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Review Article

Growth in turbine size and technological development of modern commercial large scale wind turbines in Türkiye

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ABSTRACT

In this study, in addition to the recent advances and tendencies in wind turbine technology around the world, the progress of commercial wind turbine technology installed in Turkey was also thoroughly examined. In this respect, several metrics for installed wind turbines including number of turbines, installed power capacity (MW), mean rated capacity (MW), mean rotor diameter (m), mean specific power capacity (W/m^2), and mean hub height (m) have been obtained between the years of 2011 and 2019. According to the obtained results, the mean rated capacity of Turkey's annual installed wind turbines advanced from 1.86 MW in 2011 to 3.52 MW in 2019. However, the mean specific power of yearly installed wind turbines declined from 423.7 W/m^2 to 314.1 W/m^2. Outcomes revealed that the growth in the size and the reduction in the specific power have contributed to the tendency of higher power outputs, and wind turbine capacity factor and power generation capacity have been on the rise in Turkey. In time, wind turbines with greater rotor diameters and hubs started to show up more observable on land. For that purpose, the proposed solution to regulate turbine visibility during site selection is the potential visibility model (PVM), which is meant to be used as an auxiliary variable.

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INTRODUCTION

Renewable energy sources (RESs) are one of the world's energy sources that have expanded the fastest in recent years [1–4]. When compared to traditional power generation technologies, renewable energy sources (RESs) present unique and affordable opportunities [5–9]. The 1990s saw a global start to the renewable energy movement, which continued to grow significantly in the 2000s. Since 2000, a number of electric power technologies and installed capacity based on RESs have significantly increased [10–15]. While 1,000 GW RES capacity worldwide was established in 2007, the progress of the most substantial renewable took place in electric production in 2019, with the world's power

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capacity attaining an estimated value of 2,588 GW at year's end and a growth of almost 9%. In the future, RESs will continue to grow at the fastest pace in the electricity sector and will provide almost 30% of global electricity demand in 2023 [16].

Among the RESs, wind energy is increasingly being utilized in the world by making an important contribution to renewable energy [17–21]. The use of wind power as a competitive and dependable source of electricity has been on the rise. Throughout the world, progress continues to be robust, involving more dynamic countries and manufacturers, thus enhancing yearly installed capacity with new investments [22–29]. Especially offshore technological progress has continuously reduced energy costs [30–34]. With the help of rapid development in the industry of wind turbines, the bottleneck supply, and extended supply chains in this area have been overcome [35]. 1.2 million people work in the wind industry globally, with China and the United States accounting for the majority of these positions. Furthermore, employment levels in Brazil, Germany, India, and the European Union are moderate [36,37].

In the contemporary era, the rapid global expansion of wind energy technology is evident, driven by its emergence as a formidable and challenging RES. By creating parts with stronger and less expensive materials, researchers studying wind turbines are still trying to find the most economical and effective ways to convert energy [38,39]. Generators, blades, direct-drive techniques and yaw and pitch control systems are just a few of the wind turbine technology advancements and improvements that have occurred recently. However, in order to increase the amount of electrical energy generated by wind turbine technology in the future, creative ways must be developed, such as lowering the cost of wind turbines through technological advancement, enhancing manufacturing operations and streamlining the manufacturing process, reducing operational and maintenance expenses, enhancing overall performance and efficiency, and augmenting the manufacturing capacity of wind turbines.

Wind power generation in the world is greatly impacted by the technological advancements in wind energy [40–44]. In recent times, the growing size of individual wind turbines has become a significant development and innovation technique in turbine technology. In general, wind turbines have grown in size over time. In the early 1980s, they were relatively small, 50 kW devices with a 15 m rotor diameter; by 2000, however, they had grown to 2 MW devices with an 80 m rotor diameter. The largest wind turbine in the world, the V164-8.8 MW, was installed in the UK in 2018. In the last 20 years, the installed capacity of wind energy worldwide has increased nearly 80 times, from 7.5 GW in 1997 to over 651 GW in 2019. Nonetheless, Turkey's potential for wind energy is 48 GW. Installed wind power capacity was at 8.06 GW at the end of 2019 and is projected to reach 12 GW by 2023.

Turkey has a notable potential for wind energy and has seen an increase in wind energy capacity [45–47]. As is well known, wind energy is now produced all over the world in addition to Europe and the US. Among RESs, wind energy has experienced the fastest global growth in recent years. However, this growth also suggests that the quantity and size of turbines will increase. Larger hub and rotor diameter turbines gradually spread and become more visible in the environment. The rise in the hub height and rotor swept area of wind turbines in Turkey and globally has resulted in a notable increase in potential visibility on the landscape of the regions. This study proposes the potential visibility model (PVM) as an auxiliary variable to control turbine visibility during the site selection process for industrial wind power production projects. The purposes of this study are to investigate (1) the recent development and trends of wind turbine technology around the world, (2) the progress of commercial large scale wind turbine technology installed in Turkey. The findings obtained from this study can help to raise our knowledge on the sensitivity of future electrical energy production from the wind. The outcomes could be useful for the wind energy researches, particularly in the sector of the physical appearance and potential visibility of the turbines, the optimal site selection of the turbines for the environmental impacts, the recent developments and innovation trends in the turbine technology, the mitigation of visual impact of wind power plants on the landscapes.

RECENT GLOBAL TRENDS IN WIND TURBINE TECHNOLOGY

Since the early 1980s, when wind turbine technology became commercially available, there have been numerous advancements. The traditional design's construction has undergone a small modification. Nonetheless, developing an efficient wind turbine capable of harnessing wind energy and converting it into electrical power remains the most significant challenge in the contemporary wind industry [48,49]. To cut expenses and provide adaptability, the majority of wind turbine manufacturers are concentrating on designing simpler turbines tailored for specific markets. Diverse new models for wind turbines, suitable for both high and low wind conditions, continue to be adjusted to meet the specific demands of individual country markets [36]. The predominant trends in the technological advancement of wind turbines include heightened reliability and efficiency, cost reduction, and increased power output per kilowatt of machinery [50–52]. Table 1 outlines the five key research and innovation priorities in wind turbine technology, namely grid and system integration, next-generation technologies, operation and maintenance, offshore balance of power plant, and floating wind, arranged in order of strategic importance [36].

Table 1. Research and innovation priorities in wind turbine technology

Priority	Key Action Areas
Grid and system integration	• Solutions for enhancing the flexibility of the energy system, encompassing ancillary services • Strategic planning and operations for expanding the grid • Advancements in storage solutions, with a particular focus on seasonal storage • The progression of hybrid systems development
Operations and maintenance	• Smart operations for wind farms • Enhanced performance management through improved data analysis and collection and analysis • Comprehensive lifetime management • Awareness of environmental factors, both internal and external conditions
Next generation technologies	• Design and operation methods informed by data • Development and validation of highly accurate models • Exploration of new-generation materials, components, towers, and support structures • Primary exploration of radical and/or breakthrough innovations • Material recycling initiatives
Offshore balance of plant	• System engineering • Design of offshore grids • Infrastructure design • Consideration of site conditions
Floating wind	• Comprehensive design of floating wind turbines • Cultivating sectoral synergies to enhance the profitability of floating design concepts • Establishing a supportive regulatory framework for floating wind power farms • Developing a resilient supply chain • Readying floating wind for market adoption and widespread distribution at a large scale

Energy Storage Systems

Transformation and storage of energy have become a research area to handle both the environmental considerations of society and pragmatic practices such as the strengthening of the growing staff of portable electronic equipment. The storage system should have an important position in the wind farm by controlling the wind energy output, allowing the wind energy to penetrate the grid further [48]. Over the past few years, manufacturers of wind turbines and researchers have been are considering and designing battery storage for offshore and onshore wind energy projects to increase capacity factors. For example, the installation of a wind-to-heat energy storage system was begun in 2017. In Germany, four wind turbines combined with pumped storage were completed. Plans have also been announced for the construction of a wind turbine that will produce hydrogen directly. In Ireland, a wind turbine manufacturer has joined forces with the US company Microsoft to incorporate batteries into its turbines as part of a project [36].

New Design-Manufacturing Process and Materials For Tower and Blade

In 2017, innovations in blade materials and production processes also continued to increase production, boost their efficiency reduce wind energy costs. In the USA, for example, fiberglass recycling and conversion of used turbine blades into new products have been initiated. In Spain, a pilot implementation was launched for the recycling of faulty or damaged turbine blades. Blades were utilized as a noise barrier in Denmark, and additional parts were intended to be used as auxiliary equipment. A European-wide promotional project has been initiated to create innovative design and production methods that facilitate recycling and extend the lifespan of composite products, such as wind turbine blades [36].

Offshore Wind Turbines

In recent years, especially in Europe, offshore wind power plants have obtained higher market shares as a result of encouraging state policies. The advantages of the generation of electricity from offshore wind power have made it immensely attractive as a potential source [54,55]. The offshore wind energy economics have shown a much faster development than the experts expected. In 2019, 6.1 GW of new offshore wind energy installations were established globally in nine markets. In general, there is offshore wind capacity with 29.1 GW installed capacity in 17 markets around the world.

New generation turbines, supply chain maturation, cost reduction in industrial logistics and in maritime transport, as well as increased competition and experience have significantly reduced coastal wind energy prices and competitively priced offshore wind power in Europe [36]. Competitive offers made in recent years show that significant cost reductions have already been realized in the offshore wind sector and there is still a 35% cost reduction potential in this sector. Of course, making these reductions would require new developments to increase the production and size of wind turbines in turbine technology. Besides, the most important cost element for the offshore market is the plant balance, which may constitute more than 50% of the development costs. Plant balance infrastructure includes access to the site, offshore grid substructure, export cables, substations, assembly and installation. In this sense, in order to maintain the existing leadership in offshore wind energy technology in Europe and the world, the progress of innovative technologies and systematic approaches in these areas is vital [53].

Hybrid Systems

One of the trends and recent technological advancements recently is integration of wind and other energy resources such as solar-wind hybrid system, wind-hydro hybrid system, wind-diesel power generation system and wind-hydrogen system [38,56]. In 2017 several companies worldwide concentrated on hybrid wind-solar photovoltaic (PV) projects. For instance, the first hybrid contract for a solar PV-wind farm was announced in India. The first utility-scale hybrid solar PV, wind, and energy storage project in Australia has started building its initial phase [36].

Floating Turbines

One of the major progress in the offshore sector recently is the work for the settlement of floating turbines that have the potential to enlarge the regions where offshore wind energy is applicable and economically feasible. The first commercial floating wind energy plant with a 30 MW power capacity was installed in 2017 close to Aberdeen, Scotland's coast. As known, the floating turbines can be installed where winds are most consistent and highest, rather than where the topography of seafloor is convenient. Therefore, floating offshore wind technology is more economical and feasible and must create a sustainable and steady supply chain to ensure its full potential [53]. The most important challenges for the floating sector are to develop an efficient supply chain and narrow the potential platform designs range [36].

Larger Machines

To reduce costs through standardization and scale, the turbines' size has been growing quickly in recent years. Wind turbine technology has generally continued to trend toward longer turbines, bigger rotor sizes, longer blades, and higher hub heights [57]. Larger turbines have continued to be advantageous for developers, particularly those operating offshore. A smaller number of cables, converters, foundations, and other resources are needed for the same power output when the turbines are larger. Project development proceeds more quickly as a result, and overall profitability rises along with decreased risk and operating and maintenance expenses. The mean capacity of the last remaining turbines in Europe doubled ten years ago in 2017 and increased by 23% to 5.9 MW [36]. A manufacturer of wind turbines revealed in 2017 a new platform suitable for small, medium, and large wind areas that is designed for 6 MW offshore wind turbines. A different manufacturer created wind turbines with a nominal power of 9 and 9.5 MW. Plans for wind turbines with a capacity of at least 10 MW were released in an effort to increase the offshore wind farms' capacity. An announcement was made regarding the investment plan to develop a 12 MW turbine over the next few years [36]. GE Renewable Energy unveiled and tested the 12 MW capacity (Figure 1), the strongest offshore wind turbine in the world, at the start of 2019 [58]. Compared to other offshore wind turbines currently on the market, the wind turbine with its 12 MW capacity (the first in the world), 107 m blade, 220 m rotor diameter, and digital features will produce more energy. It will be able to generate 67 GWh of renewable energy annually, which is enough to power 6,000 households in Europe.

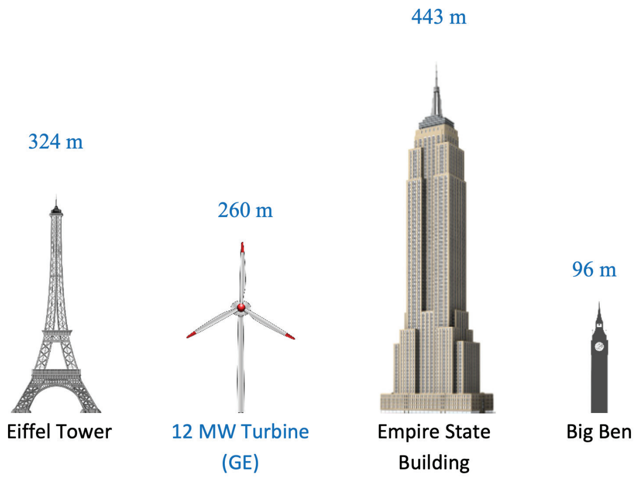


Figure 1. The world's strongest offshore wind turbine, 12 MW capacity.

Operational Efficiency Software Systems

In recent years, wind turbine manufacturers have developed various digital solutions to enter new revenue streams. For example, in 2017, a software program was developed to increase efficiency and facilitate repairs. In addition, operational efficiency software was introduced to reduce costs. Some large wind turbine manufacturers, operators and developers have begun to use drones to control and even clean wind turbines, thus reducing costs and increasing worker safety [36].

GROWTH IN WIND TURBINE SIZE IN EUROPE AND THE WORLD

History of wind power goes back over 3000 years ago and people started using it to produce electrical energy about 130 years ago [59]. The first large wind machine with a 12 kW electrical production capacity was established in Cleveland, Ohio in 1888, and the use of 25 kW machines worldwide was common particularly in Denmark in the last period of World War I. After World War II, the developments in large wind machines maintained especially in Denmark, Germany France, and the UK. In Denmark, a three-blade wind turbine with a capacity of 200 kW operated successfully until the beginning of the 1960s. Later, horizontal-axis wind turbines with a design approach that emerged in the 1970s were developed in Germany [60].

The increase in wind turbine size and rated capacity is one of the most recent technological advances. In order to keep up with the increased wind speeds at higher elevations, wind turbines have seen significant height and size increases. In addition to its size, wind turbines' rated capacities have increased dramatically over the past 40 years, which has resulted in a sharp decline in energy costs. Thus, the technology of wind turbines has advanced from an idealistic state to a well-known component of the energy generation sector. Figure 2 presents the history of the sizes of leading commercial wind turbines up to the present [61]. As seen from the figure, wind turbines have grown significantly in size and rated capacity. The rated capacity of commercial horizontal axis wind turbines was approximately 50 kW in the early 1980s. These commercial turbines had a 20 m rotor diameter and a nominal capacity of 100 kW in 1985. They achieved 2 MW in 2000 with a rotor diameter of 80 m. The most well-known wind turbines in 2005 had rated capacities of roughly 750 kW, and only 22% of newly constructed wind turbines had MW-level capacity. As a result, some wind turbine manufacturers have produced commercial wind turbines with MW-level output, with rated capacities ranging from 0.6 MW to 1 MW or higher [48]. In 2006, larger machines with a capacity of approximately 6 MW were developed primarily due to advancements in offshore wind turbine technology [62,63].

The largest wind turbine in the world, with a 6 MW rated capacity, was installed in Emden, Germany, in 2008, when the mean rated capacity of wind turbines reached 1.5 MW [62]. In 2010, the rated capacity range of commercial wind turbines was typically between 1 MW and 6 MW, and larger wind turbines with a 7-10 MW power capacity were under construction. In the meantime, with these advances, innovative technologies were developed to optimize wind turbine performance. New materials were introduced to minimize operating and production costs [50]. Wind turbines' mean rated capacities increased from 1.6 MW to 2 MW between 2009 and 2014. In 2014, the commercial wind turbines achieved a rated capacity of 8 MW, with rotor diameters of up to 164 m. In 2016, the maximum total altitude of a wind turbine (up to the tip of the rotor blade) increased to about 230 m. Besides, the mean turbine size worldwide reached to 2.16 MW. The mean hub height of the new commercial wind turbines was 128 m, and 50% of them altered between 119 to 141 m. In 2017, the hub heights of the wind turbines installed in the world varied between 50 and 178 m. In the same year, the mean rated capacity of the installed wind turbines was above 2.4 MW. In 2018, the largest wind turbine of 8.8 MW power capacity having a rotor diameter of 164 m was installed in the UK [64]. With a 12 MW capacity, 107 m blade length, and 220 m rotor diameter, the world's strongest offshore wind turbine was unveiled at the start of 2019 by GE Renewable Energy.

The global and European installed wind power capacity cumulatively between 2008 and 2018 is shown in Figure 3. The figure illustrates a rapidly increasing trend in the capacity of wind power installations during the given interval. By the end of 2019, the total installed wind power capacity was estimated to be 651 GW, while the cumulative capacity of installed wind power worldwide was 120.7 GW in 2008. The global wind power industry installed 51 GW of energy capacity in 2019 [64–66]. Total onshore and offshore wind capacity in the European continent reached 205 GW in 2019 to provide 14% of the EU's electricity last year.

Figure 4 presents the cumulative wind power installations by country in Europe. As seen from the figure, Germany leads Europe in installed capacity, followed by Spain, the UK, France, and Italy. The installed capacity of the other five countries namely Turkey, Sweden, Poland, Portugal, and Denmark have higher than 5 GW. Four

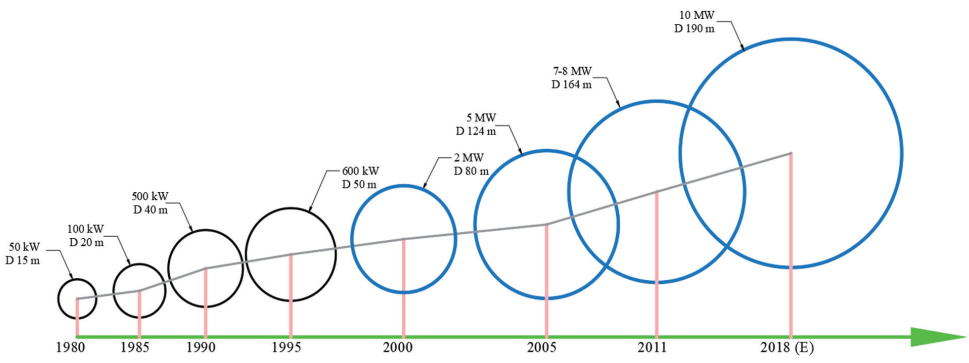


Figure 2. The history of the sizes of leading commercial wind turbines up to the present.

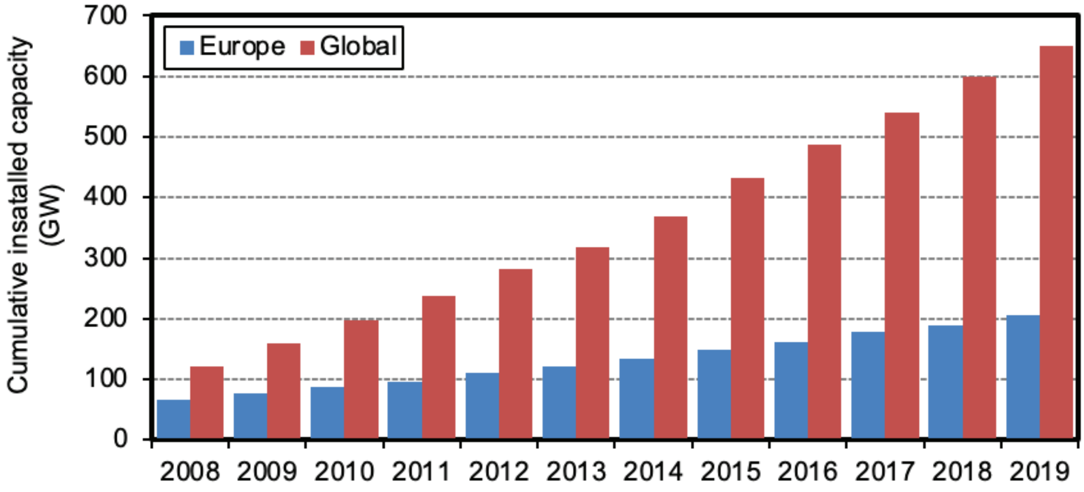


Figure 3. The global and European installed wind power capacity cumulatively between 2008 and 2018.

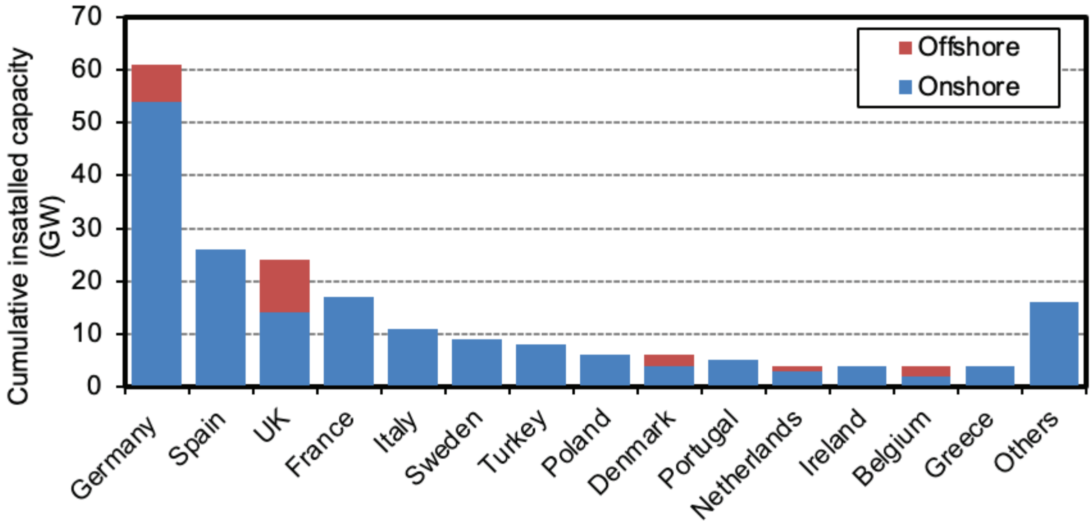


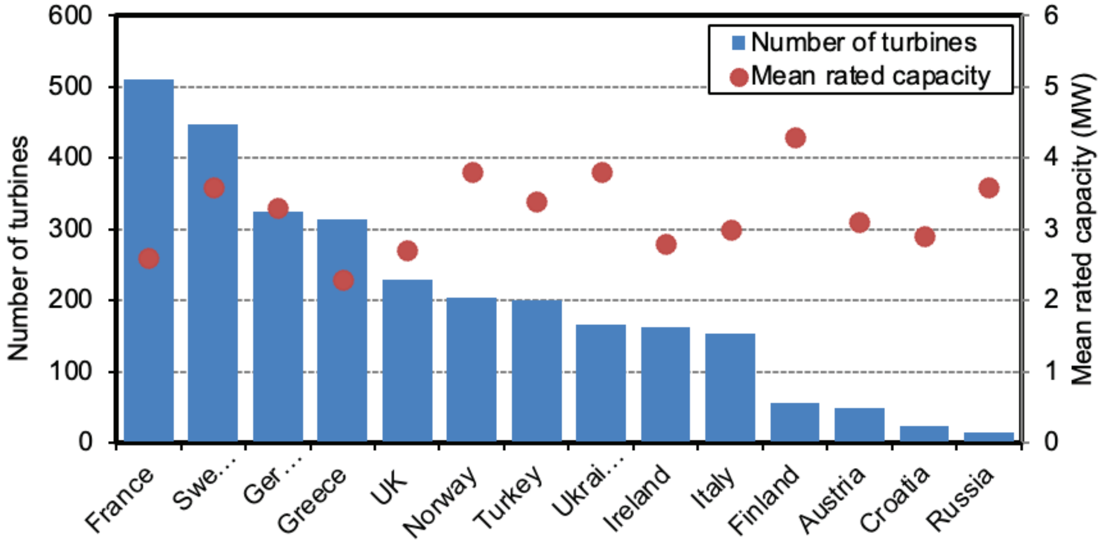
Figure 4. Cumulative wind power installations by country in Europe.

additional countries (the Netherlands, Ireland, Belgium and Greece) have over 3 GW of installed capacity [64]. In 2019, Turkey added 687 MW, thus, achieved a total of 8,057 MW installed wind power capacity.

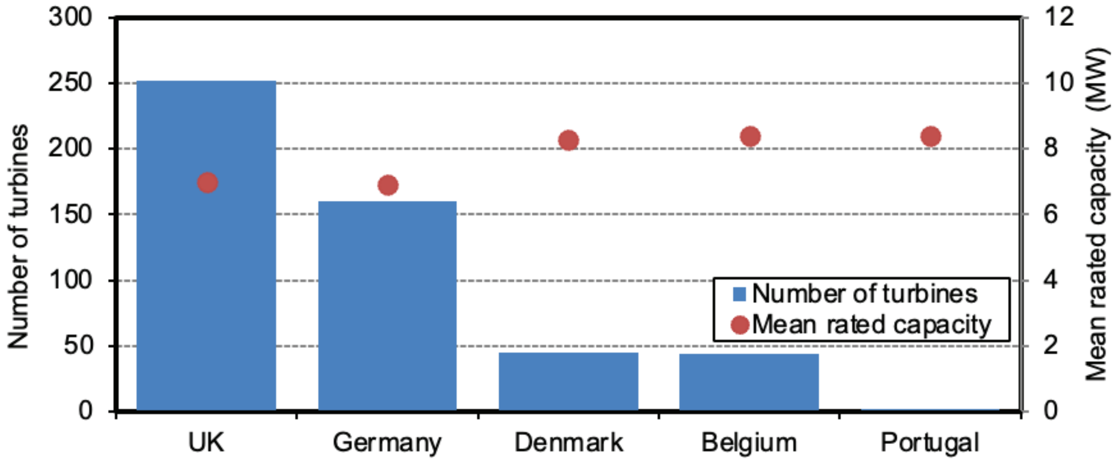
The mean rated capacity and the number of newly installed onshore and offshore wind turbines in 2019 are shown in Figure 5. The figure illustrates how the types and sizes of wind turbines installed in European countries differ significantly from one another. Finland has the highest mean rated capacity of any country's onshore wind turbines, at 4.3 MW. At 2.3 MW, Greece had the lowest mean power rating. Existing data from 14 countries indicates that Europe's weighted mean rated capacity for onshore wind turbines was 3.1 MW. The average rated capacity of newly constructed offshore turbines was 7.2 megawatts in 2019. Portugal and Belgium host the largest wind turbines in the world. In Germany, Belgium, and Portugal, three wind turbines with a rotor diameter of 164 meters and a rated capacity of 8 points 4 megawatts were installed. Conversely, Denmark's annual mean rated capacity for offshore wind turbines was 8.3 MW. The UK had the largest with a 7 MW capacity, [64].

GROWTH IN WIND TURBINE SIZE IN TURKEY

Known to be one of Europe's developing countries, Turkey is split between the continents of Asia and Europe, with the majority of its territory in Anatolia and the remainder in southeast Europe, bordered by the Aegean, Mediterranean, and Black seas [67,68]. With the 18th largest economy in the world, Turkey is considered a developing nation. Due to the country's growing population and



a) onshore



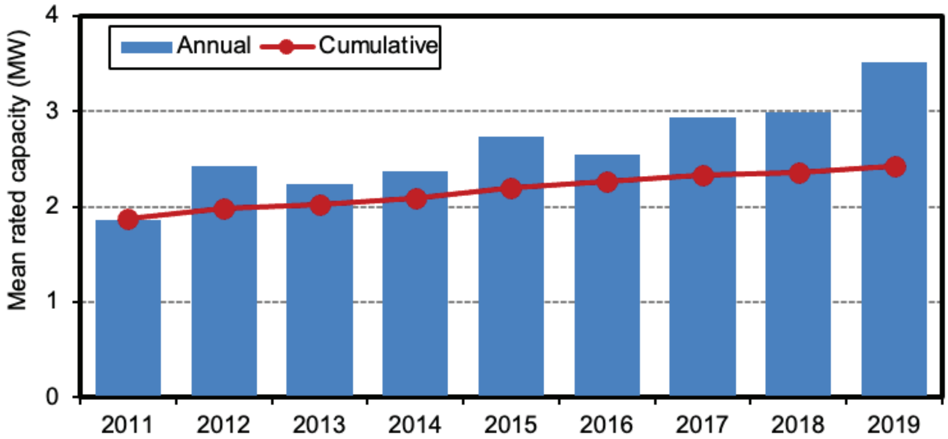
b) offshore

Figure 5. Number of installed turbines in 2018 and their mean rated capacities.

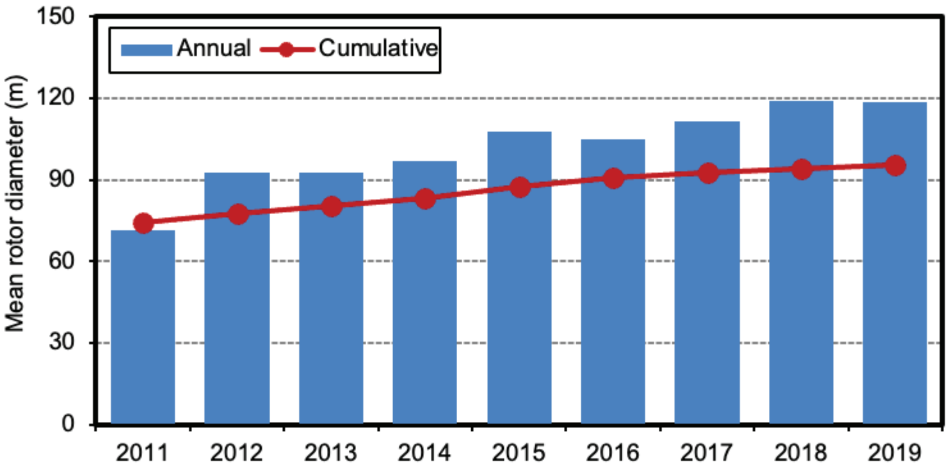
expanding economy, Turkey's needs for electrical energy have been steadily increasing. Power plants including solar, geothermal, wind, hydro, and thermal varieties produce electricity in Turkey. To date, no nuclear energy has been utilized to produce electricity. The fastest-growing installed capacities in the nation are those of thermal and hydropower [69,70]. Nonetheless, the installed capacities of geothermal, solar, and wind power are relatively small. By 1923, when the Republic of Turkey was founded, Turkey's installed power generation capacity and total electricity generation were only 33 MW and 45 GWh. Nonetheless, Turkey produced 302,552 GWh of electricity overall in 2019. Regarding the production of electricity in 2019, the share of thermal power plants accounted for 57.39 percent, or 169,534 GWh. 29.38% and 7.40%, or 88,879 GWh and 21,500 GWh, respectively, came from wind and hydropower, according to research [71].

The first wind turbine in Turkey, a Vestas 55 kW unit, was set up at the Golden Dolphin Hotel in Çeşme, Izmir, in 1985. On November, 1998, three 500 kW wind turbines (Enercon E-40) were installed in Alaçatı, Izmir, as part of the first commercial installation of modern wind turbine technology. The largest commercial wind turbine as of 2019 is 4.5 MW, with a 149 m. rotor diameter. As can be observed, wind turbine technology installed in Turkey has advanced quickly over time, becoming a more significant component of the nation's electricity market. The size of every wind farm in Turkey has grown in tandem with this development. The power of wind turbines installed in Turkey has increased. Because the cost of producing renewable energy from wind has decreased thanks to the use of the newest turbine technologies, which have longer blades that can harness more wind and produce more electricity.

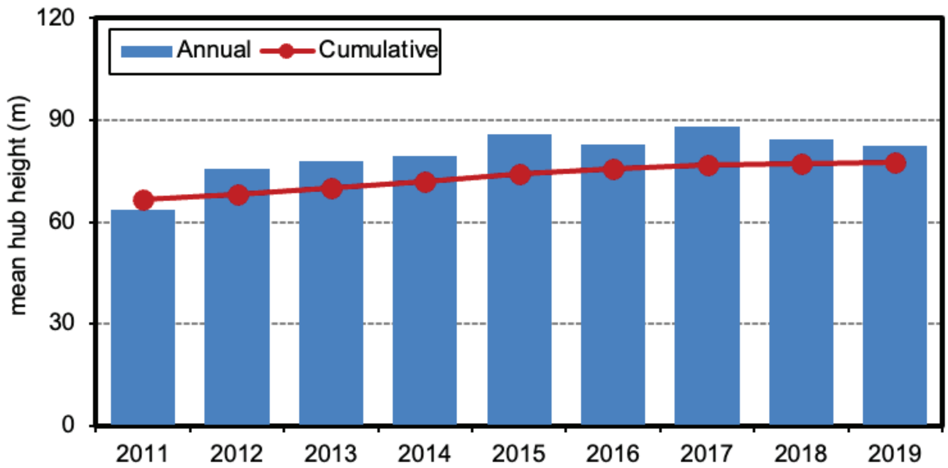
Since 2010, Turkey has experienced a significant revolution in wind energy. Increased hub heights and swept area due to advanced technologies resulted in higher capacity factors in wind turbines between 2011 and 2019. Figure 6 depicts the increase in wind turbine dimensions and size in Turkey since 2011. The figure illustrates how quickly wind



a) mean rated capacity



b) mean rotor diameter



c) mean hub height

Figure 6. The growth in size and dimension of wind turbines in Turkey.

turbine technology has advanced in Turkey in recent years. For instance, in 2011 the total installed onshore turbines had a mean rated capacity of about 1.88 MW. By 2019, this mean rated capacity had reched to 2.43 MW, a 29% increase. The mean rotor diameter reached to 95.6 m in 2019, increasing by 29 % compared to 2011. In addition, the mean hub height increased by 17% compared to 2011 and reached 77.6 m.

Turkey possesses excellent wind resources, particularly in the basins of Izmir, Hatay, Çanakkale, and Balıkesir. Based on the geographic distribution of wind turbines, the Aegean, Mediterranean, and Marmara regions exhibit greater concentrations. Figure 7 illustrates how cumulative installed wind turbine capacity in Turkey increased from 1,809 MW to 8,057 MW between 2011 and 2019. This increase was attributed to government policies, technological advancements in wind turbines, and the growing cost competitiveness of wind energy. In 2019, 687 MW of wind power capacity was installed.

Today, in Turkey and other countries, wind turbines or farms have already become an integral part of the landscape. The increase in wind farms and wind turbines in Turkey is depicted in Figures 8 and 9, respectively. Turkey now has 3,306 wind turbines overall as of 2019, up from 963 in 2011. Turkey now has 198 wind farms with a combined 8,057 MW of generating capacity. As per the state policy on electricity generation from renewable energy sources, Turkey's wind turbine and farm numbers are expected to rise significantly in the next ten years. On the other hand, this development will significantly impact how wind turbines and farms appear in the landscape. The visual effect of wind farms on the landscape is a subjective matter. Large-scale wind farms create problems for regional climate and communications services. Social research and technology developments can be used to solve problems. Therefore, impact reduction technologies and measures at various scales should be taken into account in the wind farm planning phase [72].

The decline in Turkey's installed wind turbines' mean specific power is depicted in Figure 10. The nameplate capacity of a wind turbine divided by the rotor swept area yields the specific power. The figure illustrates how Turkey's

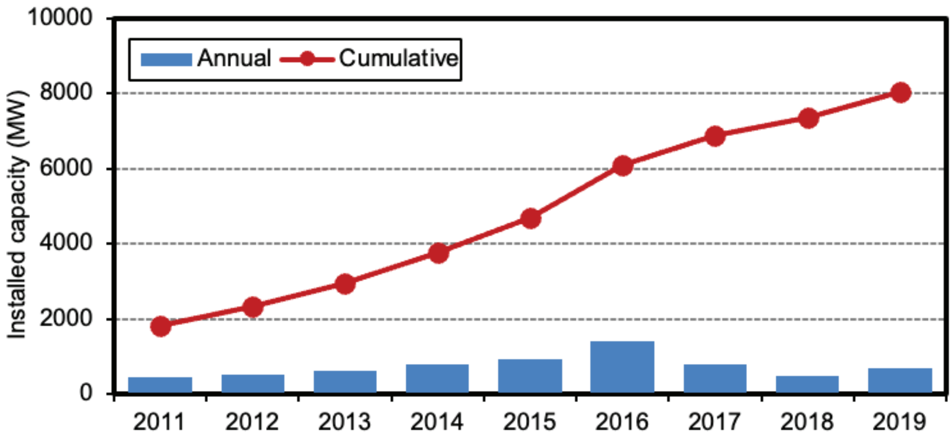
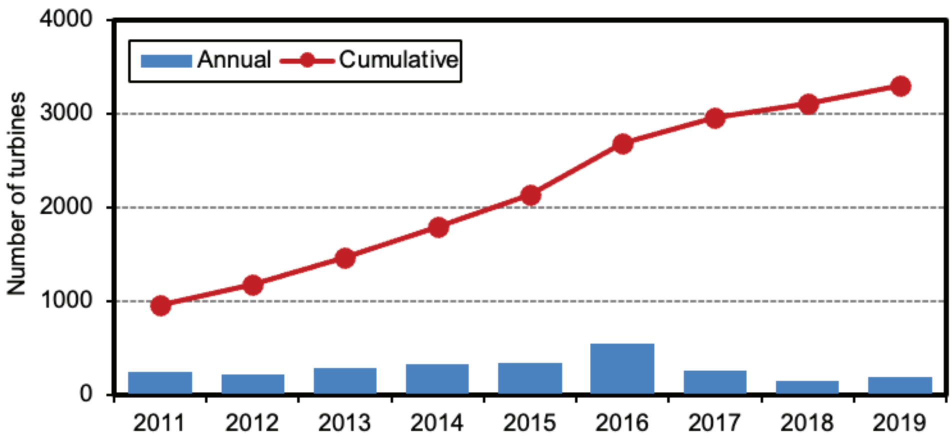
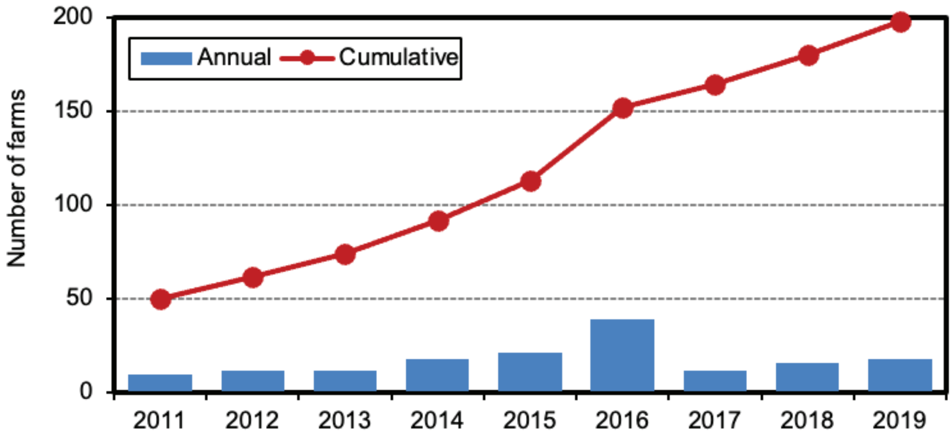


Figure 7. Installed wind turbine capacity in Turkey.



Figures 8. The growth in the number of wind turbines in Turkey.



Figures 9. The growth in the number of wind farms in Turkey.

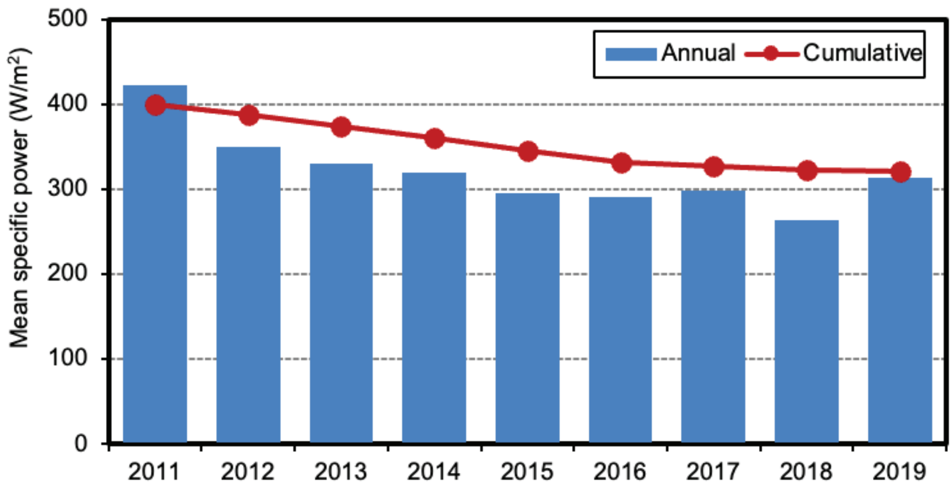


Figure 10. The decrease in the mean specific power of wind turbines installed in Turkey.

annual installed wind turbines' mean specific power dropped from 423.7 W/m^2 in 2011 to 314.1 W/m^2 in 2019. Larger rotors and higher hub heights for installed wind turbines in Turkey have formed as a result of years of global advancements in manufacturing and design engineering. Therefore, the tendency toward higher capacity factors has been aided by the increase in size of these components. Put differently, the mean specific power of wind turbines has decreased due to the presence of large, powerful turbines with long blades. Larger rotor turbines are known to have higher capacity factors due to the fact that their spinning blades cover a greater area and consume more energy. Greater access to higher wind speeds was made possible by using the taller towers to increase hub height in regions with positive wind shear, which decreased the cost of wind energy. Due to the wind turbines' longer blades, the rotor diameter and, consequently, the rotor swept area, increased especially quickly. Simultaneously, the mean nameplate capacity increased somewhat. The low specific power turbines were first intended for locations with low wind speeds, but the results indicated that they were being installed more widely across the nation, even in places with high wind speeds.

The installed wind turbines in Turkey showed a linear increase in rated capacity as a function of rotor diameter and hub height (Figures 11–13). Furthermore, a trend of linear increase was noted between the hub height and rotor diameter. As can be seen from the figures, Turkey has continued to increase its turbine capacity in addition to its tendency towards larger turbines. The rotor diameters of the turbines installed in 2019 have been between 92 and 149 meters with a mean length of 125 meters. On the other hand, the hub heights of the turbines installed in 2019 have been between 78 and 110 meters with a mean value of 87 meters, while the rated capacities of the turbines have been between 2.35 MW and 4.5 MW with a mean value of 3.5 MW.

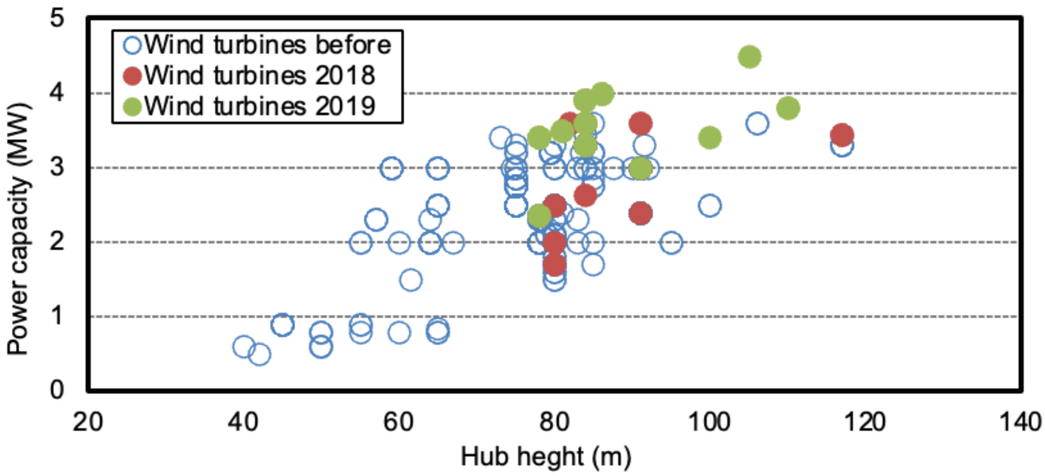


Figure 11. Correlation between power capacity and hub height for installed wind turbines in Turkey.

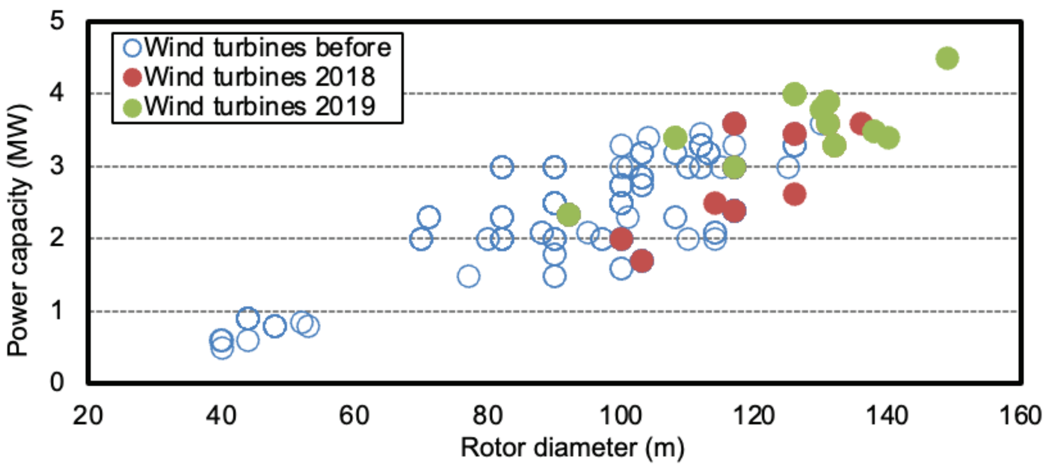


Figure 12. Correlation between power capacity and rotor diameter for installed wind turbines in Turkey.

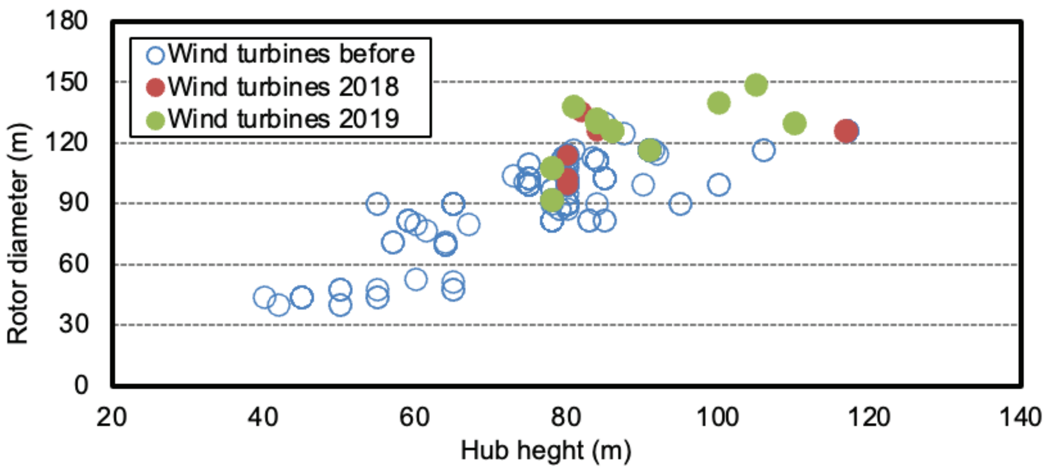


Figure 13. Correlation between rotor diameter and hub height for installed wind turbines in Turkey.

CONCLUSION

Modern commercial wind turbines have grown to multiple megawatts in size and have become more dependable and cost-effective in recent years. The average rated capacity of wind turbines that have been installed worldwide has grown since 1999; in 2017, wind turbines with an mean capacity of 2.4 MW were installed. The study determined the wind turbines installed in Turkey and their potential visibility. A thorough evaluation was conducted of the wind turbines' technological advancements, wind power potential, techno-economic viability, physical appearance, and technical attributes. The following is a summary of the study's findings:

- There are currently 198 wind farms in Turkey, consisting of 3,306 turbines, which produce 8,057 MW of generating capacity.
- As of 2019, the biggest commercial wind turbine available in Turkey is 4.5 MW, with a 149 m diameter rotor. The average installed wind turbine's rated capacity, rotor diameter, and hub height are roughly 2.43 MW, 95.06 m, and 77.06 m, respectively.
- In Turkey, the yearly average specific power of installed wind turbines dropped from 423.7 W/m^2 in 2011 to 315 W/m^2 in 2019.
- The enlargement of the rotor-swept area and hub height of wind turbines in Turkey has significantly elevated their potential visibility across the landscape in the regions.
- It is anticipated that Turkey's wind farm and turbine count will rise significantly over the next ten years as a result of the government's renewable energy policy. The aesthetic appeal of the wind farms and turbines in the landscape will be greatly affected by this development.
- In Turkey, the newest models of wind turbines feature a larger rotor swept area, which allows them to harness more wind and produce more electricity. This lowers the cost of producing renewable energy.
- Turning wind turbines into smaller wind farms with smaller hub heights has been made possible by Turkey's expanding rotor swept area.
- Turbine power coefficient and output have increased due to an increase in the rotor swept area per power capacity.
- There is a trend in Turkey where the rated capacity of wind turbines was growing linearly in relation to the hub height and rotor diameter

As a result, wind turbine technology has been developing by continually optimizing turbine design, enhancing overall turbine efficiency, and improving turbine performance. However, it is recommended that the potential visibility model has been applied before the establishment of wind turbines in terms of environmental impact in the regions.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Can A. The statistical modeling of potential biogas production capacity from solid waste disposal sites in Turkey. J Clean Prod 2020;243:118501. [CrossRef]

[2] Cooney C, Byrne R, Lyons W, O'Rourke F. Performance characterisation of a commercial-scale wind turbine operating in an urban environment, using real data. Energy Sustain Dev 2017;36:44−54. [CrossRef]

[3] Bilgili M, Bilirgen H, Ozbek A, Ekinci F, Demirdelen T. The role of hydropower installations for sustainable energy development in Turkey and the world. Renew Energy 2018;126:755−764. [CrossRef]

[4] Sharifishourabi M, Alimoradiyan H, Atikol U. Modeling of hybrid renewable energy system: The case study of Istanbul, Turkey. J Therm Eng 2016;2:990−994. [CrossRef]

[5] Liu TY, Tavner PJ, Feng Y, Qiu YN. Review of recent offshore wind power developments in China. Wind Energy 2013;16:786−803. [CrossRef]

[6] Askarzadeh A. Optimisation of solar and wind energy systems: a survey. Int J Ambient Energy 2017;38:653−662. [CrossRef]

[7] Kankal M, Bayram A, Uzlu E, Satilmiş U. Assessment of hydropower and multi-dam power projects in Turkey. Renew Energy 2014;68:118−133. [CrossRef]

[8] Koç C. A study on the development of hydropower potential in Turkey. Renew Sustain Energy Rev 2014;39:498−508. [CrossRef]

[9] Celik A, Javani N. Wind turbine blade flapwise and edgewise bending vibration analyses using energy methods. J Therm Eng 2016;2:983−989. [CrossRef]

[10] Ozcan M. The role of renewables in increasing Turkey's self-sufficiency in electrical energy. Renew Sustain Energy Rev 2018;82:2629−2639. [CrossRef]
[11] Chattopadhyay M, Chattopadhyay D. Renewable energy contingencies in power systems: Concept and case study. Energy Sustain Dev 2020;54:25−35. [CrossRef]
[12] Xu M, Buyya R. Managing renewable energy and carbon footprint in multi-cloud computing environments. J Parallel Distrib Comput 2020;135:191−202. [CrossRef]
[13] Lin B, Zhu J. Determinants of renewable energy technological innovation in China under CO2 emissions constraint. J Environ Manage 2019;247:662−671. [CrossRef]
[14] Yao S, Zhang S, Zhang X. Renewable energy, carbon emission and economic growth: A revised environmental Kuznets Curve perspective. J Clean Prod 2019;235:1338−1352. [CrossRef]
[15] Sun X, Huang D. An Explosive Growth of Wind Power in China. Int J Green Energy 2014;11:849−860. [CrossRef]
[16] REN21. Renewables 2018 Global Status Report. Available at: https://www.ren21.net/wp-content/uploads/2019/05/GSR2018_Full-Report_English.pdf. Accessed February 21, 2024.
[17] Bilgili M, Ozbek A, Sahin B, Kahraman A. An overview of renewable electric power capacity and progress in new technologies in the world. Renew Sustain Energy Rev 2015;49:323−334. [CrossRef]
[18] Bulut U, Muratoglu G. Renewable energy in Turkey: Great potential, low but increasing utilization, and an empirical analysis on renewable energy-growth nexus. Energy Policy 2018;123:240−250. [CrossRef]
[19] Wang S, Wang S. Impacts of wind energy on environment: A review. Renew Sustain Energy Rev 2015;49:437−443. [CrossRef]
[20] Jones CR, Richard Eiser J. Understanding "local" opposition to wind development in the UK: How big is a backyard? Energy Policy 2010;38:3106−3117. [CrossRef]
[21] Zheng CW, Li CY, Pan J, Liu MY, Xia LL. An overview of global ocean wind energy resource evaluations. Renew Sustain Energy Rev 2016;53:1240−1251. [CrossRef]
[22] IRENA. Wind Power Technology Brief. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA-ETSAP_Tech_Brief_Wind_Power_E07.pdf. Accessed February 21, 2024.
[23] Mendecka B, Lombardi L. Life cycle environmental impacts of wind energy technologies: A review of simplified models and harmonization of the results. Renew Sustain Energy Rev 2019;111:462−480. [CrossRef]
[24] Kazimierczuk AH. Wind energy in Kenya: A status and policy framework review. Renew Sustain Energy Rev 2019;107:434−445. [CrossRef]
[25] Köktürk G, Tokuç A. Vision for wind energy with a smart grid in Izmir. Renew Sustain Energy Rev 2017;73:332−345. [CrossRef]
[26] Gualtieri G. A comprehensive review on wind resource extrapolation models applied in wind energy. Renew Sustain Energy Rev 2019;102:215−233. [CrossRef]
[27] Ahmed AS. Wind energy characteristics and wind park installation in Shark El-Ouinat, Egypt. Renew Sustain Energy Rev 2018;82:734−742. [CrossRef]
[28] Tagliapietra S, Zachmann G, Fredriksson G. Estimating the cost of capital for wind energy investments in Turkey. Energy Policy 2019;131:295−301. [CrossRef]
[29] Kılıç B. Determination of wind dissipation maps and wind energy potential in Burdur province of Turkey using geographic information system (GIS). Sustain Energy Technol Assess 2019;36:100555. [CrossRef]
[30] Park J, Kim B. An analysis of South Korea's energy transition policy with regards to offshore wind power development. Renew Sustain Energy Rev 2019;109:71−84. [CrossRef]
[31] Igwemezie V, Mehmanparast A, Kolios A. Current trend in offshore wind energy sector and material requirements for fatigue resistance improvement in large wind turbine support structures - A review. Renew Sustain Energy Rev 2019;101:181−196. [CrossRef]
[32] Emeksiz C, Demirci B. The determination of offshore wind energy potential of Turkey by using novelty hybrid site selection method. Sustain Energy Technol Assess 2019;36:100562. [CrossRef]
[33] Argin M, Yerci V, Erdogan N, Kucuksari S, Cali U. Exploring the offshore wind energy potential of Turkey based on multi-criteria site selection. Energy Strateg Rev 2019;23:33−46. [CrossRef]
[34] Cali U, Erdogan N, Kucuksari S, Argin M. TECHNO-ECONOMIC analysis of high potential offshore wind farm locations in Turkey. Energy Strateg Rev 2018;22:325−336. [CrossRef]
[35] IEA. Technology Roadmap - Wind Energy 2013. Available at: https://www.iea.org/reports/technology-roadmap-wind-energy-2013. Accessed February 21, 2024.
[36] ENERGIA. Renewables 2018 Global Status Report (REN21) Released. Available at: https://energia.org/renewables-2018-global-status-report-ren21/. Accessed February 21, 2024.
[37] Celik AN. A techno-economic analysis of wind energy in southern Turkey. Int J Green Energy 2007;4:233−247. [CrossRef]
[38] Wilburn DR. Wind energy in the United States and materials required for the land-based wind turbine industry from 2010 through 2030. USGS Sci Invest Rep 2011:5036. [CrossRef]
[39] Saidur R, Rahim NA, Islam MR, Solangi KH. Environmental impact of wind energy. Renew Sustain Energy Rev 2011;15:2423−2430. [CrossRef]

[40] Chen J. Development of offshore wind power in China. Renew Sustain Energy Rev 2011;15:5013−5020. [CrossRef]
[41] Karthikeyan N, Kalidasa Murugavel K, Arun Kumar S, Rajakumar S. Review of aerodynamic developments on small horizontal axis wind turbine blade. Renew Sustain Energy Rev 2015;42:801−822. [CrossRef]
[42] Korompili A, Wu Q, Zhao H. Review of VSC HVDC connection for offshore wind power integration. Renew Sustain Energy Rev 2016;59:1405−1414. [CrossRef]
[43] Lin YT, Chiu PH, Huang CC. An experimental and numerical investigation on the power performance of 150 kW horizontal axis wind turbine. Renew Energy 2017;113:85−93. [CrossRef]
[44] Maheri A. Simulation of wind turbines utilising smart blades. J Therm Eng 2016;2:557−565. [CrossRef]
[45] Sener B, Aytac S. The renewable energy potential of Turkish coasts and a concept design of a near shore sea platform. J Therm Eng 2017;3:1211−1220. [CrossRef]
[46] Cetin B. Parametric analysis of electrical energy production by wind energy for Bozcaada. J Therm Eng 2019;5:271−276. [CrossRef]
[47] Kavak Akpınar E. Statistical analysis of wind speed distribution with Sinop-Turkey application. J Therm Eng 2019;5:277−292. [CrossRef]
[48] Islam MR, Mekhilef S, Saidur R. Progress and recent trends of wind energy technology. Renew Sustain Energy Rev 2013;21:456−468. [CrossRef]
[49] Kumar Y, Ringenberg J, Depuru SS, Devabhaktuni VK, Lee JW, Nikolaidis E, et al. Wind energy: Trends and enabling technologies. Renew Sustain Energy Rev 2016;53:209−224. [CrossRef]
[50] Tong W. Fundamentals of wind energy. WIT Trans State Art Sci Engineer 2010;44:1755−8336. [CrossRef]
[51] Pishgar-Komleh SH, Akram A. Evaluation of wind energy potential for different turbine models based on the wind speed data of Zabol region, Iran. Sustain Energy Technol Assess 2017;22:34−40. [CrossRef]
[52] Lehtola T, Zahedi A. Solar energy and wind power supply supported by storage technology: A review. Sustain Energy Technol Assess 2019;35:25−31. [CrossRef]
[53] ETIPWIND. Strategic Research and Innovation Agenda 2018. Available at: https://etipwind.eu/wp-content/uploads/2018-Strategic-Research-Innovation-Agenda.pdf. Accessed February 21, 2024.
[54] Söderholm P, Pettersson M. Offshore wind power policy and planning in Sweden. Energy Policy 2011;39:518−525. [CrossRef]
[55] Argin M, Yerci V. Offshore wind power potential of the Black Sea region in Turkey. Int J Green Energy 2017;14:811−818. [CrossRef]
[56] Singh S, Singh M, Kaushik SC. A review on optimization techniques for sizing of solar-wind hybrid energy systems. Int J Green Energy 2016;13:1564−1578. [CrossRef]
[57] McKenna R, Ostman P, Fichtner W. Key challenges and prospects for large wind turbines. Renew Sustain Energy Rev 2016;53:1212−1221. [CrossRef]
[58] Nathan S. GE launches world's most powerful offshore wind turbine. Available at: https://www.theengineer.co.uk/content/news/ge-launches-world-s-most-powerful-offshore-wind-turbine/. Accessed February 21, 2024.
[59] Leung DYC, Yang Y. Wind energy development and its environmental impact: A review. Renew Sustain Energy Rev 2012;16:1031−1039. [CrossRef]
[60] Kaldellis JK, Zafirakis D. The wind energy (r)evolution: A short review of a long history. Renew Energy 2011;36:1887−1901. [CrossRef]
[61] Blaabjerg F, Ma K. Future on power electronics for wind turbine systems. IEEE J Emerg Sel Top Power Electron 2013;1:139−152. [CrossRef]
[62] RAENG. Wind Energy: implications of large-scale deployment on the GB electricity system. Available at: https://raeng.org.uk/media/duifixd5/wind_report.pdf. Accessed February 21, 2024.
[63] ETIPWIND. Wind Energy: A Vision for Europe in 2030. Available at: https://etipwind.eu/files/reports/TPWind-Vision-for-Europe.pdf. Accessed February 21, 2024.
[64] WindEurope. Wind energy in Europe in 2018: Trends and statistics. Available at: https://windeurope.org/about-wind/statistics/european/wind-energy-in-europe-in-2018/. Accessed February 21, 2024.
[65] EWEA. Offshore wind in Europe. Available at: https://www.ewea.org/fileadmin/files/library/publications/reports/EY-Offshore-Wind-in-Europe.pdf. Accessed February 21, 2024.
[66] GWEC. Global Wind Report 2018. Available at: https://solarprosumer.com/wp-content/uploads/lib025-gwec-global-wind-report-april2019.pdf. Accessed February 21, 2024.
[67] Bilgili M. A global review of wind power installations and their development in Turkey. CLEAN - Soil, Air, Water 2009;37:195−202. [CrossRef]
[68] Bilgili M, Şahin B. Electric power plants and electricity generation in Turkey. Energy Sources, Part B Econ Planning, Policy 2009;5:81−92. [CrossRef]
[69] Saidur R, Islam MR, Rahim NA, Solangi KH. A review on global wind energy policy. Renew Sustain Energy Rev 2010;14:1744−1762. [CrossRef]
[70] Kaplan YA. Overview of wind energy in the world and assessment of current wind energy policies in Turkey. Renew Sustain Energy Rev 2015;43:562−568. [CrossRef]
[71] Turkish Electricity Transmission Corporation. Electricity Statistics 2019. Available at: https://www.teias.gov.tr/turkiye-elektrik-uretim-iletim-istatistikleri. Accessed February 21, 2024.
[72] Dai K, Bergot A, Liang C, Xiang WN, Huang Z. Environmental issues associated with wind energy - A review. Renew Energy 2015;75:911−921. [CrossRef]