

Global Growth in Offshore Wind Turbine Technology

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Abstract

Due to the commissioning of floating wind units, the latest technological developments, significant growth, and improvements in turbines, developments in offshore wind power capacity are estimated to increase faster than in the last two decades. The total installed offshore wind power capacity, which is currently 35 GW, is predicted to be approximately 382 GW by 2030 and approximately 2,002 GW by 2050. For this reason, attempts are proposed to lower levelised cost of electricity (LCOE) for offshore wind power generation more than for other energy sources. In this study firstly, the global growth in the nominal capacity and size of offshore wind turbines over the last twenty years is examined. Then, the effects of this increase in nominal capacity and size on the LOCE, total installation cost (TIC), and turbine capacity factor are investigated. In parallel with this development, the changes in distance to shore and water depth for installation offshore wind power plants are reviewed according to the years. In addition, the effects of this global growth on wind farm capacity, turbine-specific power capacity, number of turbines per GW, and area needed per GW are investigated and discussed in detail.

1. Introduction

One of the biggest threats of this century is climate change, and it is already affecting many parts of the world significantly. Increasing greenhouse gas emissions from the energy sector cover two-thirds of the global total and are among the important and influential sources on the effects of climate change. Therefore, it becomes imperative to make technological breakthroughs towards clean, sustainable, and renewable energy sources by making radical changes for energy technologies worldwide, driven by the need to end climate change and provide affordable energy sources (IRENA 2021a).

In recent years, limiting global average temperature increment to no more than 1.5°C above pre-industrial levels and ensuring that all sectors of the economy achieve zero CO₂ emissions by the second half of this century have been one of the most pressing challenges in the world (IRENA 2020a). According to the Baseline Energy Scenario (BES), energy-related emissions are predicted to increase from 34 Gt in 2019 to 43 Gt by 2050, at a compound annual rate of 0.7%. This expectation will likely result in a temperature increase of 3°C or more in the second half of the century. According to the Planned Energy Scenario (PES), energy-related emissions are expected to increase slightly by 2030 and drop to around 33 Gt, which is today's level, by 2050. This expectation will likely lead to a global temperature increase of 2.5°C in the second half of this century. On the other hand, according to IRENA's Transforming Energy Scenario, energy-related emissions will fall to about 10 Gt or 70% less than today's level by 2050 at a compound rate of 3.8% per year, and the predicted temperature increase will be well below 2°C. In this respect, renewable energy sources, energy efficiency, and electrification in energy consumption are vital in achieving these emissions reductions (IRENA 2019; IRENA 2020b).

With batteries and other enabling technologies, renewable energy technologies have proven effective and cost-effective in every country for a growing range of applications. Today, renewable energy sources – whether for direct energy use or feedstocks – show more potential in the world than ever before. This makes them very important to achieve zero emissions (IRENA 2020a). Currently, renewable technologies already dominate the global energy market for new sustainable energy production. Among renewable energy sources, wind energy is the fastest-growing electricity production technology (Singh and Parida 2013). Wind is an increasingly affordable and cost-effective source of electricity in many markets, and it will be completely cost-competitive in the coming years. Many innovative solutions are being developed to make the power system and grids more resilient, allowing for higher and more cost-effective use and diffusion of onshore and offshore wind energy systems (IRENA 2020c).

Offshore wind energy technology is one of the rapidly developing renewable energy systems in the last decade. With remarkable technology cost reductions, deliberate breakthroughs and advancements, and increased supply chain efficiencies, it has seen significant acquisitions in different markets, which has paved the way for further investment. Thanks to these features, offshore wind has become an attractive technology worldwide. Because offshore wind often allows higher and more consistent wind sources to be used, countries have developed large-scale wind farm projects near to densely populated coastal locations common in many places around the world. This capability makes a critical contribution to the existing position of low-carbon technologies to decarbonize the power sectors of many countries. By the end of 2020, a total of 35.3 GW of offshore wind power capacity had been established in the world, of which 90% was operated in the North Atlantic Ocean and North Sea. The United Kingdom, China, Germany, the Netherlands, Belgium, and Denmark are leading this setup. Thus, significant developments have occurred in offshore wind in the last decade and this development is expected to continue to play an essential role in future power generation systems (IRENA 2021b).

Much research has been done on offshore wind energy, and many publications have appeared on the subject (Argin et al. 2019; Emeksziz and Demirci 2019; Bosch et al. 2019; Tavares et al. 2020; Basset et al. 2021; İlkiliç and aydin 2015; Satir et al. 2018; Kılıç 2019; Effiom et

al. 2016; Argin and Yerci 2017; Tercan et al. 2020). However, limited studies have been conducted on the global growth in offshore turbine technologies. For example, Arshad and O'Kelly (2013) reviewed the offshore wind-turbine structures in terms of geometric size and rated power-generation capacity, cost, foundation options available, challenges, and attractions of wind-power generation. Diaz and Soares (2020) aimed to determine the existing status of offshore wind farms worldwide and conducted an overview of critical types of equipment, including foundations, operators, turbines, etc. Cali et al. (2018) conducted the techno-economic feasibility analysis for offshore wind power plant projects in three of the Turkey's most promising wind locations. Soares-Ramos et al. (2020) analyzed the trends and status of existing offshore wind farms above 150 MW in Europe. This work discussed the latest information and trends on wind turbine size and capacity, investment cost, turbine model, water depth, distance to shore, transmission technology, type of foundation, and voltage array systems were discussed. Lacal-Arántegui et al. (2018) analyzed cost reduction factors in installing foundations and turbines, which are shown as the most crucial cost elements of offshore wind farms. Igwemezie et al. (2019) reviewed the current offshore wind industry trend and material requirements for improving fatigue resistance in support structures of large wind turbines. Wu et al. (2019) reviewed the current state of knowledge regarding geotechnical and structural issues affecting the types of foundations considered for support structures of offshore wind turbines and made recommendations for future research and development. Li et al. (2020) reviewed the current status of offshore wind power technology, the development trend of offshore wind power, the complex marine environment, deep-sea power transmission, and expensive equipment installation costs faced by offshore wind conversion technology in the world.

Offshore wind energy technologies have developed tremendously globally in recent years, and their installation has increased. This development has resulted in a significant reduction in the LCOE and the TIC of turbines. Moreover, the evolution of large offshore wind farms has been leading to a revolution in the current scenario. This evolution also causes many research necessities for different participants of wind power projects such as turbine manufacturers, structures constructors, system planners and operators, and other participants. According to the literature study, socially and politically, offshore wind power plants have a negligible noise and visual impact with the distance to shore. However, the impact on marine ecosystems should be analyzed in more detail. In this study, for this reason, the development of offshore wind turbine technology was reviewed in detail. Detailed information on the global growth in offshore wind turbine technology and the key technological trends emerging in this energy system were provided. In offshore wind technology, deployed capacity, technological situation and outlook, anticipated future potential were reviewed. The novelty of this study is highlighted below:

- To reveal the global growth in nominal capacity and size of offshore wind turbines over the two past decades,
- To review the effects of this increase in nominal capacity and size on LOCE, TIC, and turbine capacity factors,
- In parallel with this development, to determine the change of water depth and distance to the shore by years in the establishment of offshore wind power plants,
- To examine and discuss the effects of global growth in offshore wind turbines' nominal capacity and size on wind farm capacity, turbine specific power capacity, the number of turbines per GW, and the area needed per GW.

2. Methodology

The primary purpose of this study is to examine and analyze the 162 offshore wind farms currently in operation worldwide, technically, technologically, and historically. For this, all offshore wind farms in the world, established from 1991, when the offshore wind farm was first established, to 2020, were identified. Then, the technological characteristics of these offshore wind farms and their turbines were determined as an annual weighted average. All necessary data for the characteristics of operational offshore wind farms and their turbines have been obtained in detail from the wind farm database 4C Offshore (2021), the Wind Power (2021), Ref (Diaz and Soares 2020; IRENA 2021c; WindEurope 2019; WindEurope 2020; WindEurope 2021; GWEC 2021). Figure 1 shows some specifications of an offshore wind farm and turbine (IRENA 2018). Table 1 gives the offshore wind farms with a capacity of at least 500 MW. The following technical and technological data regarding offshore wind farms and turbines have been obtained and calculated over the years:

- Turbine capacity (MW)
- Rotor diameter (m)
- Hub height (m)
- Levelised cost of electricity (LCOE) (2020 USD/kWh)
- Total installed cost (TIC) (2020 USD/kW)
- Wind farm capacity (MW)

- Number of wind turbines
- Sea surface area needed to install an offshore wind farm (km²)
- Water depth (m)
- Distance from shore (km)
- Turbine capacity factor (%)
- Turbine specific power capacity (W/m²)
- Number of turbines per GW
- Area needed per GW (km²)

Table 1
Offshore wind farms with a capacity of at least 500 MW

Country	Wind farm	Com. year	Installed capacity (MW)	Number of turbines	Foundation	Turbine model	Hub height (m)	Water depth (m)	Distance from shore (km)	Sea surface area (km ²)
United Kingdom	Hornsea One	2019	1,218	174	Monopile	Siemens SWT-7.0MW-154	113	30	120	407.34
Netherlands	Borssele 1&2	2020	752	94	Monopile	SG 8.0MW-167DD	116.5	38	22	112.58
Netherlands	Borssele 3&4	2020	731.5	77	Monopile	Vestas V164-9.5MW	100	22.5	31	121.94
United Kingdom	East Anglia One	2020	714	102	3-Leg jacket	Siemens SWT-7.0MW-154	90	40	45.4	162.82
United Kingdom	Walney Extension	2018	659	40+47	Monopile	Vestas V164-8.25MW Siemens SWT-7.0MW-154	110	37	19	149.13
United Kingdom	London Array	2013	630	175	Monopile	Siemens SWT-3.6MW-120	87	12.5	20	106.9
Netherlands	Gemini	2017	600	150	Monopile	Siemens SWT-4.0MW-130	88.5	32	85	69.58
United Kingdom	Beatrice 2	2018	588	84	Jacket	Siemens SWT-7.0MW-154	101	45	13.5	131.33
Germany	Gode Wind 1 and 2	2017	582	97	Monopile	Siemens SWT-6.0MW-154	111	31	45	69.372
United Kingdom	Gwynt and Mor	2015	576	160	Monopile	Siemens SWT-3.6MW-107	84.4	20	16	67.98
United Kingdom	Race Bank	2018	573.3	91	Monopile	Siemens SWT-6.3MW-154	105	15	27	62.36
United Kingdom	Greater Gabbard	2012	504	140	Monopile	Siemens SWT-3.6MW-107	77.5	26	26	146.13

3. Results And Discussion

3.1. Global Growth in Installed Power Capacity

Figures 2 and 3 present the changes in the global installed capacity of offshore wind turbine technology as cumulative and annual. As can be seen from the figures, offshore wind power installation has overgrown since 2007. The first offshore wind power plant was

established in Vindeby in eastern Denmark in 1991. The Vindeby wind farm consisted of 11 onshore turbines producing 450 kW each and a cumulative capacity of 5 MW. Since then, the Vindeby wind farm has become an influential pioneer in the European offshore wind industry. With this breakthrough, offshore wind power plants in Europe showed significant development. In the 2000s, the installation of offshore wind farms in the Southern North Sea, Baltic Sea, and the Irish Sea progressed rapidly since these seas have strong winds on average of over 8 m/s and relatively shallow water depths of less than 50 m. The cumulative installed power of offshore wind energy increased to 67 MW in 2000. In 2013, 1,567 MW offshore wind installations contributed to 11,159 MW of installed wind energy capacity. As of 2015, 3,230 turbines were installed in 84 offshore wind farms with a total power capacity of 11,027 MW in 11 European countries.

By the end of 2017, the global installed offshore wind power capacity increased to 20 GW. A 4.3 GW offshore wind farm was installed in 2018. In 2020, 90% of the global offshore wind market was represented by European companies. Fifteen new offshore wind farms started generating electricity, and nearly 6.1 GW of offshore wind capacity was installed in the world in 2020. Currently, 162 offshore wind farms are installed worldwide, and 26 offshore wind power plants are under construction. The total installed offshore wind capacity was 35.3 GW at the end of 2020. As seen in Figure 4, in 2020, cumulative capacity reached 10.2 GW in the UK, which has the world's largest offshore wind industry with the lowest costs. In addition, China, Germany, the Netherlands, Belgium, and Denmark were the countries that contributed to the increase in global installed capacity, enabling the offshore wind market to grow remarkably. Outside of Europe, China added approximately 3 GW in 2020, bringing its total installed capacity to approximately 10 GW. However, according to the International Renewable Energy Agency (IRENA), offshore wind will need to increase tenfold by 2030 to support the necessary energy sector transformation and meet the Paris Agreement goals. The total installed offshore wind power capacity is predicted to be approximately 382 GW by 2030 and approximately 2,002 GW by 2050 (Figure 5).

3.2. Turbine Capacity and Size Analysis

Due to its open and smooth sea location, ability to generate GWs quickly, and high energy output per m², offshore wind energy is a highly viable alternative for cost-effectively powering densely populated coastal areas. Thanks to advances in installation, foundations, access, operation and system integration, and turbine technologies, it has made it possible to move into deeper waters and further offshore to achieve locations with more significant energy capacity. In the last ten years, offshore wind energy technology has attained significant maturity, has become the most advanced technology among renewable energy sources. As shown in Figure 6, wind turbines' nominal capacity and size have historically increased due to continuous and conscious research and development (R & D) processes (Quest Floating Wind Energy 2021). With this growth, foundation and cabling costs have been reduced, while at the same time, costs have been reduced by increasing the energy captured per MW of nominal capacity. The 15 MW turbine, which has the highest wind turbine rating globally, is scheduled to be first tested in 2022 and go into power generation in 2024.

Figure 7 shows the growth of offshore wind turbine capacity between 2000 and 2020. As can be seen from the figure, the wind turbine capacity has shown a great improvement over time. When the world's first offshore wind power plant was built in Denmark in 1991, the turbine power capacity was just 450 kW. Since this installation, the offshore wind turbine size has grown significantly. The global average offshore wind turbine size reached 1.5 MW in 2000. In Europe in 2009, the average turbine power capacity of an offshore wind turbine was about 3 MW. The average turbine size was higher than 7.2 MW for new installations in Europe in 2019 [9]. Global weighted average nameplate capacity increased 150% from 3 MW in 2010 to 7.5 MW in 2020. Wind farms installed in 2020 had a 10% higher wind turbine power capacity.

Figure 8 presents the change in the global weighted-average turbine size for offshore wind over time. The figure shows that rotor diameter and hub height increased in parallel with higher turbine capacity values. Growth in rotor diameter is of great importance as it causes greater energy extraction from wind turbines and more uniform power output throughout the year. Rotor diameters expanded from 112 m to 157 m in the decade from 2010 to 2019, an increase of 40%. On the other hand, hub height increased from 83 m in 2010 to 108 m in 2019, an increase of 30%. With these growing turbine sizes, wind farms grew from 83 MW in 2011 to 301 MW in 2020.

Capacity factors of the wind turbines in offshore wind power plants vary due to the technology used, wind farm configuration, and differences in meteorology between wind farm sites. Between 2010 and 2020, the global weighted average capacity factor of yearly installed offshore wind turbines varied between 35% and 45%. The capacity factor for newly established projects in 2020 ranged from 33–47%. Wind turbines with larger swept areas and higher hub heights can have more electricity collection capability and increase their capacity.

Global R&D activities in recent years have focused on manufacturing larger wind turbines, as evidenced by the practices of turbine manufacturers. For instance, the Danish wind turbine market Vestas investigates a larger offshore wind turbine with a nameplate

capacity of 17 MW for future release and installation. Recent developments under consideration have shown that turbine sizes can reach 20 MW within ten or two years. Given the continued evolution of turbine size growth, capacity factors are expected to be between 36% and 58% by 2030 and 43–60% by 2050, compared to an average of 43% in 2018.

3.3. Cost Analysis

The changes in the global weighted average LCOE and TIC for offshore wind technology between 2010 and 2020 are shown in Figure 9. As seen from the figure, the global weighted-average LCOE of newly installed offshore wind turbines decreased from USD 0.162/kWh in 2010 to USD 0.084/kWh in 2020, a decrease of 48% in 10 years. On the other hand, between 2007 and 2014, the LCOE increased as projects began to shift into deeper waters. For example, it peaked at 0.180 USD/kWh in 2007 and 0.179 USD/kWh in 2008, followed by a sharp decline after 2014. The LCOE for offshore wind in the world's leading countries has decreased sharply. For example, in 2020, the lowest weighted average LCOE value was obtained in China at USD 0.084/kWh.

The global weighted average TIC of offshore wind farms has increased from approximately USD 2592/kW in 2000 to over USD 5500/kW in 2008. Between 2008 and 2015, offshore wind farm installations were carried out in areas further from shore and into deeper waters, with a global weighted average TIC of around USD 5000/kW over that period. This cost started to decline after 2015 and fell relatively quickly to 3185 USD/kW in 2020. Installation costs of offshore wind technologies peaked in 2011-2012 due to projects being located in deeper waters, farther from shore, and using more advanced technology. In contrast to onshore wind installations, offshore wind farm installations became more costly and resulted in significantly longer lead times due to the difficulties of O&M installation in harsh marine environments. Also, the project development and planning for offshore wind power plants are more complex than for onshore projects. The fact that the construction is more and takes longer increases the TICs. Due to their offshore location, these projects also have higher construction costs and grid connectivity. However, effects such as standardization of turbine and foundation designs, increased industry maturity, industrialization of production for offshore wind farm components at local centers, and a decrease in the complexity of installation practices have resulted in cost savings. Installation times and costs per unit capacity have declined due to manufacturer experience, utilize of specialized vessels planned for offshore wind studies, and increases in turbine size for a turbine that amortizes installation attempts over larger capacities than ever before. In addition to the fact that offshore wind farm installations are in deeper waters and farther offshore, there has also been a tendency towards higher hub heights, more efficient and durable blades, and higher capacity turbines. Thanks to these technological features, these turbines, which are specially designed for the offshore sector, are in a position to capture more energy. This is very important for decreasing the LCOE of offshore farms.

3.4. Farm Capacity and Installation Analysis

Figure 10 shows the change in the global weighted average wind farm capacity for offshore wind over time. The figure shows that the average wind farm capacity increased parallel with higher turbine capacity values and years. Moreover, it is evident from the figure that offshore wind farms established in Europe are slightly larger compared to the average offshore wind farm values in the world. The first large-scale offshore wind power plant started power generation in Denmark in 2002 with 160 MW. After that, globally installed offshore wind farm capacities have increased rapidly over the past two decades. In 2020, the average offshore wind farm size reached 301 MW and 325.5 MW in the world and Europe, respectively. The world's largest offshore wind power plant Hornsea 1 was installed in the UK, with a capacity of 1.12 GW.

Figure 11 shows the evolution of the number of wind turbines, and sea surface area needed to install offshore wind farms in Europe over time. Europe currently has a total of 25 GW of offshore wind installed capacity, corresponding to 5,402 wind turbines in 12 countries. The total sea surface area covered by 116 offshore wind farms is about 3,820 km². As seen from the figure, in Europe, the number of offshore wind turbines and the sea surface area needed for offshore wind farm installation have increased over time. For example, while the number of turbines established in 2001 was 20 and the needed sea surface area was 0.3628 km², 703 offshore wind turbines were installed on a sea surface area of 839.9 km² in 2018. In 2020, 358 offshore wind turbines were installed on an area of 303.4 km². In addition, it is seen that the number of turbines and the needed sea surface area increase in parallel with the increase in wind turbine capacity over time.

Figure 12 shows the evolutions of the global weighted average water depth and the distance from shore for offshore wind over time. As can be seen from the figure, offshore wind projects worldwide were established in shallow nearshore waters in the early 2000s, while they were established later in deeper waters and further offshore. At the same time, it is seen that turbine capacities increase in parallel with this development. This growth has resulted in the increased foundation, grid connection, and installation costs. This increase accelerated the total installed cost of the offshore wind turbine as designs were developed. The offshore wind farms commissioned in 2000 were approximately 6.5 km from the shore, 8 m water depths, and an average turbine power capacity of 1.6 MW. These numbers

have increased significantly over time. In 2020, the average offshore turbine power capacity reached 7.5 MW, while the weighted average distance to shore and water depth increased to 29 km and 33.6 m, respectively.

3.5. Technological Growth Analysis

Over three decades of research and development, offshore wind has established itself as a cost-competitive power generation option for mature industries and governments. This has resulted in a robust offshore wind supply chain in the countries bordering the North Sea and the Baltic Sea through collaboration between European markets and experienced stakeholders. Currently, a single offshore wind turbine now has more capacity than the combined output of the world's first two offshore wind farms. With new technological advances such as floating foundations, an alternative geographic range of opportunities is paving the way by enabling offshore wind turbines to be established in deeper waters. From a technological, location-specific, and technological connectivity perspective, it appears that the key emerging trends in offshore wind are primarily the fabrication of more extensive offshore wind turbine technologies, floating foundations, use of multifaceted foundations and structures, development of combined power generation technologies, creation of offshore energy centers for sustainable and renewable energy power generation, green hydrogen production with different offshore renewable energy technologies, and airborne wind power systems.

Offshore wind turbine technology achieves higher turbine capacity factors and more stable wind power output due to less wind shear and turbulence and higher average wind speeds. This effect causes offshore wind output to have a higher value for the electrical system than onshore wind. The most common trend in the design of wind turbine technologies today is to increase turbine efficiency while reducing turbine costs. For this, the hub height and rotor sweep area of the turbines are increased. On average, if turbines' hub height and rotor swept area grow faster than their power capacity, the specific power capacity will decrease. This causes an increase in the capacity factor of the turbine. As in Europe, wind turbines in the latest offshore turbine technology models today have a larger rotor sweep area, using more wind and generating more electricity. This reduces the cost of renewable energy generation. Thus, offshore wind turbines are becoming more powerful all over the world.

Specific power is defined as a measure of the wind turbine nameplate capacity divided by the rotor swept area. Figure 13 shows the evolutions of the global weighted average capacity factor and specific power capacity for offshore wind over time. As seen from the figure, the global weighted average capacity factor and specific power capacity values for offshore wind turbines installed between 2010 and 2019 range between 35%-45% and $316\text{W}/\text{m}^2$ - $461\text{W}/\text{m}^2$, respectively. The specific power capacity of the annual installed wind turbines in the world decreased from $461\text{W}/\text{m}^2$ in 2011 to $350\text{W}/\text{m}^2$ in 2019. On the other hand, the turbine capacity factor increased from 38–42% from 2011 to 2019. Since the wind turbine's power output is directly related to the rotor swept area, an increase in the rotor swept area results in more power output from the wind for a turbine of the same power capacity. This means that there is a decrease in the specific power capacity of the turbine. A decrease in the specific power capacity causes the turbine power output and power coefficient to increase significantly for the same wind speeds. This increase in the rotor swept area of turbines has also resulted in lower energy costs worldwide, as larger wind turbines can generally deliver electricity at a lower cost than smaller wind turbines.

As a result, the growth in turbine size results in increased wind turbine efficiency because larger turbines with larger swept areas provide higher capacity factors for the same resource quality. Technological developments that increase capacity factors and reductions in TICs, O&M costs, and capital costs have resulted in cost reductions for offshore wind farms. The larger rotor turbines have higher capacity factors because the spinning blades sweep a wider area and utilize more energy. By using taller towers to increase hub height in areas with positive wind shear, greater access to higher wind speeds was achieved, reducing wind energy costs. The growth in the rotor diameter and thus in the rotor swept area was remarkably rapid, as the wind turbines were mounted with longer blades. At the same time, there was a modest increase in the mean nameplate capacity. Results showed that the turbines with low specific power were initially designed for low wind speed sites and were increasingly installed throughout the country, even in areas with high wind speeds, because of their low cost in various wind speed regimes.

Figure 14 shows the decrease in the number of turbines per GW between 2001 and 2020 in Europe. This figure reveals that the number of turbines per GW has decreased since 2001 significantly. For example, while the number of turbines per GW of annual installed offshore turbines in 2001 was approximately 500, this value dropped to 122, decreasing by 76% in 2020. A decrease in this metric may suggest less visibility per power capacity. Figure 15 shows the change in the sea surface area needed per GW for yearly installed offshore wind farms between 2001 and 2020 in Europe. This figure shows that the area needed per GW increased from 129.19 km^2 in 2002 to 236.80 km^2 in 2019. However, this value has changed over the years since 2001, showing a fluctuating situation. For example, the area needed to establish a 1 GW offshore wind farm in 2020 is calculated as 103.56 km^2 .

4. Conclusion

The analysis results obtained as a result of this study are presented below:

- Wind energy, together with solar energy, will transform the global electricity sector in the coming years. Offshore and onshore wind will produce more than one-third (35%) of total electricity worldwide by 2050, thus becoming a significant generation source. The global cumulative installed offshore wind capacity is estimated to reach 382 GW by 2030 with an increase of more than ten-fold, and to reach 2002 GW by 2050 (almost sixty-fold) compared to installed capacity in 2020 (35 GW).
- One of the general trends in wind turbine technology is to produce larger machines. During recent years, the size of the turbines has been increasing quickly to lower costs by scale and standardization. This trend is expected to continue towards longer blades, larger rotor sizes, extended machines, and higher hub heights. Especially offshore developers will continue to benefit from larger turbines as far as possible.
- It has also been observed that offshore wind farms are moved to deeper waters and farther seas to obtain more power output from the wind.
- The global cumulative installed offshore wind power capacity has increased more than eleven-fold from 3.1 GW in 2010 to 35 GW in 2020.
- The global weighted-average LCOE of offshore wind declined by 48% between 2010 and 2020, from USD 0.162 to USD 0.084/kWh, with a 9% reduction year-on-year in 2020.
- Between 2010 and 2020, global weighted-average TICs declined 32% from USD 4706/kW to USD 3185/kW. The global weighted-average TIC peaked at USD 5513/kW in 2008 and then decreased by 42% to USD 3185/kW in 2020.
- Advances in technology, including longer blades with higher hub heights, larger turbines, and reach to better wind speeds, have increased offshore wind farms' global weighted average capacity factor. For example, the global weighted average capacity factor increased from 29% in 2001 to 45% in 2017, and then this factor dropped to 40% in 2020 as China increased its share in global distribution.
- TIC and LCOE reductions were driven by technological advances and the industry's growing maturity. Many factors have contributed to cost reductions, including greater product standardization, developer experience, manufacturing industrialization, economies of scale, and regional production and service centers. In addition, this cost reduction has been facilitated by the benefits of generation policies that support the growth of renewable energy, precision distribution, and the scale seen in the industry today.
- The trend of the rated capacity of installed wind turbines increased linearly relative to the hub height and rotor diameter. In addition, a linearly increasing trend between the rotor diameter and hub height was observed. Together with the tendency towards larger-sized turbines, there has also been a continuing increase in turbine capacity.

Declarations

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Figures

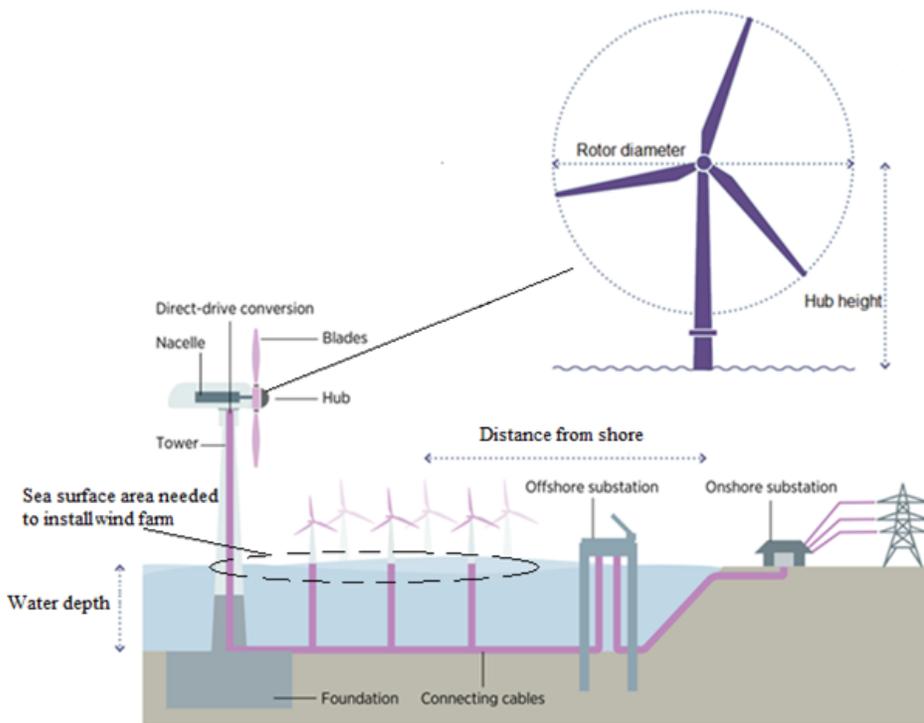


Figure 1

An offshore wind farm and turbine (IRENA 2018)

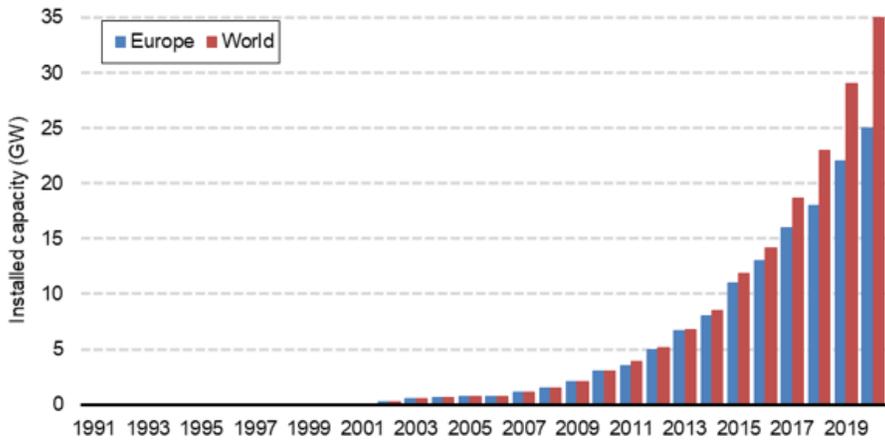


Figure 2

The change in the cumulative installed offshore wind power capacity in the world

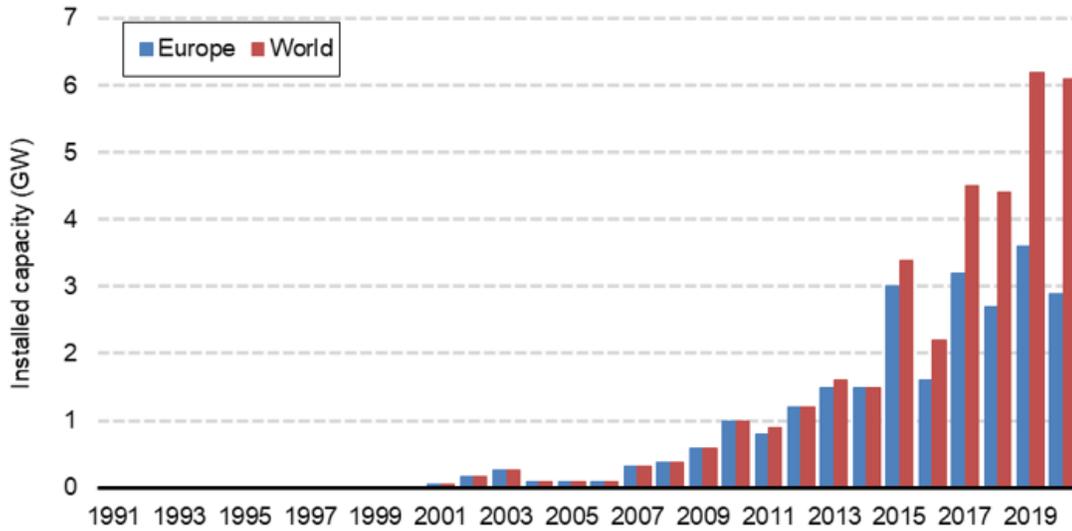


Figure 3

The change in the yearly installed offshore wind power capacity in the world

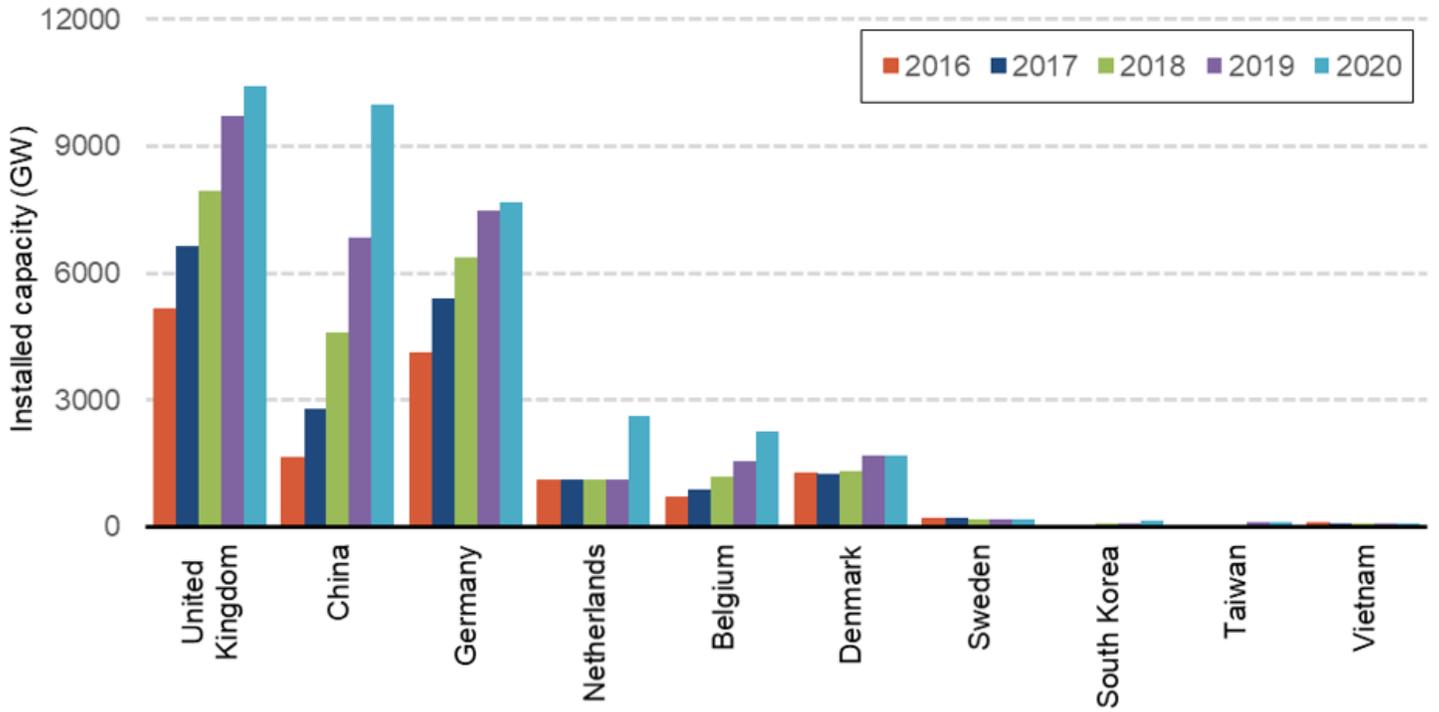


Figure 4

The top 10 offshore wind markets in total installation capacity

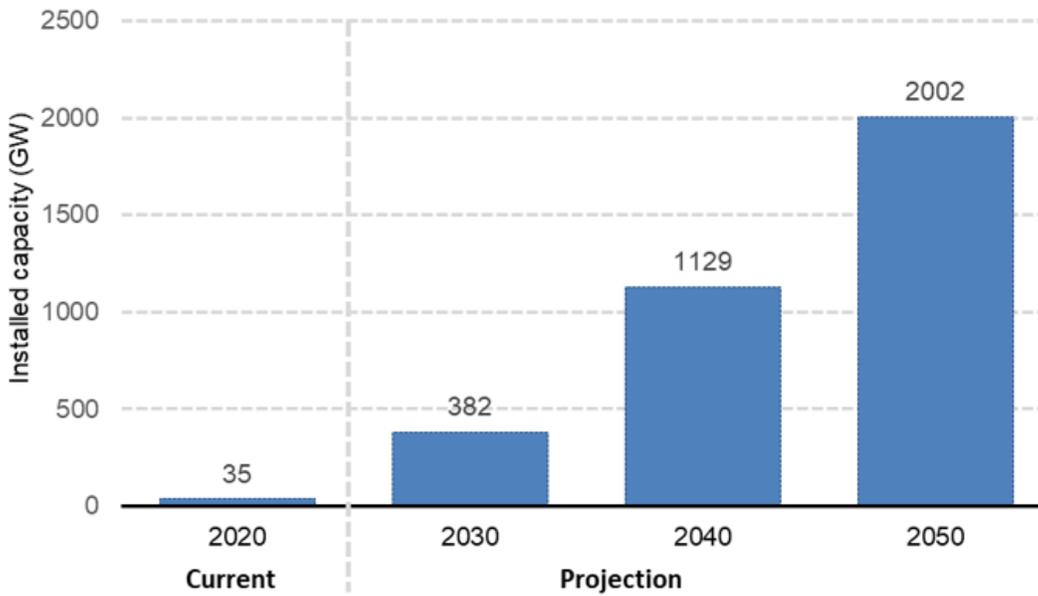


Figure 5

Offshore wind current and projected capacity, 2020-2050

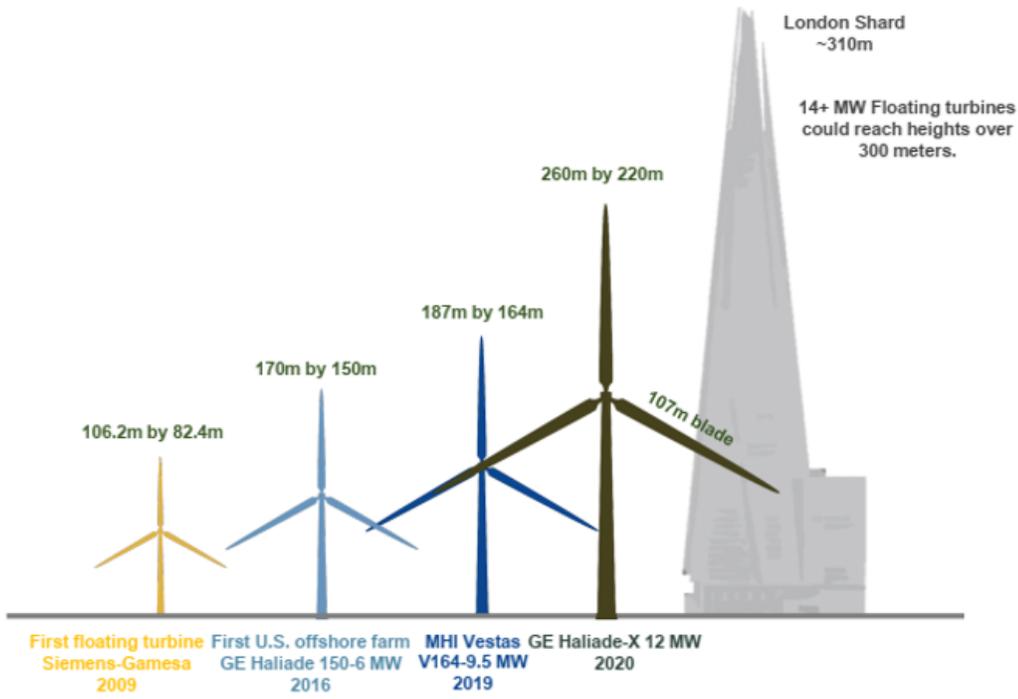


Figure 6

Global growth in the nominal capacity and size of wind turbines (Quest Floating Wind Energy 2021)

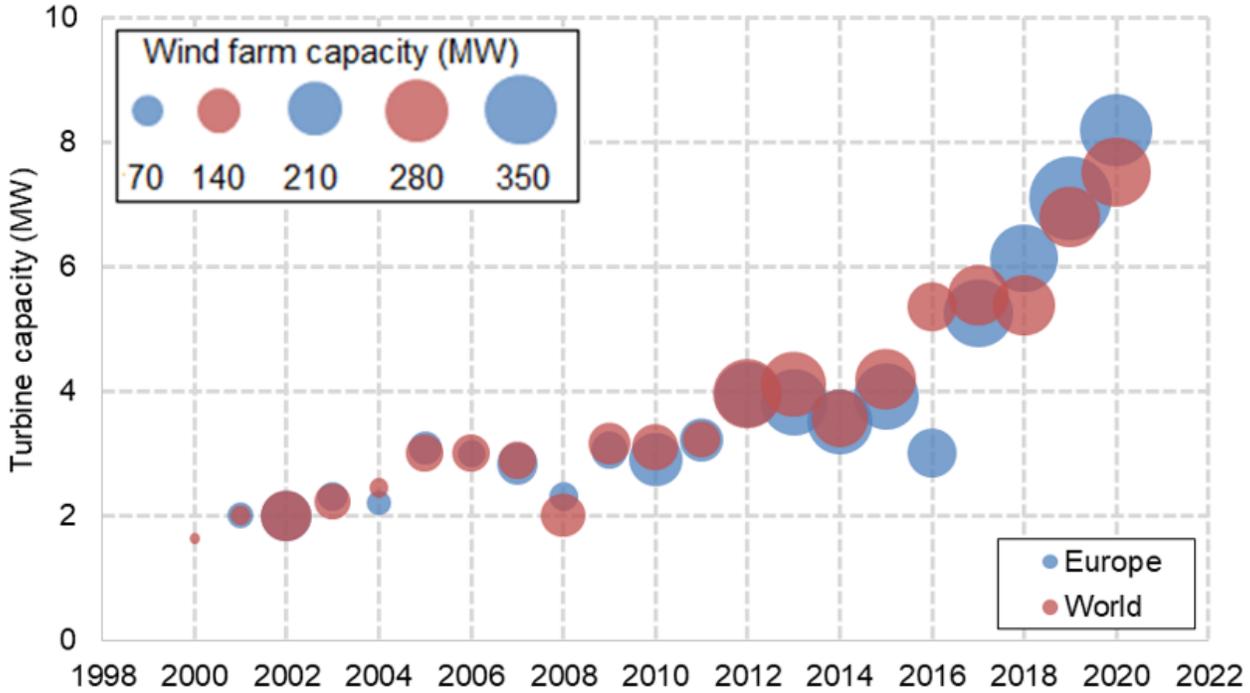


Figure 7

The evolution of offshore wind turbines over time

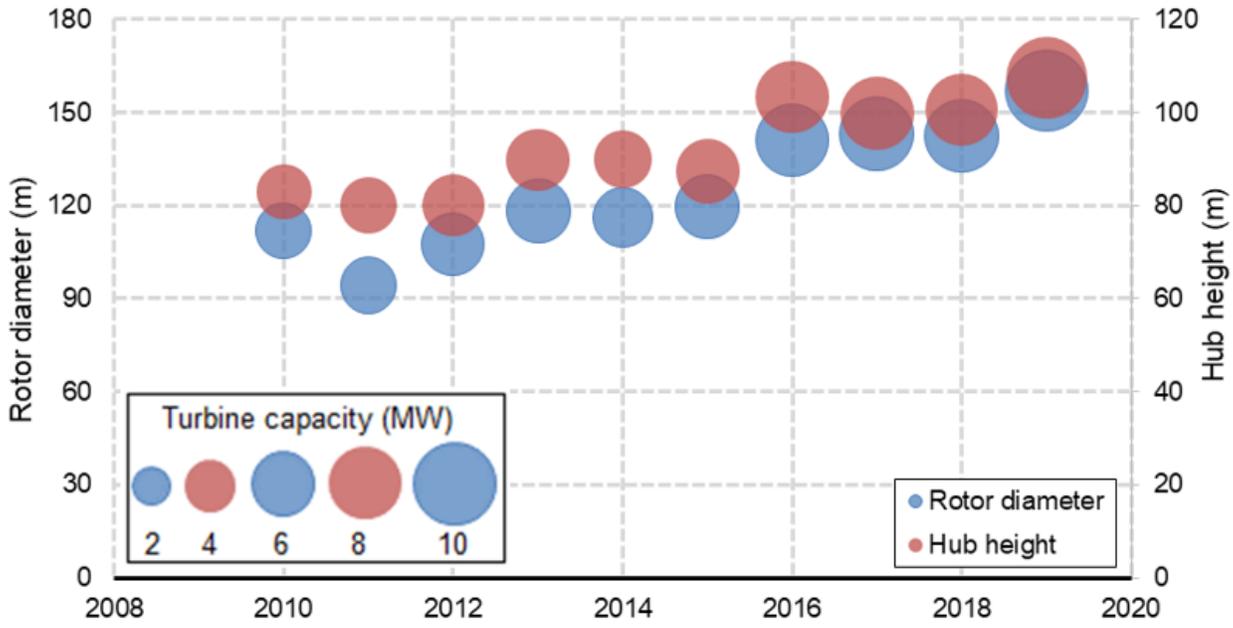


Figure 8

The change in the global weighted-average turbine size for offshore wind

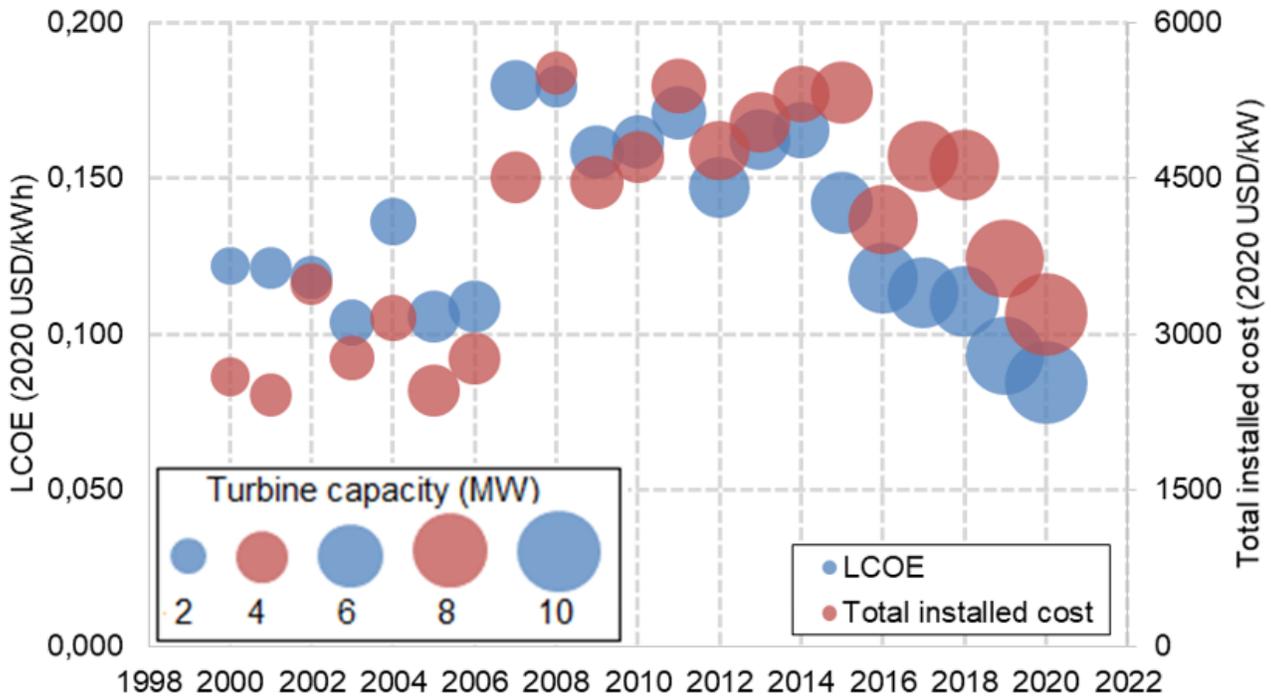


Figure 9

The changes in the global weighted average LCOE and TIC for offshore wind

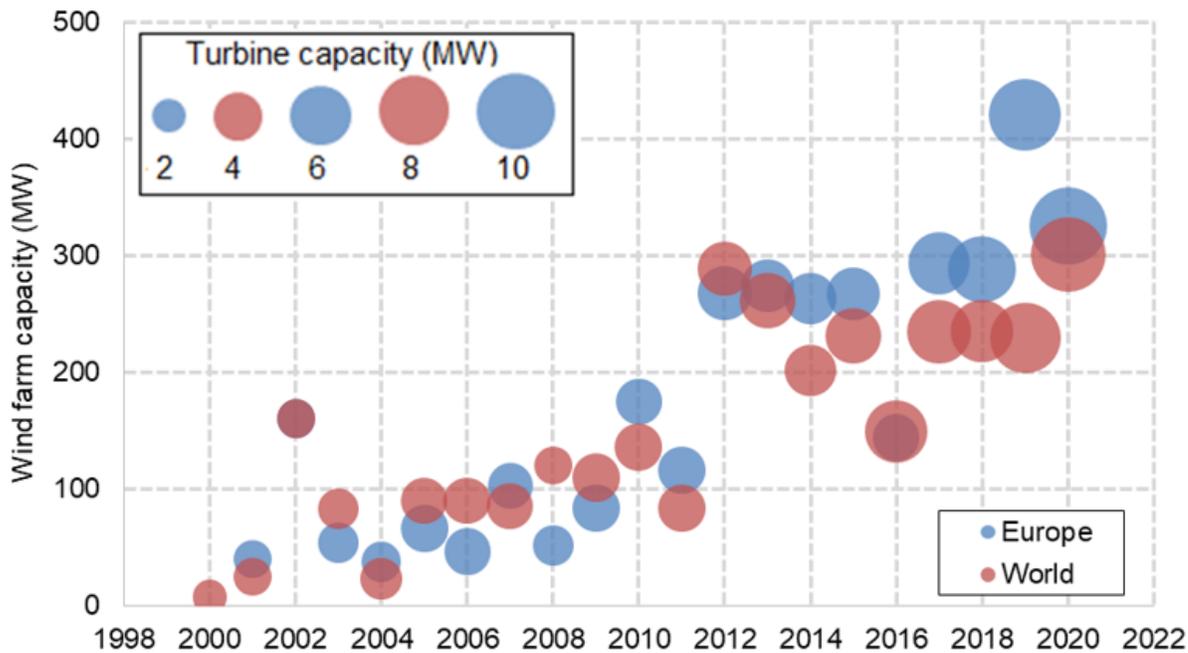


Figure 10

The change in the global weighted average wind farm capacity for offshore wind

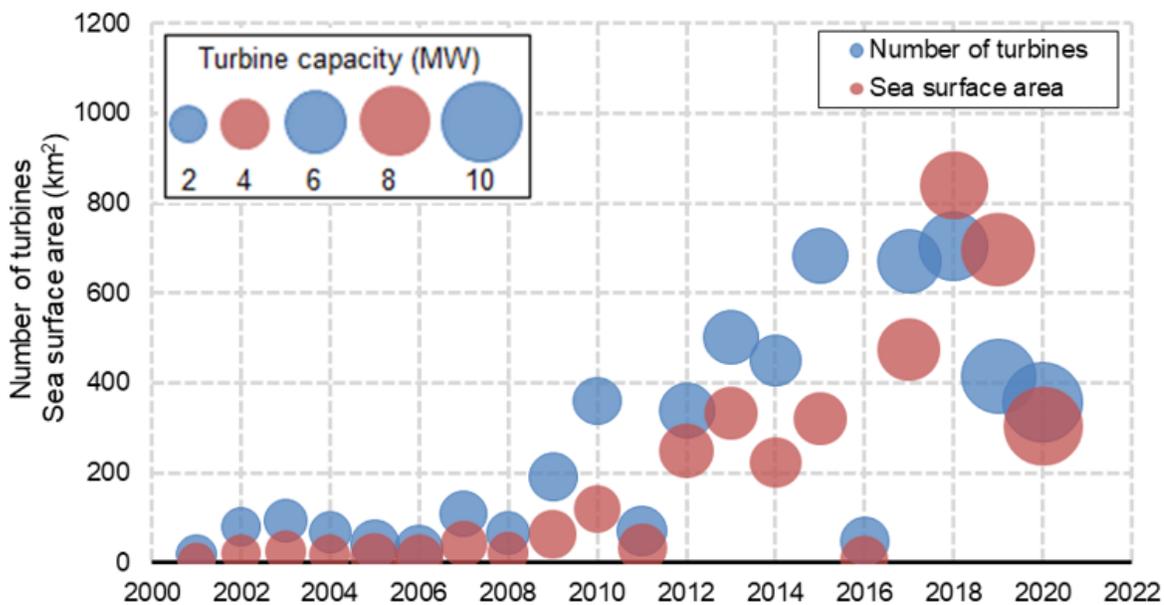


Figure 11

The evolution of the number of wind turbines, and sea surface area needed to install offshore wind farms in Europe over time

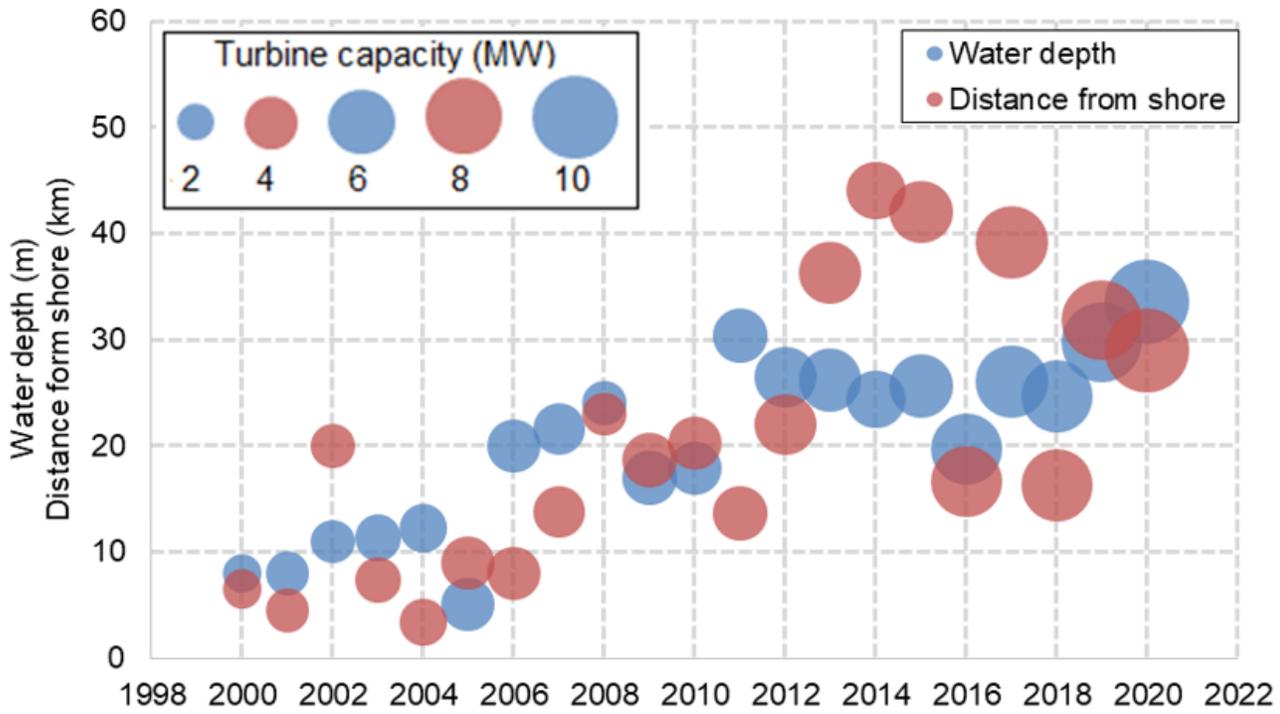


Figure 12

The evolutions of the global weighted average water depth and distance from shore for offshore wind over time

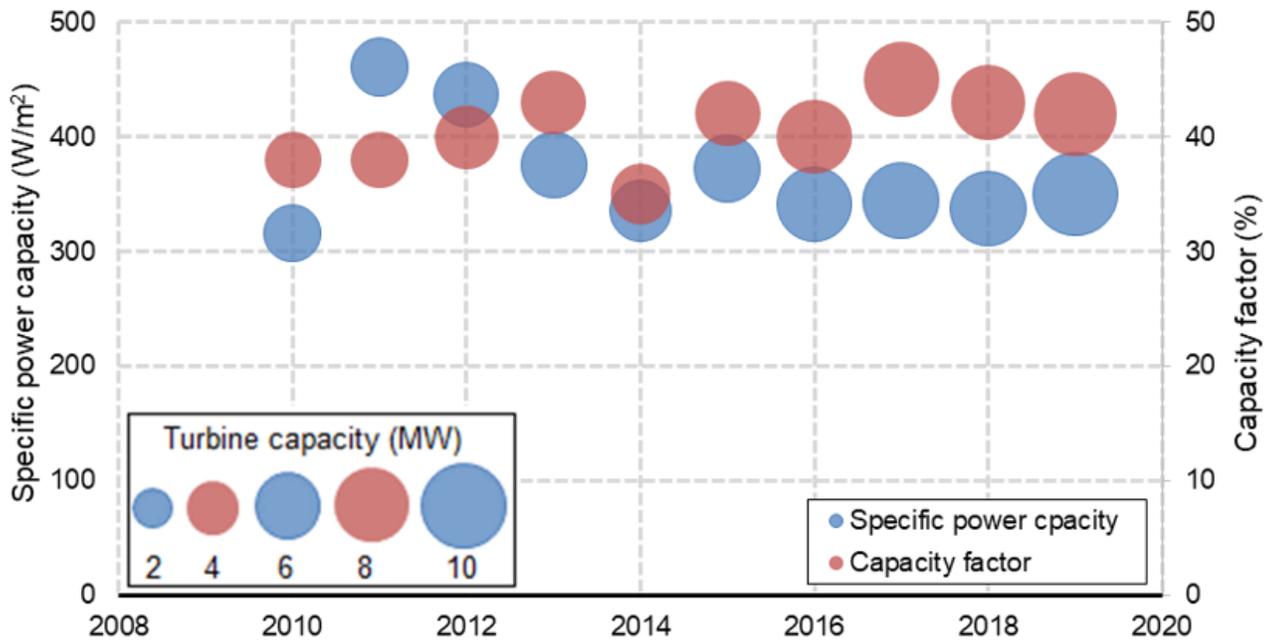


Figure 13

The evolutions of the global weighted average capacity factor and specific power capacity for offshore wind over time

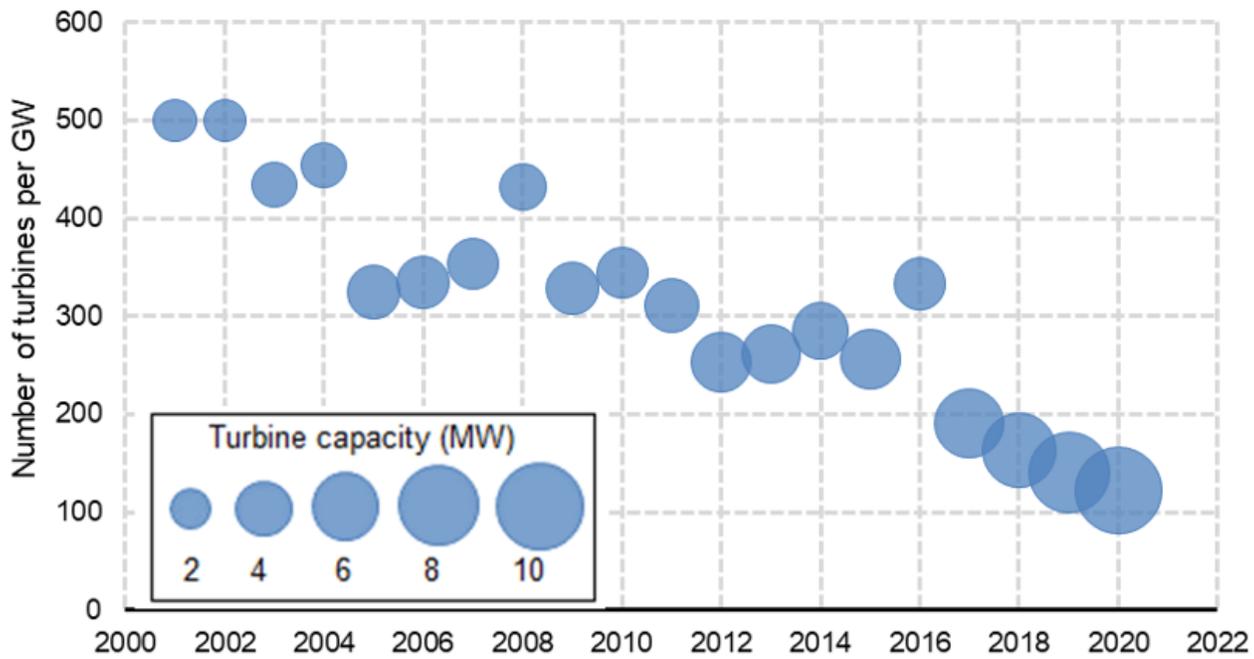


Figure 14

The decrease in the number of turbines per GW between 2001 and 2020 in Europe

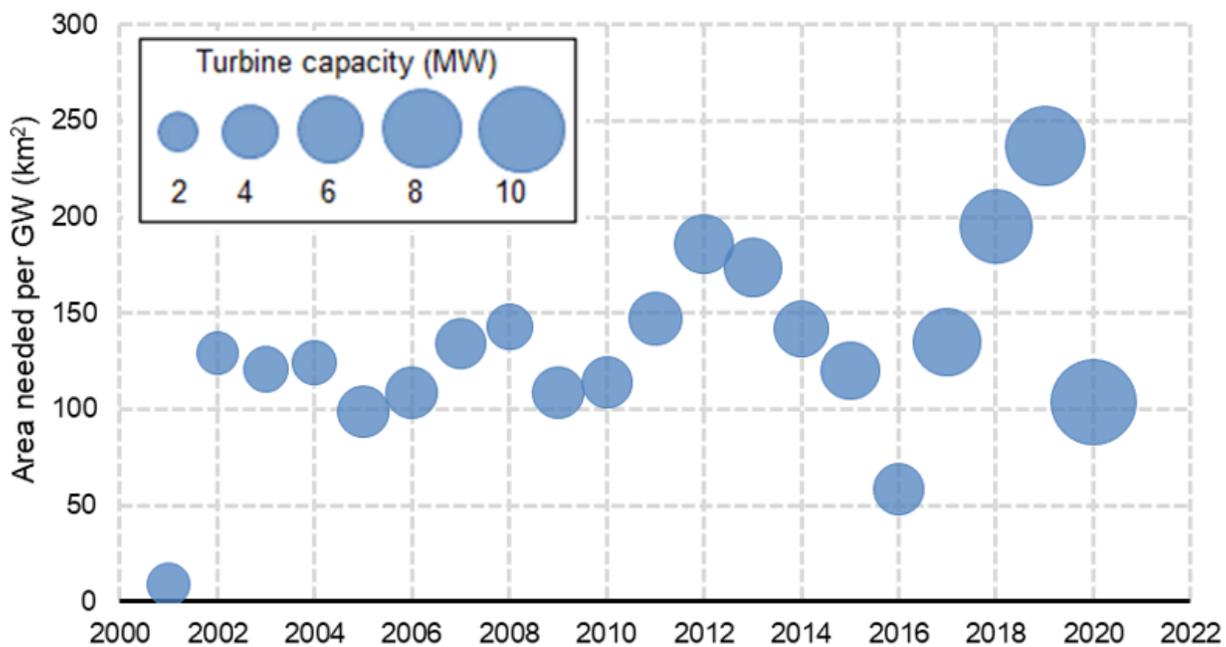


Figure 15

The change in the area needed per GW between 2001 and 2020 in Europe

Supplementary Files

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