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Comparative Analysis of Global Onshore and Offshore Wind Energy Characteristics and Potentials

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Abstract: Wind energy, which generates zero emissions, is an environmentally friendly alternative to conventional electricity generation. For this reason, wind energy is a very popular topic, and there are many studies on this subject. Previous studies have often focused on onshore or offshore installations, lacking comprehensive comparisons and often not accounting for technological advancements and their impact on cost and efficiency. This study addresses these gaps by comparing onshore and offshore wind turbines worldwide in terms of installed capacity, levelized cost of electricity (LCOE), total installed cost (TIC), capacity factor (CF), turbine capacity, hub height, and rotor diameter. Results show that onshore wind power capacity constituted 98.49% in 2010, 97.23% in 2015, and 92.9% in 2022 of the world's total cumulative installed wind power capacity. Offshore wind capacity has increased yearly due to advantages like stronger, more stable winds and easier installation of large turbine components. LCOE for onshore wind farms decreased from 0.1021 USD/kWh in 2010 to 0.0331 USD/kWh in 2021, while offshore LCOE decreased from 0.1879 USD/kWh in 2010 to 0.0752 USD/kWh in 2021. By 2050, wind energy will contribute to 35% of the global electricity production. This study overcomes previous limitations by providing a comprehensive and updated comparison that incorporates recent technological advancements and market trends to better inform future energy policies and investments.

Keywords: offshore wind energy; onshore wind energy; renewable energy; wind characteristics; wind turbine

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1. Introduction

Wind energy has distinguished itself among various renewable energy sources (RESs) due to its notable advantages of reliability, safety, and lack of pollution [1,2]. In general, the winds blowing across the Earth can be categorized into two main types: onshore winds and offshore winds, thereby making wind power generation consist of onshore and offshore wind farms. There are a wide variety of studies in the literature related to onshore wind turbines [3,4] and offshore wind turbines [5,6]. In 2022, an additional wind energy capacity of 77.6 GW was integrated into global energy networks, increasing the total installed wind energy capacity to 906 GW, representing an increase of 9% compared to 2021 [7]. The onshore wind energy installed capacity added to the total global installed production in 2022 reached 68.8 GW, contributing to the total global onshore wind energy installed capacity reaching 842 GW with an annual increase of 8.8%. In addition, last year, 8.8 GW of new offshore wind power installed capacity was added to the grid, bringing worldwide offshore wind power installed capacity to 64.3 GW by the end of 2022 [8]. Global Wind

Energy Council (GWEC) anticipates that 680 GW of wind power will be added worldwide between 2023 and 2027, with offshore wind power installed capacity accounting for 130 GW of this total. China is going to continue to lead installations for onshore wind power with an installed capacity of 300 GW, followed by Europe with an installed capacity of almost 100 GW. Offshore wind power will play an increasingly significant role in the world, with over 60 GW of installed capacity added between 2023 and 2025 and over 68 GW between 2026 and 2027 [9].

Ozato et al. [10] calculated the stochastic LCOE for five points on the Brazilian coast and concluded that the northeastern part of Brazil is the most competitive location for offshore wind farms in terms of wind energy production. Yildirim [11] conducted a techno-economic analysis of three different regions in Türkiye. In his study, the LCOE values varied between $81.4/MWh and $104.4/MWh. Pao et al. [12] created an aero-structural-control co-design process that resulted in a 25% decrease in the LCOE. Feng and Shen [13] optimized an offshore wind farm in Denmark, taking a variety of wind turbines with various hub heights into account to minimize the LCOE. According to Wang and Prinn [14], a significant portion of the world's energy needs could be met by massive offshore wind energy. However, this would result in a small (0.2 °C) cooling of the ocean's surface where wind farms are located. Karipoğlu et al. [15] used Multi-Criteria Decision-Making (MCDM) and Geographical Information Systems (GIS) guidance to assess the feasibility of a desired offshore wind farm for Türkiye's coastal area. Bahaj et al. [16] utilized a cost-effective technique for offshore wind farm planning in the Arabian Peninsula by combining GIS, representative cost ratio (RCR), and analytic hierarchy process (AHP). Consequently, numerous assessments of offshore wind energy potential have been conducted globally, and these studies are documented in the literature. Some of these evaluations focus on specific regions, including Europe [17], Africa [18], China [19,20], and the U.S. [21,22], India [23], Brazil [24], Japan [25], and the entire world [26].

In recent years, especially with the popularity of offshore wind energy, countries such as Türkiye, Vietnam, South Korea, and Brazil have conducted several studies to access this abundant resource they have [27]. Park and Kim [28] examined the potential of offshore wind energy in South Korea, focusing on a review of government policies and support programs and an analysis of offshore resources in particular. Do et al. [29] conducted a survey of 39 experts from research institutions, civil society, government agencies, and industry regarding key barriers and solutions to the development of the offshore sector in Vietnam. Yildirim et al. [30] outlined the necessary political and economic measures that should be taken to facilitate the development of offshore wind power in Türkiye. The deployment of floating turbines represents a significant advancement in the offshore wind turbine industry. Unlike traditional turbines that need to be placed where the seafloor topography is suitable, floating turbines can be positioned where winds are strongest and most consistent, potentially expanding economically viable areas for offshore wind power. In 2017, Statoil's 30 MW Hywind Scotland project, the first commercial floating wind farm, became operational close to the cost of Aberdeen. Despite this milestone, the floating sector still faces challenges, such as narrowing the spectrum of possible platform designs and establishing an efficient supply chain. Nevertheless, there is a growing pipeline of projects in Europe and plans for projects worldwide, indicating that floating turbines move beyond the demonstration stage and attract investment [31]. To realize the full potential of floating offshore wind technology, a reliable and sustainable supply chain will be necessary. This technology has already proven to be economically sustainable and attractive. No winner design has yet been chosen because there are still several distinct concepts in competition. To enable the industry to obtain the best solutions that match its needs, there must be substantial research assistance and support [32]. Huang et al. [33] investigated locations with high potential for onshore wind turbines and estimated the wind energy capacity of China.

Vieira et al. [34] aimed to assess the financial and economic viability of Portugal's existing onshore wind farms using publicly available data. They found that onshore

wind projects in Portugal do not show exceptional profits based on estimated farm yield, investment costs, and established feed-in tariffs. Huang et al. [33] investigated locations with high potential for onshore wind turbines and predicted China's wind power capacity. They also examined the impact of resource use by a 100-year-old wind turbine farm on the reduction of CO_2 emissions, land cover, materials used, and labor required. Karamountzou and Vagiona [35] developed and presented a methodological framework for spatial analysis, as well as an evaluation of the suitability and sustainability of Greece's existing wind farms. The study found that 81.4% of the existing wind farms are located in suitable areas. Tu et al. [36] developed an integrated method to assess the cost-competitiveness and grid parity potential of China's onshore wind power at fine spatial resolution using updated parameters. The results indicate that the overall onshore wind energy potential is 54.0 PWh. Wind power's average levelized cost is expected to fall from CNY 0.39 per kWh in 2020 to CNY 0.30 and 0.21 per kWh in 2030 and 2060, respectively. In 2020, 2030, and 2060, 28.3%, 67.6%, and 97.6% of the technical potentials will keep power costs lower than coal. Tu et al. [36] used data from 2006 to 2015 to evaluate the learning rate of Chinese onshore wind power and projected that the LCOE of wind power would decrease to CNY 0.34 kWh^{-1} in 2025. Considering this, China's real LCOE for onshore wind has decreased by 48% in the past ten years. Feng and Wencheng [37] proposed a method for predicting onshore wind power costs (LSSA-BP) using an improved sparrow algorithm-optimized neural network. When compared to a single manual estimation of costs method, the LSSA-BP forecasting method can be utilized for more reasonable and scientific onshore wind power cost forecasting, reducing the deviation caused by human subjective factors. Diogenes et al. [38] provided a systematic review of barriers to the implementation of large-scale onshore wind farms, analyzing them by economic context, location, level of onshore wind energy diffusion, and impact. They discovered that three of the most commonly noticed barriers were unsupportive and uncertain government policies, insufficient consideration of externalities, and an inadequate transmission grid. Chen et al. [39] analyzed the grid parity of onshore wind generators in the near future and stated that it is not easy to achieve the grid parity of existing onshore wind generators. To use wind energy more effectively and at a higher capacity, the cost of one unit of electrical energy must be further reduced.

According to the U.S. Department of Energy (DOE), offshore wind turbines are presently estimated to be 1.5 times costlier than onshore turbines of similar size [40]. Koch and Jacobsen [41] utilized three different methods to estimate the LCOE of 12 GW onshore and offshore wind power capacity in Denmark. According to them, when evaluating significant increases in wind capacity and taking high estimates into account for nationwide acceptance costs, it is not evident that onshore wind has a distinct cost advantage over offshore wind. They stated that expanding onshore wind moderately and considering only local acceptance factors did not yield a cost advantage. Li and Yu [42] presented a detailed investigation, including statistical analysis of the onshore, nearshore, and offshore wind energy potential in Lake Erie near Cleveland, Ohio. Statistical wind evaluations encompass parameters such as the Weibull shape and scale factors, wind power density, and turbulence intensity. According to the results of this study, offshore locations are expected to generate a minimum of 1.7 times the energy output compared to onshore and nearshore sites. Moreover, offshore wind turbines have the potential to generate a higher power output during peak hours in both spring and winter. This shows that offshore wind turbines provide benefits over their onshore counterparts in Lake Erie. Li et al. [43] presented a comparative assessment of the onshore and offshore wind energy characteristics and their potential in the southeast coastal region of China by considering wind records acquired from onshore and offshore wind measurement towers. They revealed that offshore wind energy is more consistent and readily accessible than onshore wind energy in the southeast coastal region. To ensure economic viability and achieve optimal annual energy production, it is advisable to select hub heights of 70 m for the onshore site and 40 m for the offshore site for the selected wind turbine.

Although onshore wind remains the primary source of wind power generation in China [43], it is worth noting that offshore wind energy is poised for significant growth in the future [20,44]. The European wind energy sector is projected to employ over 375,000 individuals by the year 2030, with 160,000 working onshore and 215,000 offshore [27]. According to Enevoldsen and Valentine [45], offshore wind farms have much more widely spaced turbines and larger equipment and produce much more power than onshore wind farms. In addition, the authors contend that an onshore project near a forest area may be a better option if onshore areas are limited and offshore costs are prohibitively high. Kaldellis et al. [46] examined published research to assess the environmental impact of offshore wind energy and compare it to onshore wind energy operations. The authors posited three key conclusions. First, the social and environmental effects of offshore wind energy are not well understood. Second, there is no clear evidence that offshore wind energy is more beneficial to fauna and flora than onshore wind energy projects. Finally, environmental impacts and energy production efficiency are affected by the development of new materials, technologies, and construction techniques. Shafiee and Dinmohammadi [47] created a mathematical tool for failure and risk mode analysis of onshore and offshore wind turbine systems based on three key factors: incurred failure costs, failure probability, and fault detection possibility. The authors revealed that their methodology improved safety and could reduce operational risks associated with unexpected failures in wind farms. Sovacool et al. [48] examined the risk of cost overruns and underruns in the construction of 51 onshore and offshore wind farms in 13 countries, completed between 2000 and 2015 [49]. There is evidence that the risk increases for larger wind farms located farther offshore and those that use new types of turbines and foundations. Onshore wind farm industries have harvested more wind power for several decades and are a mature alternative for maximizing wind power generation. Offshore wind power harvesting, on the other hand, is currently receiving increasing recognition due to its reliability and robust wind speeds, insignificant harm to the surroundings, limited constraints on the dimension of wind power conversion systems, etc. Barzehkar et al. [50] addressed the selection of suitable sites for offshore wind power plants in the Baltic Sea, utilizing various decision support tools. They found that suitable sites are mainly nearshore in shallow waters, especially in the southwest Baltic Sea. Khan et al. [51] aimed to provide a comprehensive review of existing control strategies for frequency regulation (FS) in the AC grid by offshore wind power plants and voltage source converter stations in the multi-terminal high voltage direct current system. In their study, different FS control topologies were compared, and potential gaps and future directions were provided. Offshore wind power conversion technologies, as opposed to onshore wind power conversion technologies, must be built on the seabed, necessitating an even more robust bearing structure [52]. Nonconventional cables must be used for the transmission of electric power, and exceptional equipment is needed for maintenance and installation activities. When compared to the cost of deploying wind power onshore, these issues significantly increase the cost of offshore wind generation [53]. Furthermore, compared to onshore wind farms, offshore wind turbine construction is a more expensive undertaking. Additionally, costs will differ significantly based on the location because of factors like water depth, sea conditions, and distance to the coast [41]. Offshore power generation can have both positive and negative impacts on marine ecosystems. Negative impacts have been reported more frequently, with a focus on marine mammals, birds, and ecosystem structures. Positive impacts are less common and mostly relate to fish and macroinvertebrates [54]. Onshore wind farms are known to have more negative environmental impacts (noise and visual impacts, ecological environment, and destruction of wildlife) and elicit a stronger response from residents. In conclusion, while onshore wind farms have cost less than offshore wind farms, their negative environmental impact has been identified as a concern [55].

2. Significance and Novelty of the Study

The objective of this research is to gain new insights into the existing literature and offer valuable insights to turbine manufacturers and government policies by presenting and comparing comprehensive characteristics of onshore and offshore wind technologies in the world [56]. To the best of the authors' observation, although it is possible to observe a few comparison studies between onshore and offshore installed wind technologies in terms of cost analysis [41], spatial and temporal analysis of wind energy potential near Lake Erie shoreline [42], and characteristics and potentials of wind energy in the southeast coastal region of China [43]. There is no worldwide comparison study in the literature that includes a comprehensive analysis regarding installed capacity, TIC, LCOE, capacity factor (CF), turbine capacity, rotor diameter, and hub height. So, for that reason, this study will be the first detailed comparison study between onshore and offshore installed wind farms in the literature. Since there is no such study in the literature, it is thought that the study is quite original and will contribute greatly to energy companies, country governments, and researchers. Technological knowledge about onshore and offshore installed wind turbines for the world, in general, can be simply obtained from different international energy reports such as "European Wind Energy Association [57], International Energy Agency [58], Global Wind Energy Council [8,27], International Renewable Energy Agency [59–64], REN21 [31,65], 4C Offshore [66] and BP Statistical Review of World Energy [67]".

However, the presented data are generally of a reporting nature. In this regard, acquiring, defining, and calculating this information is highly significant within certain academic disciplines, enabling a thorough analysis of its impact on various parameters. Therefore, within the scope of this study, technological data regarding onshore and offshore wind turbines installed in the world were acquired, and then these data were defined within specific academic contexts and historically elucidated its effects. The novelty and primary objectives of this study are briefly explained as follows:

- To examine and compare the growth and effects of larger rotor diameters and higher hub heights on onshore and offshore installed wind farms.
- To analyze and compare the effects of these increments in size on turbine capacity in onshore and offshore installed wind farms.
- To observe and compare the influences of this growth in wind turbine size and turbine capacity on the LCOE, TIC, and CF in onshore and offshore installed wind farms.

3. Materials and Method

The energy found in the wind is mostly the kinetic energy of the vast amount of air over the surface of the globe [68]. For wind, the mass of air passing through a certain area for a certain period of time is taken into account [69]. Where ρ, A, v, and t are the density of air (kg/m^3), the turbine swept area (m^2), the wind speed (m/s), and the time, respectively. The following equation [70], which provides the available power, is the kinetic energy divided by the required time:

$$P = \frac{1}{2}\rho A v^3 \tag{1}$$

This equation shows that the power available from the wind increases with the cube of the wind speed, making higher wind speeds particularly valuable for wind energy production [71]. The output of electrical power can be expressed as [72]:

$$P_e = PC_p\eta_m\eta_g \tag{2}$$

$$C_p = 4a(1-a)^2 \tag{3}$$

Here, C_p is the turbine performance coefficient, which is a function of the pitch angle and tip speed ratio. The power coefficient C_p is calculated using Equation (3), where a denotes the flow induction factor. The Betz limit, which is the greatest value of C_p, is

theoretically determined to be 0.59. By modifying the turbine rotational speed under the wind speed, the variable wind speed turbine can monitor the maximum C_p. The generator's efficiency is symbolized as η_g, and the efficiency of the mechanical transmission is denoted as η_m.

The capacity factor (CF) is important for determining the best turbine site match. It reflects the turbine's ability to harness the energy contained in the moving air. It also serves as an important metric for determining the financial viability of a wind project. The ratio of the average output power, $P_{avg,}$ of a wind turbine for a certain period to its potential output, if operated at rated capacity for the entire period, is known as the CF of the turbine. P_r is the rated power capacity of the turbine [42]. This calculation can be expressed in the following manner [73]:

$$CF = \frac{P_{avg}}{P_r} \tag{4}$$

The total installed cost (TIC) and LCOE are both important concepts in the energy sector [74]. LCOE is a metric used to assess and compare the cost-effectiveness of different energy generation sources over their operational lifetime. It represents the average cost per unit of electricity generated over the plant's lifetime, taking into account all costs (capital, operations, maintenance, etc.) and expected energy production. The large capacity increase necessitates a substantial financial outlay for the installation and selection of the appropriate storage to control the excess power produced and to sustain times when wind is not available. Given the critical role that energy storage plays in facilitating the integration of wind power, the additional cost of energy storage should be included in the LCOE calculation to provide a more realistic assessment of the overall costs and benefits of wind energy projects.

For the wind energy LCOE calculation, first, the components need to be identified [75]. These components are Operational Expenditure (OPEX), Annual Energy Production (AEP), and Capital Expenditure (CAPEX). Discount Rate (r) and Lifetime (n). CAPEX is the upfront cost of constructing a wind farm [76]. OPEX is the ongoing maintenance and operational cost [10]. AEP is the amount of energy the wind farm is expected to produce each year [43]. A discount rate expresses the rate used to discount future cash flows to the present value. Lifetime indicates the operational lifetime of the wind farm, usually in years [77]. Second, annualized capital costs are calculated [78]. Capital costs are annualized using the annuity factor, which is calculated as follows:

$$\text{Annuity Factor} = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{5}$$

Later, the annualized capital cost (ACC) is calculated as [79]

$$\text{ACC} = \text{CAPEX} \times \text{Annuity Factor} \tag{6}$$

Annual operational costs (OPEX) are simply the ongoing costs of operating a wind farm. The annualized capital costs and annual operating costs add up to the total annual cost [10]. This term is calculated as

$$\text{Total Annual Cost} = \text{ACC} + \text{OPEX} \tag{7}$$

The annual energy production (AEP) can be estimated based on the wind farm's capacity factor and total installed capacity [80].

$$\text{AEP} = \text{Capacity} \times \text{Capacity Factor} \times \text{Hours per Year} \tag{8}$$

Finally, the LCOE is calculated by dividing the total annual cost by the annual energy production [81]:

$$\text{LCOE} = \frac{\text{Total Annual Cost}}{AEP} \tag{9}$$

TIC is calculated by referencing relevant cost factors acquired from the existing literature. TIC for a wind energy project includes all the costs associated with bringing the wind farm to operation. These costs can be broken down into several categories, such as turbine costs, balance of plant (BoP), soft costs, and contingency [82]. The turbine costs include the cost of the wind turbine itself (nacelle, rotor blades, tower) and the total number of turbines in the wind farm. To determine the balance of plant (BoP) cost, foundation costs (costs related to the foundations for the turbines), electrical infrastructure (costs for electrical systems, including cabling, substations, and grid connection), and civil works (costs for access roads, buildings, and other infrastructure) are considered. Soft costs include permitting and environmental studies (costs for obtaining permits and conducting environmental impact assessments), development costs (costs related to project planning and development, such as land acquisition and legal fees), and insurance and financing costs (costs for insurance, financing fees, and interest during construction). Finally, contingency refers to emergency or contingency funds to pay for unforeseen costs and budget overruns. TIC calculation for wind energy is explained below [76].

$$\text{TIC} = (\text{Cost per Turbine} \times \text{Number of Turbines}) + \text{BoP Costs} + \text{Soft Costs} + \text{Contingency} \quad (10)$$

The rotor swept area is calculated employing Equation (11). Then, the rotor diameter can be easily found using the rotor swept area, as is clear in Equation (12) [83].

$$A = \frac{2P_e}{\rho v^3 C_p \eta_m \eta_g} \quad (11)$$

$$D_r = \sqrt{\frac{4A}{\pi}} \quad (12)$$

The data presented in the Figures in this study were obtained from referenced reports [58,60,63,65]. In addition, the data presented in the tables in this study were obtained from referenced reports [60,62,64]. The technical and technological parameters in these references were collected and calculated over the years. Figures 1 and 2 present the particular specifications of offshore and onshore wind farms and turbines.

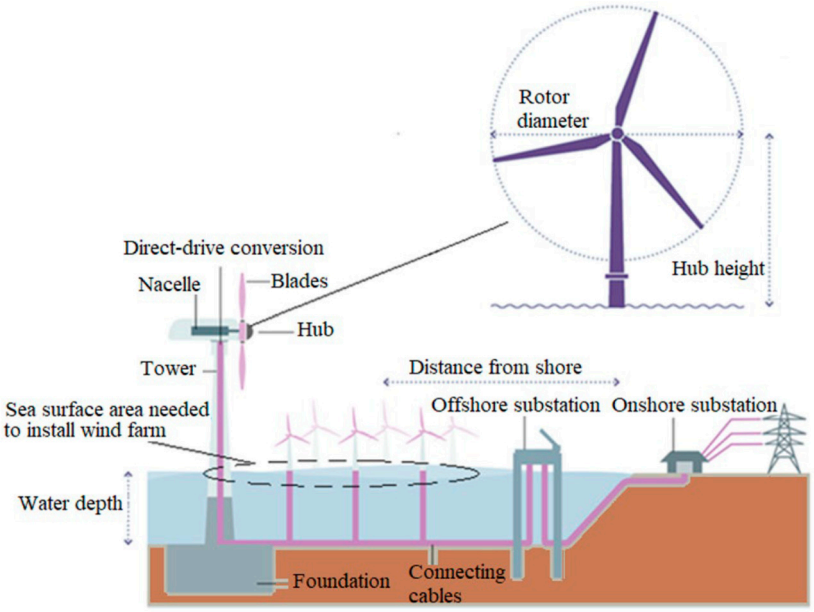


Figure 1. Particular specifications of an offshore wind farm and turbine [84].

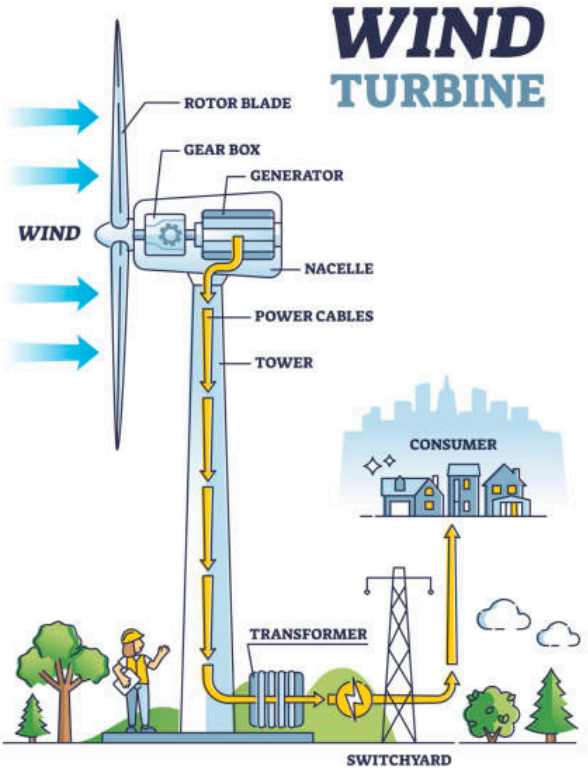


Figure 2. Particular specifications of an onshore wind farm and turbine [85].

- Installed capacity (GW)
- TIC (2022 USD/kW)
- LCOE (2021 USD/kWh)
- Capacity factor (CF) (%)
- Hub height (m)
- Turbine capacity (MW)
- Rotor diameter (m)

4. Results and Discussion

4.1. Installed Wind Power Capacity

The shares of global electricity production in the world's electric power plants for the years 2011, 2012, 2021, and 2022 are demonstrated in Figure 3. According to this figure, the share of fossil fuels is observed to be higher than the share of any other power generation technology in 2022, as in other years. However, the decrease in the use of fossil fuels from 68% in 2011 to 62% in 2022 and the increase in the use of renewable energy sources from 20.4% in 2011 to 29.9% in 2022 is a pleasing and promising situation. This situation shows us that while the use of fossil fuels is decreasing, the world is turning to cleaner, environmentally friendly, and efficient renewable energy sources for its energy needs. Even today, thermal power plants continue to maintain their position as the most important source of electricity generation worldwide [86]. However, it is widely accepted that fossil fuel-based thermal power plants cause environmental pollution through the release of acidic gases and particulate emissions. In fact, they also play a significant role in the production of CO_2 emissions, which is a greenhouse gas responsible for global warming. From 2011 to 2022, among renewable energy sources, the remarkable increase in the share of power is the use of wind power, as its share increased from 2% to 12.1%. On the other hand, there has been no considerable change in the share of power for other electricity generation technologies in the past ten years. This makes the use of wind energy ahead of other energy production technologies today. For this reason, due to the demand of investors, wind energy technology has become one of the fastest-developing energy systems

technologies in the world and has also become the fastest-growing energy production sector in terms of investment [87]. Wind energy harvesting has experienced rapid growth both in Europe and worldwide [88]. As a result of these developments, wind power plants have a significant role in the global energy markets. According to the cumulative installed capacity of renewable energy sources between 2017 and 2022 indicated in Figure 4, the installed capacity of wind is predicted to increase from 540 GW in 2017 to 923 GW in 2022, corresponding to a percentage increase of 70% during five years. Furthermore, it is expected that the installed capacity of wind power will reach 3101 GW, 6525 GW, and 8365 GW in 2030, 2040, and 2050, respectively. For this reason, it can be said that wind energy will become one of the most important renewable energy sources in the world in the coming years. According to Aswani et al. [89], it is expected that by 2050, offshore and onshore wind energy will become the primary energy sources and contribute to 35% of the world's electricity production. In the following sections, a comparative analysis of wind turbines will be demonstrated.

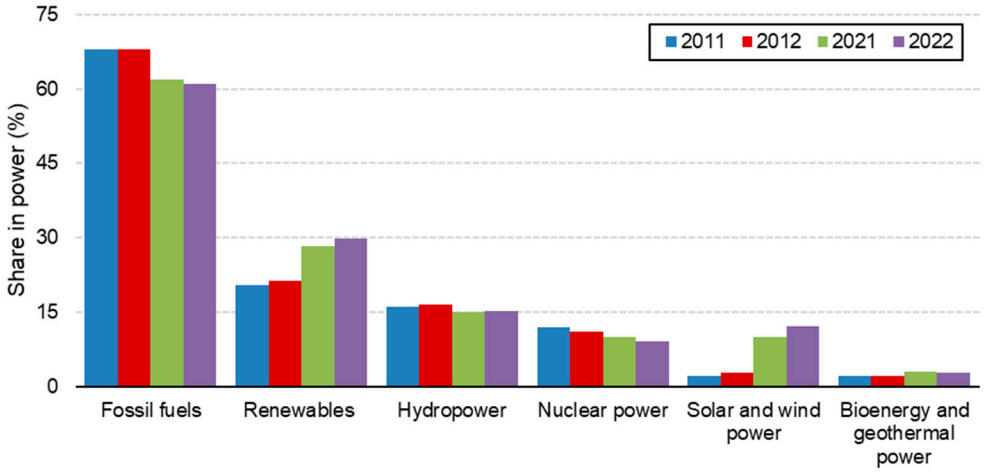


Figure 3. Share of renewable electricity Generation, by Energy Source between 2011 and 2022.

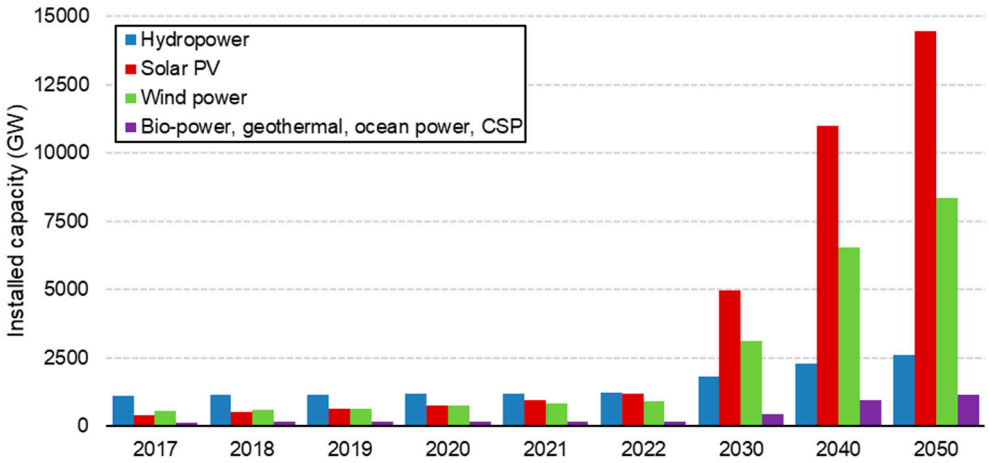


Figure 4. The cumulative installed capacity of renewable energy sources between 2017 and 2022 to achieve net zero scenarios for 2030, 2040, and 2050.

Figure 5 demonstrates the annual distribution of global onshore and offshore installed wind power capacity between the years 2010 and 2022. According to this figure, the onshore installed wind power capacity is always higher compared to offshore installed wind power capacity for the observed years. For example, in 2020, the annual onshore installed wind power capacity was 88.4 GW, while the offshore installed wind power capacity was 6.9 GW in the same year. Furthermore, 2020 is a record-breaking year for the onshore installed

wind power capacity. On the other hand, the biggest difference between the installed capacity of onshore and offshore wind turbines was observed in 2020, with a difference of 81.5 GW [77]. Onshore wind power generation has a history spanning over a thousand years, whereas offshore wind power generation is a more recent development. Additionally, the higher installation costs and the challenges posed by adverse weather conditions during construction have limited the popularity of offshore wind power technology until more recent times. However, with the development of technology and increasing efficiency of offshore installed wind power generation, problems related to the employment and efficient use of offshore wind turbines have begun to be overcome. For instance, the difference between the installed capacity of onshore and offshore wind turbines was reduced to 51.4 GW in 2021 and 60 GW in 2022. For that reason, it can be said that the popularity and employment of offshore wind turbines progressively increased over the years due to the developing technology and increasing efficiency of offshore installed wind power generation [90]. If the trend of offshore installed wind power generation is examined, an increasing trend in wind power generation can be observed year by year. The largest increase in the installed capacity of offshore wind turbines was detected in the years from 2020 to 2021, with a percentage increase of 205.8%.

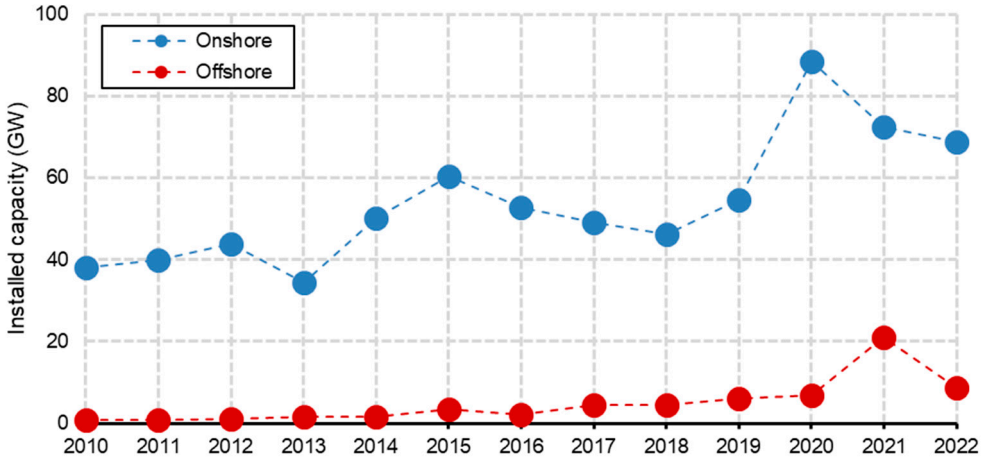


Figure 5. The progress in the annual installed capacity of onshore and offshore wind farms in the world between the years 2010 and 2022.

The cumulative onshore and offshore installed wind power capacities in the world are presented in Figure 6 for the period from 2010 to 2022. According to this figure, the cumulative onshore installed wind power capacity constitutes 98.49% in 2010, 97.23% in 2015, and 92.9% in 2022 of the world's total cumulative installed wind power capacity. Furthermore, it can be interpreted that the increment rate of the cumulative offshore installed wind power capacity is higher than the cumulative onshore installed wind power capacity for a specific year compared to the previous year. For instance, from 2019 to 2020, while the cumulative offshore installed wind power capacity increased by 24%, the increment rate was 14.17% for the cumulative onshore installed wind power capacity. This increment rate is observed as 55.56% and 9.17% for the cumulative offshore and onshore installed wind power capacities, respectively, for years from 2020 to 2021. As can be understood from the above explanations, the employment and popularity of offshore wind turbines have increased over the years. This is mainly because wind conditions are generally stronger and more consistent offshore due to the absence of obstacles such as hills, valleys, forests, and rugged terrain [91]. As a result, offshore wind turbines can achieve significantly higher production per installed unit. So, higher wind speeds, which usually increase with distance from the shore, improve the efficiency of the process. Furthermore, offshore turbines can be larger than onshore turbines because large turbine components

can be transported more easily by the sea. Because of all these reasons, the interest of companies and researchers in offshore wind turbines has increased.

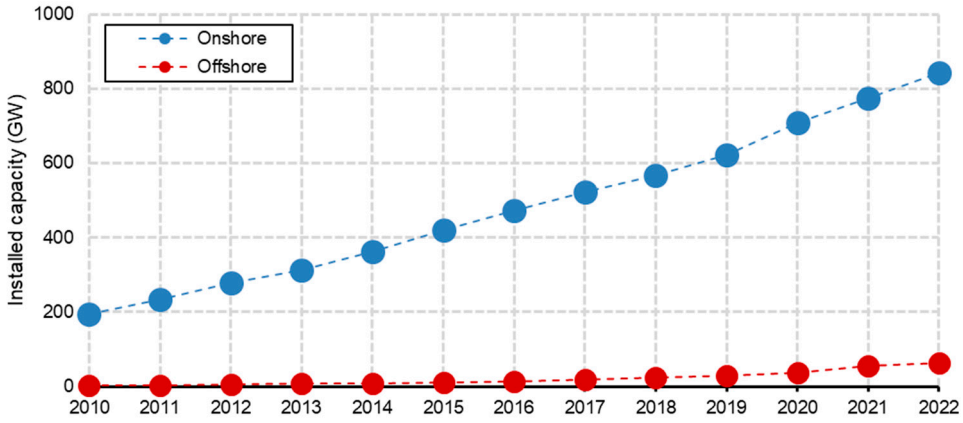


Figure 6. The progress in the cumulative installed capacity of onshore and offshore wind farms in the world between the years 2010 and 2022.

4.2. Cost Analysis

Figure 7 illustrates the fluctuations in the TIC for onshore and wind turbine farms between 2010 and 2022. According to Figure 7, while considerable changes in TIC were observed for offshore wind turbines from 2010 to 2022, the TIC of onshore wind turbines did not change remarkably during this period. Furthermore, while the TIC of offshore wind turbines is observed to be 5217 USD/kW in 2010, 5902 USD/kW in 2015, and 3483 USD/kW in 2020, the cost of onshore wind turbines has also been reduced to 2179 USD/kW in 2010, 1843 USD/kW in 2015, and 1496 USD/kW in 2020. The installation costs of offshore wind farms reached their peak in 2011. This increase can be attributed to several reasons, including the fact that offshore wind turbine installations are located further from the coast, in deeper seawaters, and involve more advanced technological equipment with higher installed capacity. Unlike onshore wind facilities, offshore wind farms have become more expensive to install due to these factors. Construction timelines have been significantly extended because of the challenges posed by harsh marine environments. Additionally, the project development, planning, and construction processes for offshore wind farms are more complex compared to onshore wind turbine installations [92]. The need for more construction details and, hence, longer lead times further increases TIC. Moreover, the offshore location of this type of project results in higher construction and grid connectivity costs. However, in Figure 3, it is clear that the TIC of offshore wind farms has continuously reduced in recent years, especially from 2017 to 2021. For instance, while TIC is observed to be 5249 USD/kW in 2017, the cost of onshore wind turbines is reduced to 3052 USD/kW in 2021, representing a reduction of 42% in comparison to the previous year. Furthermore, the differences in TIC between offshore and onshore wind farms are observed to have reduced over the years. For example, the disparity between the two values was equivalent to 3400 USD/kW in 2017 and reduced to 1634 USD/kW in 2021. Here, cost savings of offshore installed wind farms have been achieved due to various factors, including the standardization of turbine and foundation designs, growth in industry experience, localization of offshore wind farm component production at regional hubs, and simplification of installation methods [40]. Costs per unit capacity and installation times have declined due to the accumulated experience of turbine manufacturers and plant installers, the use of vessels specially designed for offshore wind farm projects, and the adoption of larger turbines that amortize installation efforts over higher capacities. Furthermore, advancements in offshore wind farm installations, such as deploying them in deeper and more remote offshore locations, have expanded the global wind power potential. There is also a trend toward constructing taller towers, using larger rotor diameters, incorporating more efficient and durable blades, using composite materials to reduce weight, and hence building higher

capacity turbines. In conclusion, with technological developments, turbines specifically designed for offshore applications can capture more energy, which has played a pivotal role in reducing the LCOE, in other words, a specific cost of one unit of energy in offshore wind farms.

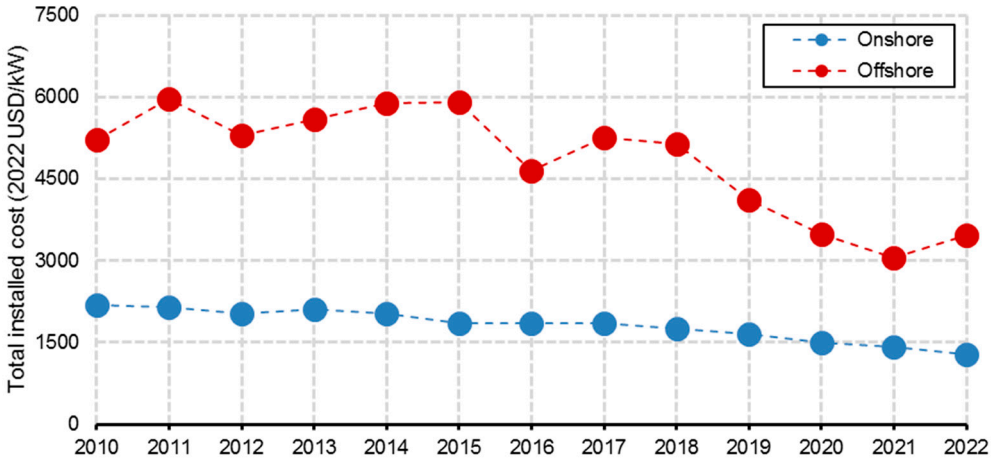


Figure 7. The progress in the TICs of onshore and offshore installed wind farms in the world between the years 2010 and 2022.

Table 1 shows the TIC assessment for onshore wind farms by nation from 2010 to 2021. According to this table of data, the TICs of China and India are observed as 1157 USD/kW and 926 USD/kW, respectively, in 2021, which are lower than the TICs of other nations in 2010. This situation can be attributed to the lower-cost structures and more established markets in China and India compared to other countries. From 2010 to 2021, Spain and Brazil stand out as the countries with the highest percentage decrease in TIC, at 54% and 58%, respectively. On the other hand, Japan experienced a 9% increase during the time frame displayed, starting in 2000 with the cost data point. Compared to more recently established markets, competitive markets exhibit greater declines in total installed costs over extended periods of time. Furthermore, this is because of various national and site-specific regulations, such as labor costs, land use restrictions, local content policies, and logistics constraints for transportation. The regional and country-weighted average TICs and percentage changes between 2010 and 2021 are shown in Table 2. According to this table, Belgium and Germany are observed as nations with the highest percentage decrease in TICs over the years. When Tables 1 and 2 are compared, one can observe that the TICs of offshore wind projects are considerably higher than those of onshore wind projects. For instance, in China, the TICs of onshore wind farms were observed as 1554 USD/kW in 2010 and 1157 USD/kW in 2021. However, these values increased to 4638 USD/kW in 2010 and 2857 USD/kW in 2021 for offshore wind farms, corresponding to a percentage increase of 198.45% in 2010 and 146.93% in 2021.

Table 1. The change in TICs for new onshore wind farm installations in different countries in the years 2010 and 2021.

Country	2010 (2021 USD/kW)	2021 (2021 USD/kW)	Percentage Change 2010–2021
United States	2509	1382	−45
Germany	2381	1712	−28
Sweden	2441	1320	−46
Italy	2679	1377	−49
United Kingdom	2330	1940	−17

Table 1. *Cont.*

Country	2010 (2021 USD/kW)	2021 (2021 USD/kW)	Percentage Change 2010–2021
India	1415	926	−35
Spain	2568	1172	−54
Canada	2824	1368	−52
France	2597	1779	−32
China	1554	1157	−26
Türkiye	2534	1281	−49
Brazil	2735	1150	−58
Japan	2878	3131	9
Mexico	2941	1471	−50

Table 2. The change in TICs for new offshore wind farm installations in different countries in the years 2010 and 2021.

Country/Continent	2010 (2021 USD/kW)	2021 (2021 USD/kW)	Percentage Change 2010–2021
Asia	4680	2876	−39
China	4638	2857	−38
Japan	5113	5550	9
Republic of Korea *	-	6278	-
Europe	4883	2775	−43
Belgium *	6334	3545	−44
Germany *	6739	3739	−45
United Kingdom	4753	3057	−36

* Nations for which data were accessible solely for projects that were commissioned in 2020, rather than in 2021.

Figure 8 shows the decline in weighted average LCOE values for global onshore and offshore installed wind farms for the years between 2010 and 2021. It can be interpreted from Figure 4 that LCOE values are higher for offshore installed wind farms compared to onshore ones for all examined years, as expected. For example, the LCOE values of onshore installed wind farms are detected as 0.1021 USD/kWh in 2010, 0.0690 USD/kWh in 2015, and 0.0331 USD/kWh in 2021, which increased to 0.1879 USD/kWh in 2010, 0.1405 USD/kWh in 2015 and 0.0752 USD/kWh in 2021 for offshore installed wind farms. As previously mentioned, project planning, development, production, and installation for offshore wind power plants are more intricate compared to onshore project processes. The installation of offshore wind turbines in harsh marine environments results in significantly longer project delivery times. The complexity of the installation process, coupled with the challenges posed by harsh marine environments, leads to considerably extended project completion times. The prolonged construction periods contribute to higher LCOE values due to the substantial initial investment costs associated with offshore wind power plants. Moreover, the depth of the sea and distances between shores and plant locations elevate construction and grid connection expenses when compared to onshore wind farm installation. On the other hand, the greatest difference in LCOE values offshore and onshore was noticed in 2011, with a value of 0.0996 USD/kWh. This can depend on the peak installation costs of offshore wind technologies in 2011, primarily influenced by projects situated in deeper offshore locations, farther from the coastline, and employing more advanced technology. The pleasing situation, according to Figure 8, is the continuous reduction in LCOE values for offshore and onshore installed wind farms over the years. Moreover,

the differences in the LCOE values of offshore and onshore installed wind farms have decreased over the years. According to Figure 8, the peak LCOE value of onshore installed wind power plants is observed as 0.1021 USD/kWh in 2010. After a slight increment, such as 1% in LCOE from 2012 to 2013, there has been a continuous decline in LCOE since after the year 2013. The weighted average LCOE of onshore wind farm installations worldwide has decreased by 44% from 0.06 USD/kWh to 0.0331 USD/kWh between 2017 and 2021, primarily due to the balance of plant costs, cost reductions, and technological advances in wind turbines. These advances in the performance and cost of global onshore wind turbine technologies have also led to increases in wind capacity, facilitating the supply of low-priced wind energy for corporates, governments, and other energy buyers. Conversely, the LCOE of offshore installed wind power plants peaked at 0.1961 USD/kWh in the year 2011, followed by a continuous decline in LCOE after the year 2014. The weighted average of the LCOE of global offshore installed wind farms declined by 29.19% from 0.1062 USD/kWh to 0.0752 USD/kWh between 2017 and 2021. The demand for and advancement of offshore wind farm technology has led to improvements in every component, resulting in a significant reduction in the specific cost of electricity generation and, consequently, a decrease in LCOE. Factors contributing to this cost reduction of electricity generation include increased product standardization, growing developer experience, advanced industrialization of production processes, improvement of economic management, the rise of offshore wind farms, the proliferation of regional production and service centers, and numerous other related factors. Moreover, this cost reduction has been facilitated by supportive, sustainable green energy policies that encourage the growth of renewable energy. Over the years, there has been a notable decrease in the LCOE of electricity production using offshore wind energy sources, and further reduction is anticipated in the coming years. According to Bilgili and Alphan [84], the total installed offshore wind energy capacity, currently 35 GW, is projected to reach approximately 382 GW by 2030 and approximately 2002 GW by 2050. Consequently, it is advisable for governments and relevant private organizations to undertake initiatives aimed at further reducing LCOE. It is noteworthy that the production potential of offshore wind energy is higher than that of other RESs.

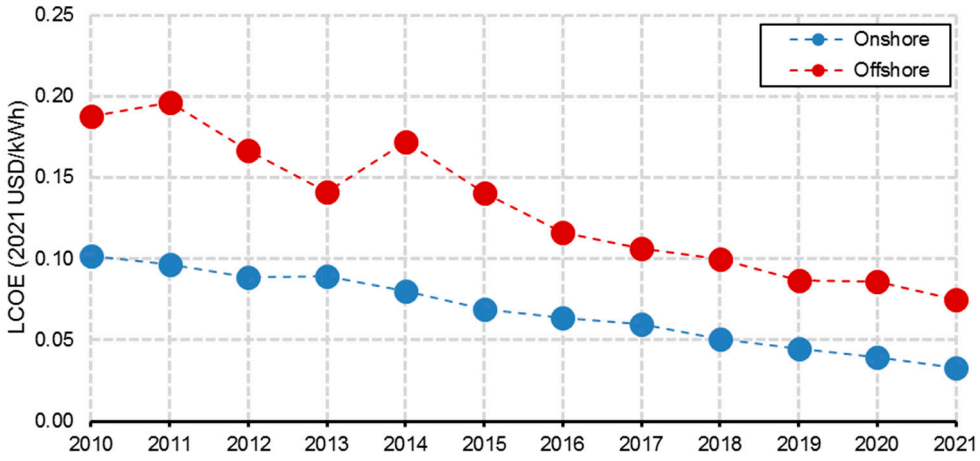


Figure 8. The progress in the LCOE of onshore and offshore installed wind farms in the world between the years 2010 and 2021.

Table 3 demonstrates the mean LCOE assessment for onshore installed wind farms by nation for the years between 2010 and 2021. According to Table 3, from 2010 to 2021, the LCOE of Türkiye decreased by 65% from 0.1280 USD/kWh to 0.0446 USD/kWh. Spain and Brazil demonstrate the greatest LCOE drop among the 15 countries by 78%. Canada follows these countries in terms of LCOE reduction, with a 73% reduction from 0.111 USD/kWh to 0.0296 USD/kWh. On the other hand, Japan has the lowest LCOE reduction, with 17%, from 0.1702 USD/kWh in 2010 to 0.1406 USD/kWh in 2021. In Table 4, the evolution of the mean LCOE values for offshore installed wind farms by country is demonstrated for years

from 2010 to 2021. It is clear from Table 4 that the United Kingdom shows the highest fall in LCOE value, with a 74% decrement. Belgium demonstrates the second greatest LCOE fall by 63%. One of the parameters affecting Japan's unique situation of experiencing a 5% increase in the LCOE from 0.187 USD/kWh in 2010 to 0.196 USD/kWh in 2021 is the rapid increase in sea depth with distance from the coastline. A notable trend in the technological development of both offshore and onshore wind turbines is the transition toward a larger capacity of wind turbines with larger rotors and higher hub heights. Recently, there has been a significant increase in the size of offshore and onshore wind turbines, including increases in hub height, rotor diameter, and capacity, and this trend is expected to continue. This expansion in turbine size significantly increases the turbine power coefficient for the same wind speeds and increases the area in the vertical direction, contributing to a reduction in the LCOE.

Table 3. The change in LCOE for new onshore wind farm installations in different countries in the years 2010 and 2021.

Country	2010 (2021 USD/kWh)	2021 (2021 USD/kWh)	Percentage Change 2010–2021
Brazil	0.1094	0.0237	−78
Canada	0.1110	0.0296	−73
China	0.0829	0.0280	−66
France	0.1346	0.0435	−68
Germany	0.1422	0.0514	−64
India	0.0899	0.0299	−67
Italy	0.1357	0.0409	−70
Japan	0.1702	0.1406	−17
Mexico	0.0988	0.0421	−57
Spain	0.1169	0.0252	−78
Sweden	0.1145	0.0364	−68
Türkiye	0.1280	0.0446	−65
United Kingdom	0.1023	0.0422	−59
United States	0.1026	0.0296	−71

Table 4. The change in LCOE for new offshore wind farm installations in different countries in the years 2010 and 2021.

Country/Continent	2010 (2021 USD/kWh)	2021 (2021 USD/kWh)	Percentage Change 2010–2021
Asia	0.187	0.083	−56
China	0.178	0.079	−56
Japan	0.187	0.196	5
Republic of Korea *	-	0.180 *	-
Europe	0.163	0.065	−60
Belgium *	0.226	0.083 *	−63
Germany *	0.179	0.081 *	−55
United Kingdom	0.210	0.054	−74

* Nations for which data were accessible solely for projects that were commissioned in 2020 rather than in 2021.

4.3. Turbine Capacity Factor Analysis

The capacity factor of wind turbines in onshore and offshore wind farms altered because of technological developments, the structure of power plants, and changes in the meteorological structure between win farms. The change in the capacity factor of onshore and offshore installed wind farms in the world between the years 2010 and 2021 is shown in Figure 9. As is clear in Figure 9, offshore installed wind farms have greater CFs since they have less wind shear and turbulence and greater mean wind velocities. This situation makes the offshore installed wind power output higher than the onshore installed wind power output. According to Figure 9, while CFs of onshore installed wind turbines were 28% in 2012, 31% in 2016, and 36% in 2020, these CFs are enhanced to the values of 40% in 2012, 40% in 2016, and 38% in 2020 for offshore installed wind farms. This corresponds to a percentage increase of 42.85% in 2012, 29.03% in 2016, and 5.55% in 2020 for offshore installed wind farms compared to onshore ones. As seen here, the difference between CFs of offshore and onshore installed wind farms has progressively reduced over the years. Figure 9 exhibits that whereas CFs of onshore installed wind farms continuously increase with the passing years, this is not the case for offshore installed wind farms. For instance, the CFs of onshore installed wind farms are observed to increase with values of 27% in 2010, 31% in 2016, 35% in 2018, and 39% in 2021. This figure shows a remarkable upward trend for CFs of onshore installed wind turbines between the years 2010 and 2021. The increase in the average capacity factor can be largely attributed to technological progress, which includes the development of larger blades, taller turbines with elevated hub heights, and the use of lower specific power wind turbines. Thanks to these innovations, capacity factors have been increased by providing more swept area per watt of the rated turbine capacity. Thus, wind turbine generators operate more frequently and often at a capacity close to their rated capacity.

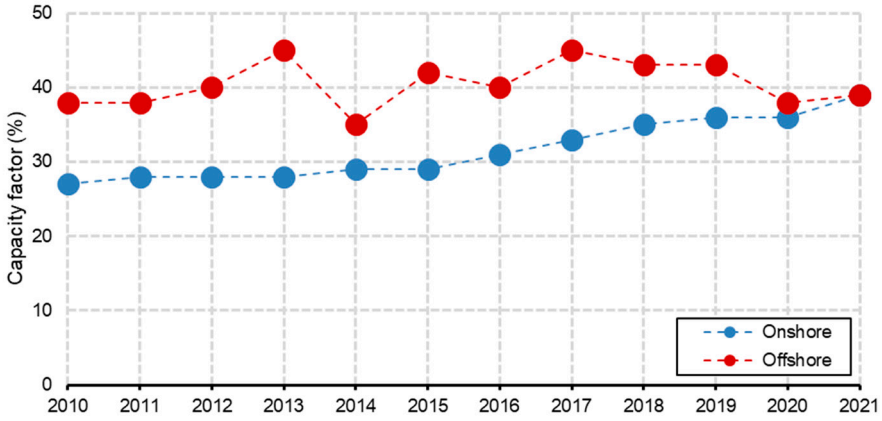


Figure 9. The progress in the capacity factor of onshore and offshore installed wind farms in the world between the years 2010 and 2021.

Table 5 exhibits the improvement in mean CFs for onshore installed wind farms by nation between the years 2010 and 2021. This table reveals that the majority of nations have demonstrated an increase in the average CFs for onshore installed turbines between 2010 and 2021. Based on the results, Japan exhibited the lowest increase of 1%; of the countries, Spain showed the greatest increase of 59%, and Mexico was the only nation that experienced a CF decrease of 1%. India, China, Türkiye, and Brazil experienced CFs increments between 40 and 55%, while the average CFs in the United States and the United Kingdom both increased by 37%. Table 6 presents the assessment of mean CFs for offshore installed wind farms by nation for the period from 2010 to 2021. The data in Table 6 reveal that the United Kingdom shows the highest increment in CFs with a 33% increment. China displays the second-highest CF increments, with an increase of 23%. Finally, Japan exhibited the lowest CF increment of 7% during the same period.

Table 5. The change in capacity factor for new onshore wind farm installations in different countries in the years 2010 and 2021.

Country	2010 (%)	2021 (%)	Percentage Change 2010–2021
United States	32.9	45.1	37
Sweden	28.6	36.9	29
Germany	24.0	27.7	15
United Kingdom	30.1	41.1	37
Italy	25.4	33.0	30
India	24.7	35.2	43
Spain	26.7	42.5	59
Canada	32.4	45.2	39
France	26.5	35.7	35
China	25.4	36.1	42
Türkiye	25.8	39.2	52
Japan	24.0	24.3	1
Brazil	36.0	51.8	44
Mexico	40.2	37.0	−8

Table 6. The change in capacity factor for new offshore wind farm installations in different countries in the years 2010 and 2021.

Country	2010 (%)	2021 (%)	Percentage Change 2010–2021
Belgium *	38	41 *	8
China	30	37	23
Germany *	46	42 *	−9
Japan	28	30	7
United Kingdom	36	48	33

* Nations for which data were accessible solely for projects that were commissioned in 2020 rather than in 2021.

Designing a wind turbine that uses wind energy and converts it into electrical energy remains a key challenge in the development of efficient, modern, and large-scale wind turbines [93]. Consequently, the primary focus of technological advancement in wind turbine technology has centered around enhancing efficiency, reliability, affordability, and increasing power output [93]. Figure 10 illustrates the growth in the global offshore installed wind turbine nameplate capacity for the years between 2010 and 2021. According to this figure, there has been significant progress in enhancing the capacity of wind turbines over the years from 2010 to 2021. For example, while the nameplate capacity was 3.1 MW in 2010 and 4.2 MW in 2015, it has since been augmented to 5.4 MW in 2018 and 6.1 MW in 2021. From 2010 to 2021, the global offshore installed wind turbine capacity increased by 97% [94]. This situation can be attributed to the rapid advancement of offshore wind turbine technology, which involves the installation of turbines at greater distances from the coastline and in deeper waters. Turbine installations in these circumstances have larger rotor diameters and higher hub heights. Increasing the wind energy capacity per turbine provides cost savings by reducing the number of turbines needed to reach the desired capacity in wind farms.

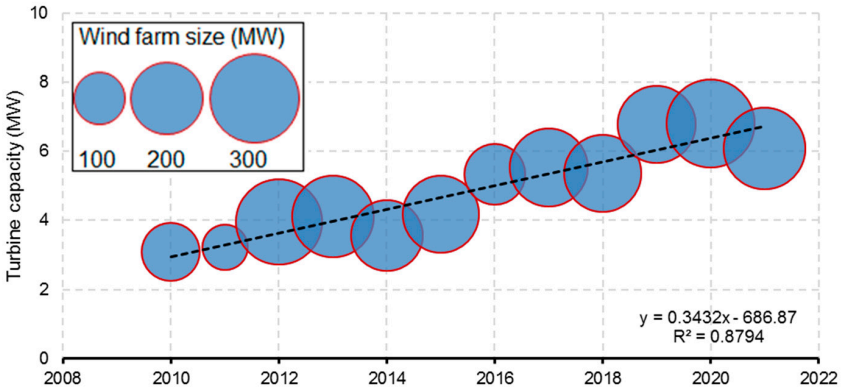


Figure 10. The progress in the turbine capacity of offshore installed wind farms in the world between the years 2010 and 2021.

Over the past two decades, there has been a significant increase in the establishment of offshore wind farms. As discussed earlier, advancements in technology and design have led to a notable increase in the size of turbines. These design enhancements encompass raising the hub height and expanding the rotor diameter of offshore turbines, resulting in an increase in the turbines' maximum power output. Simultaneously, offshore wind farm capacities have also seen a corresponding rise in parallel with these technological improvements and design developments. In Figure 6, the mean yearly capacities of wind farms demonstrate a growth from 136 MW of power in 2010 to 262 MW by the year 2021. This corresponds to a percentage increase of 92.96% in the wind farm capacities with the passing years from 2010 to 2021. The increased capacity of wind farms has also led to the expansion of sea surface areas where these farms have been installed.

Table 7 depicts the assessment of the mean nameplate capacity of recently established onshore wind projects in various countries from 2010 to 2021. According to this table, in 2021, the average turbine capacities show significant change for Brazil, Canada, and Sweden compared to 2010, with percentage increments of 121%, 116%, and 108%, respectively. Brazil, which shows the greatest increment in average turbine capacity, enhanced its average turbine capacity from 1.80 MW in 2010 to 3.98 MW in 2021. On the other hand, India, China, and Japan are the countries showing the lowest average turbine capacities in 2021, with values of 2.02 MW, 3.01 MW, and 3.02 MW, respectively.

Table 7. The change in average turbine capacity for new onshore wind farm installations in different countries between 2010 and 2021.

Country	2010 (MW)	2021 (MW)	Percentage Change 2010–2021
Brazil	1.80	3.98	121
Canada	2.05	4.27	108
China	1.47	3.01	105
France	2.10	2.71	29
Germany	2.00	4.08	104
India	1.30	2.02	55
Japan	2.00	3.02	51
Sweden	1.84	3.97	116
Türkiye	2.40	4.17	74
United Kingdom	2.10	3.45	64
United States	1.80	3.07	71
Vietnam	-	4.24	-

When Figure 10 and Table 7 are compared, it can be clearly seen that the average turbine capacity of offshore installed wind farms is always higher than that of onshore installed wind farms for all examined years. This is because there is a substantial increase in energy production per installed unit due to the generally stronger and more stable winds at sea. Additionally, greater wind speeds, which tend to increase further from the coastline, enhance the overall efficiency of the process [95]. Moreover, offshore wind turbines can be larger than those on land, as it is more feasible to transport large turbine components by sea. Finally, the lower wind shear and turbulence in offshore installed wind farms make the average turbine capacity to be higher compared to that of onshore installed wind farms.

4.4. Turbine Size Analysis

In regions characterized by relatively low wind velocities, wind turbines equipped with longer rotor blades can exhibit enhanced efficiency in harnessing the available wind, in contrast to wind turbines with smaller rotor blades. This capability to generate increased wind power at lower wind velocities can significantly contribute to the advancement of wind energy in various nations. Consequently, there has been a global trend toward enlarging the rotor diameter of wind turbines over time. Figure 11 illustrates the growth in the rotor diameter of offshore wind turbines in the world for years between 2010 and 2021. According to Figure 11, the weighted average rotor diameter of global offshore wind turbines increased from 112 m in 2010 to 160 m in 2021, corresponding to a percentage increase of 43%. Furthermore, it is clear from Figure 11 that the average rotor diameter of global offshore wind turbines progressively increases for each year compared to the previous year from 2010 to 2021. Furthermore, from 2010 to 2021, the turbine capacity generally tends to increase in parallel with the increase in the rotor diameter. For instance, the value of turbine capacity increased from 3.1 MW in 2010 to 4.2 MW in 2015 and 6.1 MW in 2021, corresponding to a percentage increase of 35.26% in 2015 and 97.05 in 2021 compared to 2010. In recent years, the trend toward more advanced and efficient wind turbines, characterized by larger rotor diameters, has led to a global increase in turbine capacities and power production.

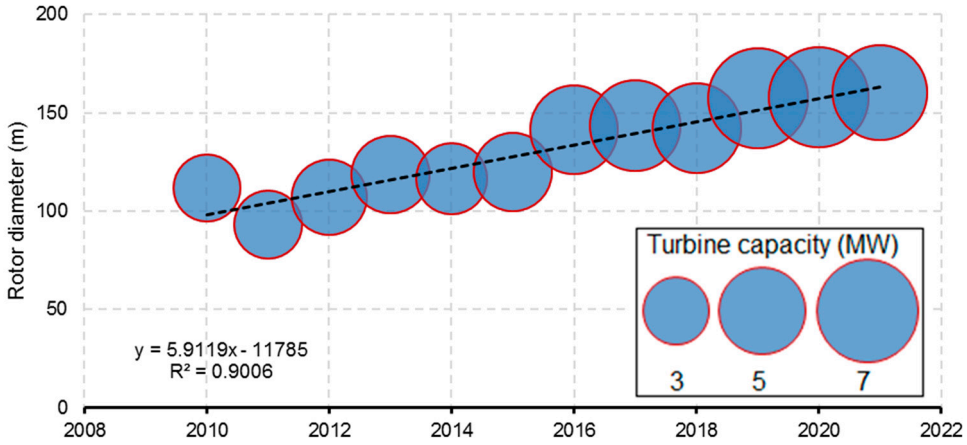


Figure 11. The progress in the rotor diameter of offshore installed wind farms in the world between the years 2010 and 2021.

Table 8 shows the weighted average rotor diameter of onshore wind turbines in various countries for the years 2010 and 2021. From 2010 to 2021, China showed the greatest percentage growth in rotor diameter, with 91%, by increasing the rotor diameter from 75 m to 143 m. Furthermore, Brazil is observed as a country showing the second greatest growth in rotor diameter with 72% by increasing the rotor diameter from 83 m in 2010 to 144 m in 2021. Sweden and Germany show the same percentage growth in rotor diameter of 61% between 2010 and 2021. When Figure 11 and Table 8 are compared, it can be said that the weighted average rotor diameter is higher for offshore wind turbines

compared to onshore ones. For example, while the global average rotor diameter is detected as 112 m in 2020 and 160 m in 2021 in Figure 11 for offshore installed wind farms, no country has reached these values, as indicated in Table 8 for onshore installed wind farms. This is a result of the rapid advancement in offshore wind turbine technology, which encompasses the placement of turbines at greater distances from the coastline and in deeper waters. Consequently, these conditions lead to the deployment of turbines with an expanded rotor diameter.

Table 8. The change in average rotor diameter for new onshore wind farm installations in different countries in the years 2010 and 2021.

Country	2010 (m)	2021 (m)	Percentage Change 2010–2021
Brazil	83	144	72
Canada	90	139	54
China	75	143	91
France	88	118	34
Germany	85	137	61
India	77	119	55
Japan	80	99	24
Sweden	90	144	61
Türkiye	91	134	48
United Kingdom	87	122	41
United States	84	129	53
Vietnam	-	146	-

As of 2021, Germany houses the world's tallest currently operational wind turbine, standing at an impressive height of 246.5 m [6]. It is a well-known fact that turbine towers are constructed to reach greater hub height to harness more energy, as wind speeds tend to increase at higher altitudes. Over the past decade, there has been a significant global increase in the average hub height of wind turbines. In areas exhibiting favorable wind shear, the utilization of taller towers to elevate the hub height enables enhanced access to higher wind speeds, leading to reduced wind energy expenses. Figure 12 shows the increment in the average hub heights of global offshore installed wind turbines between 2010 and 2021. According to this figure, the average hub heights of offshore installed wind farms in the world increased by 26.79%, growing from 83 m in 2010 to 105 m in 2021. Here, the greatest average hub height of offshore wind turbines was observed in 2019 at 108 m. When the increment of the offshore turbine's average hub height in Figure 12 is compared with the increment of the offshore turbine's average rotor diameter in Figure 11, it can be clearly seen that rotor diameters have exhibited a more pronounced growth rate compared to hub heights over the years. As it can be remembered, the percentage growth rate in rotor diameter is 43% from 2010 to 2021, and the percentage increment rate in hub heights is reduced to 26.79% for the same years. Although the rotor diameters and hub heights have experienced growth over time, this increase has brought about certain limitations. For example, large wind turbine blades for onshore wind farms can be more difficult to install and transport.

Table 9 presents the progression of the average hub heights for new onshore wind farm installations in various countries during the period from 2010 to 2021. According to data, Japan takes the lead, experiencing a substantial increase of 80% as the weighted average hub height for turbines escalated from 74 m in 2010 to 134 m in 2021. Following closely, Brazil and Germany exhibited the second and third highest increments in weighted average hub height, with gains of 41% and 40%, respectively. In 2021, the United Kingdom and Vietnam

emerged as countries with the lowest weighted average hub heights, registering 71 m and 85 m, respectively. During the period from 2010 to 2021, the United Kingdom exhibited a growth rate of 4%. Türkiye's onshore wind turbine sector also saw substantial progress as the weighted average hub height soared from 105 m in 2021, marking a remarkable 33% increase from the 79 m recorded in 2010.

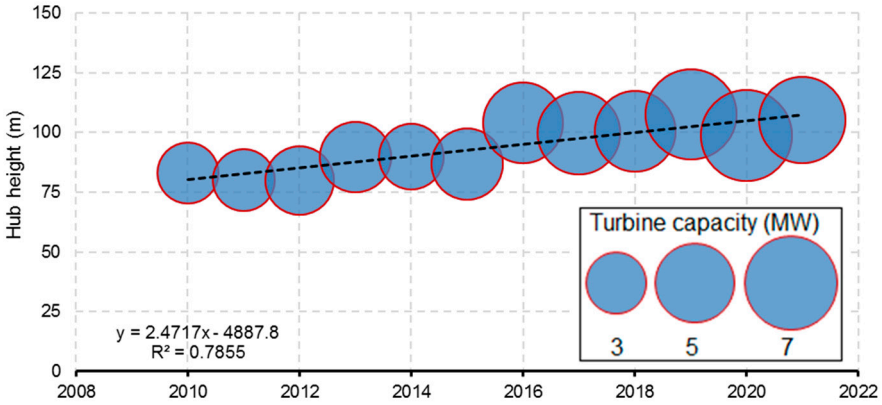


Figure 12. The progress in the hub height of offshore installed wind farms in the world between the years 2010 and 2021.

Table 9. The change in average hub height for new onshore wind farm installations in different countries in the years 2010 and 2021.

Country	2010 (m)	2021 (m)	Percentage Change 2010–2021
Brazil	79	112	41
Canada	78	104	32
China	79	100	26
France	84	108	30
Germany	106	148	40
India	70	90	29
Japan	74	134	80
Sweden	95	130	37
Türkiye	79	105	33
United Kingdom	68	71	4
United States	80	96	20
Vietnam	-	85	-

The trend toward more advanced and efficient wind turbine technologies, characterized by larger rotor diameters and higher hub heights, has grown significantly. One of the most notable results of this trend is the decrease in wind turbine-specific power, which is inversely proportional to increasing turbine size. Concurrently, this trend has resulted in significant reductions in energy costs. As a result, wind turbine technology has evolved from an aspirational concept to an established component of the energy generation industry [6].

Larger turbines offer the advantage of requiring foundations, fewer cables, converters, and other resources to generate the same power output. This leads to faster project development, reduced operating and maintenance expenses, lower risks, and improved overall profitability. Current research on technological progress highlights the significance of dimensional and technological improvements in large-scale wind turbines. As a result,

wind turbines with extended blades, expanded rotors, elevated hub heights, and reduced specific power, combined with higher capacity factors, are expected to assume a more significant role in energy systems of the future. This is due to their ability to cost-effectively generate electricity under more favorable conditions. Many older wind farms, especially those located onshore, are nearing the end of their economically useful lifetimes. On the other hand, the conclusion drawn from the review work is that increasing hub heights and rotor diameters, as well as continued innovations and technological advances for larger-capacity turbines, will increase the efficiency for the same location despite the higher specific cost increase per unit power.

4.5. Impact of Geographical Factors and National Policies on Wind Energy

There are several important issues to consider when comparing geographical and national policy factors regarding their impact on wind energy. First of all, the effects of geographical factors are listed as follows [96]:

- **Wind resource availability:** This includes wind speed and consistency, which vary significantly depending on the geographic location. Coastal areas and those with higher altitudes generally have better wind resources.
- **Terrain:** The local terrain affects wind patterns. Smooth, open terrains allow for more consistent and stronger winds, while rough or mountainous terrains may cause turbulence and reduce wind efficiency.
- **Distance to transmission lines:** Proximity to existing transmission infrastructure impacts the feasibility and cost-effectiveness of connecting wind farms to the electric grid.
- **Environmental impact:** Geography influences the environmental impact of wind power, including effects on wildlife, landscapes, and local communities.
- **Climate:** Climate patterns determine seasonal variations in wind availability, affecting the reliability of wind power as an energy source.

These factors collectively influence the suitability and efficiency of wind power installations at different geographical locations. Expected future trends in geographical factors regarding wind energy can be listed as increasing offshore projects, floating wind turbines, land use and site optimization, integration with other land uses, environmental and social considerations, and climate change adaptation.

Secondly, the effects of national policy factors are listed as follows:

- **Subsidies and incentives:** Government subsidies, tax credits, and incentives can significantly reduce the cost of wind power development and encourage investment in renewable energy [97].
- **Regulatory framework:** Regulations related to permitting, zoning, environmental assessments, and grid connections play a crucial role in the feasibility and timeline of wind power projects [98].
- **Energy market structures:** Market rules, such as feed-in tariffs, renewable portfolio standards, and power purchase agreements, influence the economic viability and competitiveness of wind power compared to other energy sources [99].
- **Research and development funding:** Government support for research, development, and innovation in wind power technologies can drive advancements and cost reductions in the sector.
- **International agreements and commitments:** Commitments to international agreements like the Paris Agreement or regional agreements on renewable energy targets can shape national policies and goals for wind power deployment.
- **Public perception and community engagement:** Government policies promoting public acceptance through community engagement, education, and transparency can mitigate local opposition to wind projects [100].
- **Electricity market integration:** Policies that facilitate the integration of variable renewable energy sources like wind into the electricity grid, such as grid modernization initiatives and energy storage incentives, are crucial for maximizing the benefits of wind power [101].

These policy factors vary widely across countries and can significantly influence the growth, competitiveness, and sustainability of wind power as part of the energy mix. When we examine the wind energy policies developed for Asia, Europe, and America [102], we see that European countries are leading the way with comprehensive wind power policies. Germany and Spain are the third and fourth largest wind power producers in the world, respectively. However, there are significant differences in approaches among the leading countries, such as Denmark, Germany, Spain, the UK, and France. In Asia, China stands out as the world leader in wind power, employing rapid development policies similar to those used for fossil fuels. On the other hand, Japan's approach is notable for its focus on environmental and sustainability constraints. In America, the United States has achieved leadership in various aspects of wind power, while Latin America shows significant potential for development in this sector. Expected future trends in national policies regarding wind energy can be listed as technological advances, decarbonization goals, energy storage and smart grids, and international cooperation [103].

5. Conclusions

In this investigation, the characteristics and advancements of wind turbine technologies installed onshore and offshore around the world were comprehensively studied and compared. In this context, the annual and cumulative installed capacities of turbines were individually examined. In addition to examining the parameters of installed capacity, the analysis of turbine characteristics encompassed the nameplate capacity, hub height, and rotor diameter. Furthermore, an economic and efficiency assessment was carried out for wind turbines installed onshore and offshore around the world. Regarding economic aspects, two parameters, namely LCOE and TIC, were considered, while in terms of efficiency, the CF parameter was examined, involving a comparison of the average values for the years 2010 and 2021. The most important outcomes of this investigation can be summarized as follows:

- The annual onshore wind power capacity consistently exceeds the annual offshore wind power capacity throughout the observed years. For instance, in 2020, the annual onshore wind power capacity was 88.4 GW, whereas the offshore wind power capacity for the same year observed was 6.9 GW.
- Starting in 2018, the global capacity for onshore wind power, which was 542 gigawatts (GW), is expected to more than triple by 2030, reaching 1787 GW, and increase nine times by 2050, reaching 5044 GW. Similarly, the global capacity for offshore wind power is projected to grow almost tenfold to 228 GW by 2030 and to approximately 1000 GW by 2050.
- It can be revealed that the growth rate of the cumulative offshore wind power capacity surpasses that of the cumulative onshore wind power capacity in a given year compared to the preceding one. For example, for years from 2020 to 2021, the cumulative offshore wind power capacity increased by 55.5%, whereas the increment rate for cumulative onshore wind power during the same period was 14.17%.
- According to the results, while considerable changes in the TIC were observed for offshore installed wind turbines from 2010 to 2022, the TIC of onshore wind turbines did not remarkably alter during this period. From 2010 to 2021, for onshore installed wind turbines, Spain and Brazil stand out as the countries with the highest percentage decrease in TIC, at 54% and 58%, respectively.
- As expected, LCOE values are higher for offshore installed wind farms compared to onshore ones for all examined years due to the higher construction costs and difficulties. From 2010 to 2021, the United Kingdom showed the highest fall in LCOE value, with a 74% decrement for offshore installed wind farms.
- The adoption of technological innovations like larger blades and turbines with increased hub heights has played a significant role in elevating the average capacity factor. While CFs of offshore installed wind turbines were 28% in 2012, 31% in 2016,

and 36% in 2020, these CFs were enhanced to the values of 40% in 2012, 40% in 2016, and 38% in 2020 for offshore installed wind farms.

- From 2010 to 2021, the global offshore installed wind turbine capacity increased by 97% due to the quick advancement of offshore wind turbine technology, which involves the installation of turbines at greater distances from the coastline and in deeper waters. For onshore installed wind turbines, Brazil shows the greatest increment in average turbine capacity and enhances its average turbine capacity from 1.80 MW in 2010 to 3.98 MW in 2021.
- There has been a global trend toward enlarging the rotor diameter of both onshore and offshore installed wind turbines over time. It has been detected that the average rotor diameter of offshore installed wind turbines is higher compared to onshore counterparts since it is possible to obtain larger rotor diameters in the case of installing the turbine farther from shore and in deeper waters. In addition to these technological advances, wind energy is becoming increasingly competitive with traditional fossil fuels in terms of cost, especially as economies of scale and technological improvements drive costs down. Wind power plays a crucial role in reducing greenhouse gas emissions and addressing climate change, making it a key component of sustainable energy transitions globally. Many countries are implementing supportive policies and incentives to promote renewable energy development, which is expected to further drive the expansion of wind energy capacity.
- It has been reported that the average hub heights of offshore installed wind farms in the world increased with a percentage of 26.79%, growing from 83 m in 2010 to 105 m in 2021. On the other hand, Japan takes the lead in wind farms installed onshore, experiencing a substantial increase of 80% from 2010 to 2021.

In the future, wind turbines with taller hubs and larger rotor diameters will increasingly dominate landscapes. To manage turbine visibility during site selection, it may be beneficial to introduce a potential visibility model (PVM) as an additional factor. Furthermore, the design of turbines must be tailored more effectively to address the considerable challenges posed by their large sizes, materials, and structural requirements. Future research will explore these challenges, particularly regarding the materials and structures used in large-scale wind turbines, alongside the implementation of the PVM model to regulate turbine visibility. Ultimately, the findings and datasets of this study can offer valuable insights for assessing wind energy availability and pertinent policy considerations on a national scale.

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