area
Offshore Wind Accelerator (OWA)		
Research area: Cables • investigations of cable monitoring systems • exploring the potential benefits and specifications of a 'universal joint' • a study to better design cables for semi-dynamic environments and reduce risk of associated failures	Main partners: SSE, EnBW, Equinor, Orsted, RWE, ScottishPower Renewables, Shell, Vattenfall, Total Energies, E-on	Cables
Research area: Electrical systems • Improve efficiency and performance of electrical systems • Assess opportunities for offshore wind to provide system services • Reduce direct costs of electrical components		HVDC transmission, System services, Innovative electrical components, Higher voltage cables, Regulation
Research area: Foundations • Assessing and mitigating risks related to larger turbines, deeper water wind farm sites, asset integrity and supply chain. • Furthering understanding, innovation and improvement of offshore operations, including site and environmental condition monitoring, installation, logistics and decommissioning. • Contributing to standardisation and the harmonisation of standards. • Engaging, supporting and developing the supply chain.		Foundations (suction caissons underwater inspection methods, innovative foundations)
Research area: Logistics and O&M • reducing vessel emissions, encouraging the development of new vessel design, improving health and safety through technology and improving operational efficiency through planning, logistics and accessibility		O&M
Research area: Yield and performance • investigating the energy yield analysis process to increase understanding, improve the industry standard, and to reduce costs		Performance & Optimisation (Global blockage effect, Floating LiDAR)
Floating Wind Joint Industry Project (JIP)		
Floating Wind Joint Industry Project addresses challenges and investigate opportunities for the deployment of large-scale commercial floating wind farms. Industry-identified innovation needs include the following areas: • Electrical systems • Mooring systems • Logistics • Turbine and foundation optimisation • Asset integrity Latest research in the project addresses Heavy lift maintenance, Tow-to-port solutions,	Main partners: SSE, EnBW, Equinor, Orsted, RWE, ScottishPower Renewables, Shell, Vattenfall, Total Energies, BP, EDF Renewables, Kyuden Mirai Energy, Park Wind, OW Ocean Winds, Tepco,	Floating offshore wind

and Mooring in challenging environments	Tohoku Electric Power, wpd	
Offshore Renewables Joint Industry Programme (ORJIP)		
ORJIP Project aims to: • fund research to improve our understanding of the effects of offshore wind on the marine environment • reduce the risk of not getting or delaying consent for offshore wind developments • reduce the risk of getting consent with conditions that reduce viability of the project Latest research (Stage 2 phase) in the project monitors seabird behaviour across operational wind farms, quantification of mortality rates, Seabird Sensitivity Mapping, underwater noise assessments, coexistence between commercial fishing and offshore renewables, Monitoring of Cable Protection Measures among others	Main partners: SDIC – Red Rock, Equinor, Orsted, RWE, Crown Estate Scotland, The Crown Estate, Shell, Total Energies, EDF Renewables, OW Ocean Winds, marine Scotland, Orjip	Environment
The Integrator		
The Integrator project aims to: • maximise the contribution of offshore wind to a low cost, flexible, predictable and low carbon energy future. The project will deliver in two phases studies defining key market factors and technology option for the integration of offshore wind (including onshore and offshore hydrogen production, direct integration of storage, ancillary services and system value)	Main partners: Carbon Trust, EnBW, Equinor, RWE, ScottishPower Renewables, Total, Vattenfall	System integration
Large scale R&D projects - offshore wind (set up under the OWA)		
R&D projects in this programme address particular industry-wide challenges, by bringing together private and public funding, expertise and know-how. Active projects include: • High Voltage Array Systems (Hi-VAS) (until 11/2022) • Verification of Buckling Assessment and Behaviour in Large Monopiles (VERBATIM) (until 2023) • Improved Fatigue Life of Welded Jacket Connections (JaCo) (until 09/2023) • Fatigue Testing of Welded Support Structures for Offshore Wind Turbines (FaWS) (until 2022) • Global Blockage Effect in Offshore Wind (GloBE) (until 12/2022, 5.9 MEUR) • Cone Penetration Testing in Silty Soils (CSi) (until end 2022)	Main partners: SSE, EnBW, Equinor, Orsted, RWE, ScottishPower Renewables, Shell, Vattenfall, Total Energies, OW Ocean Winds among others	Installation, Environment, Foundation Since 2011, 25 Discretionary Projects 43 MGBP 11 MGBP of public funds

Source: JRC, 2022.

Classification organisation DNV (NO) initiated 6 joint industry project in the wind energy domain and is currently opening another 8 new joint industry projects. Research focuses on establishing research standards and recommended practices in floating offshore wind, measurements, sensors, O&M, environmental aspects, turbine technology and offshore support structures among others [DNV 2022a] (see ***Table 11***).

Table 11. DNV joint industry projects in the area of wind energy.

Project/Research Area (Description)	Consortium	Research Area
Design of floating offshore wind turbines and impacts of energetic steep and breaking waves Provide a field, experimental and numerical database of energetic steep or breaking waves effects on floating offshore wind turbines and provide improved certification documents (2020 - 2023).	Cerema, EDF, ENSTA Bretagne, Equinor, EOLFI, Ifremer, Ismar. MorphoSense, SAIPEM, SHOM, Sustainable Energy, Total, Unitech, University of Rhode Island	Floating offshore wind
Alleviating cyclone and earthquake challenges for wind farms (ACE 1) Development of design procedures and tools for seismic design of wind turbine structures in order to provide clarity, safety and reliability as well as a state-of the-art review of extreme wind speed determination in cyclone areas (2021-).	LOGE, CDEE, WPD, GE Renewable Energy, Obayashi, COWI, JanDeNul, Kajima, Ørsted, Pacificoenergy, Naval Energies, Vestas, SGRE, Shimizu RWE/EON, JGC, CFXD (COP), Equinor, MVOW, Ramboll,	Environmental, Turbine technology

	Hai Long, ITRI	
LIDAR-measured turbulence intensity Collect and evaluate the current state-of-the-art and the state of research and to develop recommendations and establish acceptance criteria to use LIDAR TI measurements for different applications, such as site assessment, load validation and power curve measurement in order to decrease uncertainties (2020-).	n.a.	Measurements, sensors, O&M, Turbine technology
Next generation blade certification standard Develop a standard for the evaluation of data-driven techniques used to detect blade damages in multi-MW turbines (2021-)	n.a.	Measurements, sensors, O&M, Turbine technology
Standardization of sandwich core test methods for the wind industry define and standardize sandwich core (blade) testing methods to generate comparability and improve data validity and reliability to increase the efficiency of product qualifications and the compatibility and interoperability between products (2021-).	n.a.	Turbine technology, Materials, Blade
Tackling leading-edge erosion Activities in this JIP include the development of Recommended Practices on a) Testing of rotor blade erosion protection systems and b) Evaluation of erosion and delamination for leading edge protection systems of rotor blades. Services are provided to both laboratories and industry (2022-)	n.a.	Turbine technology, O&M, Materials, Blade
Certification of installation aids equipment for fixed offshore wind farms The JIP aims for a decision tool and reference that can be used by all stakeholders during the specification; design; manufacture; procurement and approval of any equipment intended for the installation and decommissioning of fixed wind turbines (2022-)	New JIP currently calling for partners	Installation
Alleviating Challenges from Earthquakes for wind farms (ACE 2) Alleviating Challenges from Earthquakes (ACE) for wind farms based on ACE 1 JIP. Focus is set on Damping, Taiwanese and Japanese Standards and Seismic analysis. Results will aim for an upgrade of DNV-RP-0585 "Seismic design for wind power plants" recommended practice (2022-)	New JIP currently calling for partners	Environmental, Turbine technology
Wind turbine blade damage detection using artificial intelligence (Blade-AI) The JIP aims at defining an approach for the third-party validation of the techniques used for the automatic processing of blade inspection data (2022-)	New JIP currently calling for partners	Turbine technology, Artificial Intelligence O&M, Materials, Blade
Early Age Cycling (EAC) of grouted connections The JIP will update EAC guidelines for the most used grouted connections in the industry and aims to develop a reliable small scale testing methodology for screening of grout materials to ensure material properties are adequate for EAC(2022-).	New JIP currently calling for partners Partners expressing the need for this JIP: CoP, COWI, DEME, ITW PP, Kent, MBS, Rambøll, RES, SAIPEM, Steisdal, Swancor Renewable Energy, Ørsted	Offshore wind support structures
Concrete for Floating Offshore Wind (FOW) JIP will gain knowledge on topics specific to concrete floaters to further develop DNV standards and update the concrete design provisions. (Q3 2022-2024)	New JIP currently calling for partners 20 partners expressing the need for this JIP:	Offshore wind support structures, Floating offshore wind
Wind Farm Control The JIP aims for evaluations of wind farm control on operating wind farms by using several industry-leading simulation tools. Moreover certification aspects of all elements of wind farm control will be addressed (2022-).	New JIP currently calling for partners	Wind farm control, Sensors

Floating offshore wind substations JIP aims to align industry best-practice allowing for an accelerated technology development and to close gaps in available substation standards enabling scaling of floating offshore wind with an acceptable level of commercial, technical, health, safety and environmental risks. The JIP build on exisitn standards of bottom-fixed solutions (Q4 2021-).	New JIP currently calling for partners 20 partners expressing the need for this JIP:	Floating offshore wind, System integration, Offshore support structures
Standardizing additive manufacturing for the energy and maritime industries The JIP aims to standardize and optimize qualification processes for Additive Manufacturing (AM), reducing cost and environmental impact of production through AM, and enable the use of AM in applicable design applications in the Energy and Maritime sector (06/2022).	New JIP currently calling for partners	Additive Manufacturing (AM)

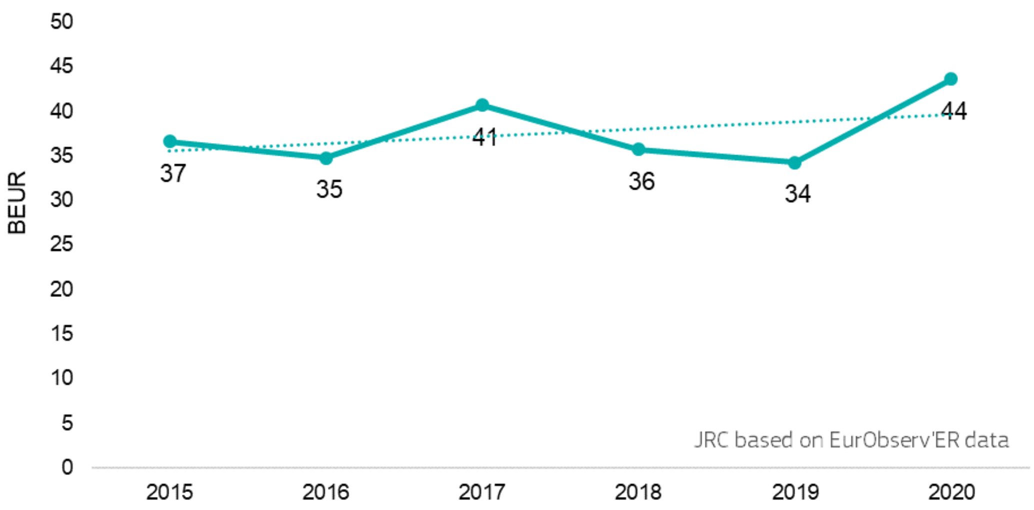
Source: JRC, 2022.

3 Value chain Analysis

3.1 Turnover

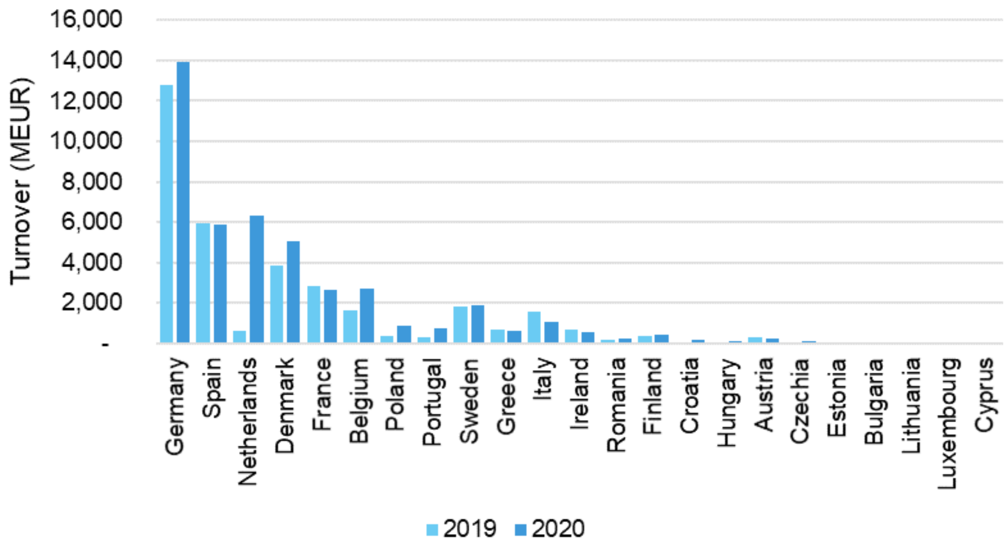
Turnover in the wind power sector accounted between EUR 35 billion and EUR 44 billion in the period 2015-2020 showing an increase of about 4% (see **Figure 64**). Turnover values are calculated using an approach which is based on an evaluation of the economic activity of the wind sector. In order to allow a comparison between EU MSs, input-output tables are used and money flows from activities in the renewable energy value chain are considered. The EurObserv'ER considers the following four activities: 1) investments 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 64. Turnover of the EU wind sector in the period 2015 and 2020.



Source: JRC based on EurObserv'ER, 2022.

Figure 65. Turnover of the wind sector in EU Member States in 2019 and 2020.



Source: JRC based on EurObserv'ER, 2022.

In 2020, turnover increased by about EUR 9.4 billion as compared to 2019. With about EUR 14 billion Germany leads in turnover, followed by the Netherlands, Spain and Denmark (see **Figure 71**). The Netherlands showed the strongest increase in this indicator as turnover values are traced by the year of wind project commissioning. Hence, the increased deployment activity in the Netherlands (0.5 GW onshore wind and 1.5 GW offshore wind commissioned in 2020) increase turnover values to about EUR 6.4 billion, an almost fivefold increase when compared to the 2015-2019 average.

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. 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 EU27 [EurObserv'ER 2022].

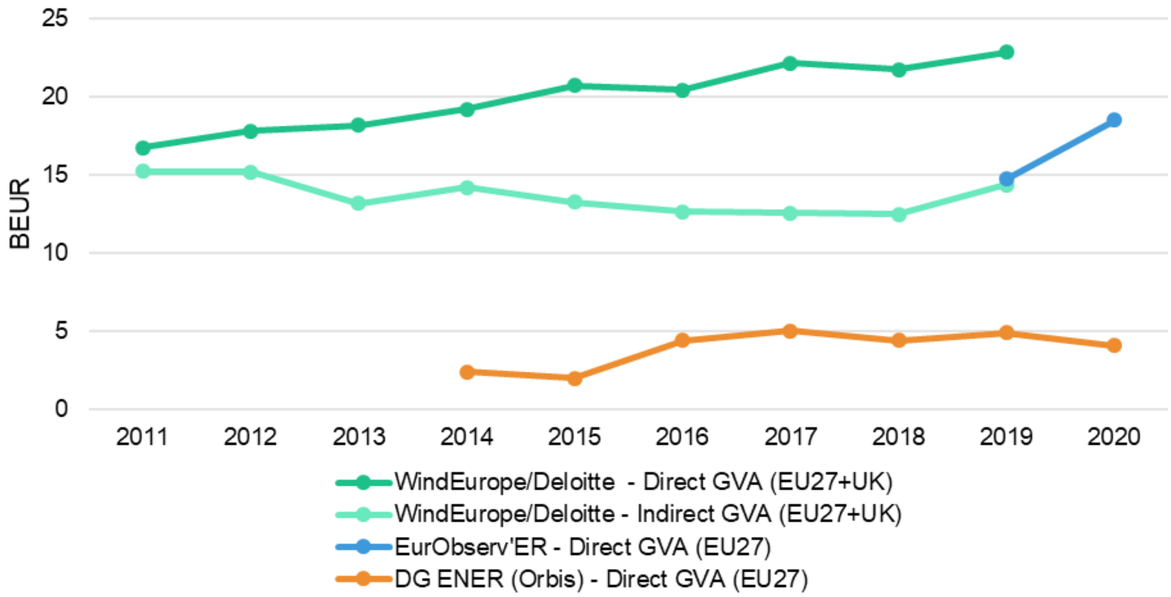
WindEurope/Deloitte (2020) combines three approaches to calculate the direct GVA (based on expenditure, value added and income) and divides the sector into seven subcategories (Onshore wind energy developers, Offshore wind energy developers, Onshore wind turbine manufacturers, Offshore wind turbine manufacturers, Component manufacturers, Service providers, Offshore wind turbine substructures). The indirect GVA is based on Eurostat input-output tables combined with an expert elicitation within the wind sector. The analysis considers 400 EU organisations within the wind sector in EU and the United Kingdom [WindEurope/Deloitte 2020].

Following the WindEurope/Deloitte (2020) methodology direct GVA increased by 36% since 2011 (EUR 23 billion) (see **Figure 66**). Analysing the GVA contribution of the wind subcategories shows that the share of onshore wind activities still accounts for about 80% of the total direct GVA, yet offshore related GVA results increased in the last decade. WindEurope/Deloitte (2020) claims delocalisation of manufacturers outside EU as the main reason that GVA values do not follow current wind energy deployment rates. Indirect GVA remained relatively constant in the period 2011-2019 with values ranging from EUR 12.5 billion to EUR 15.2 billion, with the largest contributions stemming from the electrical equipment sector and the machinery and equipment sector.

Direct GVA values calculated by EurObserv'ER (2022) increased to EUR 18.5 billion in 2020, a 26% increase as compared to the previous year. With about EUR 6 billion Germany leads in direct GVA, followed by the Netherlands (EUR 2.7 billion), Spain (EUR 2.4 billion) and Denmark (EUR 2 billion). Moreover, strong growth in direct GVA as compared to 2019 can be observed in Belgium, Poland and Portugal, countries experiencing a rise in wind energy installations (see **Figure 67**).

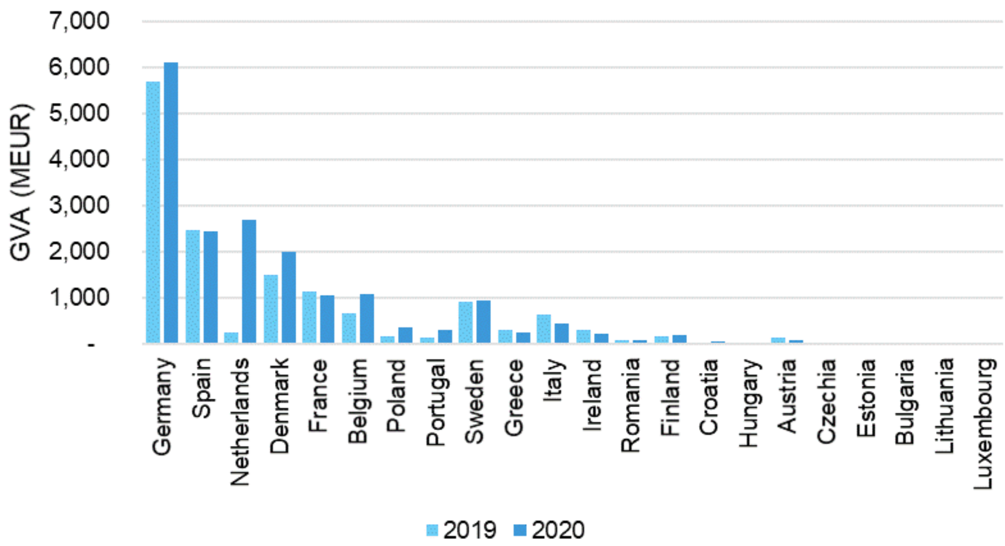
A DG ENER study estimates the GVA of the wind turbine manufacturing sector by analysing ORBIS data of the Top 5 OEMs in the EU wind sector and their subsidiaries, active in producing and assembly of the main components (blades, generators, gearboxes, etc.). The total value added for EU27 increased from EUR 2.37 billion in 2014 to EU 4.06 billion in 2020, an increase by 71%. In this period the contribution to the value added comes mainly from the increasing cost of employees, as the total EBIT of the investigated manufacturers declines since 2016 [DG ENER 2022].

Figure 66. Gross Value Added (GVA) of the EU wind sector in 2019 and 2020.



Source: JRC based on EurObserv'ER and WindEurope, 2022.

Figure 67. Direct Gross Value Added (GVA) of the EU wind sector in 2019 and 2020.



Source: JRC based on EurObserv'ER, 2022.

3.3 Environmental and Socio-economic Sustainability

Table 12. Environmental and Socio-economic Sustainability

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) (see also chapter 4.3). 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 2022b]*:* *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 2022a] *Net energy payback time: 7.4 months* ***EPBT of wind power plants in scientific literature (exemplary):*** [Wagner et al. 2011, Bonou et al. 2016]*:* *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 et al. 2022].
Water use	***Exemplary 100 MW onshore wind plant with Vestas V136-4.2MW wind turbines*** [Vestas 2022b]*:* ***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 2022b]*:* *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 & Jacobson 2021]
Soil health	*Exemplary 100 MW onshore wind plant with Vestas V136-4.2MW wind turbines* [Vestas 2022b]*:* ***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 & 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 and Borate show a high supply risk* *See chapter 4.3.1*
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) (see chapter 2.8.7).* *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 2.2.4 (on future deployments) and chapter 3.4 (on the industrial value chain)*
Trade impacts	*Yes, see chapter 4.2 on trade*
Market demand	*Yes, see chapter 2.2.4 (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]. *In 2022, the European Commission has launched a public consultation on how to improve permit-granting procedures for renewables projects. 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 2022ae]. *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) summarizes 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 synthesized 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 2022b, Vestas 2022c].
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 section 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 (see chapter 2.8.8)* *Cyber security: see for example cyber-attack on remote control of Enercon turbines in 02/2022 (see chapter 2.8.8)*
Energy security	*No information*
Food security	*No information*
Responsible material sourcing	*No material was identified in relation to EU REGULATION (EU) 2017/821 requirements*

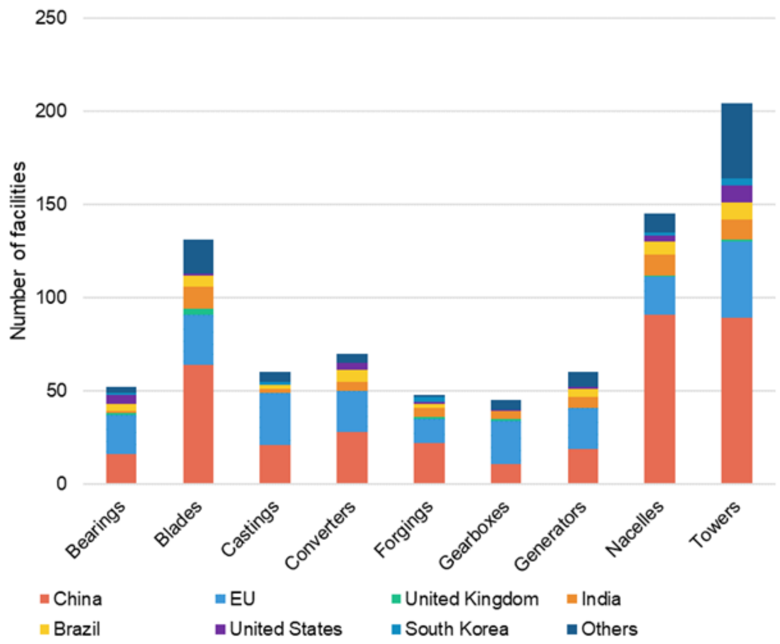
Source: JRC, 2022

3.4 Role of EU Companies

3.4.1 EU position in the supply chain of wind components

The wind energy sector has evolved into a global industry. WindEurope/WoodMackenzie (2020) identifies about 800 manufacturing facilities, 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][21]. 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 68. Operational manufacturing facilities of wind energy components (global)



Source: WindEurope/WoodMackenzie, 2020

Figure 70 to **Figure 75** aim to track the market shares on manufacturing capacities of the main wind energy components based on the location of manufacturing (e.g. blades, generators, gearbox, nacelle). For other

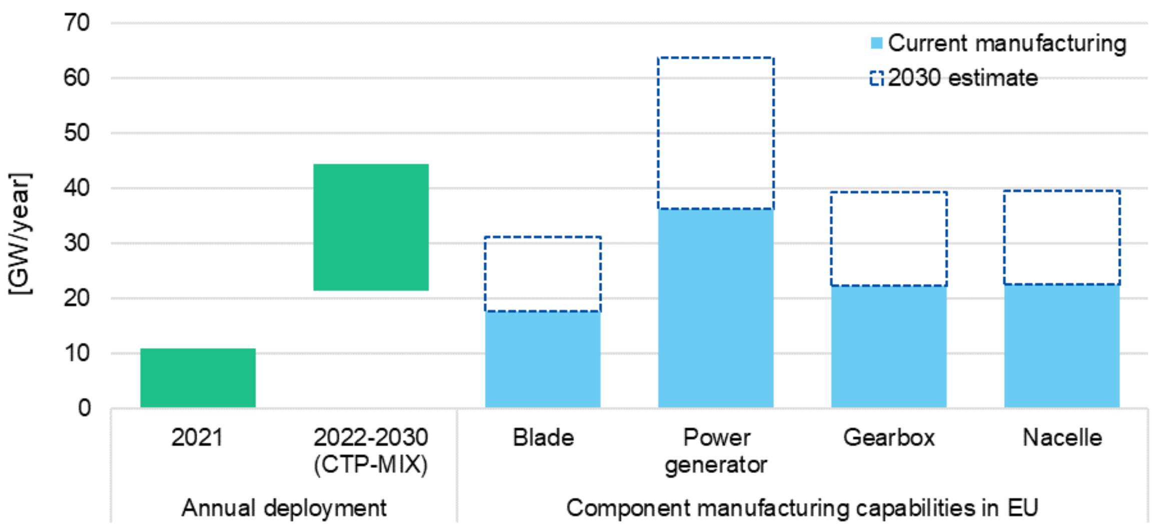
[21] The WindEurope/WoodMackenzie (2020) data set covers Tier1 and Tier2 component manufacturers of the following components: Nacelle, Bearings, Blades, Converters, Gearboxes, Generators, Castings, Forgings, Towers.

components where market shares based on manufacturing capacities were not available an estimate is provided based on the number of manufacturing facilities in the respective market (e.g towers, forgings, converters, castings, bearings) (see **Figure 76**).

Along with its leadership position in wind capacity deployment, China hosts the majority of manufacturing capacities of major wind energy components. China's market share ranges between 33% (bearings) and 58% (gearbox) across all major wind energy components. EU manufacturing ranks second showing market shares from 11% (blades) to 47% (castings), followed by India, the US and Brazil.

Supply chain capabilities and potential bottlenecks. Results of the scenario modelling of the 2030 Climate Target Plan (CTP-MIX scenario) envisage cumulative wind energy deployments reaching 439 GW by 2030 (of which 73 GW offshore). Assuming a continuously increasing annual deployment and replacement of decommissioned capacity (ranging from 0.6-8.7 GW/year) annual additions needed in the period 2022-2030 will range between 22.5 to 44.5 GW/year (with an average of 32.1 GW/year). Current manufacturing capabilities in EU easily cover the current demand in major wind energy components. However, as annual deployment rates need to show up to a fourfold increase to reach the ambitious 2030 targets supply chain bottlenecks might emerge if components are sourced from EU MSs. Based on current estimated manufacturing capabilities **Figure 69** assumes that manufacturing might increase towards 2030 by 76% if EU manufacturers are able to follow technological progress of wind turbines at their present factories. This is based on the assumption that the average rated capacity of the wind turbines in EU increases at the same rate as in the last decade from 2.2 MW in 2010 to 3.9 MW in 2020 (a 76% increase) towards about 6.9 MW in 2030. Based on this estimate, manufacturing capacities match the average 2022-2030 build-out rate, however investments in the manufacturing supply chain will be needed to avoid new import dependencies and to match the accelerated deployment from in the second half of the decade and from 2030 onwards.

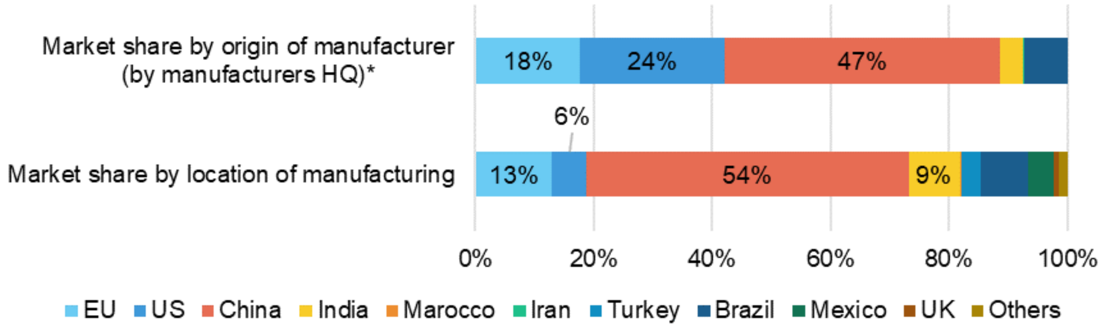
Figure 69. Current and future annual wind energy deployment rates towards 2030 targets and manufacturing capabilities of major wind energy components in EU



Source: JRC, 2022.

Blades. The global blade manufacturer market encompasses about 30 manufacturers with an estimated production capacity of 135 GW/year. By country of origin, blade manufacturers from China hold the biggest market share (47%), followed by companies from the US (24%) and the EU (18%). Analysing the market share of blade manufacturers based on the location of manufacturing unveils an even stronger dominance by Chinese suppliers with 54% of the estimated production capacity located in China (EU: 13%, India: 9%, Brazil: 8%, US: 6%).

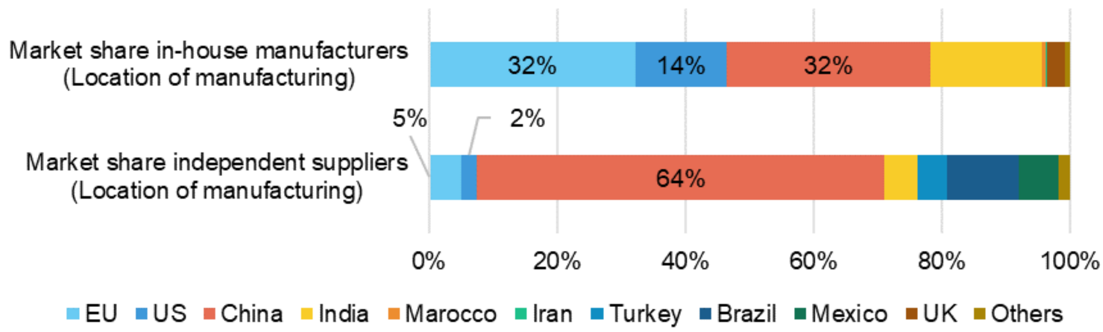
Figure 70. Estimated market share of blade manufacturers (by origin of company) and by location of manufacturing
* Unknown production capacities in Taiwan (Tien Li Offshore Wind Technology) and South Korea (Human Composites)



Source: JRC based on GWEC, 2022.

The market share based on the location of manufacturing (see lower row of **Figure 70**) can be divided into OEMs that have their own blade manufacturing capability (in-house manufacturers) and independent blade manufacturers (see **Figure 71**). About 29% of the estimated global production capacity is sourced from in-house manufacturers, whereas independent suppliers capture 71% of the market. By location, EU shows a strong tendency towards in-house blade manufacturing (32% of all in-house manufactured blades) whereas only 5% of the capacity provide by independent suppliers is manufactured within the EU. Contrarily, China is home of the majority of all independent blade manufacturers with about 64% of the capacity sourced from this type of manufacturer. Most of the main wind turbine OEMs (except Goldwind (CN) and Windey (CN)) have both in-house capabilities to produce wind turbine blades and a high diversification by sourcing blades from independent manufacturers (except Dongfang (CN) relying on in-house capacity only). Moreover, with ZhouZhou Times New Material (CN) and Aeolon (CN) two Chinese independent blade manufacturers have established cooperation with EU OEMs (e.g. Vestas, SGRE, Nordex) [GWEC 2020b].

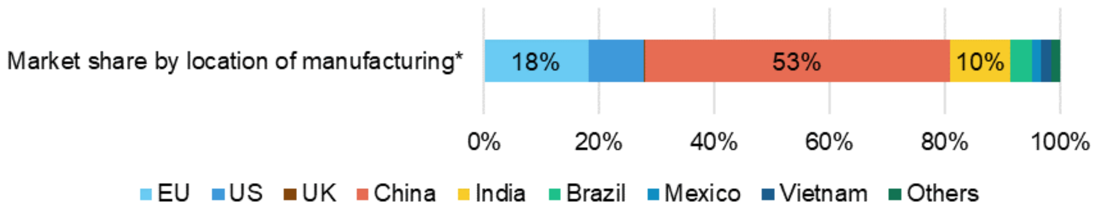
Figure 71. Estimated market share of in-house and independent blade manufacturers by location of manufacturing



Source: JRC based on GWEC, 2022.

Power generators. It is estimated that there are about 33 manufacturers of power generators worldwide with about 13 companies originating from China (EU: 8 companies). Based on the location of manufacturing China leads in estimated production capacity of generators with a market share of about 53%, followed by EU (18%), India (10%) and the US (9%) (see **Figure 72**).

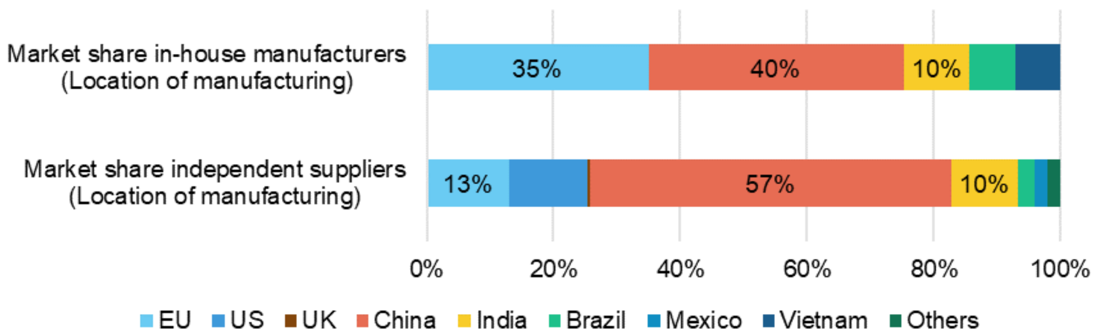
Figure 72. Estimated Market share of generator manufacturers by location of manufacturing
* Production capacities are distributed equally among the countries of manufacturing locations in case only aggregated values are available. Unknown production capacities of 8 companies located in Taiwan, South Korea, Japan, India, Brazil and Russia



Source: JRC based on GWEC, 2022.

About 24% of the estimated global production capacity is sourced from in-house manufacturers, whereas independent suppliers capture 76% of the market. About half of the leading wind turbine OEMs have in-house manufacturing of power generators including EU market leaders such as Vestas, SGRE and Enercon as well as GE Renewables (US) and SANY (CN). Moreover all leading OEMs diversify their supply chain by sourcing power generators form multiple suppliers [GWEC 2021b]. In terms of manufacturing location both in-house and independent suppliers are located China with estimated production capacities of 40% and 57%, respectively. Again a stronger tendency towards in-house manufacturing (35%) of companies producing power generators in EU is observed (see **Figure 73**).

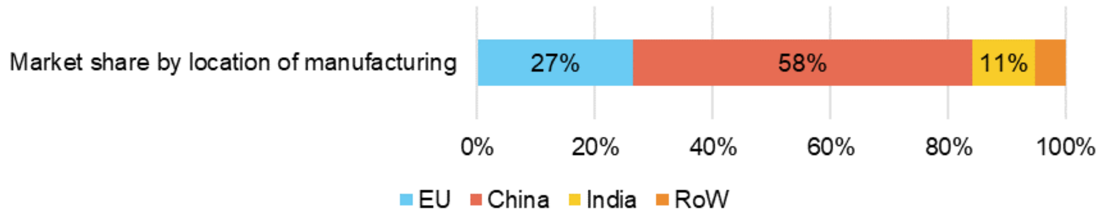
Figure 73. Estimated market share of in-house and independent generator manufacturers by location of manufacturing



Source: JRC based on GWEC, 2022.

Gearbox. GWEC (2019) estimates the global gearbox manufacturing capacity with about 84.3 GW. With about 58% the majority of gearbox manufacturing capacity is located in China, followed by companies in EU (27%) and India (11%). Among the main turbine OEMs only SGRE has dedicated in-house manufacturing capabilities. The Independent suppliers ZF (DE), Winergy (DE) and NGC (CN) are the most relevant gearbox suppliers providing their products to multiple of the leading wind turbine OEMs [GWEC 2019].

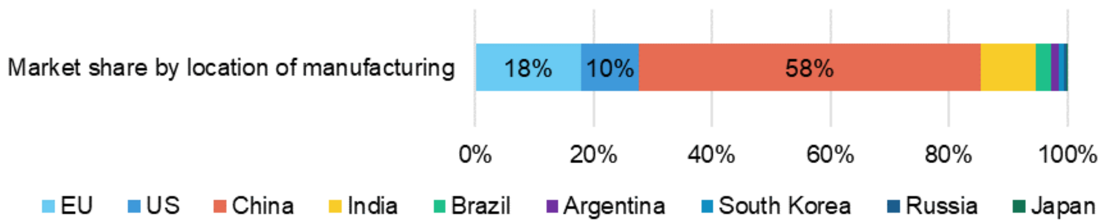
Figure 74. Estimated market share of gearbox manufacturers by location of manufacturing



Source: JRC based on GWEC, 2022.

Nacelle. 91 of the 145 nacelle manufacturing facilities worldwide are located in China (EU: 20 facilities, India: 11) [WindEurope/Wood Mackenzie 2020]. The global estimated nacelle production capacity is at about 126 GW, with about 58% of the market located in China, mostly supplying its domestic market. EU based manufacturing ranks second (18%) followed by nacelle production in the US (10%) and India (9%) [BNEF 2021].

Figure 75. Estimated market share of nacelle manufacturers by location of manufacturing

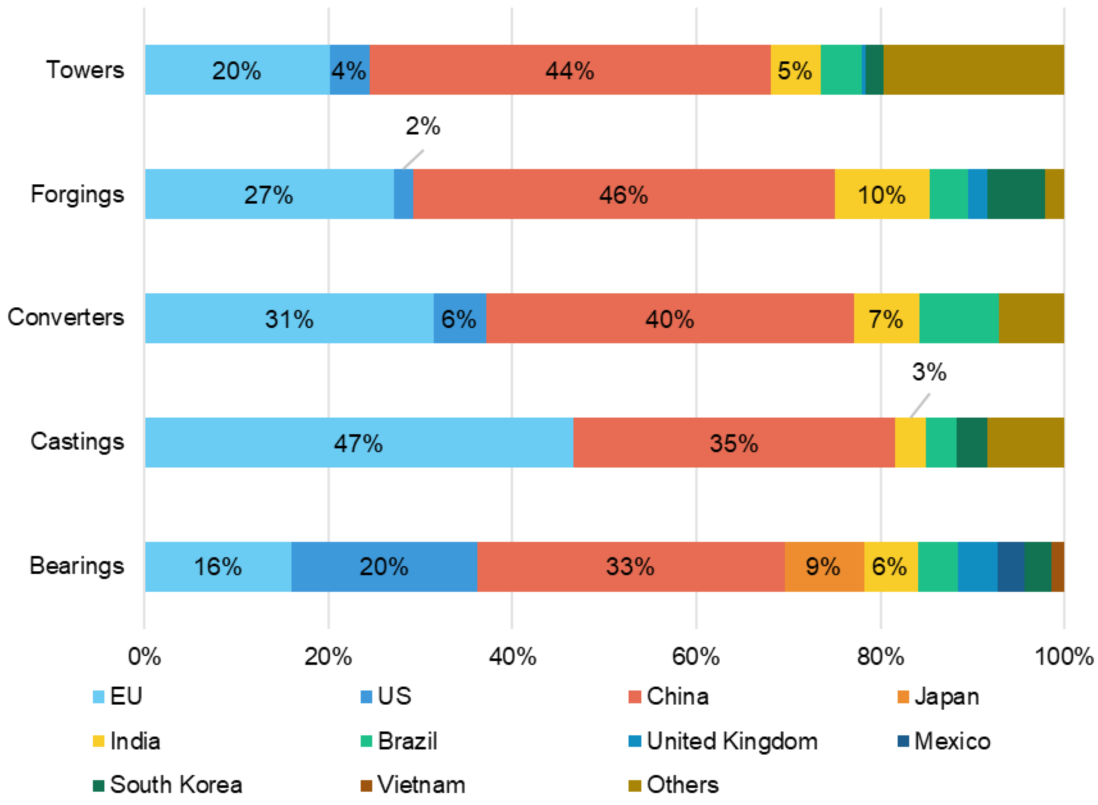


Source: JRC based on BNEF, 2022.

Other components. Other wind energy components in the supply chain include towers, forgings converters, castings and bearings. As data availability is limited on production capacities of these components an estimate based on the number of manufacturing facilities is provided (see **Figure 76**)

With the exception of castings, China is leading in all components with market shares ranging from 33% to 46%. EU manufacturing of these components is strong with market shares ranging between 16% and 47%. There is some evidence that tower manufacturing correlates with local deployment given the transportation challenges of the component and the low technical barriers to set up new facilities at the location of wind farm deployment (also compare correlation with cumulative wind deployment of respective countries in chapter 2.2). The market for bearings sees strong competition from multiple countries such as China, EU, the US, Japan and India as the component is also experiencing strong demand from other industrial sectors (e.g. automotive industry) [BNEF 2021].

Figure 76. Estimated market share of manufacturers of other components by number of factories and location of manufacturing



Source: JRC, GWEC, 2022, WindEurope, 2021.

The key EU manufacturers locate the majority of their production facilities in EU building on a strong domestic market and historically grown supply chains. However, component manufacturing capabilities of EU companies exist in all major wind markets. The main wind energy OEMs (Vestas (DK), SiemensGamesa (DE-ES), Enercon (DE) and Nordex (DE)) and component manufacturers set up manufacturing facilities in multiple global regions with presences outside EU concentrating particularly in the United Kingdom, the United States, India and China (see **Table 13**) [GWEC 2019, RN 2019, GWEC 2020b, Enercon 2021, GWEC 2021b, IEC 2021, Enercon 2022b, Nordex 2022, ORBIS 2022, SGRE 2022b, Vestas 2022d]. Apart from being present in the leading markets with respect to wind energy deployment, the relocation of manufacturing facilities outside EU is influenced by low labour costs (e.g. Bosnia, Serbia, Turkey, Morocco, India), local content requirements and trade barriers (e.g. United Kingdom, Taiwan, China) [Yuan et al. 2015, WPM 2021c].

Table 13 Global presences and component manufacturing capabilities (share of total production) of main EU wind companies
Note: X marks entries where a manufacturing location but no production capacity or no country specific shares of production capacity was available
* Cooperation between Vestas (DK) and Tien Li (TW): In 2020 Tien Li (TLC) finalised a sub-supplier contract with MHI Vestas to manufacture blades for turbines to be delivered in upcoming Taiwanese projects

Company (country)	Component	EU	RoEU					Americas				Asia Pacific			Africa
		EU27	United Kingdom	Turkey	Bosnia	Serbia	Russia	United States	Mexico	Brazil	Argentina	India	Taiwan	China	Morocco
Vestas (DK)	Blade	53%	X				X	29%	X			9%	*	10%	
	Generator	X												X	
	Yaw System - Drive & Brake (offshore)	X	X												
	Yaw System - Bearing (offshore)	X	X												
	Control systems	X												X	
	Nacelle	X						X			X	X		X	
SiemensGamesa (SGRE) (DE-ES)	Blade	51%	X					17%				8%		22%	2%
	Generator	X										X		X	
	Gearbox	X												X	
	Yaw System - Drive & Brake (offshore)	X	X												
	Yaw System - Bearing (offshore)	X	X												
	Nacelle	X											X		
Enercon (DE)	Blade	X		X			X			X					
	Generator	80%										20%			
The Nordex Group (DE)	Blade	48%						40%	6%			6%			
	Nacelle	X						X				X			
Ingeteam (ES)	Generator	X						X				X			
Elin Motoren GmbH (AT)	Generator	20%			40%							40%			
Winergy (DE)	Generator	X				X								X	
	Gearbox	X						X				X		X	
ZF Wind Power (DE)	Gearbox	X						X				X		X	

Source: JRC analysis based on IEC, ORBIS, GWEC, Enercon, SiemensGamesa, Nordex, Vestas, 2022.

The following sections identify the structure and main players in the EU supply chain for wind rotors, for both onshore and offshore wind sectors, according to the following supply chain categories:

1. **Project developers and owners** – Companies developing wind farms or holding stakes through M&A in projects, thus owning the components (WTG (rotors)) of the wind farm
2. **Tier 1 component manufacturers** – Companies involved in the manufacturing and assembly of the main components. This includes the following components: blade, shaft, foundation, gearbox, generator, nacelle (and nacelle assembly), substation (offshore), power converter, tower, transformer
3. **Tier 2 component manufacturers** – Companies producing smaller sub-components that merge, integrate or enable the proper operation of main components: blade bearing, control system, HV export cables, inter-array cables, main bearing, pitch system, switchgear, turbine controller, yaw system components.[22]

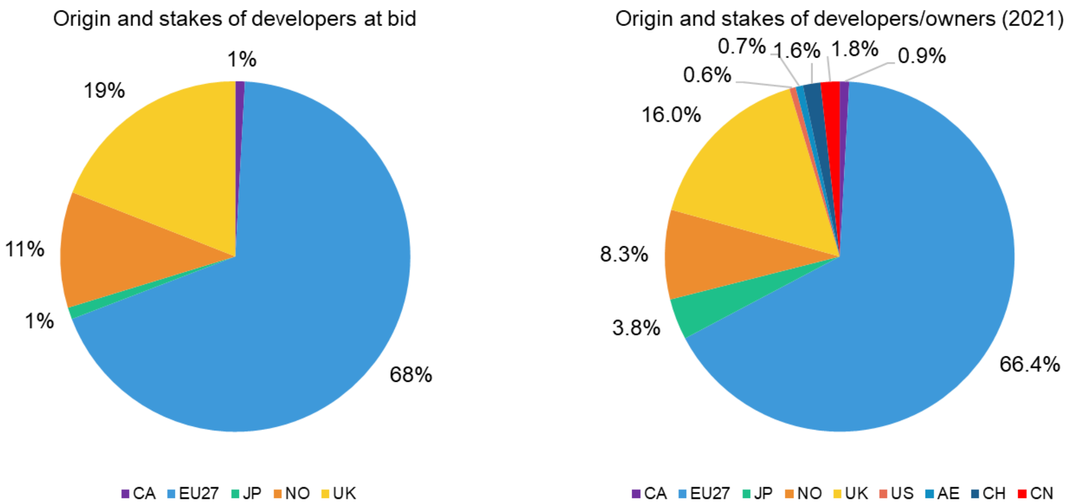
Tier 3 component manufacturers providing specialised solutions and innovations for the wind sector are not covered in this section but are included in the macroeconomic indicators (e.g. chapter 2.5).

Moreover, the different players in the EU supply chain are analysed by manufacturing location and country of origin. The sourcing strategy of the various original equipment manufacturers (OEMs) is identified through current market shares of their latest wind turbine models deployed in the EU27, and information on the wind turbine model component suppliers as reported in the latest component certificates of international certification bodies.

3.4.2 Project developers and ownership

Across all EU countries, a cumulative offshore wind capacity of about 20.6 GW has been allocated through competitive tendering procedures, which are expected to be commissioned until 2025. With about 12.6 GW of offshore capacity, the top five developers (Ørsted, Vattenfall, RWE Renewables (innogy SE), SSE Renewables and Equinor) account for more than 60% of the ownership of the allocated capacity. Since the announcement of their successful bid, EU developers have kept their ownership almost stable at about 66% (losing only 2%) of the total competitive tendered offshore capacity (see **Figure 77**).

Figure 77 Developers and ownership of allocated capacity in competitive offshore tenders in Europe until 2020



Source: JRC analysis, 2021.

[22] Tier 1 and Tier 2 categorisation and reported component suppliers based on the JRC Wind Manufacturers Database

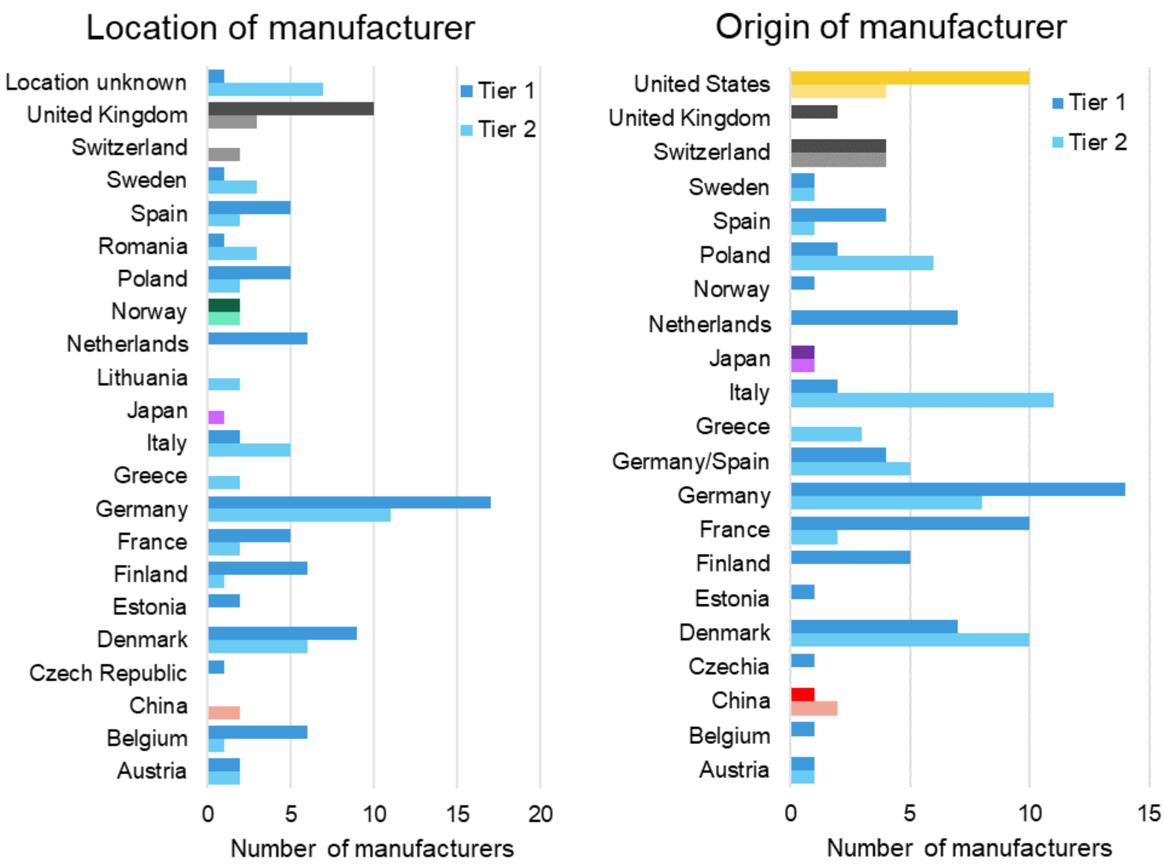
Notably, the latest competitive tender schemes in the Netherlands and the United Kingdom (Hollandse Kust Noord and UK CfD Allocation Round 3) saw a strong presence of the European O&G majors (Equinor, Shell, Eni, Total) stepping into the field of offshore wind development. A small share of projects is held by non-European companies stemming from Japan (Diamond Generating E.L., Kansai Electric Power, J-Power/Electric Power Development, Mitsubishi UFJ), China (Red Rock Power, China Resources Company, CTG Corp.), Switzerland (Partners Group), Canada (Enbridge Inc.), VAE (Masdar) and the United States (Global Infrastructure Partners).

In the onshore wind developer market, the ownership structure is much more fragmented. About 1900 project developers and 3000 project owners developed onshore wind projects that came into operation in the last decade. Energy utilities (Enel, EDP, EDF, Engie, RWE) lead in holding most of the deployed capacity in this period, with foreign players also among them, such as CGN (China).

3.4.3 Offshore manufacturing supply chain

The European manufacturing supply chain for offshore wind at Tier 1 and Tier 2 level (see categorisation of components in chapter 3.4.1) builds mainly on companies from EU Member States. Tier 1 and Tier 2 suppliers have 138 facilities located in the EU, of which about 84% are of EU origin. Tier 1 suppliers are located in the leading EU offshore wind markets around the North Sea and Baltic Sea, such as Germany, Denmark, the United Kingdom, the Netherlands and Belgium, as well as in countries that can leverage a strong onshore wind supply chain (Spain) or that host a specific Tier 1 component (Finland: transformer manufacturers).

Figure 78 Manufacturers of the European offshore manufacturing supply chain. Location (left) and origin (right) of Tier 1 and Tier 2 component suppliers
Note: Includes facilities with joint onshore and offshore component production



Source: JRC Wind Manufacturers Database, 2021.

Moreover, suppliers of offshore wind components can be found all over Europe, even in landlocked countries. There is only some indication of Tier 2 components coming from non-European companies in China and Japan (see **Figure 78**). 78% of the identified offshore wind facilities are owned by manufacturers from the EU, followed by companies from the US (10%), Switzerland (6%), China (2%), Japan (1.5%) and the United Kingdom (1.5%).

Offshore supply chain capabilities and potential bottlenecks. The EU offshore market has further consolidated in recent years, following Senvion's insolvency at the end of 2019 and Vestas's buying out of Mitsubishi Heavy Industries (MHI) from their offshore wind joint venture in 2020 [WPM 2020d, WPM 2020e]. With SiemensGamesa RE, Vestas and General Electric RE, there are currently three offshore original equipment manufacturers (OEMs) with manufacturing capabilities in EU waters. Today, the three main offshore OEMs have an estimated 6.5-8 GW of nacelle assembly capacity at European ports (see **Table 14**) [WindEurope/Wood Mackenzie 2020]. This is sufficient to supply current deployment needs of about 3 GW of new offshore wind farms every year, however capabilities will need to increase to about 11 GW/year by 2030 to satisfy the offshore wind deployments in European waters (EU27, NO and UK). 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 (based on scenario modelling of the 2030 Climate Target Plan (CTP-MIX scenario)), necessitating additional investments in the offshore wind supply chain (see **Figure 79**).

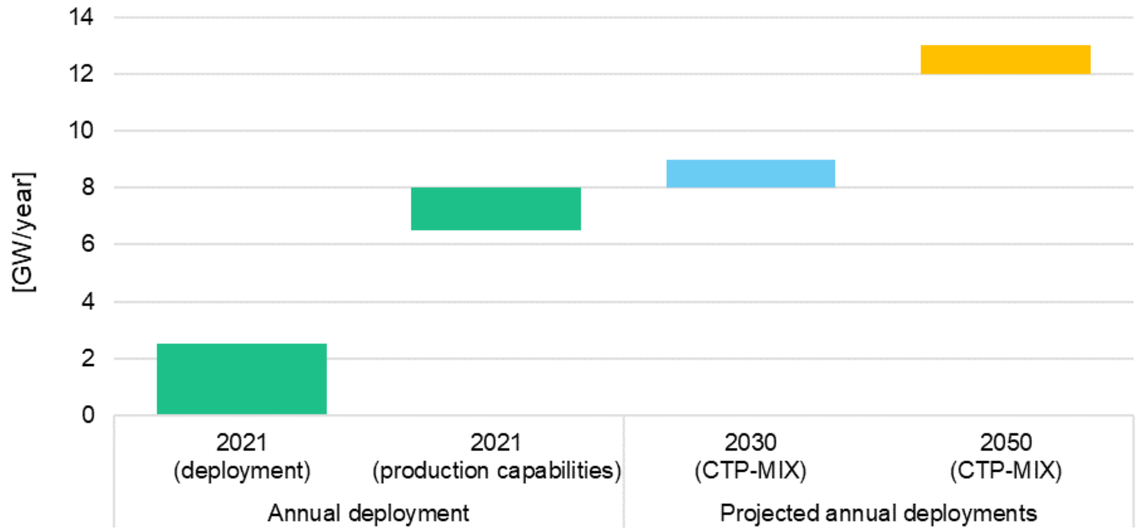
Table 14. Location and estimated production capacity of the leading offshore wind manufacturers (nacelles and blades) in Europe

Offshore manufacturer	Location/port of Blade or Nacelle assembly factories	Country	Sea basin	Offshore nacelle production capacity estimate [GW/year]
Siemens Gamesa	Bremerhaven Cuxhaven Aalborg Alexandra -Green port Hull	Germany Germany Denmark United Kingdom	North Sea North Sea North Sea (Kattegat) North Sea	4
Vestas	Port of Lindø (Munkebo) Nakskov (Zealand) Esbjerg (Sydjylland) Isle of Wight	Denmark Denmark Denmark United Kingdom	Baltic Sea (Danish straits - Great Belt) Baltic Sea North Sea North Sea (English Channel)	2
GE Renewable & LM Wind Power	Cherbourg Saint Nazaire Lunderskov Castellón	France France Denmark Spain	North Sea (English Channel) Atlantic Ocean Baltic Sea (not at coast, close to Kolding) Mediterranean Sea (not at coast)	0.5 (2)

Source: JRC, 2022, WindEurope/Wood Mackenzie, 2020.

These ambitious deployment figures mean a significant increase in the provision of offshore wind components and hence manufacturing capabilities at EU ports. Annual demand for main wind components (nacelle, towers, transition pieces, foundations) is estimated ranging at about 740-870 units per year (blades: 2200-2600 units/year) assuming that the average rated offshore turbine capacity increases from 12 MW in 2030 to 15 MW in 2050. Moreover, there is the need for 6 to up to 17 offshore substations per year depending on technology choice (HVAC or HVDC). Based on these assumptions, the demand for array cabling is estimated at about 1200 km/year and 1450 km/year in 2030 and 2050, respectively. Assuming an average distance to shore of about 70 km, the demand for offshore export cables will increase from 1680 km/year in 2030 to about 2430 km/year in 2050 (see **Figure 80**).

Figure 79. Current EU offshore wind deployment and production capabilities and projected annual offshore wind energy deployment rates of the 2030 Climate Target Plan (CTP-MIX scenario)
Note: Production capabilities include offshore facilities of SGRE in the United Kingdom

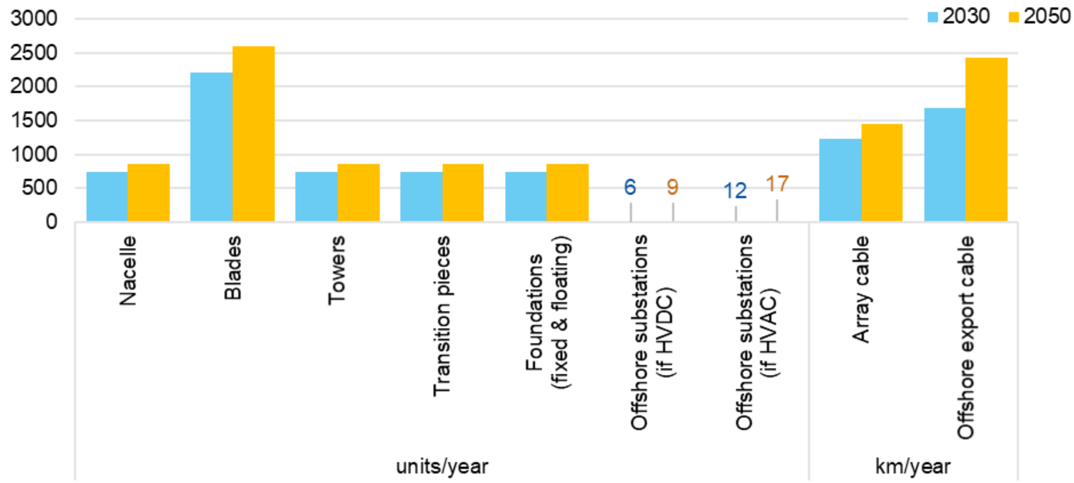


Source: JRC, 2022.

Most active ports dealing with offshore wind in EU are in the North Sea (e.g. Eemshaven, Port of Amsterdam, Port of Den Helder) but also in the Baltic Sea (e.g. Port of Ronne A/S, the Atlantic Ocean, e.g. Port of Bilbao), and in the Mediterranean Sea (e.g. Port-La-Neuvelle) Ports play an important role in continued cost reductions and increased build-out times of offshore renewables. They will also have a central role in delivering renewable hydrogen from offshore renewables and decommissioning ageing offshore infrastructure. Port operations can include onshore transportation and storage, load-out, pre-assembly, fabrication, O&M, decommissioning, and other services. While gaining experience from working with offshore wind, ports will require a plan for space allocation and accommodation of the various renewable energy sources, as other technologies mature. Floating structures and substructures will require significant assembly and storage area compared to bottom-fixed technologies. Future turbines of 18 MW and above could require monopiles of 12 m diameter, while floating substructures could have as much as a 36 m diameter, which is a tenfold increase in the surface area. The expected yard size that is required to fabricate the structures is on average about 10 ha, while some manufacturers require up to 40 ha [Carbon Trust 2015, Arup 2020, Anchor Qea 2021] (see also **Table 21** for comparison of yard area with newly developed facilities in the UK).

In order to deliver on the offshore wind targets in European waters until 2030, WindEurope estimates the investment needs for new port infrastructure and upgrading of existing ports at about EUR 6.5 billion [WindEurope 2021]. This includes investments in existing facilities, the building of new port terminals, decommissioning facilities, adaptions of ports to host floating offshore wind, hydrogen infrastructure and the infrastructure related to energy islands operations and products (see ***Table 15***).

Figure 80. Estimated demand for major wind energy components in EU by 2030 and 2050 based on the deployment rates of the EU2030 Climate Target Plan (CTP-MIX scenario)
Note: Assuming an average offshore wind turbine capacity of 12MW and 15MW in 2030 and 2050.



Source: JRC, 2022, WindEurope, 2021.

Table 15. Investment needs and costs for infrastructure works in EU ports

Investment item	Cost per investment	Number of investments (no of ports)	Total investment
Upgrading/extending facilities for a port already in the bottom-fixed offshore wind business	EUR 20-80 million	30	EUR 1 billion
Building a new energy port/terminal for bottom-fixed offshore wind (around 15-20ha)	EUR 80 – 110 million	15-20	EUR 2 billion
Building a decommissioning facility/refurbishing an existing facility in the port	EUR 5-10 million	5	EUR 50 million
Floating port adaptations or new terminal	EUR 200 million	6	EUR 1.5 billion
Infrastructure for renewable hydrogen production in ports	EUR 100 million	10	EUR 1 billion
Accommodating energy island operations, products, and related infrastructure	EUR 500 million	2	EUR 1 billion

Source: WindEurope, 2021.

With 48 jack-up vessels in operation and nine more under construction Europe has about half of the 100 operational jack-up vessels globally. China follows closely, with 42 jack-up vessels and nine more under construction. Other Asian countries operate 8 jack-up vessels (5 vessels under construction) whereas only 2 jack-up vessels (1 vessels under construction) are currently in North America. Depending on weather conditions, jack-up vessels are capable of installing one turbine per day, while heavy-lift vessels can install 1.5 to 2 foundations per day. Offshore installation operations in Europe are almost exclusively driven by European companies. In the Asia-Pacific region (excluding China), European companies (mostly UK and Norwegian) have a significant market share, at least in the short term, because they have not experienced any bottlenecks in Europe. However, Europe is facing an oversupply of inadequate jack-up vessels, as only seven of them have the crane capacity and hook height sufficient to install wind turbines of 12 MW and above. Heavy-lift vessels in Europe are mostly used for installation and transportation of monopiles, jackets, and substations. At present only 15 heavy-lift vessels have a lifting capacity above 2500 t which is needed for projects hosting 10 MW+ wind turbines. As a result European companies invest in upgrading relatively new vessels (e.g. DEME Group upgrading it installation vessels) or by ordering new vessels capable to install next generation wind turbines. European companies have ordered (mostly in China) nine jack-up vessels, with a delivery date of 2022-2025, which would be large enough to install next-generation offshore wind turbines of up to 20 MW. Furthermore, five heavy-lift vessels have been ordered to install ultra-large foundations and turbine installations. If the jack-up vessels and heavy-lift vessels are delivered on time, European offshore installations should not face bottlenecks until 2026. The Chinese supply chain is facing similar problems, as the rush by developers to complete projects before the expiration of feed-in tariffs is likely to cause an over-capacity of installation vessels from 2022. If the European supply chain continues to be pressured by cost decreases, the Chinese supply chain could exploit the domestic over-capacity and enter the European market. At the same time, although Chinese companies increased their capabilities (the vessel fleet has increased by 600% since 2015), a lack of experience in installing offshore wind projects provides the potential for foreign subcontractors to enter the market. A recent example includes the suction installation services performed by SPT Offshore (NL) for the first suction pile jacket in the South China Sea [WPM 2019b, Energy Iceberg 2020, GWEC 2020c, SPT Offshore 2020, Kuokkanen et al. 2022].

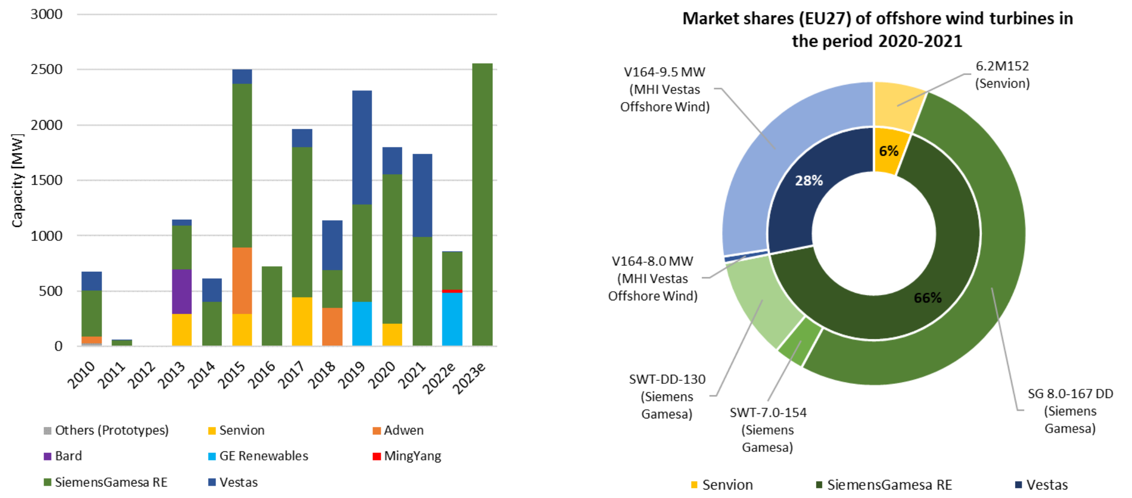
Floating offshore projects face challenges in the relative motion between the lift vessel and floating turbine, which will result in increasing demand for dynamic positioning systems and other motion-compensation systems. Recently, the wind turbine manufacturer Vestas, in collaboration with the developer Parkwind and the vessel operator Heerema, introduced a dual-crane vessel that enables floating installation involving dynamic lifting. Alternative lifting solutions, such as climbing crane technology, could also play a role, lowering installation costs (by not using expensive jack-up vessels), but requiring advance knowledge of future turbine specifications and possible adaptions to turbine designs. The O&M jack-up vessels currently used in the offshore wind sector will not be suitable for servicing floating offshore wind farms, as they must operate in deeper waters and in some cases need a higher hook height [Carbon Trust 2020, Carbon Trust 2021, Ocean Energy Resources 2021, WoodMackenzie 2021, Kuokkanen et al. 2022].

EU market shares and component sourcing strategy. In the period 2021, SiemensGamesa RE and Vestas held together a market share of 94% in EU27 countries (see **Figure 81**). Moreover, GE Renewable Energy currently tests its 12 MW GE Haliade-X in Maasvlaakte (Port of Rotterdam), which first produced power in November 2019 and will have its first commercial installation at the Dogger Bank C offshore wind farm (UK). However, wind turbine certificates published by the IEC (International Electrotechnical Commission) reveal that all offshore OEMs have established their own supply chain and sourcing strategy for the subcomponents of their offshore wind rotors (see **Table 16** and **Table 17**) [IEC 2021]. Wind turbine rotors by Siemens RE and Vestas deployed in 2020 build on a strong European supply chain, with most of the components being sourced from EU companies. Yet both OEMs source some components from non-EU countries, highlighting the importance of trade relations (UK) and of maintaining the EU's competitive advantage in offshore wind against its main competitors (e.g. China). Vestas manufactures blades, shaft and yaw components in the United Kingdom and some of its switchgears in Norway, Japan and China. Similarly, SiemensGamesa RE has a strong UK-based production of blades, shaft and yaw components, yet the company seems to diversify its production more markedly among different countries. The company has, for example, certified TMB (Zhejiang Tianma Bearing Group Limited), a company based and producing in China, as a component supplier. The diversification in sourcing of components by SiemensGamesa RE seems to become more pronounced for the most recent certified offshore wind turbines. **Table 17** shows that the SG 10-200 DD turbine builds on several additional Chinese component manufacturers for the shaft, yaw system and generator as compared to the SG 8.0-167 DD model.

Based on current component certificates, component manufacturing of EU deployments of the upcoming Haliade X model by GE Renewables is expected to be located in EU Member States.

In 2021, Chinese OEM MingYang entered the EU offshore wind market by securing a deal to supply 10 offshore wind turbines to the 30 MW Port of Taranto (Beleolico) offshore wind project (replacing the previously planned Senvion turbines), which will be the first commercial EU offshore wind farm in the Mediterranean Sea (end of 2021). MingYang will execute the project from its EU HQ in Germany while turbines seem to be shipped from China. Moreover, monopiles will be provided by a Spanish manufacturer (Haizea Wind Group) [OE 2021, WPM 2021d].

Figure 81 Market shares (EU27) of offshore wind OEMs in the period 2010-2023 (left) and market shares in the period 2020-2021 and the respective offshore wind turbine models deployed (right).



Source: JRC Wind Manufacturers Database, 2021.

Table 16 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 17 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)	

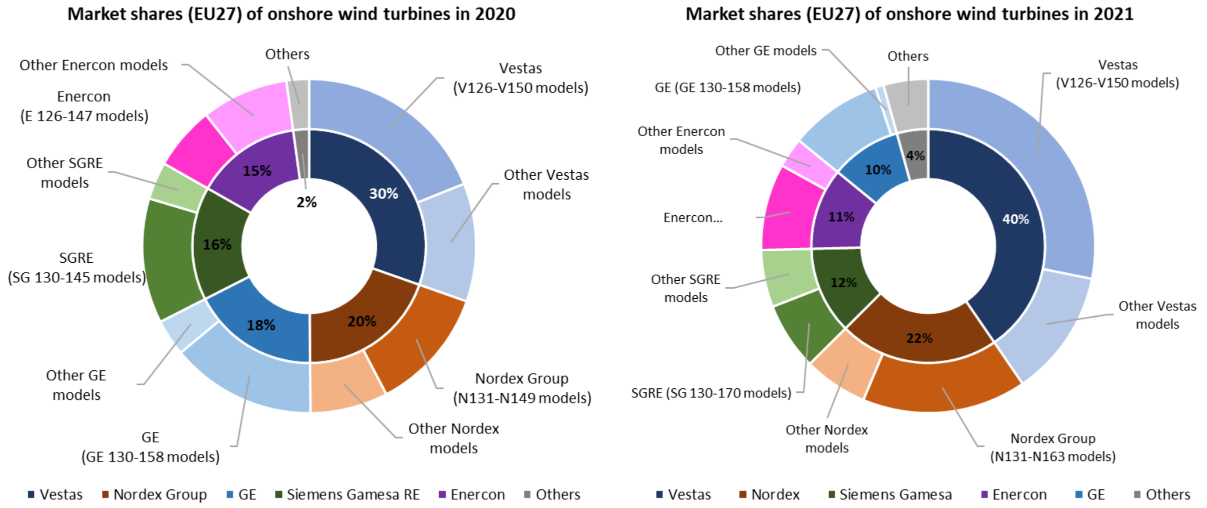
*Certificate mentions SiemensGamesa A/S in Denmark

Source: JRC, IEC, 2022.

3.4.4 Onshore manufacturing supply chain

In 2020 and 2021, EU companies held between 80% and 90% of the EU onshore wind rotor market, respectively. The rated capacity of onshore wind turbines continues to increase towards models above 3 MW, increasing their annual market share within the EU from 2% in 2010 to about 81% in 2020 [JRC 2020a]. This means an increase in the wind blade size of current onshore wind rotor models, with OEMs installing more than 60% of their models in the 120 m to 150 m rotor diameter range (see **Figure 82**).

Figure 82 Market shares (EU27) of onshore wind OEMs in 2020 and 2021 and the respective onshore wind turbine models deployed
Note:



Source: JRC Wind Manufacturing Database, 2021.

As in the offshore sector, European OEMs mainly source their onshore wind rotor components from companies based in EU Member States. Component certificates of some recent onshore models confirm the competitiveness of Chinese manufacturers in some components, such as blade bearings and shafts. Given the global scale of the onshore wind industry, European OEMs seem to source their components from multiple suppliers (in contrast to the offshore case) and cooperate with component suppliers with a global manufacturing footprint (e.g. pitch system, bearing of the Vestas V150) (see **Table 18)**.

Table 18 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-	SKF (SE/AT-DE-FR-SE)	

	RO-CN-IN-PH)		
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.

3.4.5 EU – UK supply chain dependencies and UK local content requirements

In December 2021 the UK government opened its biggest renewable energy allocation round (AR 4) of the Contracts for Difference (CfD) scheme. It aims to secure 12GW of renewable energy capacity with GBP 200 million and GBP 24 million allocated to bottom-fixed offshore wind and floating offshore wind projects, respectively (total budget of AR4: GBP 285 million)[23]. A novelty in this round concerns the introduction of a local content criteria in the application process. In order to qualify for AR4, applicants of offshore wind projects (<300 MW) need to provide a Supply Chain Plan approved by the Secretary of State for BEIS to the National Grid Electricity System Operator (National Grid ESO) [BEIS 2021b, OW 2021a].

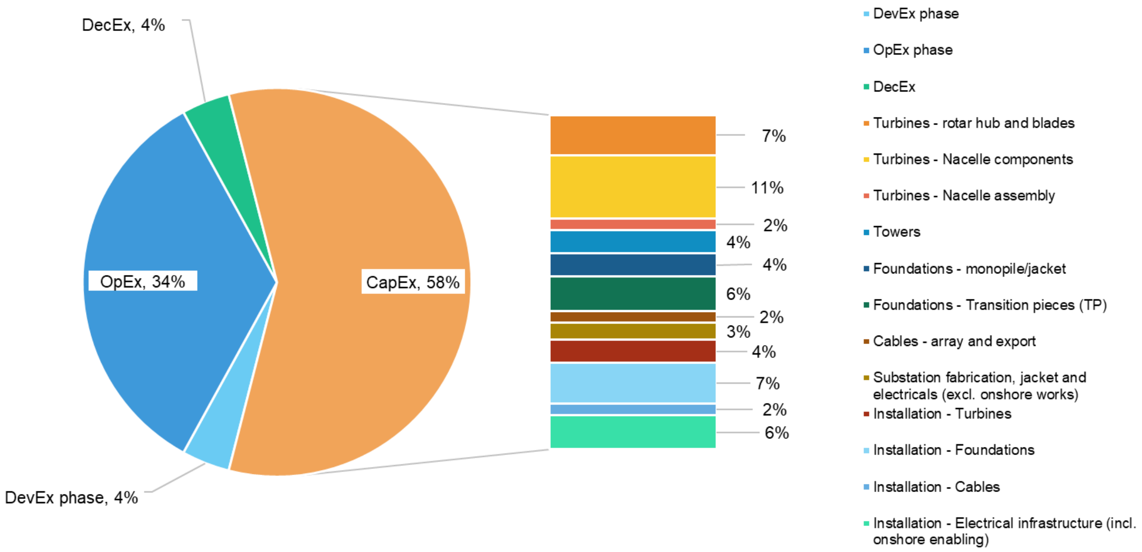
In March 2022, EU requested consultations with the United Kingdom at the World Trade Organization (WTO) on the UK's discriminatory practices when granting support for green energy projects as the subsidies for offshore wind energy projects favour UK over imported content [EC 2022af].

The scoring criteria of UK local content of the Supply Chain Plan is based on the project's lifetime expenditures and divided into the main project phases (DevEx, CapEx, OpEx and DecEx). Moreover, applicants need to specify in detail the level of local content of the CapEx phase given its importance in lifetime expenditures (see **Figure 83** on the weighting of UK local content).

In February 2022, the UK launched a consultation in order to reform the Contracts for Difference (CfD) scheme in view of allocation round 5. Potential changes include the extension of Supply Chain Plans to floating offshore wind [OW 2022a].

[23] Applications were due 14/01/2022, with final auction results expected in summer 2022.

Figure 83 Weighting of project lifetime expenditure in BEIS Allocation Round 4 Supply Chain Plans for determination of UK local content



Source: JRC based on BEIS, 2022.

The emphasis on UK local content in AR4 is in line with the UK's Offshore Wind Sector Deal aiming for global leadership in the offshore wind industry by providing a forward visibility in future Contracts for Difference rounds, increasing the UK local content of projects to 60% by 2030, increasing exports fivefold by 2030 (to GBP 2.6 billion) and by investing up to GBP 250 million into the UK supply chain through the Offshore Wind Growth Partnership (OWGP) programme to increase competitiveness [BEIS 2019]. The OWGP programme is managed by ORE Catapult and focuses on direct support to supply chain companies through strategic capability assessments, advisory services and grant funding. Funding is provided by the Offshore Wind Industry Council (OWIC) members, supply chain match and regional collaborations. By mid-2022 at total of 131 projects have been supported allocating GBP 12.7 million. Latest projects awarded with grants in the OWGP Innovation Grant Funding Competition, Development Grant Funding Competition and the funding calls on 'Competitiveness from advanced manufacturing techniques', 'Advanced sensors, IoT and communication solutions for offshore wind' 'Cross-Sector Support' and 'Open Funding' saw in total 35 (in total they claim 47 projects funded by OWGP grants) UK companies funded addressing challenges in the following areas [OWGP 2021, OWGP 2022a, OWGP 2022b, OWGP 2022c, OWGP 2022d]:

- offshore wind site development and consenting, including optimising site selection, environmental monitoring and compensation methods, subsea surveys, and data analysis techniques (11 projects)
- fabrication and turbine assembly, wind farm surveillance and bolt maintenance (5 projects)
- advanced manufacturing techniques, advanced sensors, IoT and communication solutions for offshore wind (7 projects)
- addressing of barriers to diversify and support the expansion of the UK supply chain and developing innovative solutions and demonstrate improved competitiveness within the supply chain (12 projects)

Moreover, the UK government launched the Offshore Wind Manufacturing Investment Support scheme in 2021 to support the delivery of manufacturing investment in the offshore wind supply chain as part of the government's ten point plan for a green industrial revolution [HM Government 2020]. The scheme provides grants to UK registered businesses for investments in manufacturing of offshore components (e.g. blades, towers, cables, monopiles among others) [BEIS 2021c].

Local content requirements (LCR) might pose a threat to the European offshore wind supply chain as they hold the potential to distort trade and cause unintended effects on investment across value chains (reduced competition, reduced technology diffusion through trade (see for example [OECD 2015])). In order to estimate potential effects of the newly introduced Supply Chain Plans in AR4 on sourcing strategy this section maps the announced contractors of subcomponents of AR4 candidate projects. The Contracts for Difference (CfD) allocation round 4 started in December 2021 with results expected by summer 2022. Thus, at the time of writing (March-May 2022) published information on subcontractors is still scarce or subcontractors are not yet decided. Still, selected conclusions can be drawn from recent announcements.

Table 19 maps the origin of subcontractors in the supply chain of candidate projects of allocation round 4 along the main project development phases of the Supply Chain Plans. For most projects the development phase is performed by UK companies (e.g. East Anglia Offshore Wind Ltd, Inch Cape Offshore Wind Farm Limited, Moray Offshore Renewables Ltd., Highland Floating Winds Ltd, SeaGreen Wind Energy Limited) or foreign organisations which formed a dedicated subsidiary in the UK (EDF Energy Renewables (FR/UK), Ørsted Limited (DK/UK)). However, there is evidence that even those projects developed by UK companies build on non-EU subcontractors in the development phase, as in the case of the Hornsea Project Three subcontracting FUGRO (NL) for site investigations [OW 2022b]. Only three projects are developed by non-UK players, namely by Vattenfall Europe Windkraft GmbH (DE), Vattenfall AB (SE) and Bechtel Infrastructure & Power Corporation and Hexicon AB (US-SE). With 58%, the CapEx phase has the highest impact on project lifetime expenditure and thus on the scoring criteria of UK local content. By mid-May 2022, information on the deployed turbine model or turbine OEM is available for seven projects. Six out of seven project announced SiemensGamesa RE as turbine supplier providing 14MW+ turbine models (e.g. SG 14-222 DD or SG 14-236 DD). One project (Seagreen) will deploy Vestas V164-10.0 MW turbines. Although both companies manufacture and assemble their turbines in the UK (SiemensGamesa RE at Green Port Hull and Vestas at Isle of Wight) many of the turbines' subcomponents are relying on an EU or even international supply chain. From a manufacturer's perspective, SiemensGamesa RE currently seems to have a more diversified turbine component sourcing supply chain than Vestas with multiple alternatives in single subcomponents and multiple non-EU component suppliers. Exemplarily, SiemensGamesa RE can source 4 main turbine components of its flagship turbine (SG 10-200 DD) from suppliers outside Europe (mostly China) whereas Vestas sources only one component from non-EU countries for its V164-9.5MW (please see section 3.4.3, **Table 16** and **Table 17** for the certified subcomponent manufacturers of latest flagship turbines of both companies). Therefore distortions in trade relations between the EU and the UK would have different consequences on the two major EU offshore wind OEMs. Information on the suppliers of other major components (Towers, Foundations, Cables) of AR4 applicant projects is scarce or subcontractors are not yet decided. Monopile foundations of the Hornsea Project Three will be provided by SeAH Wind Limited (UK) a subsidiary of South Korean pipe manufacturer SeAH Steel Holdings (KR) unveiling its plans to build a GBP 300 million XXL monopile factory on Teesside in Northeast England [OW 2022c]. In case of the Seagreen project, jacket foundations, transition pieces and suction caissons are manufactured outside the UK by Lamprell (UAE) in Hamriyah port (UAE) [OW 2022d]. The Moray West project will deploy export cables manufactured by Nexans (FR) in plants in Halden and Rognan (NO), Charleston (US) and Charleroi (BE). Moreover, cable installation will be performed by the cable-laying vessel Nexans Skagerrak (under NO-flag) [OW 2021b]. All known installation activity on the Seagreen project are provided by non-UK companies, turbine installation and involved transports are performed by installation contractor Cadeler's (DK) giant wind farm installation vessel Wind Osprey while foundation jacket installation was performed by Seaway 7 (NO) and SAIPEM (PT) [OW 2021b, OW 2021c, OW 2021d]. Installation services of the investigated projects operate exclusively from UK ports (Great Yarmouth, Buckie harbour, Nigg, Blyth, Montrose, Seaton). Operation and maintenance (O&M) of projects, for which this information was available, will be executed from Lowestoft, Grimsby, Buckie harbour, Great Yarmouth, Scrabster and Montrose (all UK). With respect to O&M, Vattenfall has named SiemensGamesa RE as preferred supplier of wind turbines for both Norfolk wind farms including a multi-year service agreement [OW 2021e]. SSE Renewables will operate the Seagreen project [OW 2021f].

Table 19 Information on the origin of manufacturers contracted for candidate projects of allocation round 4 along the project phases assessed in the Supply Chain Plans.
Note: Please see Annex 2 for table including detailed footnotes

UK based manufacturing	
n.a.	no information available or not yet decided
0	Manufacturing or service provided outside UK
1	Existing manufacturing location of component in UK / Service (O&M, Installation) performed from UK port
2	Manufacturing location of component in multiple countries (including UK)
3	No information on sourcing of component for the project, yet existing or upcoming manufacturers in UK

	Blyth Offshore Demonstrator - phase 2	East Anglia Hub - ONE North	East Anglia Hub - THREE	East Anglia Hub - TWO	Hornsea Project Three	Inch Cape	Moray West	Norfolk Boreas	Norfolk Vanguard	Pentland	Seagreen	Seagreen 1A	TwinHub
Phases (based on SCP -Scoring categories)													
DevEx phase (4%)	1	1	1	1	1**	1	1	0	0	1	1	n.a	0
CapEx phase (58%)													
Turbines - rotor hub and blades	n.a.	1	1	1	n.a	n.a	1	1	1	n.a	1	n.a	n.a
Turbines - Nacelle components	n.a.	2	2	2	n.a	n.a	2	2	2	n.a	2	n.a	n.a
Turbines - Nacelle assembly	n.a.	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	1	n.a	n.a
Towers	n.a.	3	3	3	3	3	3	3	3	n.a	3	3	n.a
Foundations - monopile/jacket	n.a.	3	3	3	1	3	3	3	3	n.a	0	3	n.a
Foundations - Transition pieces (TP)	n.a.	3	3	3	3	3	0	3	3	n.a	3	3	n.a
Cables - array and export	n.a.	3	3	3	3	3	3 (0)***	3	3	n.a	3	3	n.a
Substation fabrication, jacket and electricals (excl. onshore works)	n.a.	n.a	n.a	n.a	n.a	n.a	1*	n.a	n.a	n.a	n.a	n.a	n.a
Installation port (info)	n.a.	1	1	1	n.a	n.a	1 (0)***	1	1	n.a	1 (0)****	n.a	n.a
Installation	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a. / 0	n.a.	n.a.	n.a.	0	n.a.	n.a.
OpEx phase (34%)	1	1	1	1	1	n.a	1	1 (0)*****	1 (0)*****	1	1	n.a	n.a
DecEx (4%)	n.a.	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a

Source: JRC, 2022.

Although the supply chain of candidate projects of allocation round 4 remains in certain CapEx components still unclear, UKs current supply chain and information on future relocations and plant extensions cover most main components.

UKs current supply chain in major wind energy components covers the entire offshore wind value chain. Yet most manufacturers of main components stem from EU27 countries and locate their subsidiaries in the UK. Moreover, subsidiaries of manufacturers from the US, Japan and South Korea are part of the current UK supply chain (see **Table 20**).

A reinforced commitment to offshore wind through the announcement of the UK government to increase the offshore wind capacity target to 50GW until 2030 as well as the introduction of a local content criteria in the application process of the latest UK renewable energy allocation round (AR4) have an effect on the future UK supply chain [OW 2022e]. Both developments seem to influence the increased interest of manufacturers and service providers in relocating their activities to UK territory. Since early 2021 about 20 announcements and Memorandums of Understanding (MoU) on relocations and plant extensions are identified indicating a strong movement of leading offshore wind companies towards the UK (see **Table 21**).

Some companies in the offshore wind value chain explicitly refer that their move to the UK is connected to latest policies. The offshore wind foundation manufacturer Navantia (ES) is setting up a subsidiary in the UK and signed a MoU with shipbuilder and offshore construction company Harland&Wolff (UK) referring to its commitments to support of the UK National Shipbuilding Strategy and Ten Point Plan for a Green Industrial Revolution [OW 2021g, OW 2022f].

Table 20 Manufacturers of major wind energy components in the UK supply chain and their origin.
Note: Origin of parent company stemming from EU27 countries (highlighted in blue), from European countries (grey) and non-European countries (red).

Component	Company	UK location	Country of origin (parent)	Estimated current capacity / other
Blades	Vestas	Isle of Wight	DK	125 blades
Blades	SiemensGamesa RE	Green Port Hull	DE-ES	250 blades
Blades	GE Renewables (Blade Dynamics)		US	IP acquisition
Generator	GE Power Conversion		US	Presence only
Generator	GreenSpur Renewables		UK	R&D
Bearings	ThyssenKrupp Rothe Erde	Durham	DE	Not reported
Bearings	NSK United Kingdom Ltd	Stevenage	JP	Not reported
Bearings	Jtekt Automotive UK Ltd	Resolven	JP	Not reported
Tower	CS Wind	Campbeltown	KR	300 units
Tower, Crane, offshore platforms	Hutchinson Engineering	Multiple (Liverpool, Widnes)	UK	30 SIPs/100 david cranes
Nacelle	SiemensGamesa RE	Green Port Hull	DE-ES	250 units
Cable connectors, mooring and anchoring solutions	FirstSubSea	Lancaster	UK	USD 16.5 million export orders
Foundation	Smulders	Newcastle upon Tyne	NL	Not reported
Power converter	Schneider Electric Ltd	Scarborough	FR	Not reported
Power converter	Schneider Electric Ltd	Leeds	FR	Not reported
Inter-array cables	Prysmian	Wrexham	IT	Not reported
Inter-array cables	JDR Cable systems Ltd	Hartlepool	PL	Not reported

Source: JRC, 2022.

Global Energy Group (UK) and Haizea Wind Group (ES) have signed an agreement to build an offshore wind tubular rolling facility for towers, transition pieces and suction buckets at the Scottish Port of Nigg which should become operational by 2023. The factory should serve both UK and international markets and provide structures to bottom-fixed and floating offshore projects [OW 2022g]. RWE (DE) signed a MoU with port operators in order to transform several Celtic Sea ports into hubs for the manufacture, assembly, and loadout of high-tech floating wind turbines and foundations [OW 2022h]. TotalEnergies (FR) announced plans to invest GBP 140 million in the Scottish supply chain and harbour infrastructure in case of the companies 2 GW offshore wind project proposal (West of Orkney Windfarm) is selected [OW 2022h]. The TELE-FONIKA Kable subsidiary JDR Cable Systems (PL) unveiled plans to build a subsea cable manufacturing facility in Cambois which should become operational in 2024 [OW 2022h]. Until 2023, SiemensGamesa RE will double the capacity of its blade factory in Hull. This would mean at least an annual production capacity of 500 blades per year when assuming the current capabilities as a benchmark (see **Table 20**) [OW 2021h]. GRI Renewable Industries (ES) announced to build an offshore tower manufacturing plant at Able Marine Energy Park, Hull (UK) with a production capacity of 100 offshore towers a year [OW 2021i]. Smulders (NL) subsidiary in Newcastle will invest in new equipment and infrastructure to enable the manufacture of offshore wind turbine transition pieces at its existing site [OW 2021i]. Vestas plans to further expand its UK offshore wind production depending on the success in AR4. The OEM signed several MoUs with project partners in the offshore towers and blades segment [OW 2021i].

Recent announcements see also significant planned and executed investments by UK companies. XLCC and Peel Ports Clydeport signed an agreement for two factories producing high voltage direct current (HVDC) subsea cables in Ayrshire from 2024 onwards (UK) [OW 2022h]. In July 2021, Wilton Engineering acquired the transition piece factory of EEW Special Pipe Constructions (SPC) in Teesside [OW 2021i].

With SeAH Steel Holdings (KR), MingYang (CN) and GE RE/LM WindPower (US) three non-European companies announced in the last year to enforce their activities in the UK. Through its subsidiary SeAH Wind Limited (UK), SeAH Steel Holdings (KR) plans to build until 2026 the world's largest monopile production facility in Teesside which will supply XXL-monopiles to the Hornsea Three project [OW 2022g]. Chinese OEM MingYang (CN) signed a MoU with the UK Department for International Trade in order to realise the company's plans to build a blade manufacturing plant, a service centre a turbine assembly factory in the UK [OW 2022g]. In 2021 construction of the Haliade-X blade manufacturing plant of GE RE/LM WindPower (US) have started in Teesworks (UK) with full commissioning planned for 2023 [OW 2022g].

BW Ideol (NO) and Ardersier Port Authority are aiming for the largest floating wind foundation fabrication, manufacturing and assembly facility in the UK. Moreover, BW Ideol (NO) together with BayWa r.e. and elicio is part of the Floating Energy Allyance which commits to local manufacturing of concrete foundations in order to maximise UK local content [OW 2021j, FEA 2022]. Cable installation of the Seagreen project will be performed by Seaway 7 (NO) with storage and mobilisation of the inter-array cables located at Port of Blyth (UK) [OW 2022h].

Another area of increased activity along the UK supply chain and involvement of EU companies concerns O&M services. In 2021, Deutsche Windtechnik opened a subsidiary in the UK to perform offshore wind maintenance service. Moreover, Vattenfall (SE) contracted HARCO Heavy Lifting (DK) to provide main component exchange services across five offshore wind farms in the UK over the next three years [OW 2021k, OW 2021l]. By 2023 RWE aims to complete its operations hub for offshore wind farms at Grimsby's Royal Dock. The investment will host specialists to perform component exchanges and offshore repairs [OW 2021i]. At the end of 2021, the UK Department of Transport and ORE Catapult launched the 'Operation Zero' aiming for the development of zero-emission O&M vessels and the associated onshore infrastructure in order to serve offshore wind farms in the North Sea. The initiative includes 28 major EU and UK companies active in the offshore supply chain. Based on the offshore wind targets formulated it is estimated that the industry will build 1400 new vessels (including 300 service operation vessels (SOVs)) until 2050, resulting in a emission reduction of 1.2 MtCO2e per year as compared to a business as usual case and up to 1400 direct jobs[24] in the UK.

Table 21 Latest announcements on relocations, plant extensions and joint ventures (in the period 2021 - 2022) in the UK supply chain of manufacturers of major wind energy components and their origin.
Note: Origin of parent company stemming from EU27 countries (highlighted in blue), from both EU27 and European countries (light blue), from European countries (grey) and non-European countries (red).

Component/Service	Company	UK location	Country of origin (parent)	Quantification of potential impact
Foundations and vessels	Navantia	unknown	ES	
Foundations (bottom-fixed and floating)	Harland&Wolf / Navantia / Windar Renovables	Not applicable (Joint Venture)	UK-ES	
Foundations - Monopiles	SeAH Wind Limited	Teesside	KR	FID: GBP 300 million 150 monopiles/year 750 direct jobs Industrial space: 90 acres
Blades, O&M, Assembly	MingYang	MoU on 3 factories (location unknown)	CN	
Foundation/support structure (Floating, concrete)	BW Ideol	Ardersier Port	NO	Industrial space: 400 acres
Towers, transition pieces, suction buckets	Global Energy Group (GEG) / Haizea Wind Group	Port of Nigg	UK-ES	FID: GBP 110 million 135 towers/year + other 400 direct jobs Industrial space: 90 acres
O&M	HARCO	At wind farm location (component exchange)	DK	
Ports, installation, O&M	RWE	Port Talbot / Pembroke Dock / Grimsby Royal Dock	DE	
Developer	TotalEnergies	Aberdeen	FR	GBP 140 million supply chain investment (planned)
Blades	GE Renewable Energy (LM	Teesworks	US	750 direct jobs

[24] Assuming that the UK captures 25% of the European O&M vessel building market

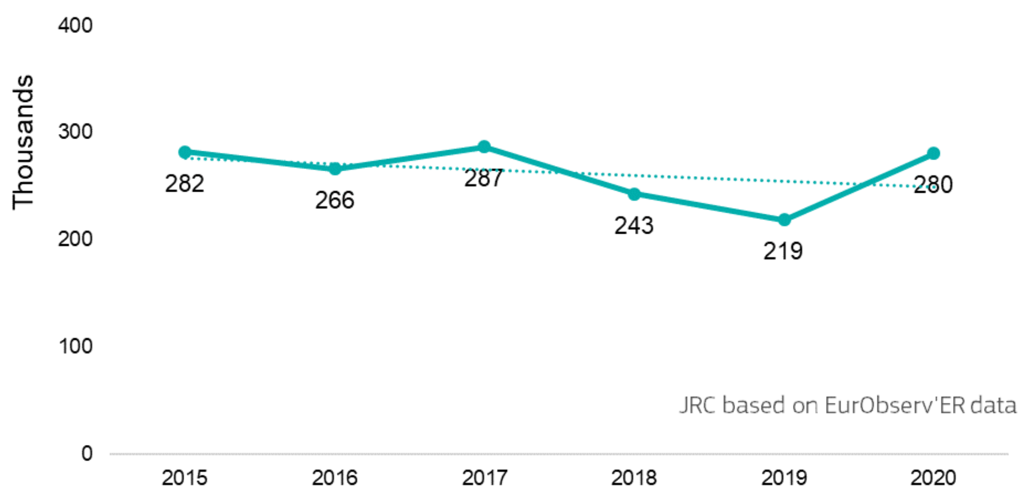
	Wind Power)			Industrial space: 400 acres Facility: 78,000m^2
Cable installation	Seaway 7	Port of Blyth	NO	
Cables - array and export	JDR Cable Systems Ltd	Cambois (Blyth)	PL	GBP 130 million[25] 170 direct jobs Facility: 69,000m^2
HVDC cable	XLCC	Ayrshire	UK	GBP 370 million (factories) GBP 200 million (vessel) 900 direct jobs Industrial space: 70 acres
O&M	Deutsche Windtechnik		DE	
Blades	SiemensGamesa RE (extension of existing facility)	Green Port Hull	DE-ES	GBP 186 million[26] 200 direct jobs Facility: 41,600m^2 added
Towers	GRI Renewable Industries	Green Port Hull	ES	GBP 78 million[7] 100 offshore towers/ year 260 direct jobs
Foundation	Smulders (extension of existing facility)	Newcastle upon Tyne	NL	GBP 70 million[7] 325 direct jobs
Transition pieces	EEW Offshore Structures Britain (OSB)	Teesside	UK	200 direct jobs
Blades and others	Vestas	North East of UK	DK	Potential 2000 direct jobs
O&M	RWE	Grimsby Royal Dock	DE	60 direct jobs Industrial space: 1.3 acres

Source: JRC, 2022.

3.5 Employment in value chain incl. R&I 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[27], 77 000 of which relate to offshore wind. Moreover, 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 offshore substructures [WindEurope/Deloitte 2020]. EU total wind energy workforce equals to about a quarter of the estimated global employment in the wind energy sector, with the majority 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 Spain and the Netherlands (see **Figure 84** and **Figure 85**).

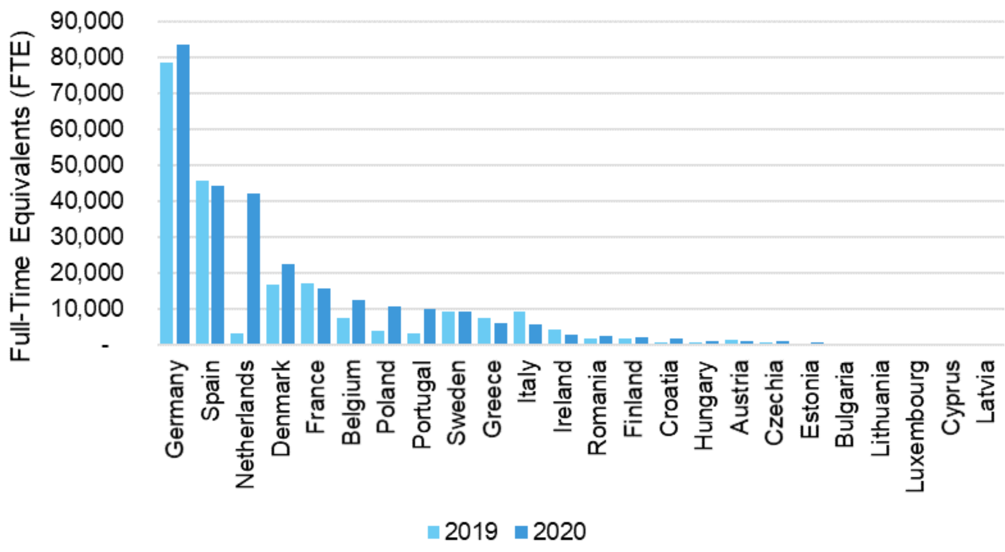
Figure 84 Evolution of direct and indirect jobs in the wind energy sector in the period 2015-2020



Source: JRC based on EurObserv'ER data.

25 Aiming for part-funding by a grant from the BEIS Offshore Wind Manufacturing Investment Support (OWMIS)
26 Partly funded by the UK government's GBP 160 million Offshore Wind Manufacturing Investment Support scheme
27 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.

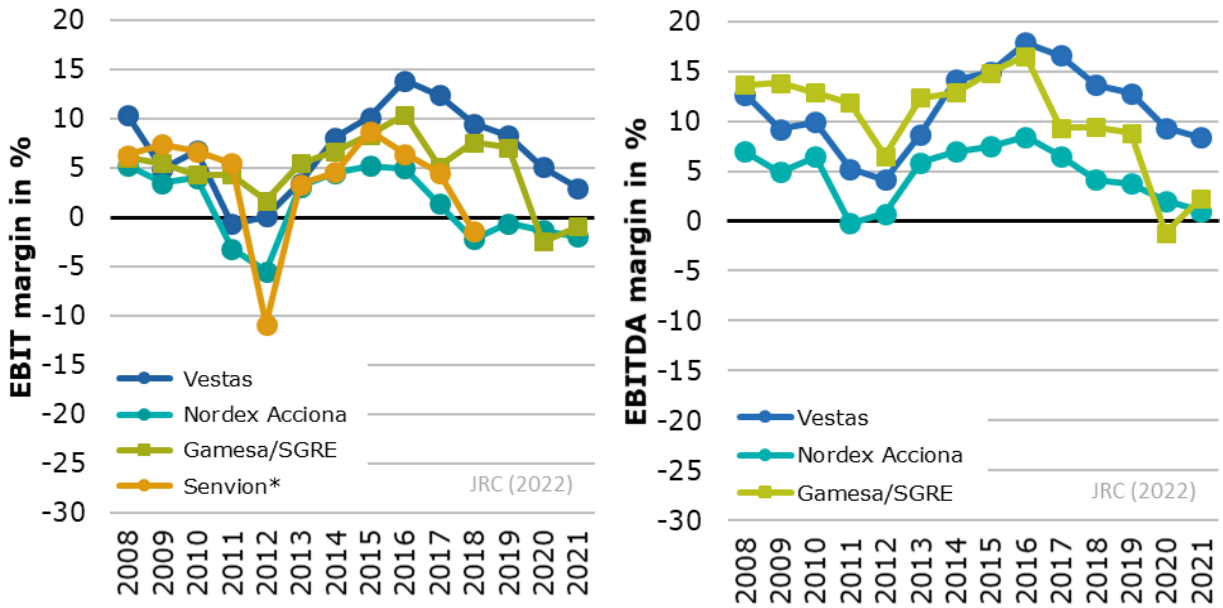
Figure 85. Employment (direct and indirect jobs) in the wind sector in 2019 and 2020.
Note: Employment expressed in full-time equivalents (FTE).



Source: JRC based on EurObserv'ER, 2022.

The trend in employment figures shows a decline in the period 2015-2019 which links to the EBIT margins of listed EU OEMs. This can be explained by high competition in turbine orders, particularly in the period 2017-2018, and increased material costs for the main turbine components. In 2020, these factors were further intensified through the impact of Covid-19, which created logistical challenges for all manufacturers. In 2021, the financial performance of the listed EU OEMs is still impacted by market imbalances caused by the global demand recovery and the supply chain continued to be affected by the pandemic. As a result, only Vestas could present a positive but decreasing EBIT margin (+3.0%), whereas NordexAcciona (-2.0%) and SiemensGamesa RE (-0.9%) reported negative figures (see **Figure 86**).

Figure 86 EBIT margin (Operating profit/Revenues) (left) and EBITDA margin (Operating profit before depreciation and amortisation/Revenues) (right) of the leading listed EU OEMs



Source: JRC, 2022.

Future scenarios estimate global wind energy jobs growing almost fivefold by 2050 at about 5.5 million jobs[28]. In order to mobilise this workforce recruiting, training and retaining skilled workers will be needed. This might include transfer of skills from the oil and gas industry to the wind sector as it is estimated that about 70% of the jobs (in FTE) in the oil and gas sector shows good or partial overlap with the offshore renewable segment. GWEC (2022) maps the following good practices in revitalizing and repurposing workforce towards the wind energy sector [GWEC 2022a]:

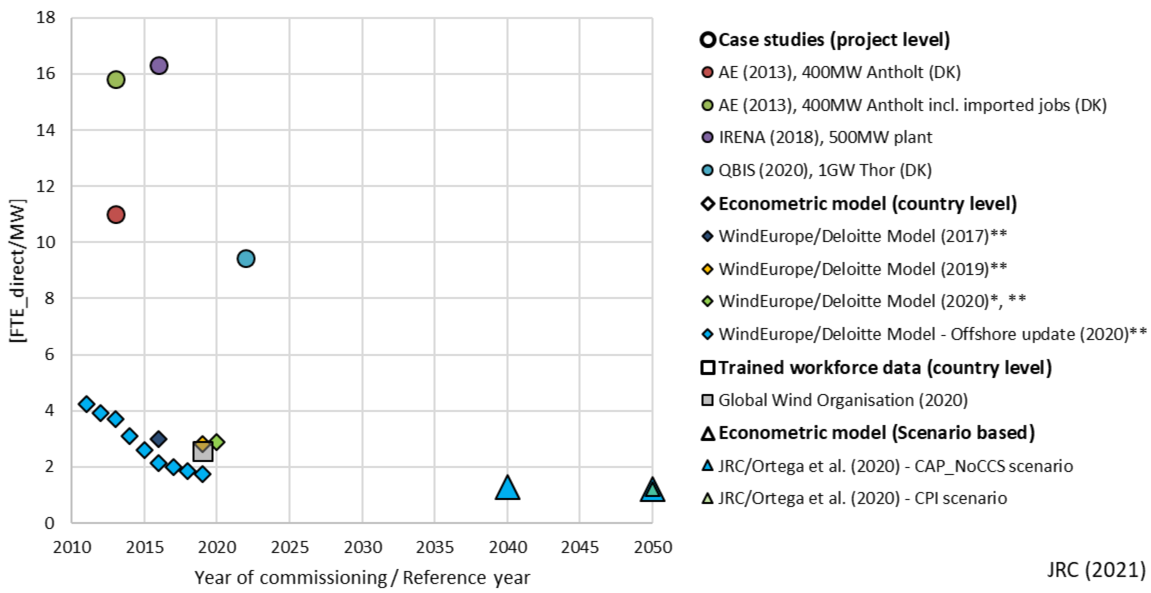
- Encouraging a social dialogue and increased stakeholder engagement with affected groups (e.g.. displaced workers, affected communities, fishing industry)
- Promoting public-private collaboration to generate local value creation
- Establishing tailored retraining and reskilling pathways for workers from carbon-intensive industries
- Promoting a diverse and inclusive workforce

3.6 Energy intensity/labour productivity

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 [IRENA 2018, QBIS 2020]. 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 87. 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.

[28] This assumes a 10-fold increase in global wind energy capacity to more than 8000 GW

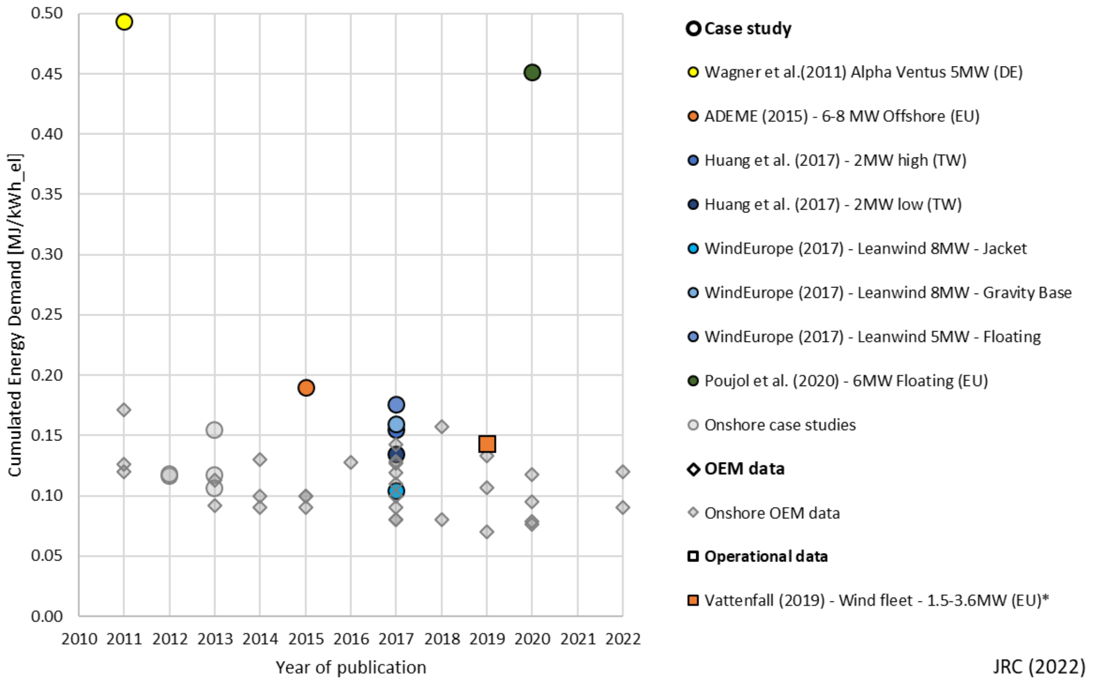
Current econometric models estimating the number of jobs using employment factors, trade data and/or contribution to GDP of the sectors involved shows direct employment figures declining from about 4 $FTE/MW_{Installed}$ in 2010 to a range of 1.8-2.9 $FTE/MW_{Installed}$ in 2020. When including indirect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

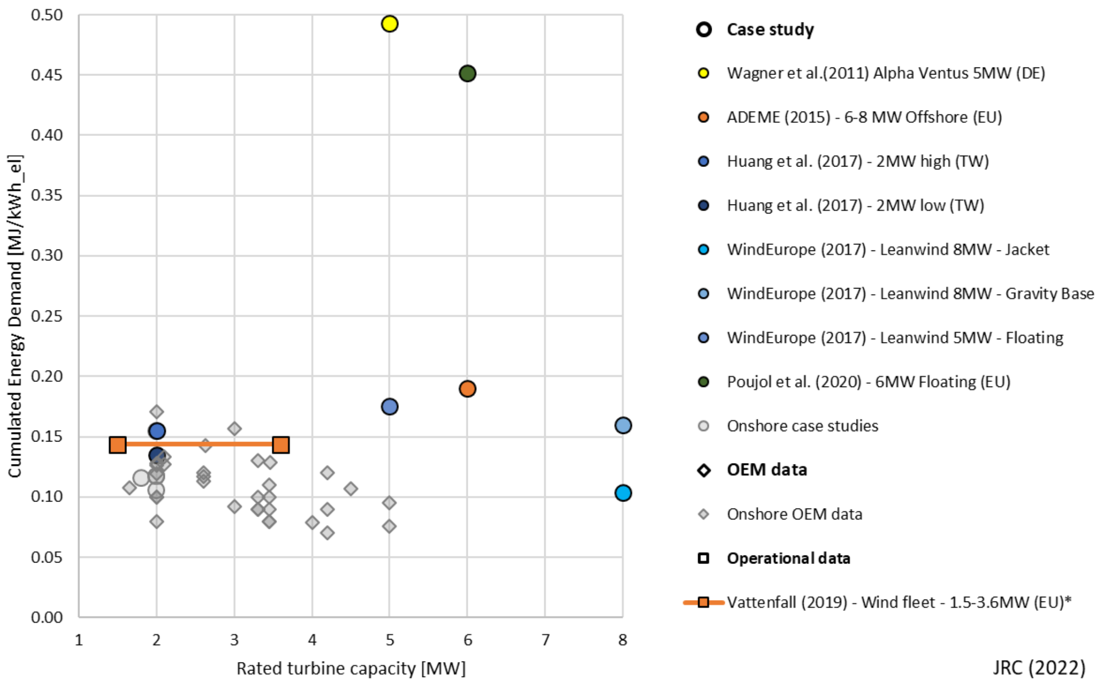
The onshore wind sector shows a lower specific labour productivity than offshore, based on the latest case studies and econometric models. Direct job estimates for single onshore wind projects are in the range 1.7-3.0 FTE/MW for projects in the period 2015-2019. Differences in this spread seem to originate in project size and geographical scope [Ejdemo & Söderholm 2015, Okkonen & Lehtonen 2016]. Econometric models at regional and national levels estimate the number of direct jobs at 0.5-2.3 $FTE/MW_{Installed}$ with European estimates declining to about 0.7 $FTE/MW_{Installed}$ in 2019 [Llera Sastresa et al. 2010, Brown et al. 2012, Dvořák et al. 2017]. Long term scenario models estimate future labour productivity for onshore wind at a similar scale, with values ranging from 0.35 to 0.9 $FTE/MW_{Installed}$ [Ortega et al. 2020].

Energy intensity. The energy intensity is analysed based on the cumulated energy demand (CED) along the lifecycle of offshore wind. The majority of life cycle analyses finds the cumulated energy demand between 0.1 and 0.19 MJ_{input}/kWh_{el}, a comparable order of magnitude when compared with the cumulated energy demand of current onshore wind turbines (see grey dots in **Figure 88**). Notably data points on floating offshore show higher values than bottom fixed offshore wind in terms of cumulated energy demand. However, a decisive factors influencing the CED, besides the life cycle inventory data used, is the chosen system boundary and assumed geographical reference (e.g. countries electricity mix and wind resource, which becomes apparent in the outlier value of Wagner et al (2011) which includes also 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, neither in terms of evolution in time nor in respect to the growth in turbine size (see **Figure 88**, bottom). So far no detailed LCA on the latest offshore wind turbines by Vestas, SiemensGamesa RE and GE was found.

The energy intensity is analysed based on the cumulated energy demand (CED) along the lifecycle of onshore wind. Life cycle analyses from both, 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 a range of about 0.08 - 0.12 MJ_{input}/kWh_{el}. **Figure 89** (bottom) shows that this decrease is driven by the continuous development of more powerful turbines up to the 5MW scale which allow to generate more electricity per input of primary energy than their predecessors.

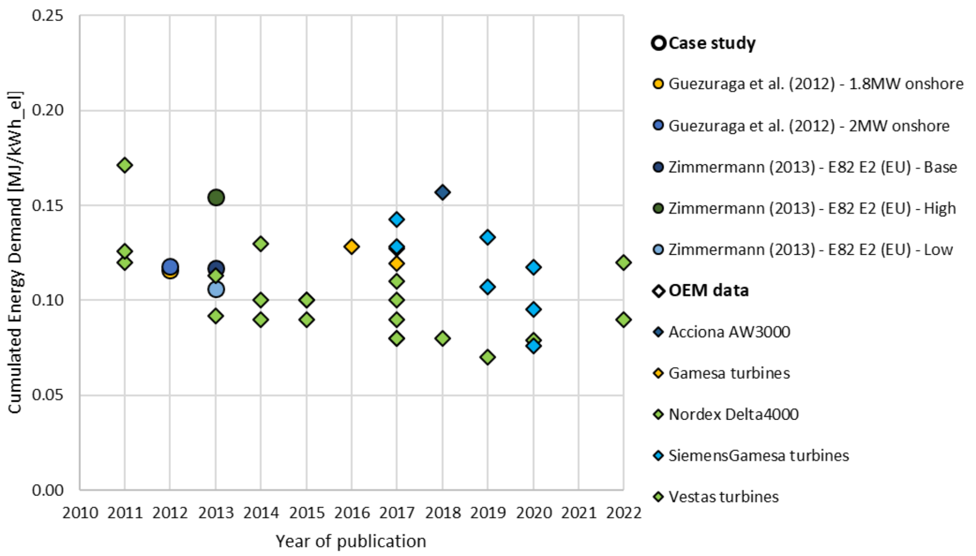
Figure 88. Evolution (top) of Cumulated Energy Demand (MJ_primary energy/kWh_el) of offshore wind turbines and the respective rated capacity (bottom) based on different case studies and OEM data. Note:* includes 57% electricity generation from offshore wind



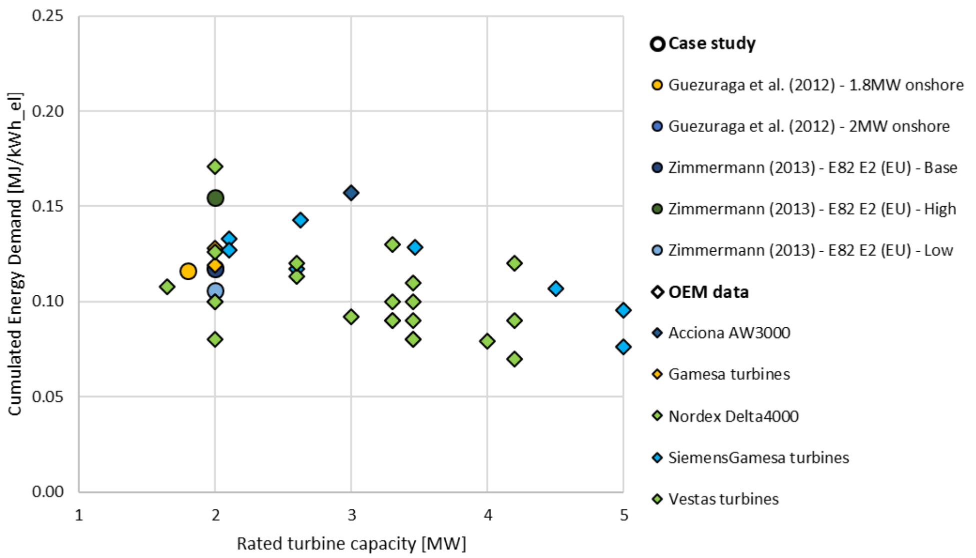


Source: JRC, 2022.

Figure 89. Evolution (top) of Cumulated Energy Demand (MJ_primary energy/kWh_el) of onshore wind turbines and the respective rated capacity (bottom) based on different case studies and OEM data



JRC (2022)



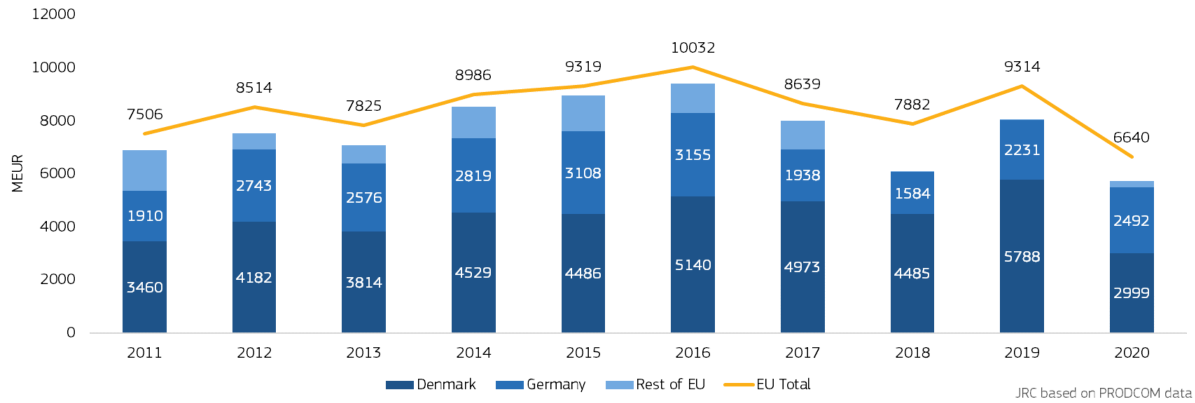
JRC (2022)

Source: JRC, 2022.

3.7 EU production Data (Annual production values)

The total production value of the wind energy value chain in the EU is shown in **Figure 90**. It remains at a relatively high level in the order of EUR 8 billion per year, since 2014. However latest figures on 2020 show a decrease in production value mainly driven by lower performance in Denmark.

Figure 90 Total production value in the EU and top producer countries



Source: JRC based on PRODCOM data, 2022.

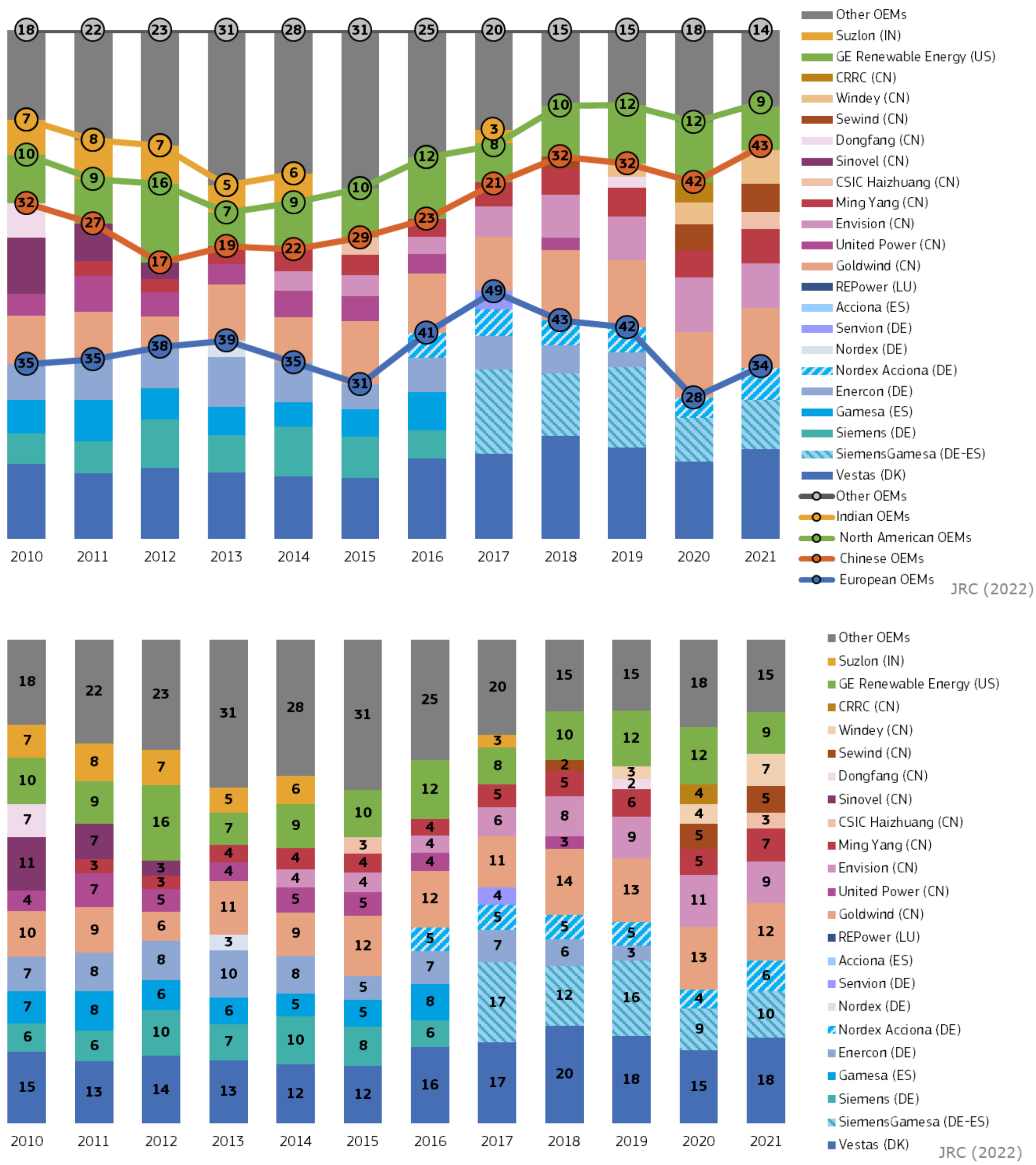
4 EU position and Global competitiveness

4.1 Global & EU market leaders (Market share)

The European Original Equipment Manufacturers (OEMs) in the wind energy sector have held a leading position in the last few years. In 2021 they ranked second behind Chinese OEMs when analysing the Top10 OEMs in terms of market share. Among the top 10 OEMs in 2021, Chinese OEMs led with 43 % of market share, followed by the European (34 %) and North American (9 %) companies (see **Figure 91**, top).

Figure 91 Market share (%) of the top 10 OEMs in wind energy (bottom) over the period 2010 – 2021 and their respective origin (top)

Note: Market shares include both onshore and offshore wind deployments



Source: JRC, 2022.

Out of the global Top10, six OEMs originate from China, three from Europe and one from the United States. With a market share of 18% Danish Vestas remained in first place, yet as in 2020 a strong share of new deployments using turbines from Chinese OEMs and GE Renewable Energy from the US can be witnessed (see **Figure 91**, bottom). This can be explained by a surge in new installations in the Chinese and US wind market.

This latest surge in Chinese wind deployment can be explained through a set of new policies targeting renewable energy integration and a shift from Feed-in-Tariffs towards a tender-based support scheme. This necessitates projects approved before 2018 to be grid-connected latest by the end of 2020 in order to receive the expiring Feed-in-Tariff.

Analysing the position of the leading European OEMs (Vestas (DK), SiemensGamesa RE (DE-ES), Nordex Acciona (DE) and Enercon) by global region confirms the leading role of European companies in the wind sector. In 2021, the leading European OEMs supplied about 90% of the turbines installed in Europe, 56% in North America, 91% in Latin America and 87% in Africa and the Middle East. An exception marks the Asia Pacific market, where the leading European OEMs cover about 7% only [GWEC 2022b]. This is mainly due to the size of the Chinese market which is dominated by Chinese manufacturers.

Chinese manufacturers are strongly consolidated in their home market. Since 2013, the penetration of foreign manufacturers has been below 7% of new capacity installed, down from 13% in 2010. In 2020 only 4.7% of the installed capacity came from non-Chinese manufacturers, with EU companies (SiemensGamesa RE and Vestas) accounting for about 2.8% [CWEA 2020, EI 2020a, CWEA 2021]. EU companies secured 1.5 GW of onshore wind orders which were installed by the end of 2020 [WPM 2019c, WPM 2020f]. In 2021, SiemensGamesa RE announced plans to end its onshore wind turbine sales in China, retaining its onshore wind production in the country just for exports to other international markets [WPM 2021e].

European turbine manufacturers still seem to lead in terms of quality and technological development, however Chinese companies are quickly improving, in particular those manufacturing key turbine components. Today Western turbines contain some key components made in China, either by Chinese or Western manufacturers (see chapter 3.4.3 and 3.4.4).

Exemplary and depending on the market supplied, the ratio of Chinese to Western components can vary from zero in the case of Enercon to nearly 90% in the case of General Electric turbines certified for the Indian market[29]. Chinese manufacturers (particularly Shanghai Electric, Envision, Goldwind and Mingyang) also dominate the Chinese offshore wind market [CWEA/GWEC/SEWPG 2020].

Partnerships with local wind developers are a prerequisite for foreign companies entering into the Chinese market. The market is dominated by power utilities owned by the central government, followed by energy companies run by local governments (**Figure 92**). Chinese OEMs and private independent power producers only own a small share of projects. So far, foreign investments are rare and often short-lived [EI 2020b] .

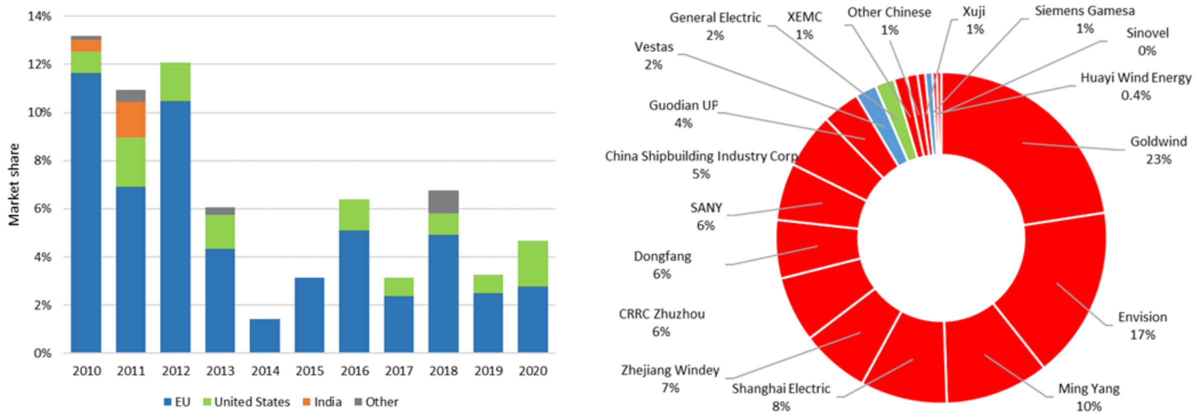
This could change in view of the expected offshore wind growth and China's nascent offshore wind supply chain. Two European project developers having recently entered the Chinese offshore wind market ((EDF, 2020; Equinor, 2019), with other major foreign offshore manufacturers developing their capabilities in the area. Despite China's significant market size, offshore wind developments are under threat from tensions in provinces adjacent to the South China Sea, as even Chinese projects (SPIC's Jinghai and Shenquen) could not secure approvals and were reportedly delayed in 2020 due to military interests [Energy Iceberg 2020c]. Cooperation in the offshore installer market might be pivotal for the Chinese offshore wind market, as installation vessel availability does not match recent deployment plans. About 39% of the global heavy-lift and jack-up vessels are located in China, with the remainder still operating in Europe.

However, only about 7% of existing vessels are capable to install turbines of the 10MW+ category [GWEC 2020c]. Although Chinese companies increased their capabilities (vessel fleet increased by factor six since

[29] See manufacturers of subcomponents in IEC certifications of Enercon and GE wind turbines: https://www.iecre.org/certificates/windenergy

2015 [WPM 2019c]), a lack of experience in installing offshore wind projects provide the potential for foreign subcontractors to enter the market [Energy Iceberg 2020d].

Figure 92 Global Market shares and origin of wind of foreign OEMs in the Chinese wind energy market in the period 2010 -2020 (left) and distribution of market shares by OEMs in 2020 (right) [CWEA 2020, CWEA 2021, Energy Iceberg 2020a].

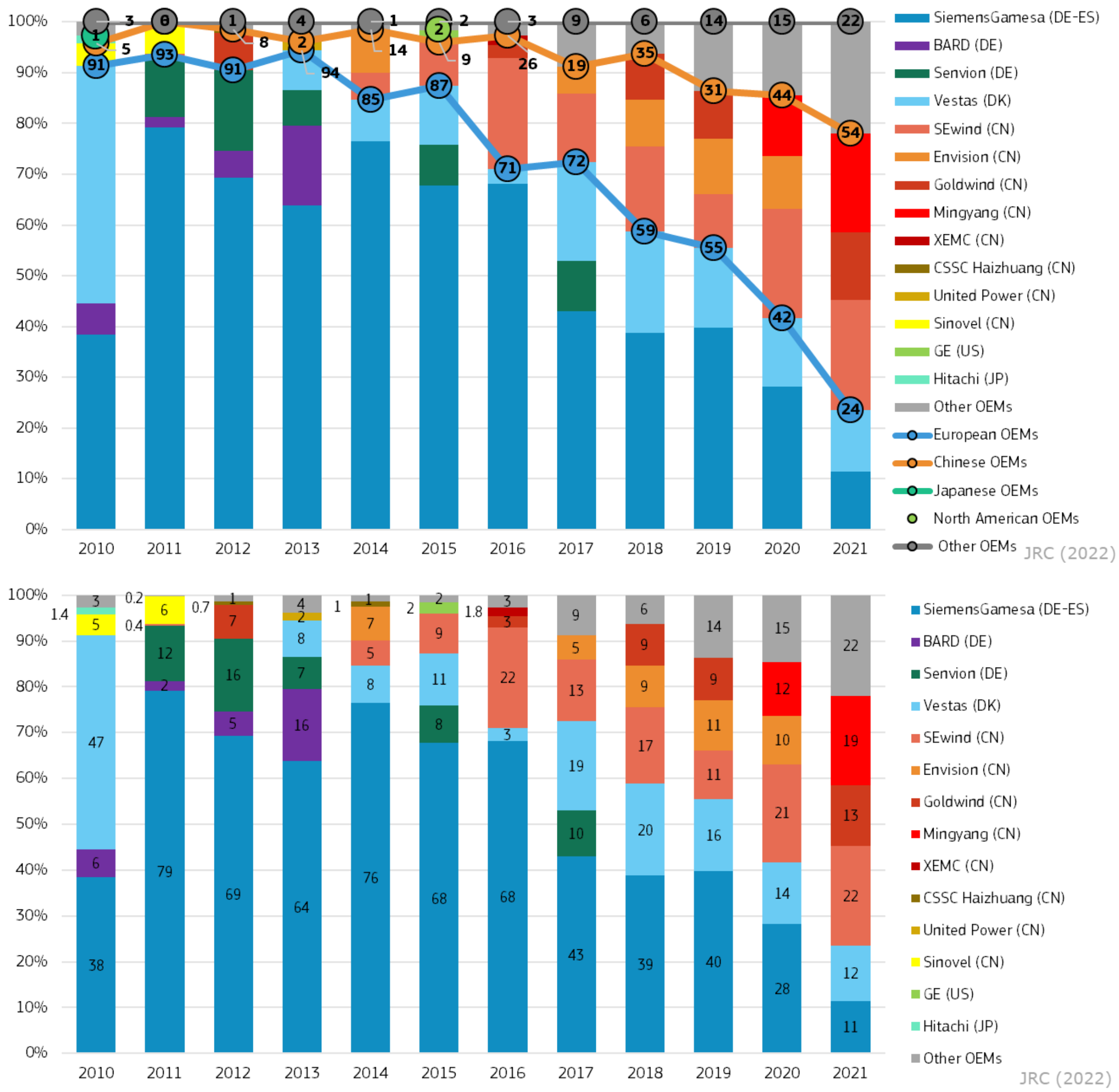


Source: JRC, 2022.

Offshore wind market shares showed an even more pronounced development driven by the Chinese market. In 2021, China installed in one year the same offshore wind capacity as EU did in cumulative terms. Similarly as in the onshore case, offshore wind projects approved before 2018 and grid connected by end of 2021 still received a Feed-in-Tariff, whereas auctions in the following two years will implement a price cap. Thus an increased deployment activity in China (16.9 GW) led to a strong increase in the market share of Chinese OEMs (54%) leading ahead of the European manufacturers (24%) when assessing their cumulative market share (see **Figure 93**, top).

Yet the European Original Equipment Manufacturers in offshore wind rank among the Top5. Vestas ranks fourth place (12%), closely followed by SiemensGamesa RE (11%), losing its top spot of 2020, while the Top3 are Chinese OEMs (SEwind (22%), MingYang (19%) and Goldwind (13%)). US-based GE did not add new offshore capacity in 2021 (see **Figure 93**, bottom).

Figure 93 Market share (%) of the top 5 OEMs in offshore wind energy (bottom) over the period 2010 – 2021 and their respective origin (top)

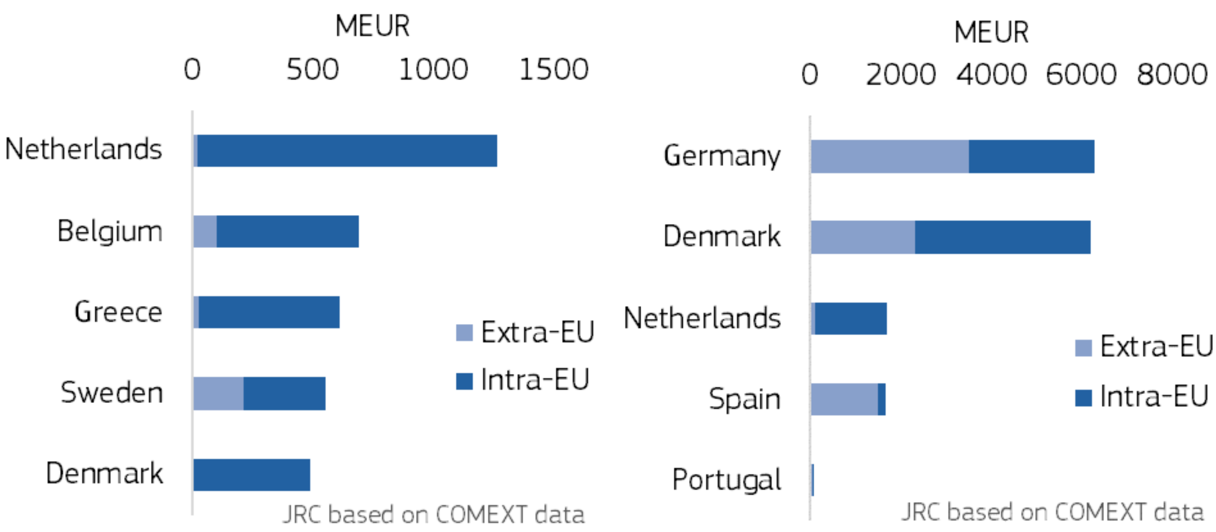


Source: JRC, 2022.

4.2 Trade (Import/export) and trade balance

The leading EU countries in importing wind-related goods come from the Netherlands, Belgium, Greece closely followed by Sweden and Denmark, with all of them sourcing the majority of wind products from within EU (intra-EU trade). Contrarily exporting countries, among them Germany and Denmark at the forefront, show a high export share towards non-EU countries (see **Figure 94**).

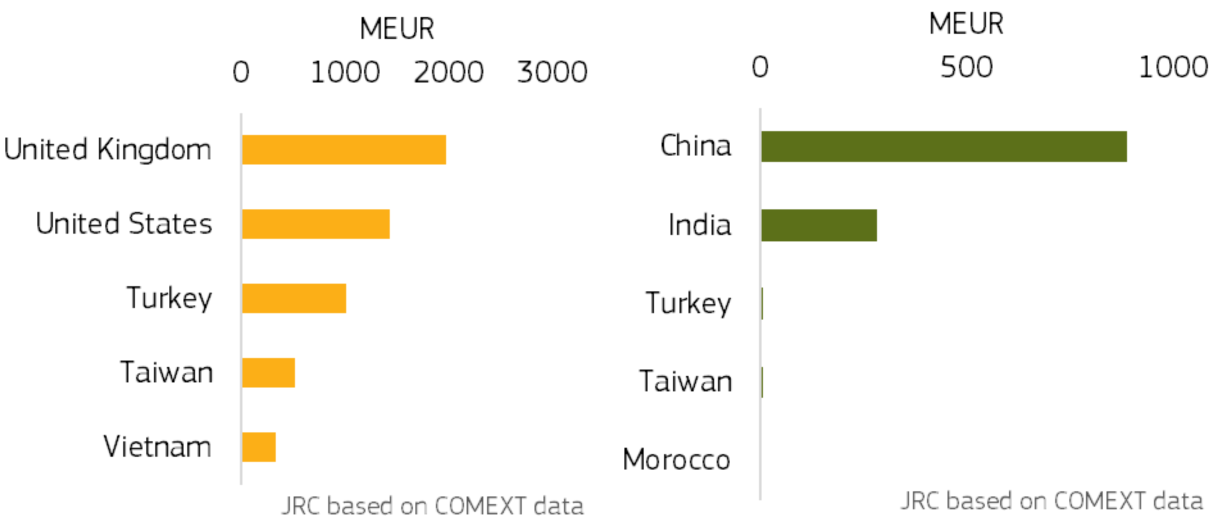
Figure 94 Top EU importers (left) and exporters (right) of wind-related goods (2019-2021)



Source: JRC based on COMEXT data, 2022.

EU's global competitors import significant value of wind related goods from EU countries. On a single country level the United Kingdom, the United States Turkey, and the emerging markets of Taiwan and Vietnam rank among the top importers of wind related goods in the period 2019 – 2021. In the same period, China and India are found as the main exporters to the EU, countries holding significant manufacturing capabilities in the wind sector (see **Figure 95**).

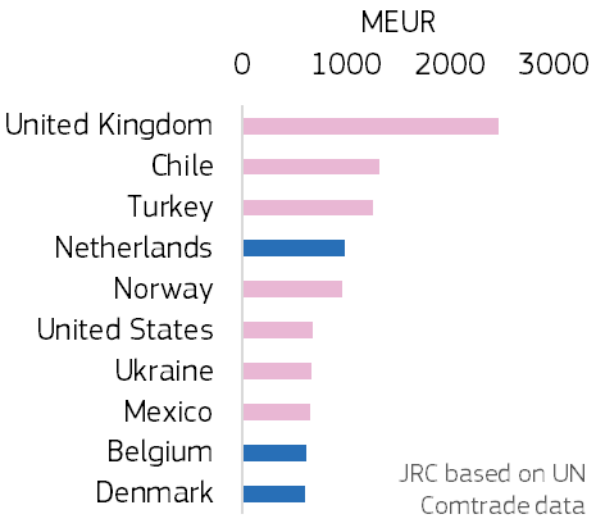
Figure 95 Top global importers from the EU (left) and top global exporters to the EU (right) of wind-related goods (2019-2021)

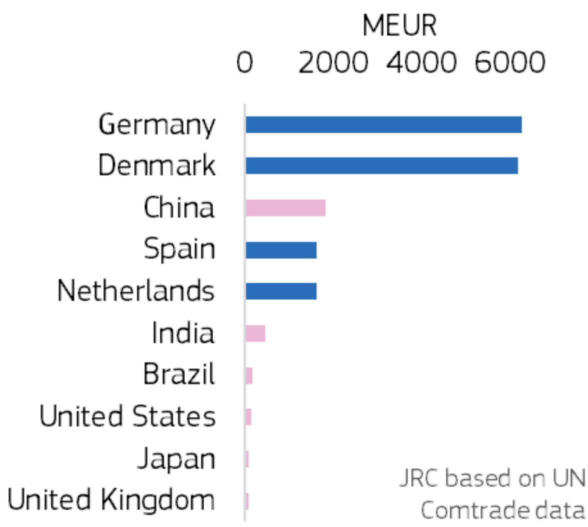


Source: JRC based on COMEXT data, 2022.

On a single country level, the United Kingdom, Chile and Turkey rank among the top importers of globally traded wind related goods in the period 2019 – 2021. The top EU countries import goods with a value of about EUR 2.2 billion. However, in the last three years the top EU countries in global export of wind-related goods showed a strong performance accounting for an export trade value of about EUR 15.7 billion (see **Figure 96**).

Figure 96 Top10 global importers (left) and top global exporters (right) of wind-related goods (2019-2021)

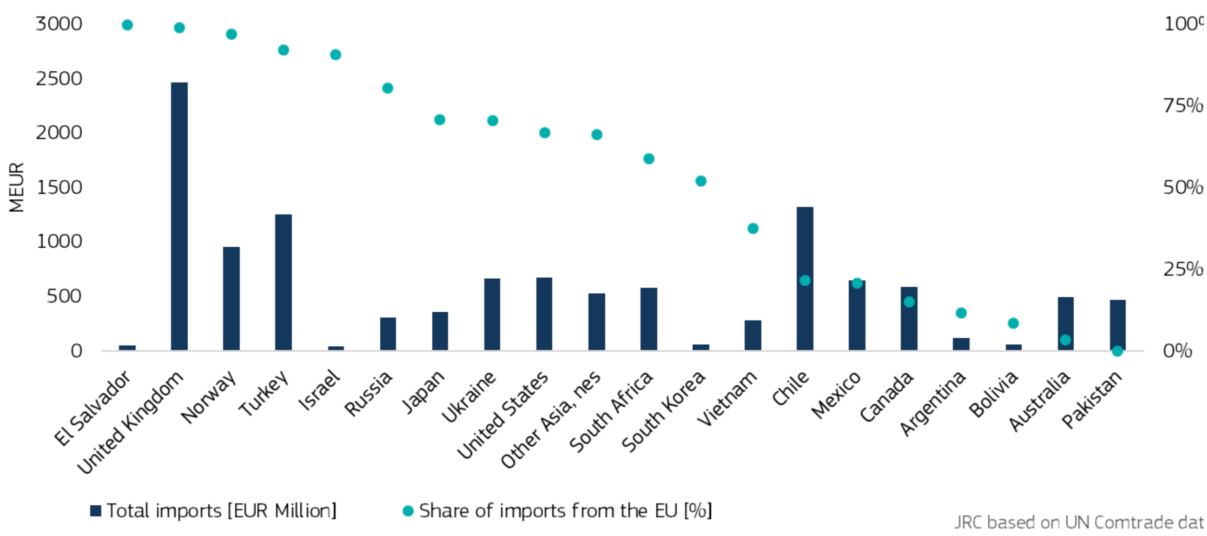




Source: JRC based on UN Comtrade data, 2022.

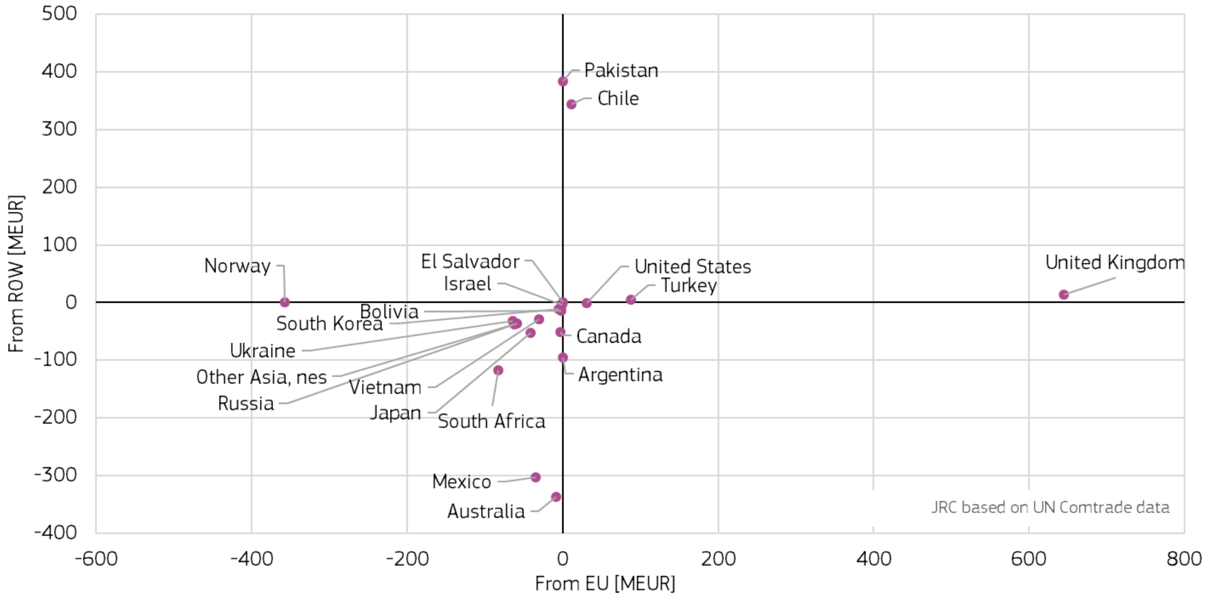
Aside from the import value imported by a country from the EU, the share of imports from the EU in the period 2019 – 2021 indicates the leading position of EU products globally. More than 12 countries show import shares above 50% stemming from EU, including some of the leading wind energy markets such as the United Kingdom (99%), the United States (67%), Turkey (92%) and Norway (97%). Lower EU import shares are found in Chile (22%), Mexico (21%), Canada (15%) and Australia (4%) (see **Figure 97**). In the last two years particularly the United Kingdom experienced a change in imports from EU, importing about EUR 623 million more in 2020-2021 than in the 2019-2020 period. Contrarily, Norway reduced its wind related imports from the EU by EUR 357 million when comparing the same time periods (see **Figure 98**).

Figure 97 Top 20 non-EU importers of wind-related goods (2019-2021)



Source: JRC based on UN Comtrade data, 2022.

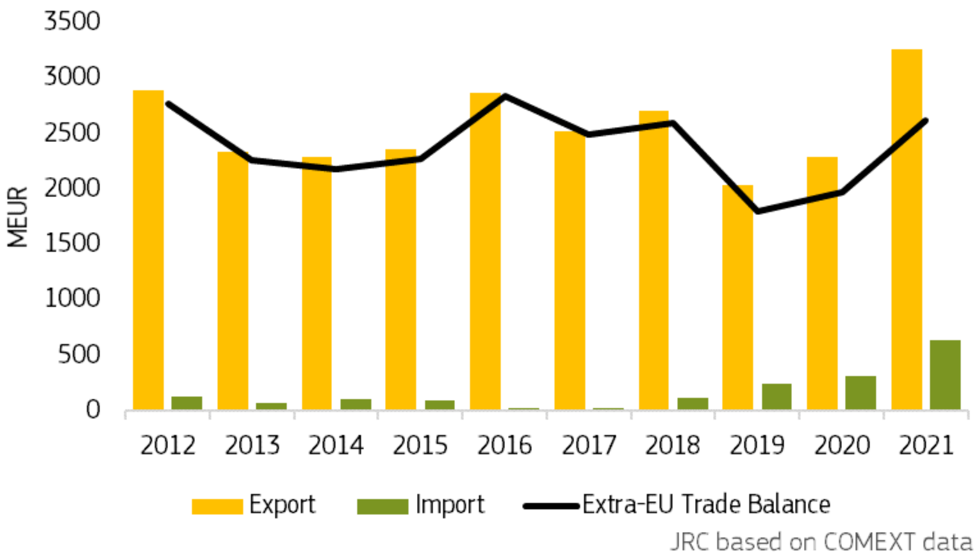
Figure 98 EU positioning in different markets of wind-related goods (2019-2021, 2-year average of change in import from the EU and ROW [EUR Million])



Source: JRC based on UN Comtrade data, 2022.

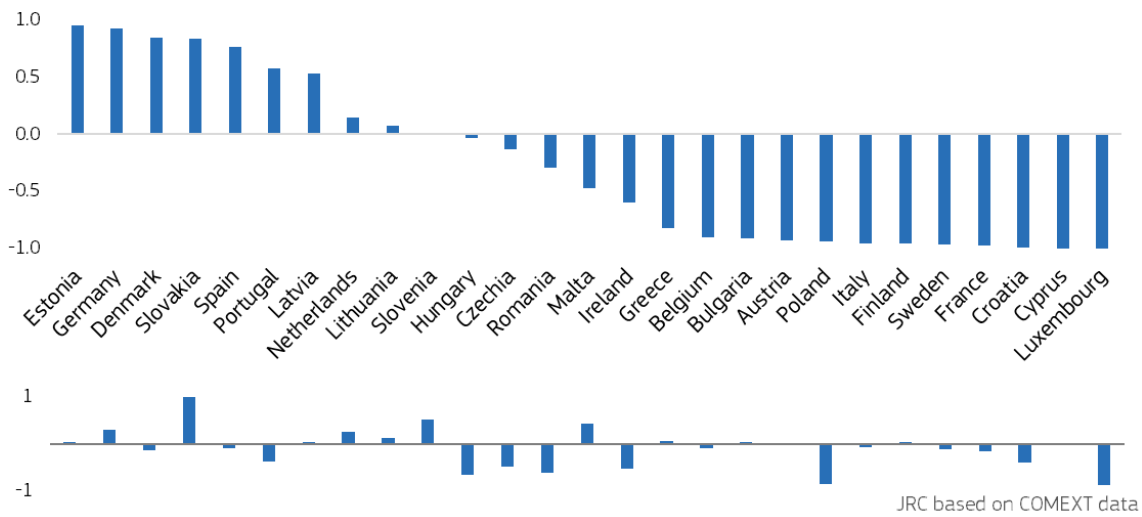
Exports of wind related goods to countries outside the EU (extra-EU trade) show a positive development. However in the last decade some stagnation can be witnessed with an overall trade balance ranging between EUR 1.8 billion and EUR 2.8 billion. Since 2018 EU imports increase mainly originating from a negative trade balance with China and India (see **Figure 99**). Among EU countries the relative trade balance (comparing periods 2019-2021 and 2016-2018) developed positively for most of the leading established markets (e.g. Germany, Denmark, Spain, the Netherlands) with the exception of France and Italy (see **Figure 100**).

Figure 99 Extra-EU trade balance of wind-related goods (2012 – 2021)



Source: JRC based on COMEXT data, 2022.

Figure 100 Relative trade balance 2019-2021 (top) and change from 2016-2018 (below)



Source: JRC based on COMEXT data, 2022.

In the last decade the United Kingdom showed a negative trade balance with the EU as a significant part of the European supply chain is located in EU countries. In 2021 the United Kingdom showed a trade deficit with EU of about EUR 1.5 billion, significantly higher than in the last 10 years averaging at around EUR 0.6 billion (see **Figure 101**, top left). However, latest policies in the United Kingdom granting support for renewable energy projects and particularly offshore wind projects), introduced a local content scoring criteria favouring UK over imported content [EC 2022af] (see also chapter 3.4.5). As such a shift in the UK-EU trade balance on wind energy related goods can be expected if the UK local content criteria prevails.

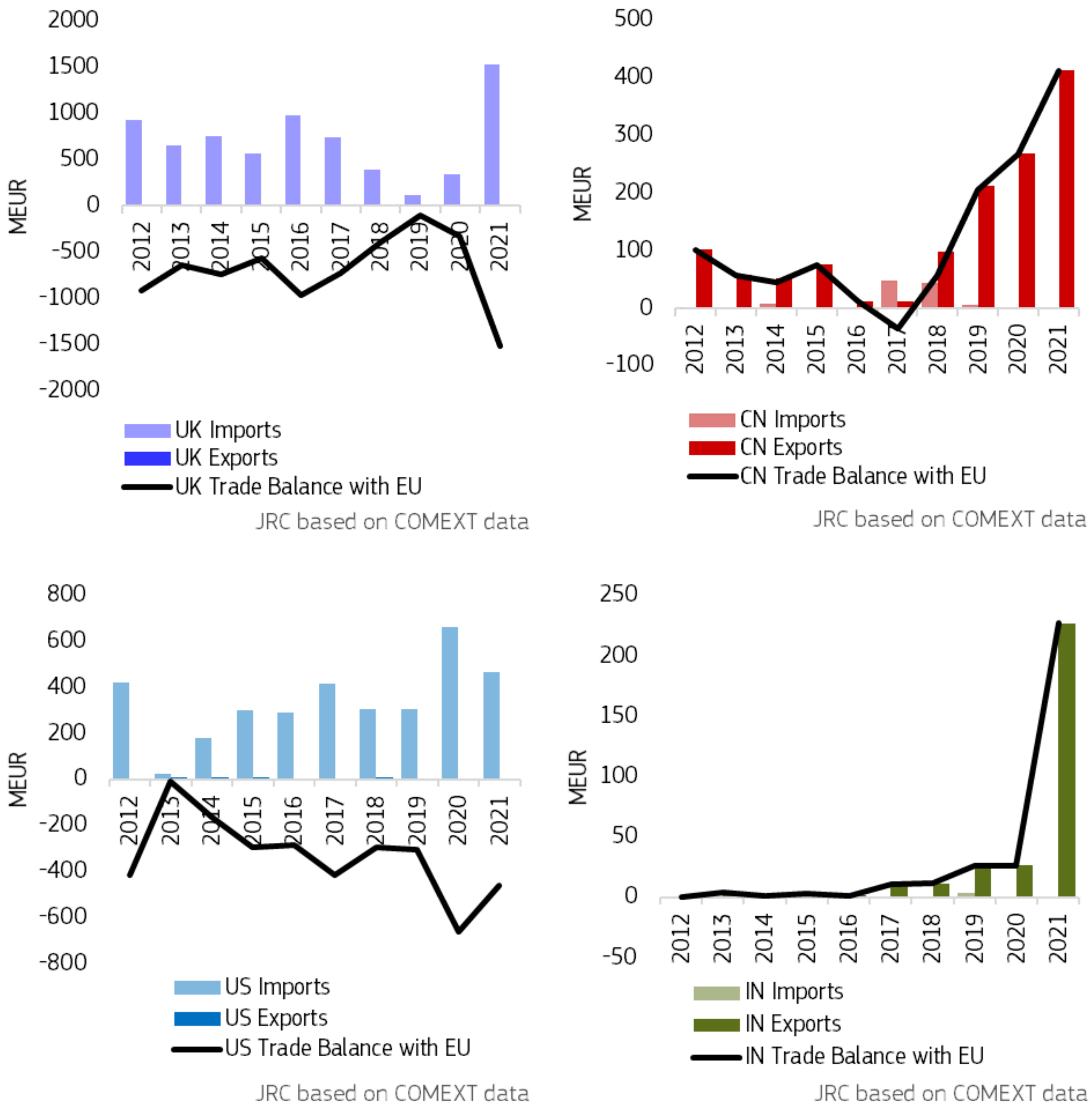
Following a set of policies protecting China's domestic market, imports of wind generating sets to China fell drastically since 2007. These policies include NRDC and State Council notices on local content requirement in 2005, import tariff and VAT exemption to domestic manufacturers for the import of key components and material of wind turbine in 2007 or direct subsidies for eligible manufacturers in 2008 [Yuan et al. 2015]. By contrast, Chinese exports rose with wind equipment being shipped globally. As such, since 2008, China experiences an increasingly positive trade balance. China's existing market barriers become apparent when assessing the trade balance with the EU. Since China's restrictive wind market policy, the trade balance clearly leans towards China, with a record surplus (trade deficit for EU) of EUR 411 million for China in 2021 (see **Figure 101**, top right). In the same period China's market size grew much stronger than in the EU.

US wind industry remains reliant on imports (see **Figure 101**, bottom left). DOE (2021) reports that EU companies show relatively high import shares to the United States for selected components. Estimates suggest that the EU held about 71% of the US imports in the trade category 'Wind-powered generating sets and nacelles' and 37% in 'Wind generators and generator parts' in the period 2012-2020, followed by imports in the category 'Wind blades and hubs' (23%) and 'Wind Towers' (18%). Total US imports stemming from EU are estimated at about USD 8 billion and largely follows the annual deployment market shares of EU OEMs in the United States ranging between 40% and 70% in the last years (with the exception of 2013 with an EU OEM market share of about 8%) (see **Figure 102**) [DOE 2021].

India showed a positive trade balance with the EU with exports surging to about EUR 227 million in 2021 (see **Figure 101**, bottom right). This can be explained as a first reaction of major wind turbine manufacturers exploring the possibility to use India as a low-cost export hub of their components as they are facing increasing costs from the ongoing US-China trade tensions [WPM 2021c]. India is expected to move from supplying its domestic demand to a country becoming an export hub for wind energy products as a consequence of increasing supply chain bottlenecks, cheap labour costs and trade tensions between major economies. This is further encouraged by latest industrial policies by the Indian government (e.g. "Make in

India”). A consortium around blade manufacturer TPI Composites plans to build a manufacturing hub in Tamil Nadu which hosts already an established wind energy supply chain and port infrastructure.

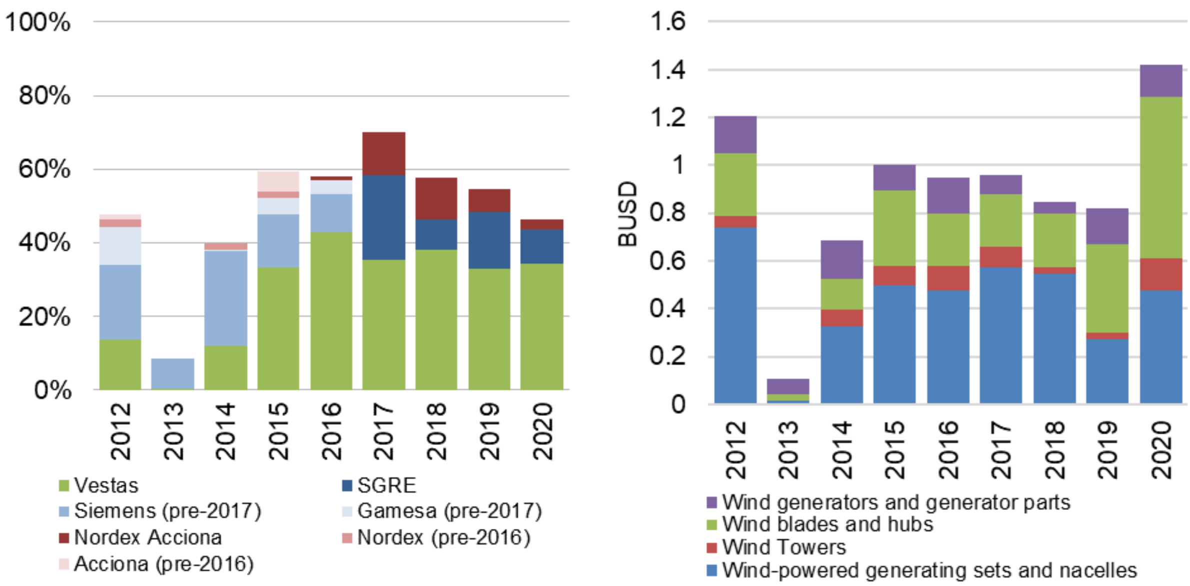
Figure 101 Trade balance of top global importers and exporters from the EU of wind-related goods (2012 – 2021)



Source: JRC based on COMEXT data, 2022.

Moreover, with Vestas a major OEM sets up an export oriented nacelle, hub and converter factory in Chennai. Nordex and Enercon signed agreements with blade suppliers located in India to supply international markets. In 2021, Enercon set up a generator production plant through its Indian supplier Coral Manufacturing Works (CMW) in Erode (IN), with first wind generators (E-138 EP3 E2 WEC type) leaving the plant in April 2022 [Enercon 2022b]. SiemensGamesa closed its onshore blade factories in Denmark and Spain in order to outsource production to countries with lower labour costs including India [GWEC 2021c].

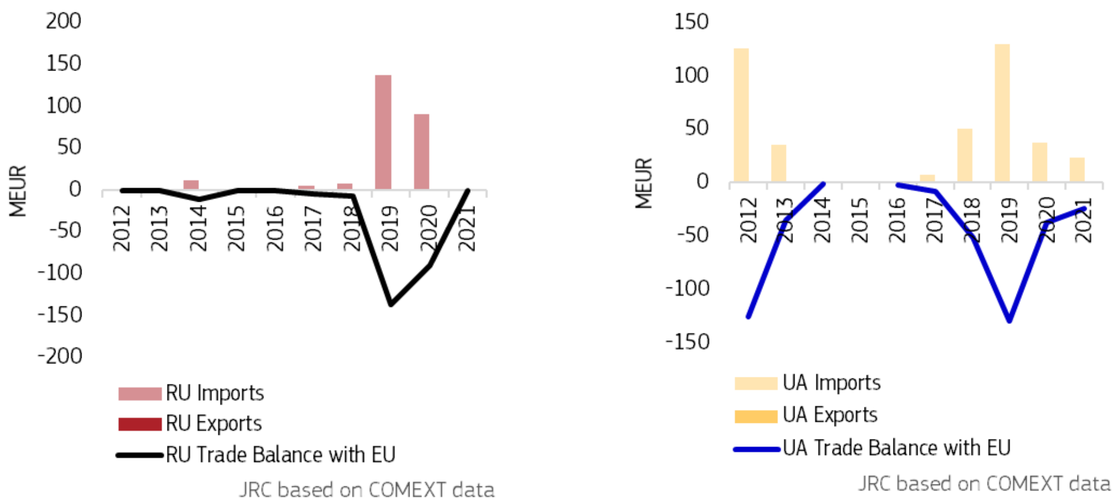
Figure 102 Market share of EU OEM in the US market (left) and US import value of selected wind turbine components originating from EU (right) in the period 2012 – 2020 [DOE 2021].
Note: Component 'Wind-powered generating sets and nacelles' includes data for nacelles only for 2020). Other trade categories can include non-wind related products



Source: JRC based on DOE data, 2022.

Both Russia and Ukraine have a negative trade balance with EU in wind energy related goods as both countries have a nascent wind energy supply chain (see **Figure 103**). Hence imports of both countries seem to follow deployment rates with Russia and Ukraine installing about 800 MW and 850 MW in the period 2018 -2020, respectively. Moreover, Ukraine showed increased onshore wind deployment of about 500 MW in the period 2011-2014. Following Russia's invasion of the Ukraine several major wind energy players announced that they will stop new investments in Russia. Energy utility Fortum (FI), the biggest wind power operator in Russia, SiemensGamesa RE (DE/ES) (having manufacturing capabilities in Russia) and Ørsted (DK) announced to refrain from new business agreements or new commercial activity in Russia until further notice [WPM 2022d]. In April 2022, Vestas (market leader and having manufacturing capabilities Russia) announced it will completely withdraw from Russia because of the country's invasion of Ukraine [WPM 2022e].

Figure 103 Trade balance of Russia and Ukraine with the EU of wind-related goods (2012 – 2021)



Source: JRC based on COMEXT data, 2022.

4.3 Resources efficiency and dependence in relation to EU competitiveness

Starting from analysing the type and quantities of the main raw materials and processed materials used in wind power plants, this chapter investigates the supply risk and critical dependencies along the supply chain. Items that present a high supply risk along the supply chain are further analysed to assess existing dependencies.

4.3.1 Raw materials and processed materials

Raw materials used in wind power plants include different rare earth materials, structural materials and metals (see **Table 22**).

Table 22 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

Source: JRC, 2022.

Table 23 shows the raw material need of the different components of a wind power plants. Light weight components such as the blades and spinner are using a range of composite materials including glass fibre, carbon fibre or polymers and plastics. Structural components and the power train are mainly composed of different metals and alloys.

Table 23 Raw materials usage in the different components of a wind power plant

Blades	Balsa wood, Glass fibres, Carbon fibre, Polyester, Epoxy, Polymer foam, Gelcoat (Styrene), Polyurethane, Steel, Copper, Aluminium, Vacuum fleece, Plastic films (various)
Generator	Cast iron, Steel (high alloyed), Steel (low alloyed), Copper
Gearbox	Cast iron, Steel (high alloyed), Steel (low alloyed)
Drivetrain	NdFeB alloy
Bearings	Steel
Nacelle	Glass fibre, Polyester, Epoxy, Styrene, Polyethylene, Cast iron (Nacelle foundation)
Shaft	Steel (high alloyed, e.g 34CrNiMo6)
Tower (steel)	Structural steel
Tower (concrete)	Concrete
Spinner	Glass fibre, Polyester
Hub	Cast iron, Steel
Cables (wind turbine)	Copper, Aluminium, Steel, Polymers, Lead
Foundation	Concrete, Steel (Steel reinforcement and anchor cage)
Wind turbine transformer (each turbine)	Steel, Copper, Aluminium, Resin
Site cables (internal wind farm (33kV) and grid connection (110kV))	Copper, Aluminium, Steel, Polymers, Lead
Wind plant transformer	Steel, Copper, Aluminium, Resin
Offshore wind monopile foundation	150mm steel plates

Source: 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 24**. Moreover, these ranges are complemented with latest material data on a recently published Vestas 4.2MW turbine.

Table 24. 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 2022e]. 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 2022e]
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.

In terms of quantity steel, cast iron and concrete are the main materials used for all wind turbine types followed by glass/carbon composites and polymers.

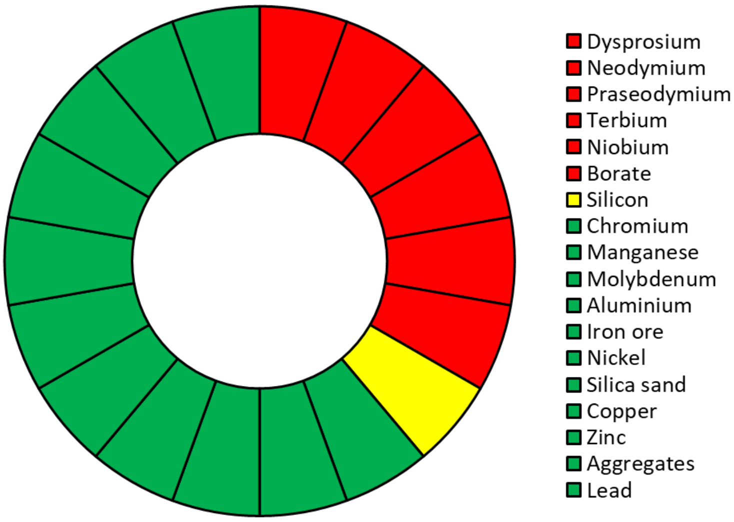
Other materials include balsa wood, a key material used in wind turbine blades (spar caps, blade cores) and Sulphur hexafluoride (SF6) a very potent greenhouse gas which is used in switchgears for medium- and high-voltage applications. The gas acts as an electrical insulator for the operation of the switchgear in each turbine and in transformer stations. The material demand for balsa wood varies strongly (estimated at around 2.9 m3/blade to 19.5 m3/blade) and manufacturers aiming for replacing balsa as a consequence of strong supply risks and soaring prices (see section 4.3.2). LCA data on latest wind turbine models of Vestas indicate that the amount of SF6 gas in wind parks is at about 235 kg/MW (with 193 kg/MW of SF6 at switchgears of the turbines and 42 kg/MW in site switchgears) [Vestas 2022e].

4.3.2 Supply risk and critical dependencies

The supply risk is analysed along the supply chain of the wind power plant spanning from raw materials and processed materials to the wind energy components.

Raw materials. The supply risk of raw materials is assessed based on the fourth technical assessment of critical raw materials for the EU (2020 Criticality Assessment) [EC 2020g]. Particularly rare earth elements used in the permanent magnets of the turbine generators are identified as critical raw materials in the wind sector. Dysprosium, Neodymium, Praseodymium, Terbium and Borate show a high supply risk as EU material sourcing relies almost entirely on a single country, namely China (with the exception of Borate being sourced from Turkey). Moreover with Niobium, used for iron-alloy metals in the main frame of the wind turbine shows a high supply risk as the EU sources 85% of it demand from Brazil (Brazil supplies 92% of the global demand).

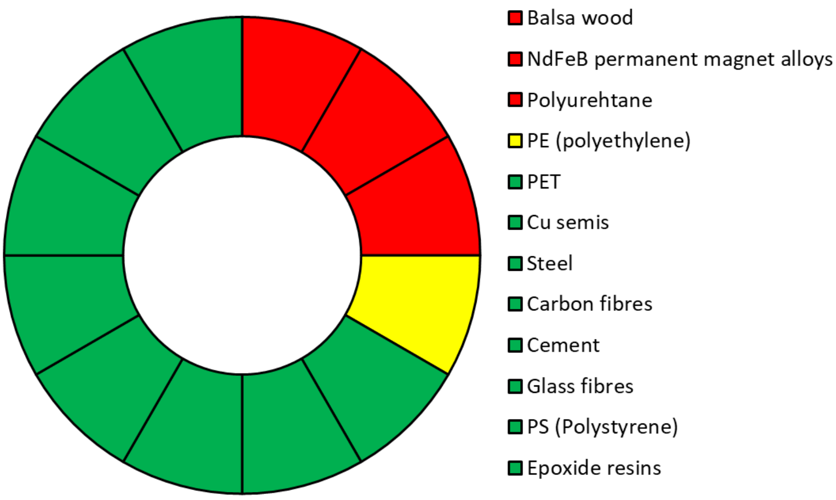
Figure 104 Supply risk of raw materials in the wind energy sector.



Source: JRC, 2022.

Processed materials. With regards to processed materials the supply risk[30] is highest for balsa wood, NdFeB permanent magnets and polyurethane.

Figure 105 Supply risk of processed materials in the wind energy sector.



Source: JRC, 2022.

With Balsa wood a renewable resource is a key material used in wind turbine blades (spar caps, blade cores) given its unique lightweight material properties (high stiffness; density ranging from 120 -160 kg/m3). Blade

[30] The supply risk is calculated taking into account the global supply of the material based on the Herfindahl-Hirschman Index (as a proxy for country concentration, the scaled World Governance Index (used as a proxy for country governance and a trade related variable of a country concerning the raw material in question

manufacturers refrain from publishing the specific balsa demand of their blade models. However, selected blade manufacturers publish their aggregated annual balsa wood demand in their annual sustainability reports (ESG reporting) [SANDIA 2014, SiemensGamesa 2021a, SiemensGamesa 2021b, TPI Composites 2021]. The specific balsa demand per blade was calculated by referring to the number of blades installed by the respective manufacturer (see **Table 25**). In 2021, latest figures suggest a specific balsa demand ranging between 2.9 m3/blade and 19.5 m3/blade[31].

Table 25. Specific demand for balsa wood in wind turbine blades reported by research and industry (estimate based on reporting).

	SANDIA	**TPI Composites**	**Siemens Gamesa**	**Siemens Gamesa**
Type of source	Research study	Sustainability reporting		
Case study	100m blade	Fleet - Annual material usage		
Year	2014	2021	2019	2021
Capacity additions [GW]	n.a.	13 GW	9.5 GW	11 GW
Average turbine capacity –fleet [MW]	n.a.	4	4	4
Average blade length [m]	100	80	80	80
Density balsa [kg/m3]	155	160	160	160
Reported balsa mass [tons]	1.3	4500	53052	25743
Specific balsa demand [m3/blade]	7.9	2.9	46.5*	19.5*

** OEM used different calculation methods in 2019 and 2021. In 2021, material needs were calculated based on the life cycle analysis of each turbine.*

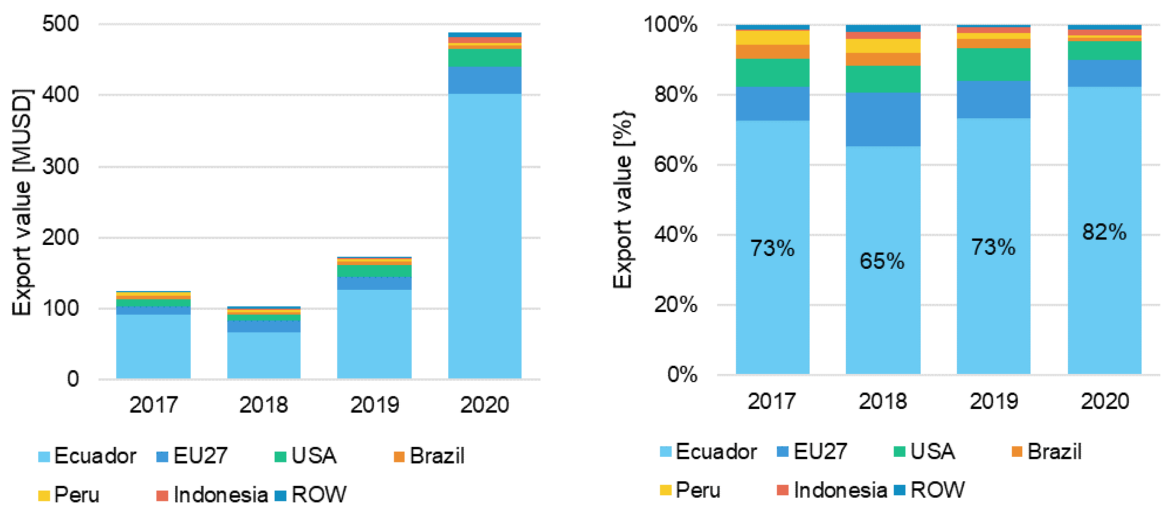
Source: JRC analysis, 2022.

Blade manufacturers experience a strong resource dependency as most balsa wood is sourced from Ecuador. Literature estimates that Ecuador supplies between 75% to 90% of the world's balsa wood demand [BNEF 2020, The Economist 2021]. Using the UN Comtrade dataset 'HS 440722'[32] as a proxy for balsa wood shows that the trade value of balsa wood exports from Ecuador account for 65% to 82%. Moreover, the total trade value surged to about USD 500 million, a fivefold increase as compared to 2018-levels (see **Figure 106**). Leading importers of balsa wood are China, the EU27 and the US followed by India, Brazil and Turkey.

[31] In 2021, a highly recognised article from The Economist claimed a specific balsa demand of 150 m3/blade, a value that cannot be confirmed after tracing the underlying source [Bortolotti et al. 2019] (Bortolotti et al. (2019) claim an overall balsa wood surface area of 1500 m2/blade building on data of the SANDIA SNL 100-03 blade [Griffith & Richards 2014]). Indeed Griffith & Richards (2014) give a specific balsa wood demand of 1229 kg/blade or 7.9 m3/blade.

[32] UN Comtrade dataset HS commodity code 440722 - Wood, tropical; virola, imbuia and balsa, sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or end-jointed, thicker than 6mm

Figure 106. Leading export countries in the export of tropical wood (virola, imbuia and balsa). Total trade value of exports (left) and export shares (right).



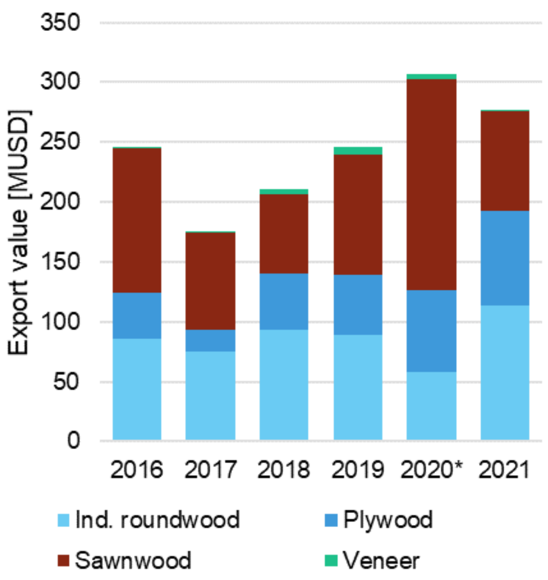
Source: JRC based on UN Comtrade, 2022.

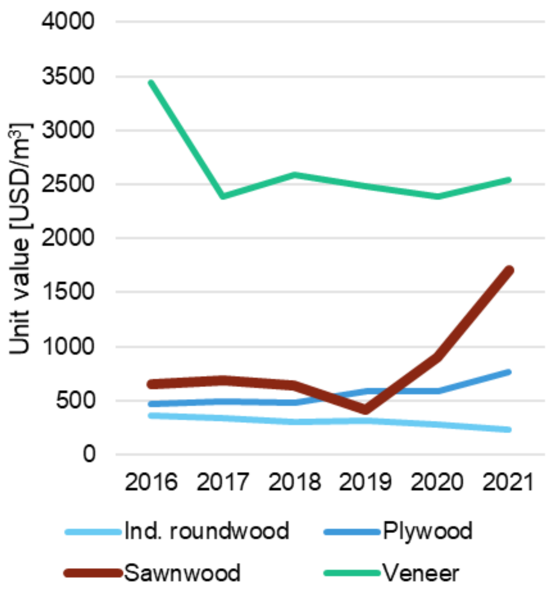
The strong increase in balsa export value originates from the latest uptake in global wind energy markets (e.g. China's deployment rush in view of the expiring Feed-In tariffs, strong performance of the US and EU markets) resulting in a supply bottleneck for balsa wood, over-logging and soaring prices. Based on UN Comtrade data it is estimated that up to 88% of Ecuadorian balsa was exported to China in 2020. The International Tropical Timber Organisation (ITTO) estimates for the respective balsa wood category (Sawnwood)[33] exported from Ecuador a fourfold increase from 415 USD/m3 in 2018 to 1705 USD/m3 in 2021 (see **Figure 107**) [ITTO 2021, ITTO 2022]. This is in line with reported prices in 2021 from balsa supplier Diab Group (SE) selling balsa wood for about 1800 USD/m3 [The Economist 2021].

The balsa wood supply bottleneck accelerated plans of countries and manufacturers to look for alternatives. Since 2020, China has planted 4 square kilometres of balsa in Xishuangbanna (Yunnan province) with first harvests planned from 2024 onwards. It is estimated that China aims to satisfy 10% of its national balsa demand [BNEF 2022c]. To some extent blade manufacturers are currently replacing balsa wood with recycled polyethylene terephthalate (rPET) or hybrid designs as it offers a cost competitive alternative. Exemplarily, blade manufacturer TPI Composites reports the materials used in manufacturing in 2021 with balsa wood and rPET accounting for 2% and 1%, respectively [TPI Composites 2021]. LM WindPower claims to introduce more recycled materials in new blades, quantifying the amount of rPET in LM blades increasing from 1.5% in 2018 to about 50% in 2020 [LM WindPower 2021]. Wood Mackenzie (2020) estimates the share of PET in the blade core material market to increase from 20% in 2018 to more than 55% by 2023 [WoodMackenzie 2020]. Biocomposite materials might be another alternative to balsa wood. Canada-based INCA Renewtech INCA BioBalsa™ a biocomposite based on hemp hurd cellulose claiming a comparable density to balsa, better compressive strength and a reduced environmental impact. A cooperation with composite supplier GURIT (CH) and production equipment specialist IPCO AB (SE/LU) foresees a large scale production facility by 2024 [CMM 2022, INCA Renewtech 2022].

33 Please find the full description of all wood categories at: https://www.itto.int/biennal_review/group_definitions/

Figure 107. Export value (left) and unit values (right) of wood products exported by Ecuador in the period 2016 - 2021.[34]





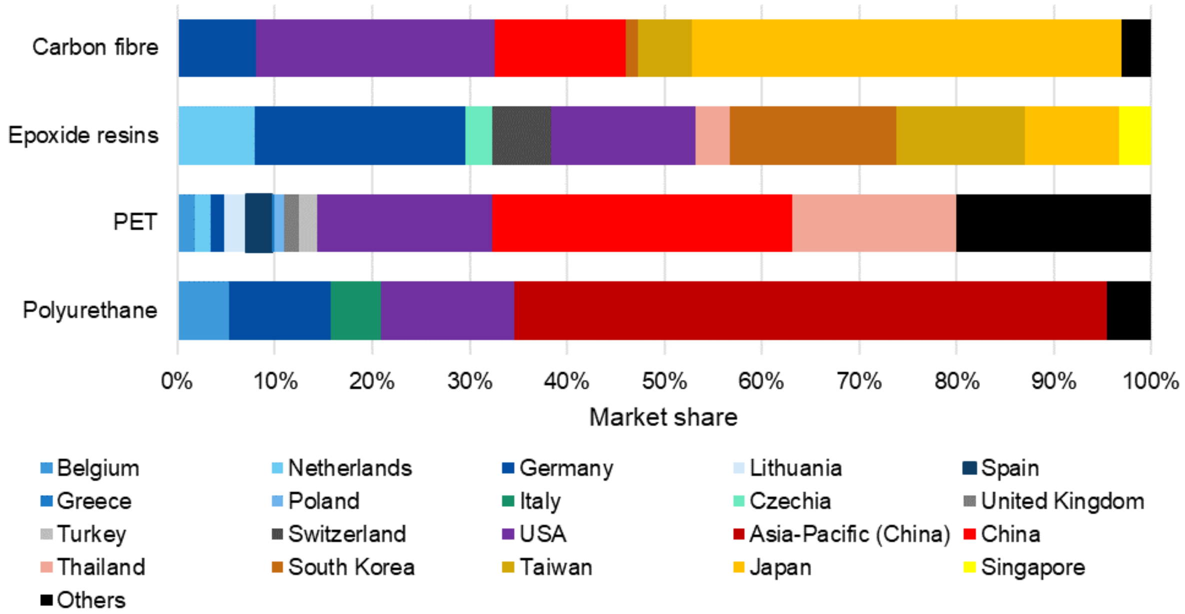
Source: JRC based on ITTO, 2022.

As in the case of raw material sourcing, China has a crucial role in the manufacturing of permanent magnets for wind turbine generators. Alves Dias et al. (2020) estimates global production shares based on the production of each operating mine and the relative distribution of in situ rare earth oxides. Based on such information, the production of neodymium, praseodymium, terbium and dysprosium makes up approximately one quarter of the global production of rare earths. The main producers are China (67 %), Myanmar (12 %), Australia (10 %) and the United States (9 %). For specific elements market diversification can be even poorer; this is the case for dysprosium and terbium, which are sourced almost exclusively from China and Myanmar. The control on primary rare earth resources for permanent magnets allowed China to expand its dominance on the downstream steps of the value chain. It is estimated that China's manufacturing capacities for permanent magnets alloys have expanded significantly, reaching 90% of global needs [Adamas Intelligence 2019] [Alves Dias et al. 2020].

Another material with critical supply risk is polyurethane which is used in the surface finish of wind turbine blades. Based on the global market size for polyurethane adhesives in 2020 about 61% of the polyurethane supplies are produced in (China/Asia-Pacific) followed by the US (14%), Germany (10%), Italy (5%) and Belgium (5%). Main EU producers include BASF (DE), Covestro (DE), COIM Group (IT) and Entec Polymers (BE). Other processed materials connected to the wind turbine blade show a lower criticality as multiple producers meet the demand of the market (see **Figure 108**) [Statista 2020, Statista 2022a, Statista 2022b, Statista 2022c, Statista 2022d].

[34] *Potentially incomplete 2020 data on export value. ITTO estimate represents only 54% of all Ecuadorian wood exports as reported by the Ecuadorian Central Bank [Banco Central del Ecuador 2022] (Data coverage of all other years at about 80%).

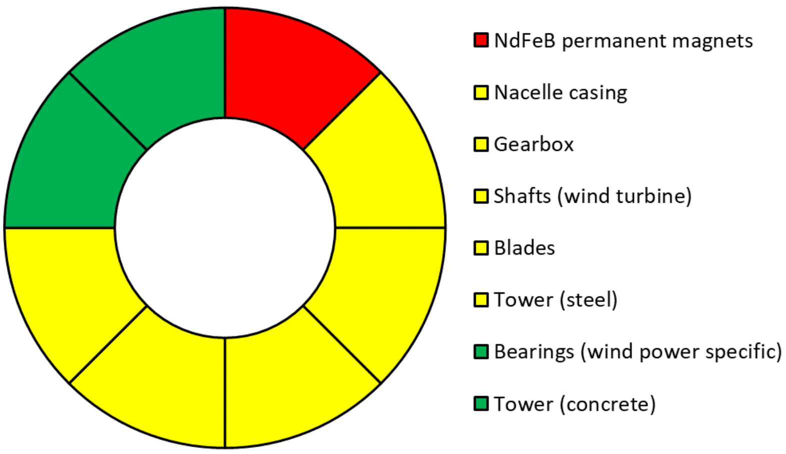
Figure 108. Global market shares in the production of polyurethane, PET, Epoxide resins and carbon fibre.



Source: JRC, 2022.

Components. As for the processed NdFeB magnet alloys the supply risk of manufactured NdFeB magnets is critical. It is estimated that China's manufacturing capacities permanent magnets are at the same scale as for the respective alloys, reaching 94% of global production of permanent magnets [ERMA 2021].

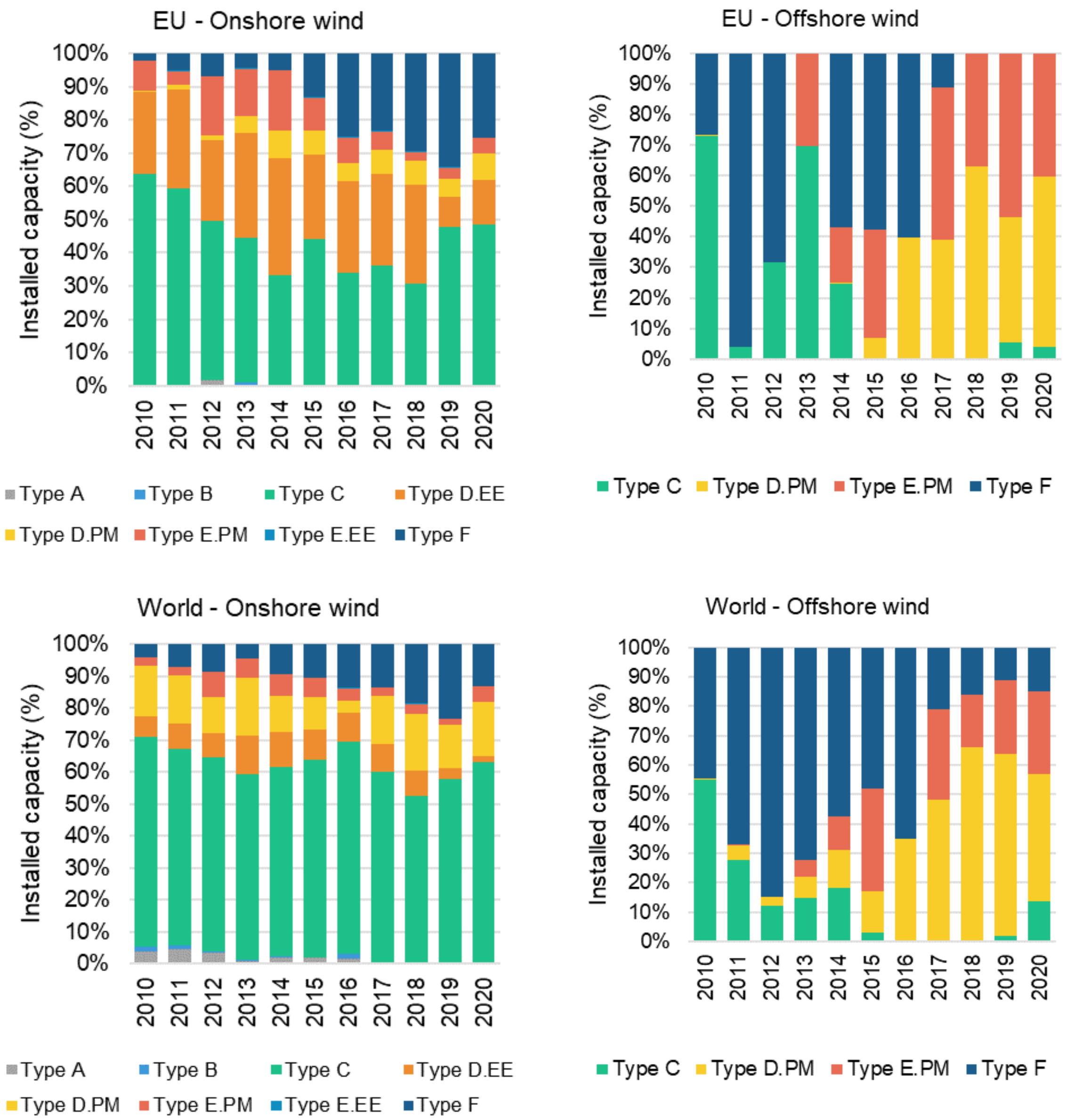
Figure 109 Supply risk of components in the wind energy sector.
Note: Please refer to section 3.4.1 for more information on supply dependencies on the main wind components



Source: JRC, 2022.

Within Europe a wide variety of drive train configurations exists for onshore wind turbines showing a trend towards direct drive configurations and hybrid arrangements. The main distinction can be made from the presence of a gearbox, the type of generator (synchronous or asynchronous) and the use of a power converter. In offshore wind, a continuous increase in drive train configurations using permanent magnets (type D-PM and E-PM) can be observed. **Figure 110** summarizes the different types of drive trains following a redefinition of the classification provided by [Hansen et al. 2004] (see graphical representation of this classification in Annex 3).

Figure 110 Annual market share of installed capacity by drive train configuration in the EU and globally. Note: *Type D.PM* and *Type E.PM* represent configurations using permanent magnets in the drive train. There is evidence that other configurations use permanent magnets in other parts of the turbine (see ***Table 24*** on material intensities and **Figure 113** on PM demand of Vestas turbines)

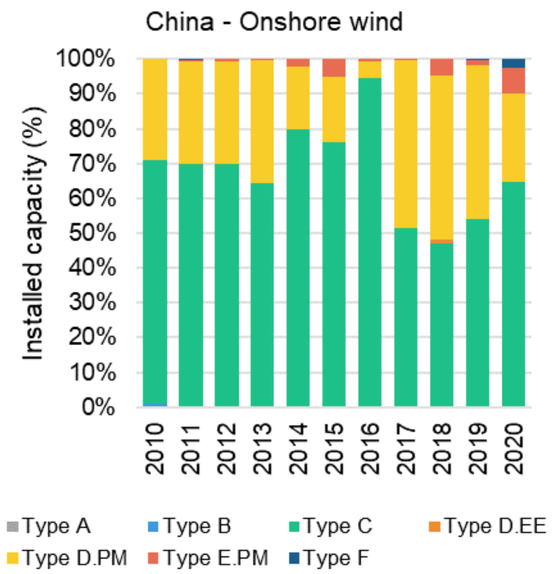


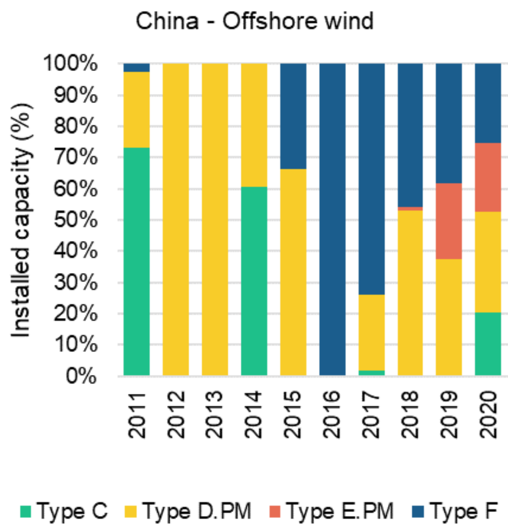
Source: JRC, 2022.

In 2020, global capacity additions using drive trains with permanent magnets were at about 17.2 GW and 4.9 GW for onshore wind and offshore wind, respectively. Still particularly in offshore wind, permanent magnets replace conventional rotor windings in generators at a much faster pace as they allow a higher power density, reduced size and weight. Since 2017 permanent magnet configurations have been the predominant design in EU offshore wind with market shares ranging between 89% and 100%. Similarly global permanent market shares account for around 72% and 22% for offshore wind and onshore wind respectively as a consequence of rising turbine sizes. Since 2018 permanent magnets configurations also lead in terms of market share in the Chinese offshore wind market (e.g. 54% in 2020). It can be expected that the demand for permanent magnets in Chinese offshore wind will soon match the EU levels as new installations use models with significantly increase rated capacity (10MW+) (see **Figure 110**).

The US onshore wind market is dominated by drive train configurations without permanent magnets, with geared high-wind speed drive trains (type C) and hybrid drive trains (type F) being ahead (see **Figure 112**) .

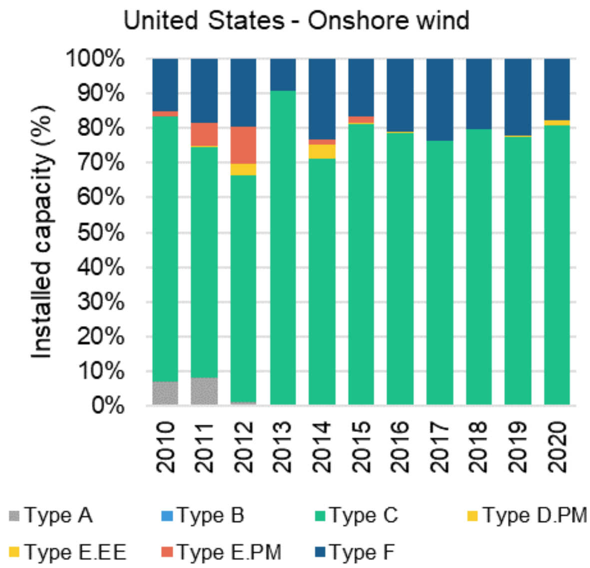
Figure 111 Annual market share of installed capacity by drive train configuration in China





Source: JRC, 2022.

Figure 112 Annual market share of installed capacity by drive train configuration in the United States
Note: Installed offshore wind capacity in the US accounted for about 42MW and uses Type D-PM drive train configuration



Source: JRC, 2022.

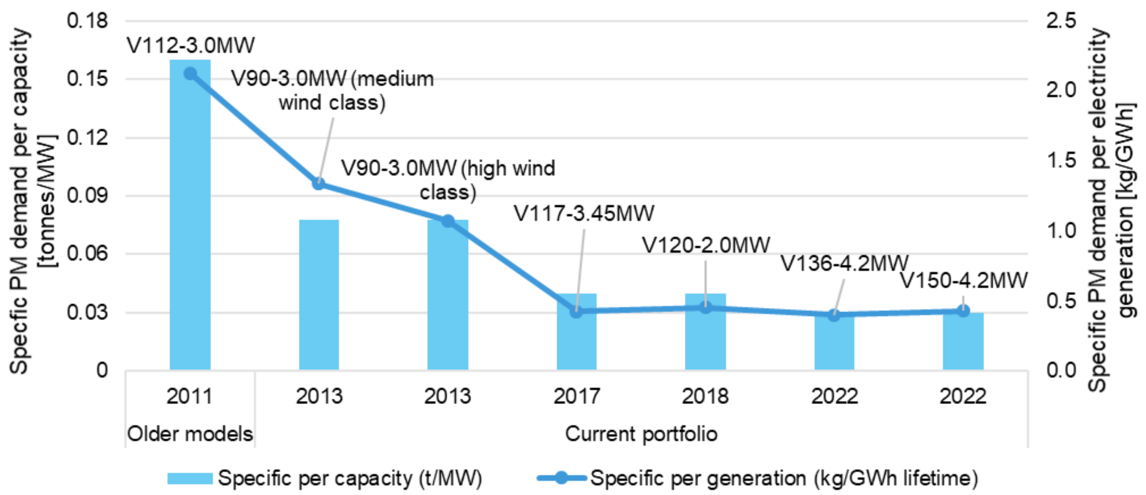
In early 2021, it was reported that China's Ministry of Industry and Information Technology investigated the effect of trade barriers (export bans) on rare earth minerals in view of US dependencies on Chinese rare earths with regards to its defence capabilities (e.g. F-35 fighter jets) [FT 2021]. The growing demand and supply risk for rare earths and the downstream production of permanent magnets force some manufacturers to move away from drive trains using permanent magnets.

Exemplarily major wind energy OEM Vestas (DK) adapted its onshore wind portfolio (2MW and 4MW platform) from permanent magnet drive trains towards hybrid drive trains (induction generators). Although not using PM drive trains there is some use of permanent magnets in other parts of the wind turbine. Vestas uses rare earth materials within the towers of all new turbine models for attaching internal fixtures (see *Type F* configurations) and in permanent-magnet generators in the older GridStreamer turbine models (e.g. the V112-3.0 MW and the 2.0 MW GridStreamer™ platform) and in the new EnVentus platform (e.g. V150-6MW, V162-6.2MW, V162-7.2MW, V172-7.2MW). Moreover, Vestas claims to have reduced the use of light rare-earth elements in the EnVentus platform and to have eliminated the use of heavy rare earth elements such as dysprosium [Vestas 2022f].

Figure 113 confirms the reduction in PM demand in Vestas wind turbines over the last decade comparing the older PM generator based models (Type E-PM drivetrains) with the current power generator models (Type C and Type F drivetrains). Based on the per electricity generated, the specific PM demand in Vestas onshore wind turbines decrease between 37% to 87% when compared to older models (e.g. the V112-3.0 MW). At the time of writing no data on the PM demand of the EnVentus platform was available.

Environmental product declarations by competitor SiemensGamesa do not give an insight into the amount of permanent magnets in use (see for example EPDs of SiemensGamesa models SG2.5-114, SG4.5-145 and others as published at the international EPD system [EPD 2022]). However, for its offshore wind turbine SG 8.0-167DD (Type D-PM drivetrains) the company states that NdFeB magnets contribute 3% to the global warming potential caused by all materials of a representative wind power plant [EPD 2022]. Based on earlier assessments of Carrara et al. (2020) it can be assumed that PM demand of direct drive configurations are up to a factor 10 higher than for their geared counterparts.

Figure 113 Evolution of PM demand in Vestas wind turbines [Vestas 2022g].



Source: JRC, 2022.

5 Conclusions

This report presents the state of the art in wind energy technology and analyses R&D development trends focussing particularly on the technology progress made in EU-funded research until end of 2021 in view of the SET-Plan targets. Moreover, this work provides an analysis on EU position and global competitiveness within the wind value chain and identifies potential bottlenecks and supply risks towards the targets formulated in the European Green Deal.

Technology State of the art and future developments

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

2021 marks another record year in global wind energy deployments. Although new onshore wind capacity decreased by 18% from the record year 2020, 72 GW mark the second strongest year in onshore wind deployment and almost a doubling of capacity additions as compared to 2010-levels. Offshore wind saw an unprecedented record year with 21 GW of new capacity installed, a more than threefold increase after a record year in 2020.

In 2021, China installed in one year the same amount of offshore installations as EU did in cumulative terms, driven by a shift from Feed-in-Tariffs towards a tender-based support scheme. Since May 2018, the Chinese National Development and Reform Commission (NDRC) requires wind energy projects to participate in tenders. Aiming for 'subsidy-free' offshore wind, only projects approved before 2018 and grid-connected by the end of 2021 will receive the more generous Feed-in-Tariff.

In 2021, EU Member States (MSs) added another 10 GW of onshore wind capacity making it the second strongest year in onshore capacity additions since 2010. EU offshore annual deployments saw only 1 GW of offshore wind capacity deployed in 2021 in EU 27 countries. Cumulative offshore wind capacity in EU MSs at the end of 2021 is at about 15.6 GW. All European sea basins (including projects installed in the United Kingdom and Norway) host a cumulated capacity of 28.2 GW.

At the end of 2021, EU MSs deployed 27 MW of floating offshore wind in EU sea basins whereas cumulative installed capacity in the United Kingdom and Norway is at 80 MW and 6 MW, respectively. There is a pipeline of projects that will lead to the installation of 530 MW of floating capacity in European waters by 2025 (of which 247 MW are deployed in EU MSs). The global market for floating offshore wind represents a considerable market opportunity for EU companies. Latest announcements of national floating offshore wind targets (particularly in Europe and Asia) suggest a substantial increase in the deployed capacity in the mid-term (up to 15.6 GW by 2030).

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

EU27 scenario modelling of the 2030 Climate Target Plan (CTP-MIX scenario) shows onshore wind deployments surging to 366 GW and 963 GW in 2030 and 2050, respectively. An even stronger relative increase is calculated for offshore wind deployments with 73 GW in 2030 and 290 GW by 2050. These scenario targets are further surpassed by the mid-term by new targets formulated in the REPowerEU Plan proposing an installed wind capacity of 510 GW by 2030. The REPowerEU plan has been presented in response of the global energy market disruption caused by Russia's invasion of the Ukraine in Spring 2022.

The remaining capacity gap of EU MS towards their wind energy targets (or estimated targets) in 2030 as expressed in their National Energy and Climate Plans is currently at about 151 GW.

Following current national targets as expressed in the MSs National Energy Climate Plans (NECPs) suggest that the Offshore Renewable Energy Strategy (ORES) target for 2030 can be achieved. Latest commitments to offshore wind suggest an even more accelerated deployment path. In May 2022, Belgium, Denmark, Germany, and the Netherlands pledged in the Esbjerg declaration to deploy at least 65 GW of offshore wind by 2030 and 150 GW by 2050 to speed up the phase-out of fossil fuels and to minimise reliance on energy imports from Russia.

Both onshore and offshore wind show continuous decline in costs and are expected to further decline on the long term towards 2050 as a consequence of scaling effects and technology development. However, since the outbreak of the COVID-19 pandemic an increase in LCoE is observed as a consequence of commodity price inflation, increasing transportation costs and supply chain disruptions. Moreover, financing costs vary considerably among EU countries. A further decrease and convergence among countries in financing costs might be achieved by focussing on de-risking debt financing by policies that implement support schemes decreasing the volatility of a projects cash flow (e.g. Contracts for Difference).

Strongest drivers of cost reduction in floating offshore wind are seen in the industrialisation of floating technology, the knowledge transfer form established offshore industries and scaling effects in the operation and maintenance of large floating offshore projects.

In the last decade, EU leads on investment in public R&D spending followed by Japan and the United States. In the last years (period 2017-2019), Japan led at country level on public R&D investment in wind energy, followed by Germany, the United States, Norway and South Korea. The Netherlands, Denmark, Spain and France were also amongst the top ten countries investing in wind energy.

However, with about 91% and 94% the majority of EU R&D funding in the wind energy sector comes from the corporate sector. EU companies are among the leading investors in R&D. Moreover, a strong representation of Chinese OEMs is observed among the Top20 global R&D investors increasing their shares lately when compared to their position since 2010.

The EU hosts about 38% of all innovators, of which about 44% are venture capital companies and 56% are corporates. Five countries host almost 80% of identified innovators. The US (1st) and the UK (5th) have a very strong base of venture capital companies while most of innovators in Japan (2nd), Germany (3th) and China (4th) are corporate innovators.

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 1% of patents being international (EU: 22%, US: 37%). Moreover, only about 4% (In the period 2017-2019) of the Chinese patenting inventions filed on wind energy technologies were high value, while high-value inventions account for about 64% of all European wind energy inventions filed.

Protection of intellectual property rights (IPR) is an important issue among competitors and markets. IP infringement remains the leading reason for the reluctance of EU companies to take their innovative technologies to China, thus hampering technology diffusion through trade.

IP litigation cases among major wind OEMs hold the potential to delay the delivery of wind energy projects posing a threat to the ambitious targets ahead (e.g. GE – SGRE case on direct drive and ZVRT-technology patents).

The number of research articles is highest in China (29%), followed by EU (20%), the United States (9%) and the United Kingdom (8%). Within EU, the leading countries in terms of deployment and first movers are showing the highest publication activity. Bibliometric indicators measuring the impact and productivity of peer-reviewed articles in the area of wind energy confirm that EU can compete with its international counterparts, leading in terms of highly cited articles and productivity indicators.

EU provides constant R&D support to the wind sector via its major funding programmes. This includes R&D activities and investments in wind energy within the within the European FP7/H2020 programme, the European Maritime, Fisheries and Aquaculture Fund (EMFAF), the LIFE programme, the NER300 programme and its successor the Innovation Fund. Since 2009 FP7 and H2020 have allocated substantial funding across all wind research R&I priorities with projects on offshore wind technology (EUR 172 million), floating offshore wind (EUR 115 million) and research on new materials & components (EUR 95 million) accumulating most of the funds.

Moreover, as the wind sector expands R&D is needed to address inter-sectoral themes (e.g. co-existence with other sectors, circularity in design, recycling, environmental impact, life-time extension). Exemplarily, R&D needs emerge in the area of circularity in design and R&D trends enabling the co-existence of offshore wind and defence activities, two areas of particular interest within the European Green Deal as formulated in the EU's Circular Economy Action Plan and the EU Offshore Renewable Energy Strategy.

Value chain Analysis

Turnover of the EU wind sector increased by about EUR 9.4 billion as compared to 2019. With about EUR 14 billion Germany leads in turnover, followed by the Netherlands, Spain and Denmark driven by strong deployment rates.

EU estimates on direct and indirect Gross Value Added (GVA) show a positive trend. With about EUR 6 billion, Germany leads in direct GVA, followed by the Netherlands, Spain and Denmark. Moreover, strong growth in direct GVA as compared to previous years can be observed in Belgium, Poland and Portugal, countries experiencing a rise in wind energy installations.

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 (4.5%). On a wind energy component level, China's market share ranges between 33% and 58% across all major wind energy components. EU manufacturing ranks second showing market shares from 11% to 47%, followed by India, the US and Brazil. Current manufacturing capabilities in EU easily cover the current demand in major wind energy components. However, as annual deployment rates need to show up to a fourfold increase to reach the ambitious 2030 targets supply chain bottlenecks might emerge if components are sourced from EU MSs only.

The European manufacturing supply chain for offshore wind at Tier 1 and Tier 2 level builds mainly on companies from EU Member States. Tier 1 and Tier 2 suppliers have 138 facilities located in the EU, of which about 84% are of EU origin. Suppliers are located in the leading EU offshore wind markets around the North Sea and Baltic Sea as well as in countries that can leverage a strong onshore wind supply chain and even in landlocked countries. There is only some indication of Tier 2 components coming from non-European companies in China and Japan.

Offshore wind turbine rotors by Siemens RE and Vestas build on a strong European supply chain, with most of the components being sourced from EU companies. Yet both OEMs source some components from non-EU countries, highlighting the importance of trade relations (UK) and of maintaining the EU's competitive advantage in offshore wind against its main competitors (e.g. China). The diversification in sourcing of offshore wind components seems to become more pronounced for the most recent certified offshore wind turbines.

In 2021, EU companies held 90% of the EU onshore wind rotor market. As in the offshore sector, European OEMs mainly source their onshore wind rotor components from companies based in EU Member States. Recent onshore turbine models confirm the competitiveness of Chinese manufacturers in some components, such as blade bearings and shafts. Given the global scale of the onshore wind industry, European OEMs seem to source their components from multiple suppliers and cooperate with component suppliers with a global manufacturing footprint.

The supply chains of offshore wind components of EU and the UK show strong overlapping, with EU companies locating significant manufacturing capabilities on UK territory.

A reinforced commitment to offshore wind through the announcement of the UK government to increase its offshore wind capacity target to 50 GW until 2030 triggers more direct investments of EU and non-EU companies in the UK. At the same time, the introduction of a local content criteria in the application process of the latest UK renewable energy allocation round (AR4) might also have negative effects on EU-UK trade relations as it holds the potential to distort trade and cause unintended effects on investment across value chains.

Wind is a strategic industry for Europe. It is estimated that the sectors offers between 240 000 and 300 000 direct and indirect jobs. EU total wind energy workforce equals to about a quarter of the estimated global employment in the wind energy sector, with the majority of all wind related jobs located in China (44%). Latest stagnation in EU wind energy deployment might be connected to fierce competition in the wind sector as indicated by declining margins of listed EU OEMs. Future scenarios estimate global wind energy jobs growing almost fivefold by 2050 at about 5.5 million jobs. However, this will need to mobilise efforts in recruiting, training and retaining skilled workers.

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 cumulated 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 to generate 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, neither in terms of evolution in time nor in respect to the growth in turbine size. So far no detailed LCA on the latest offshore wind turbines by Vestas, SiemensGamesa RE and GE was identified.

EU position and Global competitiveness

The European Original Equipment Manufacturers (OEMs) in the wind energy sector have held a leading position in the last few years. In 2021 they ranked second behind Chinese OEMs when analysing the Top10 OEMs in terms of market share. Among the top 10 OEMs in 2021, Chinese OEMs led with 43 % of market share, followed by the European (34 %) and North American (9 %) companies. This can be explained by a surge in new installations in the Chinese and US wind market.

The latest surge in Chinese wind deployment can be explained through a set of new policies targeting renewable energy integration and a shift from Feed-in-Tariffs towards a tender-based support scheme. This necessitates projects approved before 2018 to be grid-connected latest by the end of 2020 (and by end of 2021 in case of offshore wind) in order to receive the expiring Feed-in-Tariff.

Chinese manufacturers are strongly consolidated in their home market. Since 2013, the penetration of foreign manufacturers has been below 7% of new capacity installed, down from 13% in 2010. In 2020, only 4.7% of the installed capacity came from non-Chinese manufacturers, with EU companies accounting for about 2.8%. Partnerships with local wind developers are a prerequisite for foreign companies entering into the Chinese market. The market is dominated by power utilities owned by the central government, followed by energy companies run by local governments.

Offshore wind market shares showed an even more pronounced development driven by the Chinese market. In 2021, China installed in one year the same offshore wind capacity as EU did in cumulative terms.

EU's global competitors import significant value of wind related goods from EU countries. Lately, China and India are the main exporters to the EU, countries holding significant manufacturing capabilities in the wind sector.

Aside from the import value imported by a country from the EU, the share of imports from the EU in the period 2019 – 2021 indicates the leading position of EU products globally. More than 12 countries show import shares above 50% stemming from EU, including some of the leading wind energy markets.

EU has a positive trade balance in wind related goods to countries outside the EU (extra-EU trade), however in the last decade some stagnation can be witnessed, due to a negative trade balance with China and India. Since China's restrictive wind market policy, the trade balance clearly leans towards China, with a record surplus (trade deficit for EU) of EUR 411 million for China in 2021. EU also showed a negative trade balance with India with imports from India surging to about EUR 227 million in 2021. This can be explained as a first reaction of major wind turbine manufacturers exploring the possibility to use India as a low-cost export hub of their components as they are facing increasing costs from the ongoing US-China trade tensions.

EU has a positive trade balance with the United Kingdom and the United States. However, latest policies in the United Kingdom granting support for renewable energy projects (and particularly offshore wind projects), introduced a local content scoring criteria favouring UK over imported content. As such a shift in the UK-EU trade balance on wind energy related goods can be expected if the UK local content criteria prevails. In the last decade, the United States remained reliant on imports from the EU as imports largely follow the annual deployment market shares of EU OEMs in the United States.

Both Russia and Ukraine have a negative trade balance with EU in wind energy related goods as both countries have a nascent wind energy supply chain. Following Russia's invasion of the Ukraine several major wind energy players announced that they will stop new investments in Russia or even withdrew their operations from Russia.

Particularly rare earth elements used in the permanent magnets of the turbine generators and within wind turbine towers are identified as critical raw materials in the wind sector. Dysprosium, Neodymium, Praseodymium and Terbium show 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, both sourced from just one non-EU country.

With regards to processed materials the supply risk is highest for balsa wood used in blades, NdFeB permanent magnets and polyurethane. Blade manufacturers experience a strong resource dependency as most balsa wood is sourced from Ecuador. Literature estimates that Ecuador supplies between 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 hybrid designs (OEMs).

When analysing wind energy components the supply risk of manufactured NdFeB magnets is critical. It is estimated that China's manufacturing capacities of permanent magnets are at the same scale as for the respective alloys, reaching 94% of global production of permanent magnets. Particularly in offshore wind, permanent magnets replace conventional rotor windings in generators at a much faster pace as they allow a higher power density, reduced size and weight. Since 2017 permanent magnet configurations have been the predominant design in EU offshore wind with market shares ranging between 89% and 100%. Similarly, global permanent market shares increases as turbine size rises at around 72% and 22% for offshore wind and onshore wind respectively.

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List of abbreviations and definitions

AD	Air defence
AWES	Airborne wind Energy Systems
CAPEX	Capital Expenditure
CED	Cumulated 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	Levelized 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

Annex 1

Table 26 R&I projects considered under JRC methodology to estimate EC funding for wind energy under FP7 and H2020 programs

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
FP7	212825	PROTEST	2008	Maintenance & monitoring	100%	1,980,119	1,980,119
FP7	213740	SAFEWIND	2008	Resource assessment	100%	3,992,400	3,992,400
FP7	218691	KITVES	2008	New turbine materials & components	100%	2,955,738	2,955,738
FP7	212966	RELIAWIND	2008	Logistics, assembly & installation	100%	5,180,767	5,180,767
FP7	219055	7MW-WEC-BY-11	2008	New turbine materials & components	100%	3,270,285	3,270,285
FP7	219048	NORSEWIND	2008	Resource assessment	100%	3,939,517	3,939,517
FP7	224548	AEOLUS	2008	Maintenance & monitoring	100%	2,500,000	2,500,000
FP7	230698	WINDFLOWER	2009	New turbine materials & components	100%	465,495	465,495
FP7	237471	VSABLA	2009	Resource assessment	100%	296,089	296,089
FP7	238576	WAUDIT	2009	Resource assessment	100%	3,984,000	3,984,000
FP7	238325	SYSWIND	2009	Maintenance & monitoring	100%	3,026,568	3,026,568
FP7	239191	PROND	2009	New turbine materials & components	100%	45,000	45,000
FP7	239462	NIMO	2009	Maintenance & monitoring	100%	3,401,900	3,401,900
FP7	239304	WINGY-PRO	2009	New turbine materials & components	100%	2,478,530	2,478,530
FP7	232155	ROOF-CAPTURE	2009	New turbine materials & components	100%	1,049,975	1,049,975
FP7	232190	WINTUR	2009	Maintenance & monitoring	100%	1,103,300	1,103,300
FP7	232362	OSGRAM	2009	Logistics, assembly & installation	100%	958,429	958,429
FP7	230719	METEORES SERVICES	2010	Resource assessment	100%	512,318	512,318
FP7	256714	HAWE	2010	Airborne wind energy systems	100%	1,920,471	1,920,471
FP7	251309	STA-DY-WI-CO	2010	Other	50%	935,868	467,934
FP7	252284	ICIEMSET	2010	Other	50%	247,028	123,514
FP7	241402	MARINA PLATFORM	2010	Floating offshore wind	50%	8,708,660	4,354,330
FP7	249801	LASTBEG	2010	Grid integration	75%	6,187,246	4,640,435
FP7	256769	DEEPWIND	2010	Floating offshore wind	100%	2,992,438	2,992,438
FP7	241421	ORECCA	2010	Offshore technology	50%	1,599,033	799,516
FP7	249812	TWENTIES	2010	Grid integration	30%	31,774,565	9,532,370
FP7	252581	NANOPERMAG	2010	New turbine materials & components	33%	202,319	67,440
FP7	273451	IRWES	2011	Other	100%	179,686	179,686
FP7	268171	TOP WIND	2011	Other	100%	897,050	897,050
FP7	283145	CLUSTERDESIGN	2011	Logistics, assembly & installation	100%	3,582,619	3,582,619
FP7	296050	DEMOWFLOAT	2011	Floating offshore wind	100%	3,563,871	3,563,871
FP7	296043	INFLOW	2011	Floating offshore wind	100%	11,934,953	11,934,953
FP7	262552	MARINET	2011	Offshore technology	50%	8,999,998	4,499,999
FP7	269202	HEMOW	2011	Offshore technology	100%	241,500	241,500

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
FP7	283277	INTELWIND	2011	Maintenance & monitoring	100%	1,087,900	1,087,900
FP7	283533	DASHWIN	2011	Maintenance & monitoring	100%	1,085,100	1,085,100
FP7	286603	RINGMAN	2011	Offshore technology	100%	1,132,700	1,132,700
FP7	259166	HIGHWIND	2011	New turbine materials & components	100%	1,499,800	1,499,800
FP7	272437	ICFLOAT	2011	Other	100%	199,550	199,550
FP7	282797	EERA-DTOC	2012	Offshore technology	100%	2,899,857	2,899,857
FP7	296012	INGRID	2012	Grid integration	50%	13,789,563	6,894,782
FP7	294933	DISKNET	2012	Grid integration	50%	505,700	252,850
FP7	309395	MARE-WINT	2012	Offshore technology	100%	3,822,753	3,822,753
FP7	306471	ACTIVEWINDFARMS	2012	Resource assessment	100%	1,499,241	1,499,241
FP7	320042	ECOWINDS	2012	Maintenance & monitoring	100%	1,757,713	1,757,713
FP7	315207	WINTUR DEMO	2012	Maintenance & monitoring	100%	1,044,000	1,044,000
FP7	312372	WINDSCANNER	2012	Resource assessment	100%	4,350,000	4,350,000
FP7	304760	WIND TURBARS	2012	Maintenance & monitoring	100%	1,066,000	1,066,000
FP7	288145	H2OCEAN	2012	Offshore technology	25%	4,525,934	1,131,484
FP7	308974	INNWIND.EU	2012	Offshore technology	100%	13,799,999	13,799,999
FP7	308793	SUPRAPOWER	2012	New turbine materials & components	100%	3,891,058	3,891,058
FP7	283292	CORETO	2012	New turbine materials & components	100%	917,400	917,400
FP7	286854	CMSWIND	2012	Maintenance & monitoring	100%	1,869,903	1,869,903
FP7	288192	TROPOS	2012	Offshore technology	25%	4,877,911	1,219,478
FP7	288710	MERMAID	2012	Offshore technology	25%	5,483,411	1,370,853
FP7	296164	SOPCAWIND	2012	Resource assessment	100%	1,950,000	1,950,000
FP7	304700	WETMATE	2012	Offshore technology	100%	1,222,000	1,222,000
FP7	315485	WINDRIVE	2012	New turbine materials & components	100%	1,586,998	1,586,998
FP7	315563	OPTIWIND	2012	New turbine materials & components	100%	1,159,875	1,159,875
FP7	318925	EDWTGT	2012	New turbine materials & components	100%	392,700	392,700
FP7	299767	ACRES	2012	Grid integration	50%	116,853	58,426
FP7	287844	COCONET	2012	Other	50%	9,000,000	4,500,000
FP7	297852	RES GRID INTEGRATION	2012	Grid integration	50%	231,547	115,774
FP7	282775	UMBRELLA	2012	Grid integration	50%	3,863,811	1,931,906
FP7	301807	PHASEMASTER	2012	Maintenance & monitoring	100%	209,033	209,033
FP7	295977	FLOATGEN	2013	Offshore technology	100%	10,153,053	10,153,053
FP7	317221	MEDOW	2013	Offshore technology	100%	3,925,537	3,925,537
FP7	618159	NUMIWING	2013	Airborne wind energy systems	100%	100,000	100,000

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
FP7	322430	OPTIMUS	2013	Maintenance & monitoring	100%	3,333,275	3,333,275
FP7	322449	WINDTRUST	2013	New turbine materials & components	100%	6,247,264	6,247,264
FP7	608396	AVATAR	2013	New turbine materials & components	100%	6,680,489	6,680,489
FP7	304753	MONITUR	2013	Maintenance & monitoring	100%	1,062,000	1,062,000
FP7	309985	WALID	2013	New turbine materials & components	100%	3,964,797	3,964,797
FP7	310531	HYDROBOND	2013	New turbine materials & components	100%	2,929,476	2,929,476
FP7	314893	WINDHEAT	2013	New turbine materials & components	100%	1,125,998	1,125,998
FP7	605067	WINDUR	2013	New turbine materials & components	100%	1,158,000	1,158,000
FP7	605138	DEICE-UT	2013	New turbine materials & components	100%	1,066,000	1,066,000
FP7	605420	HEXATERRA	2013	Offshore technology	50%	1,198,998	599,499
FP7	614020	LEANWIND	2013	Logistics, assembly & installation	100%	9,986,231	9,986,231
FP7	308864	iGREENGrid	2013	Grid integration	50%	4,336,217	2,168,109
FP7	334577	CNT-IN-FRPC	2013	New turbine materials & components	100%	100,000	100,000
FP7	315925	MERIKA	2014	Other	50%	3,950,000	1,975,000
FP7	618122	NEWA	2014	Resource assessment	100%	4,335,329	4,335,329
FP7	624562	MESOWAKE	2014	Resource assessment	100%	352,176	352,176
FP7	605013	TOWERPOWER	2014	Maintenance & monitoring	100%	1,469,000	1,469,000
FP7	605451	AUTOWINSPEC	2014	Maintenance & monitoring	100%	1,018,000	1,018,000
FP7	609795	IRPWIND	2014	Other	100%	9,822,218	9,822,218
FP7	604215	CARBOPREC	2014	New turbine materials & components	50%	5,968,027	2,984,014
FP7	612531	MARINCOMP	2014	Offshore technology	50%	2,376,057	1,188,029
FP7	607596	SURFSUP	2014	Other	100%	587,134	587,134
FP7	612581	PLENOSE	2014	Other	50%	281,400	140,700
H2020	651752	SEAMETEC	2014	New turbine materials & components	50%	50,000	25,000
H2020	652138	Briareo	2014	New turbine materials & components	100%	50,000	50,000
H2020	640741	LIFES 50plus	2015	Floating offshore wind	100%	7,274,838	7,274,838
H2020	643167	AEOLUS4FUTURE	2015	Maintenance & monitoring	100%	3,811,805	3,811,805
FP7	627270	OHMWIT	2015	Maintenance & monitoring	100%	273,197	273,197
FP7	632601	LAAME-CROW	2015	New turbine materials & components	100%	710,790	710,790
H2020	654634	TELWIND	2015	Floating offshore wind	100%	3,498,530	3,498,530
H2020	691173	REACH	2015	Airborne wind energy systems	100%	2,675,132	2,675,132
H2020	689772	HPC4E	2015	Resource assessment	33%	1,998,176	666,059
H2020	671868	I-WSN	2015	Maintenance & monitoring	33%	50,000	16,667
H2020	657652	Riblet4Wind	2015	New turbine materials & components	100%	3,307,172	3,307,172

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
H2020	642682	AWESCO	2015	Airborne wind energy systems	100%	2,999,015	2,999,015
H2020	675659	ICONN	2015	Other	50%	845,838	422,919
H2020	642108	AWESOME	2015	Maintenance & monitoring	100%	2,862,074	2,862,074
H2020	673976	POSEIDON	2015	Floating offshore wind	50%	1,144,150	572,075
H2020	666624	IRWES	2015	New turbine materials & components	100%	1,696,380	1,696,380
H2020	674741	ELISA	2015	Offshore technology	100%	2,497,863	2,497,863
H2020	666793	AMPYXAP3	2015	Airborne wind energy systems	100%	2,500,000	2,500,000
H2020	698686	SE-NBW	2015	Logistics, assembly & installation	100%	50,000	50,000
H2020	692644	URBAVENTO	2015	New turbine materials & components	100%	50,000	50,000
H2020	698136	WITRO	2015	Resource assessment	100%	50,000	50,000
H2020	698883	LiraTower	2015	New turbine materials & components	100%	50,000	50,000
H2020	683875	MEWi-B	2015	New turbine materials & components	100%	50,000	50,000
H2020	673137	CLOUD DIAGNOSIS	2015	Maintenance & monitoring	100%	50,000	50,000
H2020	672559	AIRCRANE	2015	Logistics, assembly & installation	100%	50,000	50,000
H2020	673202	EeC WITUR	2015	Maintenance & monitoring	100%	50,000	50,000
H2020	663597	MeRIT	2015	Grid integration	50%	50,000	25,000
H2020	672729	Omniflow	2015	New turbine materials & components	50%	50,000	25,000
H2020	646517	DemoWind	2015	Offshore technology	100%	7,783,160	7,783,160
H2020	656024	EcoSwing	2015	New turbine materials & components	100%	10,591,734	10,591,734
H2020	684591	Opti-LPS	2015	New turbine materials & components	100%	50,000	50,000
H2020	673782	FLOATMAST	2015	Offshore technology	100%	50,000	50,000
H2020	666257	Eciwind	2015	New turbine materials & components	100%	1,307,305	1,307,305
H2020	674094	OPTILIFT	2015	Offshore technology	33%	50,000	16,667
H2020	673106	MONOFFSHORE	2015	Offshore technology	33%	50,000	16,667
H2020	663185	ANGELS	2015	Offshore technology	33%	50,000	16,667
H2020	652629	MARIBE	2015	Other	25%	1,977,951	494,488
H2020	691919	ELICAN	2016	Offshore technology	100%	11,181,987	11,181,987
H2020	685842	EIROS	2016	New turbine materials & components	25%	7,993,169	1,998,292
H2020	685445	LORCENIS	2016	New turbine materials & components	25%	7,653,530	1,913,383
H2020	730747	POWDERBLADE	2016	New turbine materials & components	100%	2,731,700	2,731,700
H2020	726776	VORTEX	2016	New turbine materials & components	100%	1,328,688	1,328,688
H2020	718755	CLOUD DIAGNOSIS	2016	Maintenance & monitoring	100%	878,129	878,129
H2020	718125	VOSS	2016	Grid integration	50%	50,000	25,000
H2020	729070	TEES	2016	Grid integration	50%	50,000	25,000

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
H2020	727477	CL-Windcon	2016	Maintenance & monitoring	100%	4,931,423	4,931,423
H2020	729363	GW-FortyForty	2016	New turbine materials & components	100%	50,000	50,000
H2020	729183	ECO-TURBINE	2016	New turbine materials & components	100%	50,000	50,000
H2020	744239	NJORD	2016	New turbine materials & components	100%	50,000	50,000
H2020	718016	SWITLER	2016	New turbine materials & components	100%	50,000	50,000
H2020	736224	Triblade	2016	New turbine materials & components	100%	50,000	50,000
H2020	734300	ABLE	2016	New turbine materials & components	100%	50,000	50,000
H2020	691732	DemoWind 2	2016	Offshore technology	100%	8,557,865	8,557,865
H2020	691714	PROMOTION	2016	Offshore technology	30%	39,327,744	11,798,323
H2020	691717	DEMOGRAVI3	2016	Offshore technology	100%	19,037,466	19,037,466
H2020	729107	GroutTube	2016	Offshore technology	100%	50,000	50,000
H2020	729786	Scubacraft	2016	Offshore technology	10%	50,000	5,000
H2020	718838	FLOW	2016	Floating offshore wind	100%	50,000	50,000
H2020	735565	Cable Sentry	2016	Offshore technology	100%	50,000	50,000
H2020	736399	EK200-AWESOME	2016	Airborne wind energy systems	100%	50,000	50,000
H2020	717857	ZephyCloud	2016	Resource assessment	100%	50,000	50,000
H2020	760353	BladeSave	2017	Maintenance & monitoring	100%	1,988,909	1,988,909
H2020	784040	FloatMastBlue	2017	Offshore technology	100%	2,048,568	2,048,568
H2020	775854	AIMS	2017	Maintenance & monitoring	33%	50,000	16,667
H2020	747921	HYPER TOWER	2017	Logistics, assembly & installation	100%	183,455	183,455
H2020	722401	SmartAnswer	2017	Other	25%	3,844,758	961,190
H2020	765585	InnoDC	2017	Grid integration	50%	3,893,200	1,946,600
H2020	761219	3D-COMPETE	2017	New turbine materials & components	33%	50,000	16,667
H2020	768016	WEGOOI	2017	Maintenance & monitoring	100%	773,185	773,185
H2020	774974	NextWind	2017	Other	100%	50,000	50,000
H2020	745625	ROMEO	2017	Maintenance & monitoring	100%	9,999,813	9,999,813
H2020	773657	TRIWIND	2017	Offshore technology	100%	50,000	50,000
H2020	782517	Wind-Drone	2017	Maintenance & monitoring	100%	50,000	50,000
H2020	783913	ZephyCloud-2	2017	Logistics, assembly & installation	100%	1,275,827	1,275,827
H2020	764717	WinWind	2017	Other	100%	2,124,463	2,124,463
H2020	778553	TRIBLADE	2017	New turbine materials & components	100%	2,095,975	2,095,975
H2020	791019	Venturas	2017	New turbine materials & components	100%	50,000	50,000
H2020	720838	NEOHIRE	2017	New turbine materials & components	100%	4,443,889	4,443,889
H2020	744518	FLOWSPA	2017	Floating offshore wind	100%	50,000	50,000
H2020	774253	Space at Sea	2017	Floating offshore wind	100%	6,766,793	6,766,793
H2020	753156	SAFS	2017	Floating offshore wind	100%	195,455	195,455
H2020	761874	SATH	2017	Floating offshore wind	100%	50,000	50,000
H2020	761072	DACOMAT	2018	New turbine materials & components	25%	5,873,915	1,468,479

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
H2020	809308	R3FIBER	2018	New turbine materials & components	25%	50,000	12,500
H2020	825833	WINDMIL RT-DT	2018	Maintenance & monitoring	100%	148,890	148,890
H2020	774426	The Blue Growth Farm	2018	Offshore technology	25%	7,602,873	1,900,718
H2020	780662	SheaRIOS	2018	Maintenance & monitoring	100%	2,716,907	2,716,907
H2020	829774	LEADFLOAT	2018	Offshore technology	100%	2,498,563	2,498,563
H2020	829644	NOTUS	2018	Maintenance & monitoring	100%	1,397,229	1,397,229
H2020	811473	LEP4BLADES	2018	New turbine materials & components	100%	1,011,623	1,011,623
H2020	836540	eolACC	2018	Maintenance & monitoring	100%	50,000	50,000
H2020	817421	X1 Wind	2018	Offshore technology	100%	50,000	50,000
H2020	817053	WindiBox	2018	New turbine materials & components	100%	50,000	50,000
H2020	816706	EOLI FPS	2018	New turbine materials & components	100%	50,000	50,000
H2020	817390	INNOWIND	2018	New turbine materials & components	100%	50,000	50,000
H2020	824339	A2MIRO	2018	Maintenance & monitoring	100%	50,000	50,000
H2020	778039	PEARLS	2018	Other	25%	405,000	101,250
H2020	791875	ReaLCoE	2018	Offshore technology	100%	24,838,258	24,838,258
H2020	818153	i4Offshore	2018	Offshore technology	100%	19,877,916	19,877,916
H2020	727680	TotalControl	2018	Maintenance & monitoring	100%	4,876,483	4,876,483
H2020	763990	UPWARDS	2018	Maintenance & monitoring	100%	3,999,918	3,999,918
H2020	817619	AURES II	2018	Other	25%	2,594,058	648,514
H2020	806844	Njord	2018	New turbine materials & components	100%	1,740,260	1,740,260
H2020	804858	AIRCRANE	2018	Logistics, assembly & installation	100%	1,487,588	1,487,588
H2020	808597	Ventura Habitat	2018	Maintenance & monitoring	100%	50,000	50,000
H2020	807460	YURAKAN	2018	New turbine materials & components	100%	50,000	50,000
H2020	808061	HEAF	2018	New turbine materials & components	100%	50,000	50,000
H2020	776559	SecREEts	2018	Other	25%	12,880,032	3,220,008
H2020	857844	FarmConners	2019	Maintenance, condition monitoring systems	100%	1,449,639	1,449,639
H2020	876355	Vertical Sky	2019	Other	100%	50,000	50,000
H2020	875698	SUNCOAT	2019	New turbine materials, components	100%	150,000	150,000
H2020	873403	COOLWIND	2019	Offshore technology	100%	2,499,999	2,499,999
H2020	881193	AWE	2019	Airborne wind energy systems	100%	2,442,116	2,442,116
H2020	860101	zEPHYR	2019	Resource assessment	100%	3,826,416	3,826,416
H2020	873395	Windrone Zenith	2019	Maintenance, condition monitoring systems	100%	1,339,397	1,339,397
H2020	861398	WinGrid	2019	Grid integration	100%	4,290,017	4,290,017
H2020	874042	SeaTwirl	2019	Floating offshore wind	100%	2,482,025	2,482,025

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
H2020	874102	EOLOGIX	2019	Maintenance, condition monitoring systems	100%	1,133,878	1,133,878
H2020	860879	FLOAWER	2019	Floating offshore wind	100%	3,500,382	3,500,382
H2020	828799	HPCWE	2019	Grid integration	100%	1,995,651	1,995,651
H2020	868808	MicroCoating	2019	New turbine materials, components	100%	50,000	50,000
H2020	843218	ASSO	2019	Floating offshore wind	100%	184,708	184,708
H2020	867710	Modvion	2019	New turbine materials, components	100%	50,000	50,000
H2020	815159	PivotBuoy	2019	Floating offshore wind	100%	3,960,065	3,960,065
H2020	849307	SATH	2019	Floating offshore wind	100%	1,902,338	1,902,338
H2020	835901	EDOWE	2019	Floating offshore wind	100%	175,572	175,572
H2020	815289	FLOTANT	2019	Floating offshore wind	100%	4,944,958	4,944,958
H2020	836347	LEWIATH	2019	New turbine materials, components	100%	50,000	50,000
H2020	848747	WindTRRo	2019	Maintenance, condition monitoring systems	100%	2,196,023	2,196,023
H2020	850339	AWESOME	2019	Airborne wind energy systems	100%	2,300,000	2,300,000
H2020	855726	TwingTec	2019	Airborne wind energy systems	100%	50,000	50,000
H2020	842231	SETWIND	2019	Other	100%	998,512	998,512
H2020	826042	ETIPWind	2019	Other	100%	726,638	726,638
H2020	798033	HSS-Wind	2019	Offshore technology	100%	195,455	195,455
H2020	793316	OFFSHORE TALL TOWER	2019	Offshore technology	100%	183,455	183,455
H2020	815083	COREWIND	2019	Floating offshore wind	100%	5,031,859	5,031,859
H2020	857631	TWIND	2019	Offshore technology	100%	795,825	795,825
H2020	880041	NBTECH	2019	New turbine materials, components	100%	1,675,538	1,675,538
H2020	885537	SIDEWIND	2019	New turbine materials, components	100%	50,000	50,000
H2020	885916	PAVIMON	2019	Maintenance, condition monitoring systems	100%	50,000	50,000
H2020	876228	TruePower	2019	Other	25%	50,000	12,500
H2020	840461	GiFlex	2019	Other	25%	191,149	47,787
H2020	867602	IGP	2019	Other	25%	50,000	12,500
H2020	821114	SUSMAGPRO	2019	Other	25%	12,977,446	3,244,361
H2020	815301	RE-COGNITION	2019	Grid integration	25%	4,990,000	1,247,500

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
H2020	860737	STEP4WIND	2020	Maintenance, condition monitoring systems	100%	2,754,946	2,754,946
H2020	101006689	HIPERWIND	2020	Floating offshore wind	100%	3,999,639	3,999,639
H2020	952960	MAREWIND	2020	Grid integration	100%	6,706,969	6,706,969
H2020	959151	Modvion	2020	New turbine materials, components	100%	2,427,762	2,427,762
H2020	878788	WindSider	2020	Floating offshore wind	100%	2,254,516	2,254,516
H2020	952979	FLAGSHIP	2020	New turbine materials, components	100%	24,920,290	24,920,290
H2020	891826	SEAFLOWER	2020	Floating offshore wind	100%	257,210	257,210
H2020	851245	INNTERESTING	2020	Floating offshore wind	100%	4,751,414	4,751,414
H2020	861291	Train2Wind	2020	Floating offshore wind	100%	4,233,354	4,233,354
H2020	955073	KoalaLifter	2020	Floating offshore wind	100%	2,030,163	2,030,163
H2020	947129	FuturePowerFlow	2020	Grid integration	25%	1,682,625	420,656
H2020	946442	Powerbox	2020	Grid integration	25%	1,955,110	488,777
H2020	957752	ROBINSON	2020	Grid integration	25%	6,994,901	1,748,725
H2020	101007142	FLOATECH	2021	Floating offshore wind	100%	4,096,355	4,096,355
H2020	101031922	PARTIMPACT	2021	New turbine materials, components	100%	224,934	224,934
H2020	969297	X1 ACCELERATOR	2021	Floating offshore wind	100%	2,447,841	2,447,841
H2020	101009363	ARCHIME3	2021	Floating offshore wind	100%	2,442,043	2,442,043
H2020	891826	SEAFLOWER	2021	Floating offshore wind	100%	257,210	257,210
H2020	101007135	XROTOR	2021	Offshore technology	100%	3,900,009	3,900,009
H2020	971145	FASTAP	2021	Grid integration	100%	2,996,935	2,996,935
H2020	971442	FIBREMACH	2021	New turbine materials, components	25%	1,704,729	426,182
H2020	101007168	OYSTER	2021	Offshore technology	25%	4,999,843	1,249,961
H2020	952966	FIBREGY	2021	New turbine materials, components	50%	6,499,590	3,249,795
H2020	101036457	EU-SCORES	2021	Offshore technology	25%	34,831,484	8,707,871

Source: JRC based on Cordis 2022

Table 27 R&I projects considered under JRC methodology to estimate EC funding for wind energy under H2020 projects completed in 2021

Framework Programme	Project Number	Project Acronym	Start year	Research area	Wind share	Project EU Financial Contribution (EUR)	EU Contribution JRC methodology (EUR)
H2020	730323	FiberEUse	2017	New turbine materials & components	25%	9,793,549	2,448,387
H2020	765585	InnoDC	2017	Grid integration	50%	3,740,101	1,870,051
H2020	774519	NEXUS	2017	Offshore technology	100%	3,337,099	3,337,099
H2020	848747	WindTRRo	2019	Maintenance & monitoring	100%	2,196,023	2,196,023
H2020	784040	FloatMastBlue	2017	Offshore technology	100%	2,048,568	2,048,568
H2020	828799	HPCWE	2019	Grid integration	100%	1,995,651	1,995,651
H2020	849307	SATH	2019	Floating offshore wind	100%	1,902,338	1,902,338
H2020	880041	NBTECH	2019	New turbine materials & components	100%	1,675,538	1,675,538
H2020	679843	WINDMIL	2016	Maintenance & monitoring	100%	1,486,224	1,486,224
H2020	829644	NOTUS	2018	Maintenance & monitoring	100%	1,397,229	1,397,229
H2020	873395	Windrone Zenith	2019	Maintenance & monitoring	100%	1,339,397	1,339,397
H2020	874102	EOLOGIX	2019	Maintenance & monitoring	100%	1,133,878	1,133,878
H2020	768016	WEGOOI	2017	Maintenance & monitoring	100%	773,185	773,185
H2020	826042	ETIPWind	2019	Other	100%	726,638	726,638
H2020	840461	GiFlex	2019	Other	25%	191,149	47,787
H2020	793316	OFFSHORE TALL TOWER	2019	Offshore technology	100%	183,455	183,455
H2020	835901	EDOWE	2019	Floating offshore wind	100%	175,572	175,572

Source: JRC based on Cordis, 2022

Annex 2

Table 28 Information on the origin of manufacturers contracted for candidate projects of allocation round 4 along the project phases assessed in the Supply Chain Plans.

UK based manufacturing

n.a.	no information available or not yet decided
0	Manufacturing or service provided outside UK
1	Existing manufacturing location of component in UK / Service (O&M, Installation) performed from UK port
2	Manufacturing location of component in multiple countries (including UK)
3	No information on sourcing of component for the project, yet existing or upcoming manufacturers in UK

	Blyth Offshore Demonstrator - phase 2	East Anglia Hub - ONE North	East Anglia Hub - THREE	East Anglia Hub - TWO	Hornsea Project Three	Inch Cape	Moray West	Norfolk Boreas	Norfolk Vanguard	Pentland	Seagreen	Seagreen 1A	TwinHub
Phases (based on SCP -Scoring categories)													
DevEx phase (4%)	1	1	1	1	1**	1	1	0	0	1	1	n.a	0
CapEx phase (58%)													
Turbines - rotor hub and blades	n.a.	1	1	1	n.a	n.a	1	1	1	n.a	1	n.a	n.a
Turbines - Nacelle components	n.a.	2	2	2	n.a	n.a	2	2	2	n.a	2	n.a	n.a
Turbines - Nacelle assembly	n.a.	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	1	n.a	n.a
Towers	n.a.	3	3	3	3	3	3	3	3	n.a	3	3	n.a
Foundations - monopile/jacket	n.a.	3	3	3	1	3	3	3	3	n.a	0	3	n.a
Foundations - Transition pieces (TP)	n.a.	3	3	3	3	3	0	3	3	n.a	3	3	n.a
Cables - array and export	n.a.	3	3	3	3	3	3 (0)***	3	3	n.a	3	3	n.a
Substation fabrication, jacket and electricals (excl. onshore works)	n.a.	n.a	n.a	n.a	n.a	n.a	1*	n.a	n.a	n.a	n.a	n.a	n.a
Installation port (info)	n.a.	1	1	1	n.a	n.a	1 (0)***	1	1	n.a	1 (0)****	n.a	n.a
Installation	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a. / 0	n.a.	n.a.	n.a.	0	n.a.	n.a.
OpEx phase (34%)	1	1	1	1	1	n.a	1	1 (0)*****	1 (0)*****	1	1	n.a	n.a
DecEx (4%)	n.a.	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a

Source: JRC, 2022.

* Assembly and fit out in UK; yet subcomponent production might be sourced from outside UK. A key part of the selection was how the Siemens Energy/Iemants consortium will bring assembly and fit out of the OTMs to the Smulders Projects UK yard. The yard, located in Wallsend, Newcastle fabricated jacket foundations for the neighbouring Moray East project, and this will see the scope of work extended. This is good news for UK fabrication and signals the return of topside work to a UK yard after a gap of several years [OceanWinds 2021].

** Subcontracted FUGRO (NL) for site investigations [OW 2022b]

*** The export cables will be manufactured at Nexans' plants in Halden and Rognan, Norway, Charleston, USA, and Charleroi, Belgium, and installed by the cable-laying vessel Nexans Skagerrak (NO-flag) [OW 2021m].

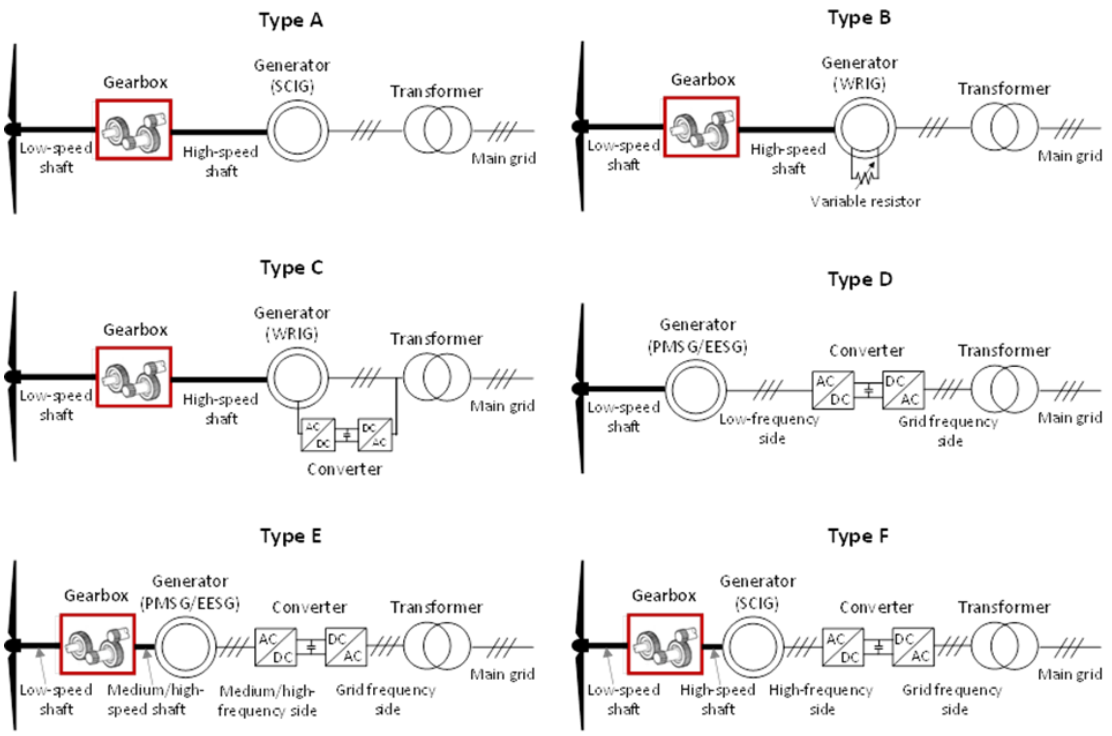
**** Components for the first turbine to be installed, including blades, nacelles, and the supporting towers, were transported to the site by installation contractor Cadeler's giant wind farm installation vessel Wind Osprey from Vestas' turbine marshalling base at Able Seaton Port in Hartlepool, North-East England. [...] Two jackets operated by main contractor Seaway 7[...] . The barge was met by the Saipem 7000 (PT) – the semisubmersible crane vessel which is used to lift each of the 2,000-tonne jackets [OW 2021b, OW 2021c, OW 2021d].

***** Vattenfall has named Siemens Gamesa the Preferred Supplier of wind turbines for the 1.8 GW Norfolk Boreas and the 1.8 GW Norfolk Vanguard wind farms offshore Norfolk, UK. The agreement includes the potential deployment of the new SG 14-236 DD offshore wind turbines and a multi-year Service agreement [OW 2021e].

Source: JRC, 2022

Annex 3

Figure 114. Drive train arrangements usually employed in commercial wind turbines.



Type	Configuration	Gearbox/Gearless	Category
A	High-speed - Squirrel Cage Induction Generator (SCIG)	Gearbox	
B	High-speed Wounded Rotor Induction Generator (WRIG)	Gearbox	Geared high-speed WT
C	High-speed Doubly-Fed Induction Generator (DFIG)	Gearbox	
D-EE	Low-speed Electrically excited synchronous generator (EESG) with full power converter	Gearless (Direct Drive)	Direct drive WT
D-PM	Low-speed Permanent magnet synchronous generator (PMSG) with full power converter	Gearless (Direct Drive)	
E-EE	Medium/High-speed Electrically excited synchronous generator (EESG) with full power converter	Gearbox	
E-PM	Medium/High-speed Permanent magnet synchronous generator (PMSG) with full power converter	Gearbox	Hybrid drive trains
F	High-speed - Squirrel Cage Induction Generator (SCIG) with full power converter	Gearbox	

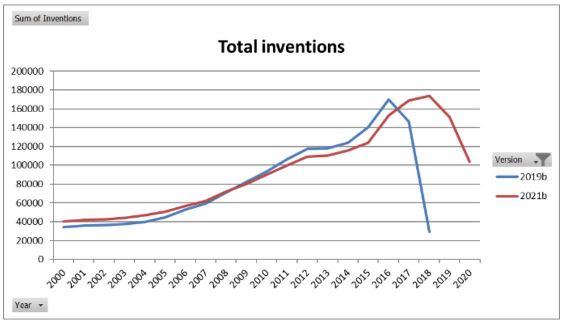
Source: JRC 2022 based on Vazquez Hernandez et al (2017). A Market-Based Analysis on the Main Characteristics of Gearboxes Used in Onshore Wind Turbines. Energies, 10(11), 1686. http://doi.org/10.3390/en10111686

Annex 4

2021b vs. 2019b - Total inventions

In 2020, a major revision of the CPC Y-tags took place. A substantial number of Y-tags has been removed, regrouped, and reviewed and patent families have been reclassified according to the new scheme[35]. As a result, 2021b version has fewer Y-tagged inventions compared to the 2019b version (Figure 115).

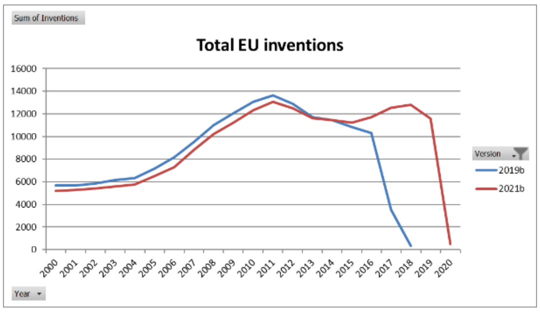
Figure 115. Total inventions with Y-tags in Patstat 2019b vs. 2021b



Source: JRC based in Patstat, 2022

Different regions have a bigger or smaller difference in the number of patents between the versions. Figure 2 shows that the total EU patents are slightly fewer between the two versions until 2016, where 2019b is limited due to the reporting delay.

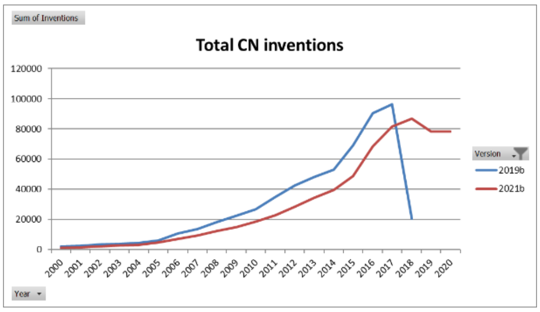
Figure 116. Total EU-based inventions with Y-tags in Patstat 2019b vs. 2021b



Source: JRC based in Patstat, 2022

In the case of China, the numbers of Y-tagged patents is much lower in the 2021b version, mainly after 2006 (Figure 3).

Figure 117. Total CN-based inventions with Y-tags in Patstat 2019b vs. 2021b

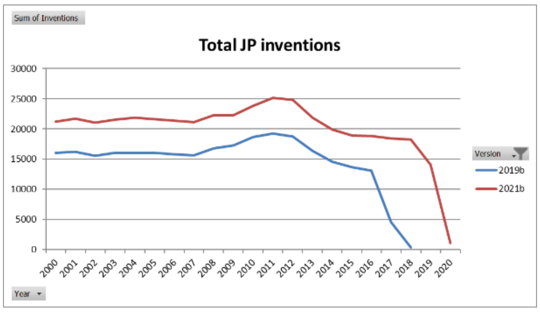


Source: JRC based in Patstat, 2022

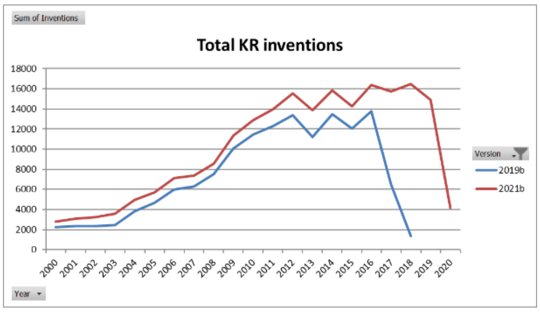
[35] EPO, 2020. Project RP0678, https://www.uspto.gov/web/patents/classification/cpc/pdf/CPCNOC935RP0678various.pdf

Japan (Figure 4a), Korea (Figure 4b), the US (Figure 4c) and the rest countries (Figure 4d), have more Y-tagged inventions in the 2021b version.

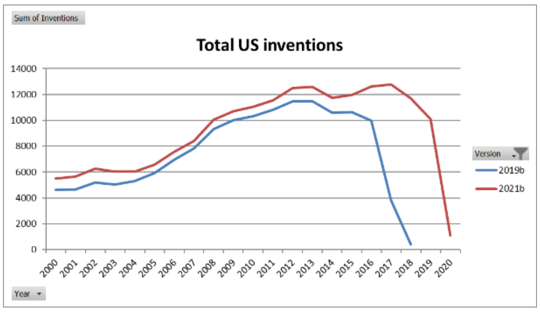
Figure 118. Total inventions with Y-tags in Patstat 2019b vs. 2021b



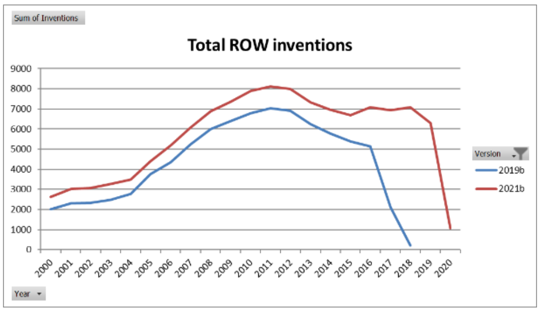
a) JP-based



b)KR-based



c)US-based

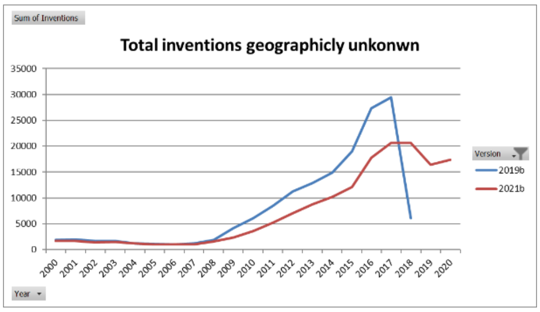


d)ROW-based

Source: JRC based in Patstat, 2022

2021b version has improved the geographical identification of the inventions, especially after 2009 (Figure 5).

Figure 119. Total inventions without origin with Y-tags in Patstat 2019b vs. 2021b

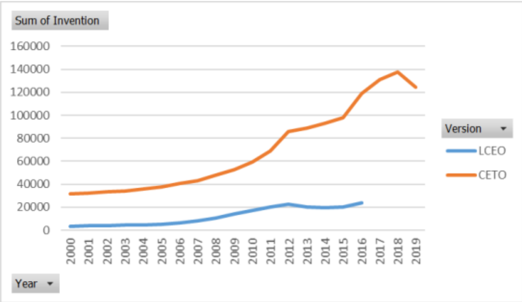


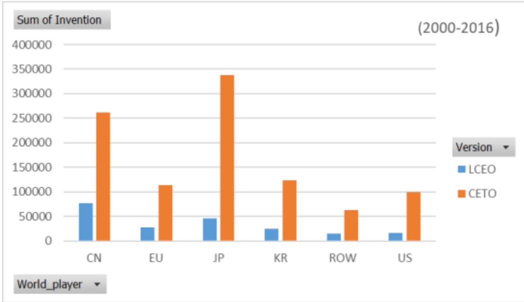
Source: JRC based in Patstat, 2022

CETO vs. LCEO – CPC selection

Due to changes in the scope and the 2020 reclassification of the CPC scheme, the selection of CPC codes has changed for most of the selected technologies. Overall, the number of inventions selected for CETO is greater than LCEO (Figure 6).

Figure 120. Total inventions in CETO vs. LCEO





a)Total

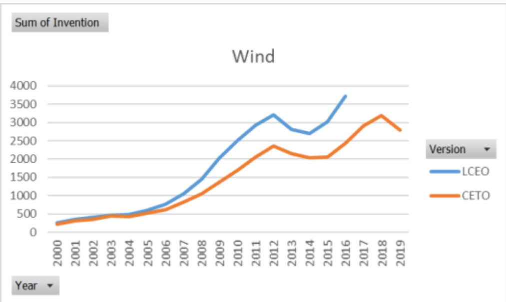
b)Break-down per regions

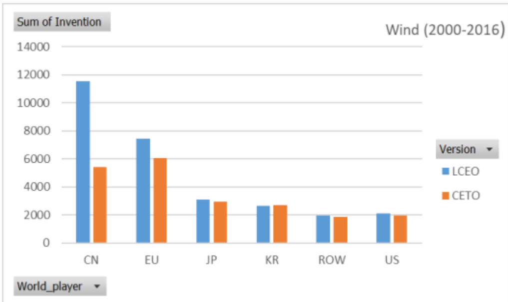
Source: JRC based in Patstat, 2022

Wind (offshore and onshore)

Some of the selected codes in LCEO (Y02E 10/721, 10/722, 10/723, 10/725, Y02P 10/726) are deleted after the reclassification. CETO includes seven codes that are maintained (Y02B 10/30, Y02E 10/70, 10/72, 10/727, 10/728, 10/74, 10/76). With the new selection of codes, CETO has a lower number of inventions, mainly after 2007, especially for China (Figure 15).

Figure 121. Total inventions selected for wind in CETO vs. LCEO





a)Total

b)Break-down per regions

Source: JRC based in Patstat, 2022

Annex 5

Table 29. TIM search string on all wind energy thematic fields and number of articles retrieved in the period 2010 - 2022.

Dataset	**Wind - all**	**Articles retrieved (2010-2022)**
Search string:	(topic:(("wind turbine" OR "wind farm" OR "wind power plant") AND(bearing OR brake OR ((drivetrain OR "drive train")AND (gearless OR "fixed speed" OR geared OR "doubly fed" OR DFIG OR "hybrid drivetrain"~2)) OR (blades AND ("gurney flap" OR airfoil OR "slender blade"~2 OR "noise reduction" OR "modular blades" OR segmented OR serration)) OR gearbox OR "gear box" OR lubrication OR "pitch system"~2 OR "pitch control"~2 OR (protection AND (lightning OR surge OR "voltage increase"~2 OR overvoltage)) OR ((power OR electricity OR current) AND "reactive compensation"~2) OR "concrete tower"~4 OR "steel concrete tower"~3 OR "hybrid tower"~2 OR "lattice tower"~2 OR "segmented tower"~3 OR "tubular steel tower"~2 OR "pitch system"~2 OR "pitch control"~2 OR "speed control"~2 OR "control conditions"~2 OR "conditions monitoring"~2 OR "yaw system"~2 OR "orientation rotor wind"~2 OR "yaw control"~2 OR transformer OR ("environmental impact"~2 OR "noise reduction"~2 OR "noise impact"~2 OR "acoustic impact"~2 OR bird) OR ("asynchronous generator"~2 OR "synchronous generator"~2 OR ((HVDC OR "high voltage direct current") AND "grid" AND (connection OR integration))OR (offshore AND "multi-terminal" AND grid)) OR (("offshore foundation"~5 AND (foundations OR modelling OR building) AND (monopile OR jacket OR foundation OR tripod OR tripile OR gravity OR suction OR bucket OR buoy OR floating OR "semisubmersible" OR "semi-submersible" OR "tension leg" OR barge)) OR "onshore foundation"~5 OR "offshore converter"~4 OR (("electric substation"~2 OR "power substation"~2) AND offshore) OR "offshore wind turbine"~2 OR anchoring OR mooring OR ("submarine cables"~2 OR "cables inter array"~2 OR "power cable"~2 OR "export cable"~2) OR ("floating foundation"~2 OR "floating platform"~2 OR "floating farm"~2 OR "floating turbine"~2) OR ((access OR maintenance OR logistic) AND offshore)) OR (repowering OR "downwind rotor"~2 OR "horizontal axis"~2 OR HAWT OR multirotor OR "multi-rotor") OR ("vertical axis" OR VAWT))) OR topic:(("airborne wind turbine"~5 OR "airborne wind farm"~5 OR "flying wind turbines"~2 OR "airborne wind energy"~2 OR "kite wind turbine"~2 OR "kite wind energy"~2 OR "kite wind farm"~2))) AND class:article	14112

Source: JRC analysis based on TIM, 2022.

Table 30. Wind energy - Total number of peer-reviewed articles per year (2010 – 2021), number of highly cited articles, FWCI and H-index of the EU MS.

Search string	EU country	total articles	highly cited articles	FWCI	H-index
Wind - all	Germany	784	89	0.97	50
Wind - all	Denmark	563	78	1.23	50
Wind - all	Spain	495	83	1.19	51
Wind - all	Italy	404	72	1.45	45
Wind - all	Netherlands	317	60	1.47	38
Wind - all	France	295	40	1.28	37
Wind - all	Portugal	172	36	1.58	33
Wind - all	Sweden	170	27	1.27	28
Wind - all	Poland	153	9	0.68	17
Wind - all	Ireland	126	32	1.66	25
Wind - all	Belgium	125	24	1.52	28
Wind - all	Greece	109	9	0.85	23
Wind - all	Finland	91	11	1.06	21
Wind - all	Romania	73	2	0.53	15
Wind - all	Austria	31	2	0.86	10
Wind - all	Cyprus	29	3	0.95	9
Wind - all	Malta	27	0	0.67	12
Wind - all	Croatia	27	4	0.91	10
Wind - all	Lithuania	15	1	0.60	6
Wind - all	Czech Republic	14	2	1.23	7
Wind - all	Latvia	12	0	0.17	5
Wind - all	Bulgaria	11	1	0.67	4
Wind - all	Hungary	10	2	1.75	3
Wind - all	Estonia	7	0	0.51	5
Wind - all	Slovenia	7	3	1.56	3
Wind - all	Slovakia	3	0	0.30	2
Wind - all	Luxembourg	1	0	0.53	1

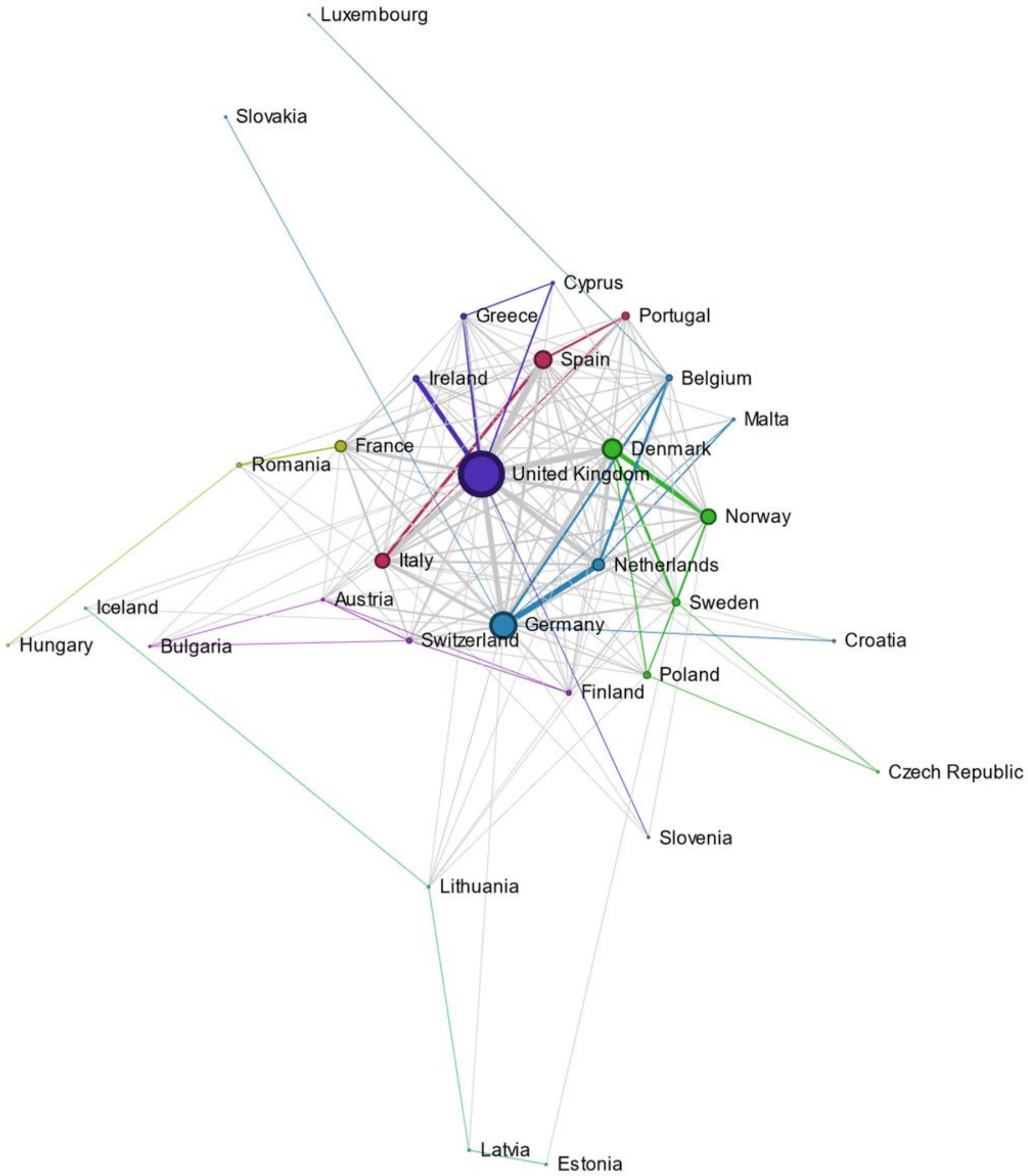
Source: JRC analysis based on TIM, 2022.

Table 31. Wind energy – Leading organisations by number of highly cited articles (2010 – 2021).

Organisation	Documents	Competitors	EU countries	# highly cited	FWCI	H-index
Norwegian University of Science and Technology	268	Norway		58	1.6	43
University of Strathclyde	219	United Kingdom		39	1.4	32
North China Electric Power University	412	China		37	0.8	33
Shanghai Jiao Tong University	305	China		34	0.9	28
Aalborg University	202	EU	Denmark	33	1.4	36
Tsinghua University	207	China		30	1.3	31
Delft University of Technology	170	EU	Netherlands	30	1.4	29
Chongqing University	307	China		25	0.9	26
Technical University of Denmark	220	EU	Denmark	25	1.1	37
XI'AN JIAOTONG UNIVERSITY	111	China		24	1.6	25

Source: JRC analysis based on TIM, 2022.

Figure 122 Wind energy - Collaboration network within Europe based on peer-reviewed articles per year (2010 – 2021)



Source: JRC based on TIM, 2022.

Table 32. TIM search string on wind energy components and number of articles retrieved in the period 2010 - 2022.

Dataset	Wind- Components	Articles retrieved (2010-2022)
Search string:	topic:(("wind turbine" OR "wind farm" OR "wind power plant") AND (bearing OR brake OR((drivetrain OR "drive train")AND (gearless OR "fixed speed" OR geared OR "doubly fed" OR DFIG OR "hybrid drivetrain"~2)) OR (blades AND ("gurney flap" OR airfoil OR "slender blade"~2 OR "noise reduction" OR "modular blades" OR segmented OR serration)) OR gearbox OR "gear box" OR lubrication OR "pitch system"~2 OR "pitch control"~2 OR (protection AND (lightning OR surge OR "voltage increase"~2 OR overvoltage)) OR ((power OR electricity OR current) AND "reactive compensation"~2) OR "concrete tower"~4 OR "steel concrete tower"~3 OR "hybrid tower"~2 OR "lattice tower"~2 OR "segmented tower"~3 OR "tubular steel tower"~2 OR "pitch system"~2 OR "pitch control"~2 OR "speed control"~2 OR "control conditions"~2 OR "conditions monitoring"~2 OR "yaw system"~2 OR "orientation rotor wind"~2 OR "yaw control"~2 OR transformer))AND class:article	5730

Source: JRC analysis based on TIM, 2022.

Table 33. Wind energy components- Total number of peer-reviewed articles per year (2010 – 2021), number of highly cited articles, FWCI and H-index of the EU MS.

Search string	EU country	total articles	highly cited articles	FWCI	H-index
Wind- Components	Germany	297	26	0.797536	32
Wind- Components	Denmark	193	24	1.148961	36
Wind- Components	Spain	175	23	1.052992	26
Wind- Components	Italy	124	25	1.542082	27
Wind- Components	France	99	22	1.752528	27
Wind- Components	Netherlands	80	13	1.493093	24
Wind- Components	Sweden	73	9	1.296214	18
Wind- Components	Portugal	53	10	1.354694	22
Wind- Components	Poland	51	4	0.83133	12
Wind- Components	Greece	40	1	0.573044	12
Wind- Components	Belgium	36	8	1.586854	15
Wind- Components	Ireland	31	7	1.510182	10
Wind- Components	Finland	26	2	0.669885	9
Wind- Components	Croatia	17	2	0.916096	7
Wind- Components	Romania	17	1	0.621995	6
Wind- Components	Austria	10	1	0.737874	5
Wind- Components	Lithuania	6	1	0.972134	4
Wind- Components	Hungary	6	1	0.795546	3
Wind- Components	Malta	5	0	0.964696	5
Wind- Components	Estonia	4	0	0.383091	3
Wind- Components	Slovenia	4	2	1.976114	2
Wind- Components	Czech Republic	4	0	0.640814	2
Wind- Components	Bulgaria	3	0	0.418566	1
Wind- Components	Latvia	2	0	0.098482	1
Wind- Components	Cyprus	1	0	0.442118	1

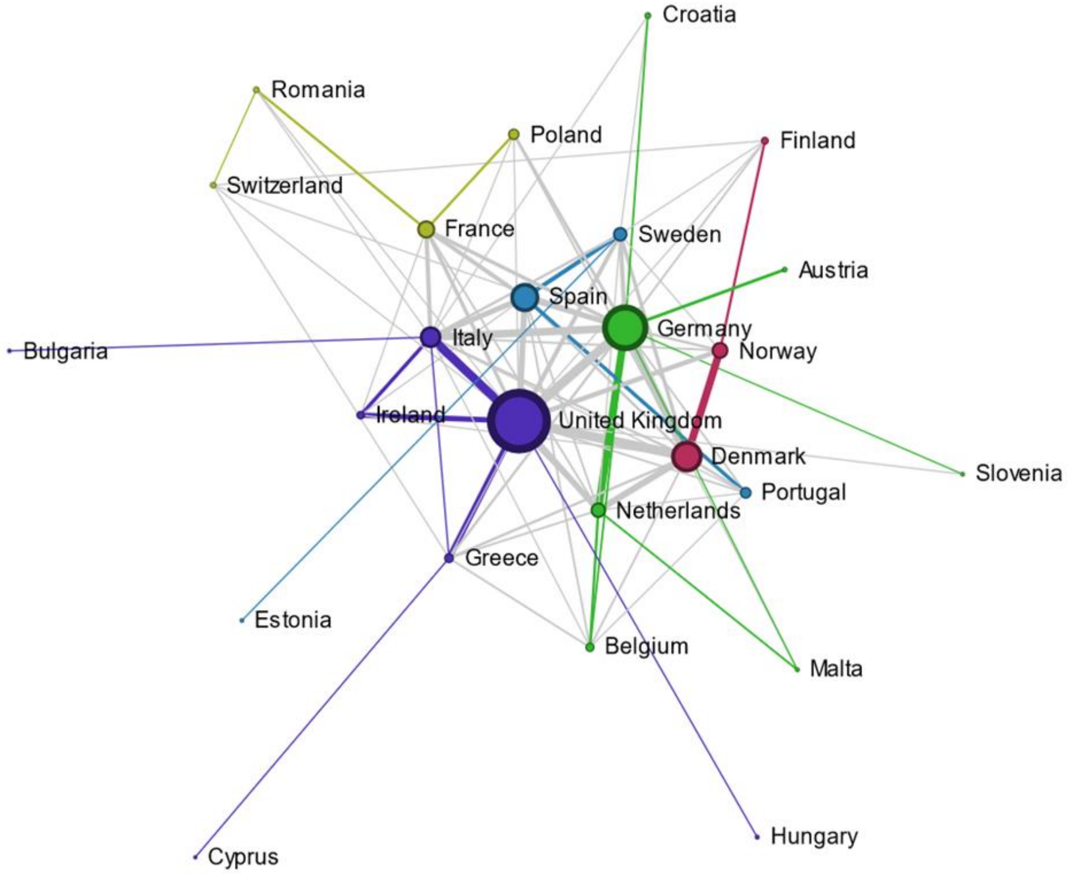
Source: JRC analysis based on TIM, 2022.

Table 34. Wind energy components– Leading organisations by number of highly cited articles (2010 – 2021).

Organisation	Documents	Competitors	EU countries	# highly cited	FWCI	H-index
North China Electric Power University	253	China		21	0.8	25
XI'AN JIAOTONG UNIVERSITY	62	China		21	2.2	24
Tsinghua University	102	China		20	1.4	25
Chongqing University	207	China		20	1.0	24
Norwegian University of Science and Technology	62	Norway		12	1.4	20
University of Science and Technology Beijing	30	China		11	2.0	15
Technical University of Denmark	93	EU	Denmark	10	1.0	23
University of Strathclyde	76	United Kingdom		10	1.1	20
Delft University of Technology	53	EU	Netherlands	10	1.8	19
Aalborg University	64	EU	Denmark	9	1.3	18

Source: JRC analysis based on TIM, 2022.

Figure 123 Wind energy components - Collaboration network within Europe based on peer-reviewed articles per year (2010 – 2021)



Source: JRC based on TIM, 2022.

Table 35. TIM search string on offshore wind energy and number of articles retrieved in the period 2010 - 2022.

Dataset	Wind - Offshore	Articles retrieved (2010-2022)
Search string:	topic:(("wind turbine" OR "wind farm" OR "wind power plant") AND (("offshore foundation"~5 AND (foundations OR modelling OR building) AND (monopile OR jacket OR foundation OR tripod OR tripile OR gravity OR suction OR bucket OR buoy OR floating OR "semisubmersible" OR "semi-submersible" OR "tension leg" OR barge)) OR "onshore foundation"~5 OR "offshore converter"~4 OR (("electric substation"~2 OR "power substation"~2) AND offshore) OR "offshore wind turbine"~2 OR anchoring OR mooring OR ("submarine cables"~2 OR "cables inter array"~2 OR "power cable"~2 OR "export cable"~2) OR ("floating foundation"~2 OR "floating platform"~2 OR "floating farm"~2 OR "floating turbine"~2) OR ((access OR maintenance OR logistic) AND offshore)))AND class:article	4179

Source: JRC analysis based on TIM, 2022.

Table 36. Offshore wind energy - Total number of peer-reviewed articles per year (2010 – 2021), number of highly cited articles, FWCI and H-index of the EU MS.

Search string	EU country	total articles	highly cited articles	FWCI	H-index
Wind - Offshore	Germany	290	27	0.88412	29
Wind - Offshore	Denmark	252	40	1.323486	37
Wind - Offshore	Spain	186	33	1.185927	35
Wind - Offshore	Netherlands	130	28	1.523515	23
Wind - Offshore	Italy	117	18	1.275636	25
Wind - Offshore	France	105	9	1.010456	17
Wind - Offshore	Portugal	72	19	1.704249	20
Wind - Offshore	Ireland	64	20	1.83702	20
Wind - Offshore	Belgium	55	11	1.788608	20
Wind - Offshore	Greece	44	6	0.949751	13
Wind - Offshore	Poland	34	2	0.62649	6
Wind - Offshore	Sweden	32	5	1.199558	10
Wind - Offshore	Finland	25	7	1.723812	11
Wind - Offshore	Cyprus	21	3	1.06853	6
Wind - Offshore	Romania	15	0	0.66588	5
Wind - Offshore	Malta	15	0	0.614189	8
Wind - Offshore	Austria	6	0	0.634011	4
Wind - Offshore	Czech Republic	3	1	1.71193	2
Wind - Offshore	Croatia	2	0	0.637445	2
Wind - Offshore	Lithuania	2	0	0.559706	2
Wind - Offshore	Bulgaria	1	0	0	0
Wind - Offshore	Slovenia	1	0	0.209193	1

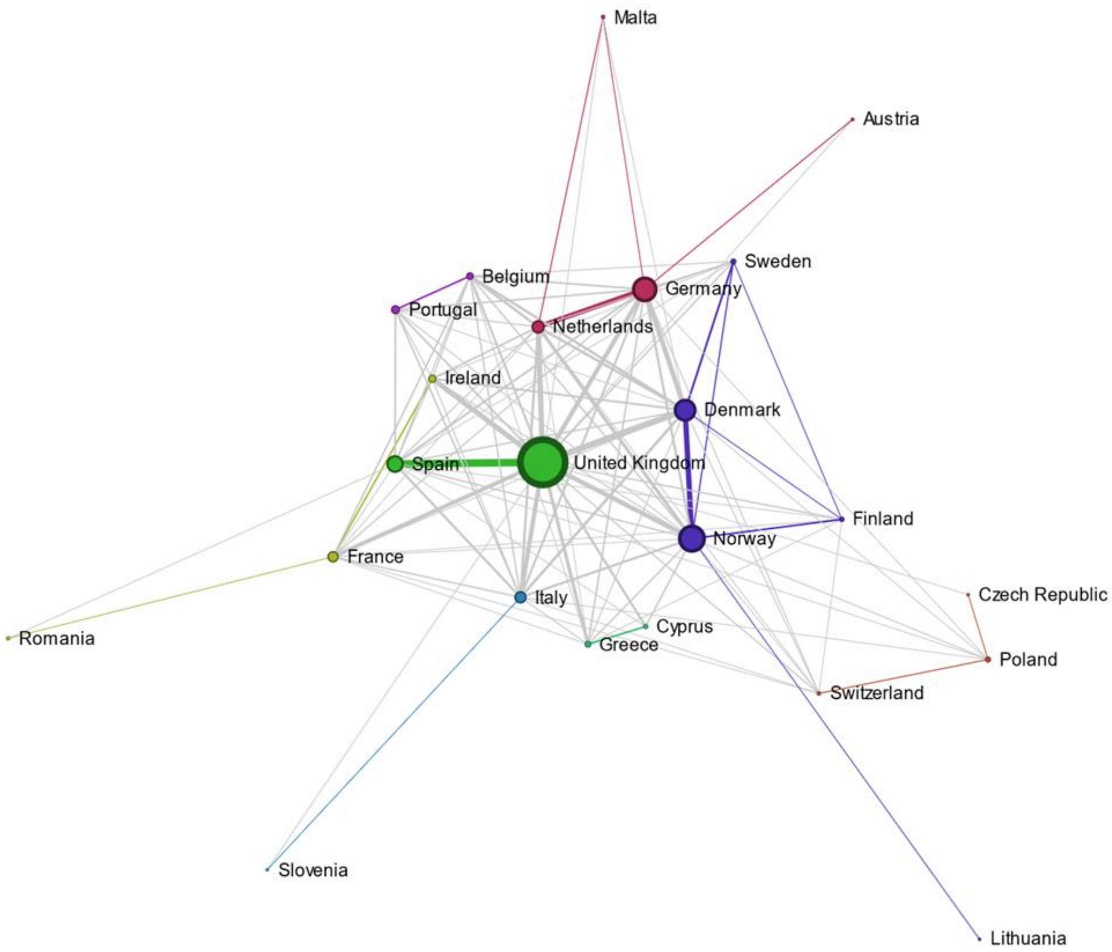
Source: JRC analysis based on TIM, 2022.

Table 37. Offshore wind energy– Leading organisations by number of highly cited articles (2010 – 2021).

Organisation	Documents	Competitors	EU countries	# highly cited	FWCI	H-index
Norwegian University of Science and Technology	211	Norway		47	1.7	38
University of Strathclyde	132	United Kingdom		25	1.4	25
Aalborg University	101	EU	Denmark	18	1.4	26
Cranfield University	61	United Kingdom		18	1.7	23
Shanghai Jiao Tong University	167	China		17	0.9	23
Delft University of Technology	68	EU	Netherlands	16	1.6	18
University of Bristol	28	United Kingdom		14	3.2	15
Technical University of Denmark	84	EU	Denmark	13	1.3	26
University of Oxford	21	United Kingdom		13	4.2	15
Universidade de Lisboa	35	EU	Portugal	12	2.0	15

Source: JRC analysis based on TIM, 2022.

Figure 124 Offshore wind energy - Collaboration network within Europe based on peer-reviewed articles per year (2010 – 2021)



Source: JRC based on TIM, 2022.

Table 38. TIM search string on grid integration and number of articles retrieved in the period 2010 - 2022.

Dataset	Wind- Grid	Articles retrieved (2010-2022)
Search string:	topic:(("wind turbine" OR "wind farm" OR "wind power plant") AND ("asynchronous generator"~2 OR "synchronous generator"~2 OR ((HVDC OR "high voltage direct current") AND "grid" AND (connection OR integration))OR (offshore AND "multi-terminal" AND grid)))AND class:article	2027

Source: JRC analysis based on TIM, 2022.

Table 39. Grid integration - Total number of peer-reviewed articles per year (2010 – 2021), number of highly cited articles, FWCI and H-index of the EU MS.

Search string	EU country	total articles	highly cited articles	FWCI	H-index
Wind- Grid	Spain	73	16	1.4	25
Wind- Grid	Denmark	65	10	1.2	19
Wind- Grid	France	55	4	1.0	16
Wind- Grid	Germany	52	17	2.0	22
Wind- Grid	Italy	24	3	1.4	12
Wind- Grid	Portugal	22	7	2.0	14
Wind- Grid	Romania	20	2	1.0	10
Wind- Grid	Ireland	19	4	1.5	7
Wind- Grid	Finland	19	5	1.5	11
Wind- Grid	Sweden	17	5	1.7	8
Wind- Grid	Poland	14	0	0.2	4
Wind- Grid	Netherlands	11	1	1.0	8
Wind- Grid	Greece	10	2	1.6	7
Wind- Grid	Belgium	6	1	1.2	4
Wind- Grid	Estonia	5	0	0.5	4
Wind- Grid	Latvia	5	0	0.3	4
Wind- Grid	Malta	2	0	0.9	2
Wind- Grid	Cyprus	2	0	0.3	1
Wind- Grid	Slovenia	1	0	0.0	0
Wind- Grid	Lithuania	1	0	0.1	1
Wind- Grid	Luxembourg	1	0	0.5	1
Wind- Grid	Austria	1	0	0.7	1
Wind- Grid	Croatia	1	1	2.4	1
Wind- Grid	Hungary	1	0	1.9	1

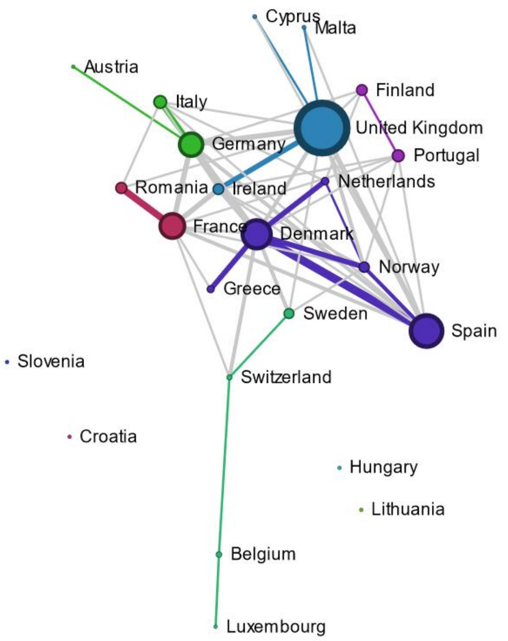
Source: JRC analysis based on TIM, 2022.

Table 40. Grid integration – Leading organisations by number of highly cited articles (2010 – 2021).

Organisation	Documents	Competitors	EU countries	# highly cited	FWCI	H-index
Huazhong University of Science and Technology	58	China		16	1.851273	23
North China Electric Power University	108	China		14	1.064534	21
Ain-Shams University	21	Egypt		9	2.401787	11
King Saud University	9	Saudi Arabia		8	5.460702	8
Ryerson University	13	Canada		8	4.637633	11
Tsinghua University	51	China		8	1.73248	17
Aalborg University	38	EU	Denmark	8	1.448879	17
CHINA ELECTRIC POWER RESEARCH INSTITUTE	49	China		8	1.188432	15
Technical University of Munich	11	EU	Germany	7	3.399426	8
University of Strathclyde	23	United Kingdom		7	1.91831	12

Source: JRC analysis based on TIM, 2022.

Figure 125 Grid integration - Collaboration network within Europe based on peer-reviewed articles per year (2010 – 2021)



Source: JRC based on TIM, 2022.

Table 41. TIM search string on wind energy & environmental impact and number of articles retrieved in the period 2010 - 2022.

Dataset	**Wind - Environmental impact**	**Articles retrieved (2010-2022)**
Search string:	topic:(("wind turbine"~2 OR "wind farm"~2 OR "wind power plant") AND ("environmental impact"~2 OR "noise reduction"~2 OR "noise impact"~2 OR "acoustic impact"~2 OR bird)) AND class:article	970

Source: JRC analysis based on TIM, 2022.

Table 42. Wind energy & environmental impact – Leading organisations by H-index (2010 – 2021).

Organisation	**Documents**	**Competitors**	**EU countries**	**# highly cited**	**FWCI**	**H-index**
British Trust for Ornithology	18	United Kingdom		4	1.4	13
Norwegian Institute for Nature Research	16	Norway		3	1.9	8
Norwegian University of Science and Technology	10	Norway		1	1.3	8
Aarhus University	14	EU	Denmark	4	1.4	7
University of the Highlands and Islands	10	United Kingdom		2	1.4	7
University of Exeter	9	United Kingdom		1	1.4	7
Technical University of Denmark	7	EU	Denmark	1	1.5	7
University of Glasgow	7	United Kingdom		4	2.2	6
Swiss Ornithological Institute	9	Switzerland		3	1.6	6
RSPB Centre for Conservation Science	7	United Kingdom		3	1.9	6

Source: JRC analysis based on TIM, 2022.

Table 43. TIM search string on airborne wind energy systems and number of articles retrieved in the period 2010 - 2022.

Dataset	Wind - Airborne wind turbines	Articles retrieved (2010-2022)
Search string:	topic:(("airborne wind turbine"~5 OR "airborne wind farm"~5 OR "flying wind turbines"~2 OR "airborne wind energy"~2 OR "kite wind turbine"~2 OR "kite wind energy"~2 OR "kite wind farm"~2)) AND class:article NOT topic:bird	183

Source: JRC analysis based on TIM, 2022.

Table 44. Airborne wind energy systems – Leading organisations by H-index (2010 – 2021).

Organisation	Documents	Competitors	EU countries	# highly cited	FWCI	H-index
Delft University of Technology	27	EU	Netherlands	2	0.9	10
ETH Zurich	10	Switzerland		1	1.8	8
University of Kansas	8	United States of America		1	1.2	8
Kyungpook National University	10	South Korea		1	1.6	6
University of North Carolina at Charlotte	10	United States of America		0	0.5	6
University of Freiburg	9	EU	Germany	1	0.9	5
SkySails GmbH	5	EU	Germany	1	1.2	5
ABB Switzerland Ltd.	5	Switzerland		1	1.4	5
University of California	6	United States of America		2	2.0	4
University of Limerick	7	EU	Ireland	0	0.2	4

Source: JRC analysis based on TIM, 2022.

Table 45. TIM search string on vertical axis wind turbines and number of articles retrieved in the period 2010 - 2022.

Dataset	Wind - Vertical axis	Articles retrieved (2010-2022)
Search string:	topic:(("wind turbine"~2 OR "wind farm"~2 OR "wind power plant") AND ("vertical axis" OR VAWT)) AND class:article	1511

Source: JRC analysis based on TIM, 2022.

Table 46. Vertical axis wind turbines – Leading organisations by number of highly cited articles (2010 – 2021).

Organisation	Documents	Competitors	EU countries	# highly cited	FWCI	H-index
CNR	14	EU	Italy	10	2.7	13
Eindhoven University of Technology	12	EU	Netherlands	10	4.8	10
University of Kansas	12	United States of America		9	4.1	10
University of Sheffield	19	United Kingdom		8	2.5	11
University of Florence	17	EU	Italy	8	2.5	15
California Institute of Technology	13	United States of America		8	3.2	12
University of Shanghai for Science and Technology	70	China		7	0.8	14
Helwan University	13	Egypt		7	2.7	8
Shanghai Jiao Tong University	29	China		6	1.4	10
University of Malaya	28	Malaysia		6	1.3	14

Source: JRC analysis based on TIM, 2022.

Table 47. TIM search string on other wind energy related research and number of articles retrieved in the period 2010 - 2022.

Dataset	Wind - other	Articles retrieved (2010-2022)
Search string:	topic:(("wind turbine" OR "wind farm" OR "wind power plant") AND (repowering OR "downwind rotor"~2 OR "horizontal axis"~2 OR HAWT OR multirotor OR "multi-rotor")) AND class:article	1670

Source: JRC analysis based on TIM, 2022.

Table 48. Other wind energy related research – Leading organisations by number of highly cited articles (2010 – 2021).

Organisation	Documents	Competitors	EU countries	# highly cited	FWCI	H-index
Shanghai Jiao Tong University	29	China		6	1.2	9
ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE EPFL	9	Switzerland		6	3.7	9
Delft University of Technology	20	EU	Netherlands	4	1.1	13
Helwan University	11	Egypt		4	2.5	5
Central South University	11	China		3	1.7	8
University of Florence	9	EU	Italy	3	1.8	9
Cranfield University	9	United Kingdom		3	1.8	6
University of Kansas	8	United States of America		3	3.3	6
CNR	7	EU	Italy	3	1.6	6
Eindhoven University of Technology	7	EU	Netherlands	3	3.7	5

Source: JRC analysis based on TIM, 2022.

Annex 6

Table 49. Circular economy strategies in the wind energy sector (processes, national & EU funding, estimated TRL) [Telsnig 2022] (06/2022 update)

Component	Collaboration/Initiative	Type of process/innovation	Volume [MEUR]	R&D Funding? [MEUR]		Estimated TRL
				EU	National	
Wind turbine blades	ZEBRA (Zero wastE Blade ReseArch)	New recycleable materials	18.5			n.a.
	CETEC project (Circular Economy for Thermosets Epoxy Composites)	Chemical (ChemCycling)	2.1		1.4	n.a.
	AIOLOS project (Affordable and Innovative Manufacturing of Large Composites)	Manufacturing (Automatisation/Digitalisation)	10.4		5.2	n.a.
	AKER – University of Strathclyde collaboration (Affordable and Innovative Manufacturing of Large Composites)	Thermal (fluidised bed)	2		1.3	3
	DecomBlades (Affordable and Innovative Manufacturing of Large Composites)	Manufacturing (Automatisation/Digitalisation)	5.4		3	n.a.
	SiemensGamesa RecycleBlades	Chemcial (Solvolysis)	unknown			6 to 8
	FibreEUse (Pyrolysis and Re-use)	Thermal (Pyrolysis)	11.9	9.8		8 to 9
	GE RE – Veolia (US) (Co-processing – Cement production)	Mechanical (Co-processing)	unknown			9
	GE RE – LaFargeHolcim and Neowa (EU) (Co-processing – Cement production)	Mechanical (Co-processing)	unknown			9
	BCIRCULAR (R3Fiber process)	Thermal (Pyrolysis & Gasification)	unknown	0.05		5 to 6
	HiPerDiF project (High Performance Discontinuous Fibre Composites)	Mechanical (Hydrodynamic alignment)	unknown		1.2	4 to 5
	Hohenstein Institute (Biotechnological recovery of fibers)	Biotechnological	unknown		0.25	1 to 2
	SusWIND initiative (Accelerating sustainable composite materials and technology for wind turbine blades)	Unknown	unknown			n.a.
	Colorado State University consortium (US) (Accelerating sustainable composite materials)	Additive manufacturing/ Recyclable materials	2.2		1.7	2 to 6
	GE Research – AMERICA project (US) (Additive and Modular Enabled Rotor Blades)	Additive manufacturing/ Recyclable materials	5.8		3.7	4 to 6
	NREL consortium (US) (Additive Manufactured Wind Blade Core Structure)	Additive manufacturing/ Recyclable materials	2.2		1.7	4 to 6

	ORNL/UMaine/Orbital Composites (US) (On-Site, High-Throughput Additive Manufacturing)	Additive manufacturing/ Recyclable materials	4.3		3.4	2 to 6
	SANDIA consortium (US) (Additive manufacturing)	Additive manufacturing/ Recyclable materials	2.2		1.7	n.a.
	UMaine consortium – MEGAPRINT (US) (Additive Manufacturing for large modular blade moulds)	Additive manufacturing/ Recyclable materials	3.0		2.4	3 to 6
	UMichigan consortium (US) (Robot-Based Additive Manufacturing of modular moulds)	Additive manufacturing/ Recyclable materials	2.9		2.3	3 to 5
	Blade repurposing (multiple initiatives)	Reprocessing	n.a.			7 to 9
Tower	GE RE – LaFargeHolcim (CH) and Cobod (DK) (3d-printing/co-processed cement)	Additive manufacturing	n.a.			6
	Modvion (Modular wooden towers)	New recycleable materials	unknown	6.55		7
Mooring	TFI (Load reducing polymer spring)	New component	unknown	0.35	undisclosed	5
Nacelle housing (Offshore wind turbine)	Greenboats – Sicomin (NFC offshore nacelle)	New recycleable materials	unknown			6 to 7
	GE/Fraunhofer/Voxeljet (Advance Casting Cell (ACC) 3D printer)	Additive manufacturing	2.6		2.6	4 to 6
Drivetrain/Generator	ECOSwing (Superconducting Wind Generator)	New component	13.9	10.6		7 to 8
	GreenSpur (UK) (Rare Earth Free Permanent Magnet Generator)	New component	unknown		1.4	5
	GE (US) (High-efficiency ultra-light low temperature superconducting (LTS) generator)	New component	unknown		18	5
	VALOMAG (Upscale of Permanent Magnet Dismantling and Recycling)	Manufacturing (H2 Decrepitiation/HDDR or Hydrometallurgy)	2.5	pending		2 to 4
	SUSMAGPRO (Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy)	Manufacturing (Sintering, HDDR, Sintering-debinding-shaping (SDS), recasting)	14.7	13		3 to 5
Grid integration - High voltage transmission	LIFEGRID (SF6-free High Voltage Circuit Breakers (HVCB))	New component	4.1	2.2		5
	SuperNode (MVDC transmission system based on superconducting cable technology)	New component	unknown			3
Grid integration - Hydrogen transport	SoluForce (Flexible Composite Pipes)	New component	unknown			8 to 9
Other / Collaborations addressing multiple components	MAREWIND (Material innovations for offshore wind life extension)	Multiple new components	8	6.7		n.a.

Source: JRC analysis based on TIM, 2022.

Annex 7

Table 50. Active wind energy projects funded by the US Department of Energy's Wind Energy Technologies Office

Project Title	Awardee	Program Area	DOE Funding Amount
Cost of Energy Reduction for Offshore Tension Leg Platform Wind Turbine Systems through Advanced Control Strategies	Alstom Renewables US LLC (GE Subsidiary)	Offshore Wind; Next-Generation Technology Development and Manufacturing	$4,130,557
Evaluating the Effectiveness of a Camera-Based Detection System to Support Informed Curtailment and Minimize Eagle Fatalities at Wind Energy Facilities	American Wind Wildlife Institute	Environmental Impacts and Siting	$781,621
Evaluating the Effectiveness of a Detection and Deterrent System in Reducing Eagle Fatalities at Operational Wind Facilities	American Wind Wildlife Institute	Environmental Impacts and Siting	$698,608
Developing and Evaluating a Smart Curtailment Strategy Integrated with a Wind Turbine Manufacturer Platform	American Wind Wildlife Institute	Environmental Impacts and Siting	$993,278
Development of a Wind Turbine Blade Surface Coating to Reduce Damage due to Lightning	Arctura, Inc.	Next-Generation Technology Development and Manufacturing	$1,150,000
Advanced Drivetrain Lubricants for Enhanced Reliability in Harsh Conditions	Argonne National Laboratory	Next-Generation Technology Development and Manufacturing	$1,000,000
Development of a Concentrated Winding Permanent Magnet Alternator for a Small Wind Turbine	Bergey Windpower Co.	Distributed Wind; Next-Generation Technology Development and Manufacturing	$147,488
Business Model for Rural Cooperative Distributed Wind Microgrids	Bergey Windpower Co. LLC	Distributed Wind	$1,209,541
Thermodynamic Profiler for the Marine Atmospheric Boundary Layer Observations	Boulder Environmental Sciences & Technology, LLC	Offshore Wind; Atmosphere to electrons: Plant Optimization and Resource Characterization	$2,160,000
Recovery of Glass Fiber Composites Fabricated from Retired Wind Turbine Blades	Carbon Rivers LLC	Next-Generation Technology Development and Manufacturing	$1,700,000
SimWIND: Software to Support Wind Siting and Environmental Challenges	Carbon Solutions LLC	Grid Integration	$200,000
Nacelle Testing for Offshore Wind Turbines with Hardware-In-the-Loop	Clemson University	Testing; Offshore Wind	$988,365
Distributed Low Power On-Blade Control for Wind Turbine Load Mitigation	Continuum Dynamics, Inc.	Next-Generation Technology Development and Manufacturing	$1,147,859
Surveying commercial fish species and habitat in wind farm areas using a suite of non-lethal survey methods	Coonamessett Farm Foundation	Environmental Impacts and Siting; Offshore Wind	$2,800,000
Removal of the Need for Boreholes for Micropile Design and Installation	Deep Reach Technology	Offshore Wind	$1,277,267
Wildlife and Offshore Wind (WOW): A Systems Approach to Research and Risk Assessment for Offshore Wind Development from Maine to North Carolina	Duke University	Environmental Impacts and Siting; Offshore Wind	$7,000,000
SMART Wind Health: Development of an Inexpensive Prognostic Condition Monitoring/Control System for Distributed Wind Turbines	eFormative Options	Distributed Wind	$150,000
Evaluation of the Turbine Integrated Mortality Reduction (TIMR) Technology as a Smart Curtailment Approach	Electric Power Research Institute, Inc	Environmental Impacts and Siting	$999,988
Wind Intelligently Integrated into Rural Energy Systems (WIIRES)	Electric Power Research Institute, Inc.	Distributed Wind; Testing	$1,499,857
Compact power converter with high waveform quality for direct-drive renewable energy generators	Fastwatt LLC	Offshore Wind; Grid Integration	$1,565,249
Additive Hybrid Tall Towers	GE Renewable Energy	Next-Generation Technology Development and Manufacturing	$5,000,000
High Efficiency Ultra-Light Superconducting Generator for Offshore Wind	General Electric	Offshore Wind; Next-Generation Technology Development and Manufacturing	$20,800,000
Ultrasonic Jet Bat Deterrent System Advancement - Research and Large-Scale Validation with Comparisons to Wind Turbine Curtailment	General Electric Company through GE Renewable Energy	Environmental Impacts and Siting	$974,212

Advancing Technology for Offshore Wind Resource Characterizations	Helios Remote Sensing Systems, Inc.	Offshore Wind; Atmosphere to electrons: Plant Optimization and Resource Characterization	$2,097,350
Hardening Wind Energy Systems from Cyber Threats	Idaho National Laboratory	Grid integration	$349,000
Enhancing Reliable and Accurate Weather Forecasts for Increased Grid Reliability for Wind with Dynamic Line Rating	Idaho National Laboratory	Grid integration	$600,000
Cybersecurity Roadmap for Wind	Idaho National Laboratory	Grid integration	$340,000
Deep Learning Malware	Idaho National Laboratory	Grid Integration	$450,000
Next Generation Power Converters for Distributed Wind Applications	Intergrid, LLC	Grid Integration; Distributed Wind	$199,500
Optimal Operation and Impact Assessment of Distributed Wind for Improving Efficiency and Resilience of Rural Electricity Systems	Iowa State University	Distributed Wind; Testing	$942,372
Passive Ultrasonic Deterrents to Reduce Bat Mortality in Wind Farms	Iowa State University	Environmental Impacts and Siting	$114,390
Full-Scale Floating Offshore Wind Turbine Platform in U.S. Outer Continental Shelf Atlantic Region	Kent Houston Offshore Engineering LLC	Offshore Wind	$9,525,000
On-Site Spiral Welding Enabling High Hub-Heights	Keystone Tower Systems, Inc.	Next-Generation Technology Development and Manufacturing	$5,000,000
Lake Erie Offshore Wind Icebreaker Project	Lake Erie Energy Development Corporation	Offshore Wind	$6,999,654
Public Acceptance Baseline Analysis	Lawrence Berkeley National Laboratory	Workforce Development, Education, and Stakeholder Engagement; Environmental Impacts and Siting	$2,673,833
Big Adaptive Rotor	Lawrence Berkeley National Laboratory	Next-Generation Technology Development and Manufacturing	$852,816
American Wake Experiment (AWAKEN)	Lawrence Livermore National Laboratory	Atmosphere to electrons: Plant Optimization and Resource Characterization	$300,000
Coupled Aero-Hydro-Mechanical Hybrid Simulation Testing of Offshore Wind Turbines Subjected to Operational and Extreme Loading Conditions	Lehigh University	Testing; Offshore Wind	$1,502,635
Mesoscale-Microscale Coupling - Model Development & Validation	Los Alamos National Laboratory	Atmosphere to electrons: Plant Optimization and Resource Characterization	$643,300
Offshore Wind Turbine Blade (85-120 meters Ultra-Long Blade) Static and Fatigue Test	Massachusetts Clean Energy Center	Testing; Offshore Wind	$1,864,997
High-Fidelity Modeling	National Renewable Energy Laboratory	Atmosphere to electrons: Plant Optimization and Resource Characterization	$6,020,453
Modeling and Validation for Offshore Wind	National Renewable Energy Laboratory	Offshore Wind	$5,115,769
Study on the Potential Application of Additive Manufacturing in Wind Turbine Components and Tooling	National Renewable Energy Laboratory	Next-Generation Technology Development and Manufacturing	$445,799
Wind Standards Development	National Renewable Energy Laboratory	Next-Generation Technology Development and Manufacturing; Testing	$3,144,603
North American Renewable Integration Study	National Renewable Energy Laboratory	Grid Integration	$1,769,973
Multiscale Integration of Control Systems (EMS/DMS/BMS)	National Renewable Energy Laboratory	Grid Integration	$42,283
WindExchange and Regional Resource Centers	National Renewable Energy Laboratory	Workforce Development, Education, and Stakeholder Engagement	$9,947,626
Technology Development and Innovation to Address Operational Challenges	National Renewable Energy Laboratory	Environmental Impacts and Siting	$147,583
Energy Sector Modeling and Impacts Analysis	National Renewable Energy Laboratory	Next-Generation Technology Development and Manufacturing; Offshore Wind	$40,499,242
Atmosphere to Electrons (A2e) Performance Risk, Uncertainty and Finance (PRUF) Analysis Support	National Renewable Energy Laboratory	Atmosphere to electrons: Plant Optimization and Resource Characterization	$4,088,125
Working Together to Resolve Environmental Effects of Wind Energy (WREN)	National Renewable Energy Laboratory	Environmental Impacts and Siting	$316,840
Eagle Topic Area 3 Funding Opportunity Announcement (FOA) Support	National Renewable Energy Laboratory	Environmental Impacts and Siting	$377,359

Big Adaptive Rotor	National Renewable Energy Laboratory	Next-Generation Technology Development and Manufacturing	$2,856,501
Enabling Autonomous Wind Plants through Consensus Control (TCF)	National Renewable Energy Laboratory	Atmosphere to electrons: Plant Optimization and Resource Characterization	$250,000
Wind Turbine Drivetrain Reliability Assessment and Remaining Useful Life Prediction (TCF)	National Renewable Energy Laboratory	Next-Generation Technology Development and Manufacturing	$100,000
Fusion Joining of Thermoplastic Composites Using Energy Efficient Processes (TCF)	National Renewable Energy Laboratory	Next-Generation Technology Development and Manufacturing	$150,000
Atmosphere to Electrons to Grid (A2e2g)	National Renewable Energy Laboratory	Grid integration	$800,000
Continental-Scale Transmission Modeling Methods for Grid Integration Analysis	National Renewable Energy Laboratory	Grid integration	$600,000
Wind Grid Integration Stakeholder Engagement	National Renewable Energy Laboratory	Grid integration	$470,718
Advanced Modeling, Dynamic Stability Analysis, and Mitigation of Control Interactions in Wind Power Plants	National Renewable Energy Laboratory	Grid integration	$700,000
Wind Power as Virtual Synchronous Generation (WindVSG)	National Renewable Energy Laboratory	Grid integration	$804,588
North American Energy Resiliency Model (NAERM)	National Renewable Energy Laboratory	Grid integration	$2,249,586
Clusters of Flexible PV-Wind-Storage Hybird Generation (FlexPower)	National Renewable Energy Laboratory	Grid integration	$4,090,000
Foundational Assistance to ISO/RTOs under Electricity Market Transformation	National Renewable Energy Laboratory	Grid integration	$3,090,000
High-Fidelity Modeling Toolkit for Wind Farm Development	National Renewable Energy Laboratory	Atmosphere to electrons: Plant Optimization and Resource Characterization	$850,000
Field Testing and Validation of Hybrid Optimization and Performance Platform (HOPP) with GE Global Research	National Renewable Energy Laboratory	Next-Generation Technology Development and Manufacturing	$500,000
Open Operational Assessment (OpenOA) with ENTR Alliance	National Renewable Energy Laboratory	Atmosphere to electrons: Plant Optimization and Resource Characterization	$249,950
Offshore Wind Turbine Digital Twin for the Prediction of Component Failures with Stiesdal Offshore Technologies A/S	National Renewable Energy Laboratory	Offshore Wind	$200,000
Grid-Forming Consortium	National Renewable Energy Laboratory	Grid Integration	$25,000,000
Evaluating Deterrent Stimuli for Increasing Species-Specific Effectiveness of an Advanced Ultrasonic Acoustic Deterrent	National Renewable Energy Laboratory	Environmental Impacts and Siting	$450,000
Wind Utility Network Deployment Acceleration (WUNDA)	National Rural Electric Cooperative Association	Distributed Wind	$2,400,000
Study on the Potential Application of Additive Manufacturing in Wind Turbine Components and Tooling	Oak Ridge National Laboratory	Next-Generation Technology Development and Manufacturing	$684,999
Optimized Carbon Fiber Composites for Wind Turbine Blades	Oak Ridge National Laboratory	Next-Generation Technology Development and Manufacturing	$358,000
Big Adaptive Rotor	Oak Ridge National Laboratory	Next-Generation Technology Development and Manufacturing	$468,935
A Heterogeneous System for Eagle Detection, Deterrent, and Wildlife Collision Detection for Wind Turbines	Oregon State University	Environmental Impacts and Siting	$562,085
Advanced Collision Detection and Site Monitoring for Avian and Bat Species for Offshore Wind Energy	Oregon State University	Environmental Impacts and Siting; Offshore Wind	$580,000
Coupled Aerodynamic and Hydrodynamic Hybrid Simulation of Floating Offshore Wind Turbines (FOWTs)	Oregon State University	Testing; Offshore Wind	$1,000,000
Baseline Data Collection on Cetaceans and Seabirds in the Outer Continental Shelf and Slope of Northern California and Oregon to Inform Offshore Wind Energy Development	Oregon State University	Environmental Impacts and Siting; Offshore Wind	$1,500,000
Distributed Market Wind Research (Market Report)	Pacific Northwest National Laboratory	Distributed Wind	$2,892,638
DOE Offshore Wind Lidar Buoy Deployments	Pacific Northwest National Laboratory	Offshore Wind; Atmosphere to electrons: Plant Optimization and Resource Characterization	$7,331,381
Lidar Buoy Science	Pacific Northwest National Laboratory	Offshore Wind; Atmosphere to electrons: Plant Optimization and Resource Characterization	$1,180,001

Working Together to Resolve Environmental Effects of Wind Energy (WREN)	Pacific Northwest National Laboratory	Environmental Impacts and Siting	$428,995
Tilt-Up Tower and Installation System to Reduce the Cost of Distributed Wind Turbines	Pecos Wind Power	Distributed Wind; Next-Generation Technology Development and Manufacturing	$1,349,304
Understanding the Golden Eagle sensory world to enhance detection and response to wind turbines	Purdue University	Environmental Impacts and Siting	$250,000
Hybrid Model-based Approach for Remote Diagnostics and Prognostics for Wind Turbines	Qualtech Systems, Inc	Next-Generation Technology Development and Manufacturing	$200,000
Abrasion/Impact Resistant Coatings for Wind Turbine Blade Protection	Resodyn Corporation	Next-Generation Technology Development and Manufacturing	$1,150,000
Wind Sensing with Digital Holography	Sanchez Engineering Services	Atmosphere to electrons: Plant Optimization and Resource Characterization	$199,699
High-Fidelity Modeling	Sandia National Laboratories	Atmosphere to electrons: Plant Optimization and Resource Characterization	$4,055,253
Wind Turbine Blade Durability and Damage Tolerance	Sandia National Laboratories	Next-Generation Technology Development and Manufacturing; Atmosphere to electrons: Plant Optimization and Resource Characterization	$6,697,329
Optimized Carbon Fiber Composites for Wind Turbine Blades	Sandia National Laboratories	Next-Generation Technology Development and Manufacturing	$599,961
Rotor Wake Measurements & Predictions for Validation	Sandia National Laboratories	Atmosphere to electrons: Plant Optimization and Resource Characterization	$16,922,617
Big Adaptive Rotor	Sandia National Laboratories	Next-Generation Technology Development and Manufacturing	$2,349,500
Cybersecurity Roadmap for Wind	Sandia National Laboratories	Grid integration	$90,000
Hardening Wind Energy Systems from Cyber Threats	Sandia National Laboratories	Grid integration	$445,987
Wind Plant Control Architecture for Efficient Energy Storage Systems Utilization for Quality Power Grid Delivery	Sandia National Laboratories	Grid integration	$400,000
Assessment Robot for Resilient Optimized Wind Energy (ARROW(e)) with SkySpecs	Sandia National Laboratories	Next-Generation Technology Development and Manufacturing	$1,000,000
Distributed Optical Sensing Platform for Subsea Cable Monitoring and Fault Detection	Sequent Logic, LLC	Offshore Wind	$206,494
Coastal Acoustic Buoy for Offshore Wind	SMRU Consulting	Environmental Impacts and Siting; Offshore Wind	$940,439
Activity-based Informed Curtailment: Using Acoustics to Design and Validate Smart Curtailment at Wind Farms	Stantec Consulting Services Inc	Environmental Impacts and Siting	$291,218
Ocean Energy Safety Institute	Texas A&M Engineering Experiment Station	Offshore Wind	$5,000,000
Innovative Deepwater Mooring for Floating Offshore Wind	Triton Systems, Inc.	Offshore Wind	$2,664,793
Effect of Fatigue on the Capacity and Performance of Structural Concrete	Tufts University	Testing; Offshore Wind	$645,020
New England Aqua Ventus I	University of Maine	Offshore Wind	$6,801,879
Demonstrating a 10-12 MW Floating Wind Turbine by 2022	University of Maine	Offshore Wind	$5,000,000
Demonstrating a Reduced-Footprint Synthetic Rope Mooring System that Minimizes Fishing Impacts and Costs for a 10+-MW Floating Wind Turbine	University of Maine	Offshore Wind	$4,800,000
Development of an Acoustics-Based Automated Offshore Wind Turbine Blade Structural Health Monitoring System	University of Massachusetts Lowell	Testing; Offshore Wind	$998,982
Lower Cost, Mass, Volume Wind Power Converter with Grid Support	WBGlobalSemi, Inc.	Grid Integration; Distributed Wind	$200,000
A Multi-Sensor Approach for Measuring Bird and Bat Collisions with Offshore Wind Turbines	Western EcoSystems Technology, Inc	Environmental Impacts and Siting; Offshore Wind	$971,532
A cost-effective wildlife activity and mortality detection system for utility scale wind turbines	Wildlife Imaging Systems LLC	Environmental Impacts and Siting	$199,991
Cost-Effective Environmental Monitoring of Offshore Wind Installations with Automated Marine Robotics	Woods Hole Oceanographic Institution	Environmental Impacts and Siting; Offshore Wind	$750,000
Improving High-Resolution Offshore Wind	Woods Hole	Offshore Wind; Atmosphere to	$8,000,000

Resource Assessments and Forecasts Using Observations	Oceanographic Institution	electrons: Plant Optimization and Resource Characterization

Source: JRC analysis based on DOE, 2022

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