

Onshore Wind Farm Development: Technologies and Layouts

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Abstract: Significantly growing wind energy is being contemplated as one of the main avenues to reduce carbon footprints and decrease global risks associated with climate change. However, obtaining a comprehensive perspective on wind energy considering the many diverse factors that impact its development and growth is challenging. A significant factor in the evolution of wind energy is technological advancement and most previous reviews have focused on this topic. However, wind energy is influenced by a host of other factors, such as financial viability, environmental concerns, government incentives, and the impact of wind on the ecosystem. This review aims to fill a gap, providing a comprehensive review on the diverse factors impacting wind energy development and providing readers with a holistic panoramic, furnishing a clearer perspective on its future growth. Data for wind energy was evaluated by applying pivot data analytics and geographic information systems. The factors impacting wind energy growth and development are reviewed, providing an overview of how these factors have impacted wind maturity. The future of wind energy development is assessed considering its social acceptance, financial viability, government incentives, and the minimization of the unintended potential negative impacts of this technology. The review is able to conclude that wind energy may continue growing all over the world as long as all the factors critical to its development are addressed. Wind power growth will be supported by stakeholders' holistic considerations of all factors impacting this industry, as evaluated in this review.

Keywords: wind energy; onshore wind farms; wind development; wind farm layout



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1. Introduction

Sustainably increasing the living standards of global populations is one of the biggest challenges for world economies. Lifting populations from poverty all over the world without compromising future generations from enjoying equal or improved living standards is the goal of sustainable development [1]. However, during the 20th century many technologies had unintended consequences. The use of hydrocarbons as fuel generated air pollution and greenhouse gases that caused climate change [2]. The use of fertilizers also caused algae blooms and a depletion of aquatic life [3]. For these reasons, any new applied solution should be sustainable, always looking to improve current standards without endangering those of future generations. This is one of the most important advantages of renewable energy. It has been shown to provide energy without any of the most deleterious disadvantages of traditional hydrocarbon fuels [4].

Increasing the use of renewable energy is one of the main components of policies to overcome challenges from climate change [5]. Expanding energy availability to communities all over the world is critical considering that clear correlations between energy usage and quality of life has been determined. Therefore, increasing energy usage will allow communities to satisfy an ever-growing number of essential needs, such as clean water, food production, health services, and education [6]. Renewable energy is an effective way of providing sustainable energy to many global communities. It has been increasing

penetrating grids all over the world, providing electricity at competitive prices without the emission of air pollutants or greenhouse gases [7]. Among renewable energy resources, wind and solar are the technologies growing at the fastest pace. For the last decade, wind energy has been the fastest-growing energy generation source in many regions and has become competitive even with natural gas. It has been forecasted that wind energy, coupled other renewable energy resources and advanced energy storage technology, has the potential to satisfy the global economy's energy needs [8].

Wind energy is a complex topic and its growth has historically been impacted by divergent factors. Some of the factors creating the highest impact are technology advancement, climate change, community environmental concerns, fuel scarcity, successful market competition, and societal concerns on its potentially deleterious implications. Previous reviews have focused on particular factors impacting wind energy growth. A broader review in the topic is relevant to better understand the main implications of the diverse factors of wind development. Some examples of works focused only on technology development are described. Sawant et al. developed a review focused on the technology and optimization of wind energy [9]. The review provided by Spyridonidou et al. focuses on the wind site-selection process, considering diverse methods and optimization approaches [10]. Herbert-Acero et al. also focused on technology, evaluating state-of-the-art methods for the design and optimization of wind farms [11]. Resource assessment technologies and methodologies were reviewed by Probst et al. providing insight on the newer tools available for accurate wind modeling at diverse heights [12]. On the other hand, the review provided by Sine et al. provides insight on the impact of the environmental movement on wind energy development [13], while the work of Yuksel et al. focuses on government financial incentives to promote wind [14].

Considering that existing reviews only focus in one factor, a holistic approach comprising all potential factors impacting wind energy growth is necessary to better understand the past performance of this industry and forecast its future growth. A comprehensive review approach allows for better comprehension of uneven historical wind energy development, with the last five decades showcasing significant periods of high activity followed by times of stagnant growth. Furthermore, the holistic review presented in this manuscript allows for a better understanding of the accelerated growth of wind energy over the last decade, namely the supplying of electricity for large economic sectors for long periods of time. This review helps to explain how wind energy is becoming the lowest electricity generation alternative in a number of regions around the world. This work aims to provide resources for a better comprehension of the diverse factors that brought onshore wind energy to its current position. This will allow for an improving incentivization and growth forecasting of the wind energy industry, understanding the parameters that need to be promoted to maintain and accelerate onshore wind energy development in the upcoming decades. This review paper is structured into six sections, integrating the diverse factors impacting wind energy growth and development. Section 1 contains the introduction, Section 2 reviews factors impacting wind energy growth, while Section 3 describes the evolution of wind equipment. Section 4 provides a broad overview of approaches to improve and optimize wind power, Section 5 integrates social acceptance and wind farm configuration, and Section 6 compiles all discussed elements into a holistic forecast overview for wind energy growth.

2. Factors Impacting Wind Energy Growth

2.1. Factors Propelling the Genesis of Wind Industry

Mankind has harnessed energy from the wind for millennia, aiding civilizations in performing diverse activities [15]. However, the origins of this technology have been lost in historical records and early uses of wind are still under evaluation by researchers. There are indications that Hammurabi in Babylon planned to use wind to irrigate land, although its implementation is still under study [16,17]. It has been claimed that Heron of Alexandria applied windmills to generate music using an organ [18]. In Persia, the use of vertical

wind equipment to mill grain was gradually developed after the seventh century AD, with more concrete records of large windmills in the 13th century, which were able to process a ton of grain per day during a four-month windy season [17]. In the 10th century, horizontal-axis cruciform windmills were developed and became prevalent in northern Europe, creating sturdier equipment capable of harnessing much more power from the wind. This equipment continued to be used to mill grains but gradually was additionally applied for drainage, pumping out water from large areas in relatively short times, at low costs. Equipment to harness wind became popular and its application was widespread in windy areas [15,19,20].

With the advent of the industrial revolution and the introduction of steam boilers and pistons, it was able to generate much more power than wind with compact equipment, and wind equipment all but disappeared from urban areas and industrial installations [21,22]. However, in regions where fuel was limited and wind was abundant, installations of wind turbines continued to flourish for agricultural purposes, to mill grain, pump water from underground reservoirs, and, later on, to generate electricity [23]. As electricity use became widespread in the 20th century, wind turbines were integrated with dynamos and supplied this resource in many locations [15,19,20]. Fuel shortages during the First and Second World Wars made many countries reevaluate the potential of wind to provide electricity without relying on imported fuels [15,24]. Wind turbines made a comeback at this time and agricultural equipment manufacturers took the lead on installing wind equipment. The first wind turbine with aerodynamic blades and a concrete tower was developed in Denmark at this time [23]. During the next three decades, significant R&D efforts were performed both in the US and Europe but competition with abundant inexpensive hydrocarbons led wind to be considered as uneconomical [19].

The oil crises of 1973 and 1979 significantly increased interest in renewable energy, as structural vulnerabilities generated by dependence on imported fuels, subject to significant variability on price and availability, were highlighted [25]. Stakeholders realized that renewable-energy-applied local resources can be accessed without significant cost once the CapEx (capital expenditures) and OpEx (operating expenses) have been prorated. Considering its many advantages, wind became one of the main components of a renewable energy portfolio. These advantages include its successful use for centuries, the fact that wind R&D never stopped after the Second World War, and that there was a significant manufacturing sector already engaged in this endeavor for agricultural purposes [26,27]. Governments and private corporations labored to transition wind turbines from smaller equipment geared to agriculture to larger industrial harvesters capable of generating larger power outputs to supply communities and industry [19]. Significant improvements were obtained during this period, with NASA aiming to develop and construct large wind turbines [23]. California's large wind energy growth in the 1980s was propelled by a combination of environmental activism, government regulations prohibiting the construction of new electricity generation plants powered by hydrocarbons, and aggressive tax incentives [19]. Denmark emerged at this time as the world's leader in wind turbine manufacturing, supplying the nascent industry with reliable and efficient equipment. Most of the turbines at Altamonte Pass, one of the first wind farms developed in California in the 1980s, were supplied by Vestas, a Danish agricultural manufacturer that transitioned into grid-scale wind energy [19].

In the 1990s, several factors propelled the development of wind energy. Energy independence continued to be a significant concern all over the world considering fluctuating changes in hydrocarbon prices and availability due to diverse political instabilities and economic downturns [20,25]. At the same time, advances in environmental science made clear to scientists and world leaders that climate change was the greatest contemporary threat to human prosperity and development. The continuing increase in the emissions of greenhouse gases was agreed to be unsustainable by the 1997 Kyoto United Nations Conference, with many nations signing a protocol agreeing to reduce these emissions [28,29]. Currently, 192 parties integrate the Kyoto Protocol [30]. One of the most promising so-

lutions to curb greenhouse gases emissions is substituting hydrocarbons with renewable energy for electricity generation. This has created great interest in wind energy from both governments and environmental organizations [31–33].

Wind energy benefits have been highlighted by life-cycle analysis, which determined that the wind industry has a short CO₂ payback period (6 to 14 months), and a payback time for energy consumption between 6 and 17 months [34]. The financial payback period of a wind farm depends on many factors, among them CapEx, OpEx, wind farm power output over time, and electricity prices [35]. It has been indicated that for wind farms installed before 2010 the financial payback time would range between 13 and 14 years [36]. However, as technology advances, payback periods have been decreasing, making wind projects financially more attractive for investors, with repayment periods as low as 10 years [35].

Community investment in local wind farms has been considered as a good option to incentivize its development and reduce social opposition to these projects [37]. For instance, in 2014 there were 12 operational community investment commercial renewable energy projects in Scotland, indicating significant interest in these projects by local communities [38]. Beery et al. indicated that incorporating local community investment in wind projects mitigated some negative effects of external investment while providing local economic participation and reducing social opposition [37]. However, as modern wind farms become more complex, larger, and more expensive, local communities will need to perform extensive risk analyses on the potential financial risks of investing in these projects. Wind energy financial expertise will need to be brought to local communities to evaluate project feasibility and the potential risk exposure for each community [39].

2.2. Government Policy Impact on Wind Development

Public research funding was a major propeller of renewable energy R&D during the last decades of the 20th century. In the US, the National Renewable Energy Laboratory (NREL), established in 1977, invested public funding in developing renewable energy technology, including wind [19]. It has generated technologies that have advanced global wind energy, among them simulation software to model wind site conditions and power generation and grid interconnexion [40,41]. In other nations, public research funding has been crucial in wind energy development as well. In Denmark, the Technical University of Denmark (DTU) has been a very important component for performing wind energy research since the 1950s through public funding to advance technology. Some of the most important developments in wind energy have emerged from these research centers [42–44]. The adoption of the three-blade rotor, its aerodynamic modeling to improve power generation, and the optimization of components to maximize power extraction, are some of the developments that have aided this industry to become competitive [19,23]. The development of simulation computer models to assess wind energy potential, power output maximization, layout optimization, and its integration to the electric grid with a high degree of resolution have provided the industry with powerful tools to create a competitive wind industry [42].

Tax incentives have been another very important element to incentivize wind energy development in many locations all over the world [45–47]. The original wind energy development in California during the 1980s was significantly aided by state tax incentives that reduced dramatically CapEx and OpEx [21,22,47–49]. The Texas Economic Development Act of 2001 allowed for coordination between local authorities, school districts, and wind industry, providing significant tax incentives for wind developers. This has provided economic incentives to install wind farms in rural areas in Texas, generating good-paying jobs, lease payments for local landowners, and significant resources for school districts. These elements have been a significant factor in the development of wind energy in Texas [50–52]. Figure 1 showcases a world map with an overview of applicable tax benefits and local taxes, as reported by the global consulting firm KPMG [53]. The category of tax benefits includes national regulations that allow for accelerated depreciation or to incentivize wind energy

consumption. These tax incentives enhance a project's return of investment and reduce long-term risks. Local taxes involve a reduction in real estate or capital taxes, contributing to installing larger and more expensive wind farms. Therefore, each one promotes different stages in the life cycle of wind facilities [54,55].

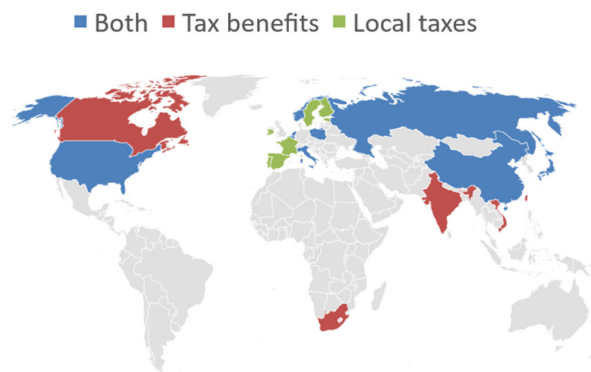


Figure 1. Map with overview of tax benefits and local taxes per country.

Feed-in tariffs have also played a relevant role promoting wind energy development in diverse global locations. From 1980 to 2010, in most regions, wind energy was significantly more expensive than electricity generated from hydrocarbon fuels [56,57]. The novelty of the technology, the low scale of the facilities and the equipment, the lack of proper financial supporting instruments, and low reliability made wind kWh more expensive than other alternatives [51,58–60]. To incentivize the development of wind energy, governments provided financially beneficial access to the electric grid to wind operators. These incentives had the goals of decarbonizing the economy, reducing greenhouse gas emissions, and providing a platform to develop an economically viable wind industry. Benefits took the form, in many instances, of long-term contracts guaranteeing preferential access to the grid and base kWh prices for wind energy [61,62]. These schemes have been implemented in many countries, including Germany, Spain, the United States, and Japan [56]. Although controversial, this strategy has been credited with generating significant interest in wind energy development and insuring the growth of renewable energy. Figure 2 highlights the feed-in tariff average and maximum values provided by countries belonging to the Organization for Economic Co-operation and Development (OECD) from 2000 to 2019. The average value is indicated in the primary vertical axis, while the maximum value is in the secondary vertical axis. These values highlight countries trying to promote the long-term generation and consumption of wind energy, reducing the risk of the projects for developers and improving the return of investment [54,55,58].

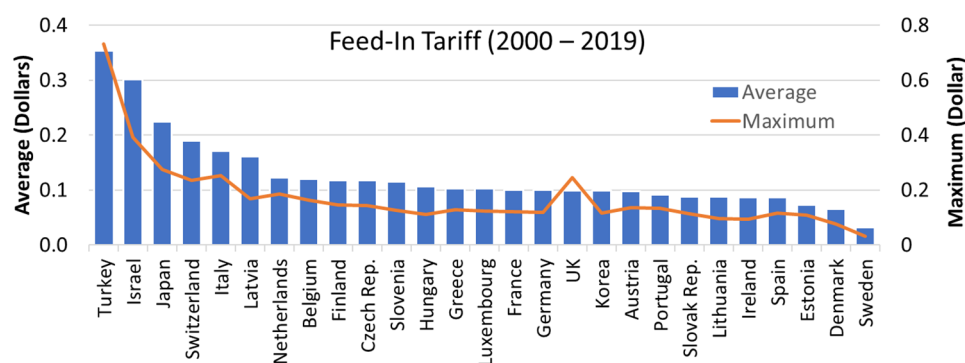


Figure 2. Feed-in tariff for wind energy by OECD countries.

Wind farms are usually located in rural or remote locations where meteorological conditions are favorable. These locations are normally far away from consumption centers and

therefore one of the main hurdles for their development is the installation of high-power transmission lines, extending in many cases hundreds of kilometers. This infrastructure is extremely expensive and complex to create [63,64]. Previous projects have generated social opposition from local communities in the path of these cables which see only disadvantages and none of the benefits from this infrastructure [65]. This may lead to significant cost increases due to complex negotiations with local communities and potential cable undergrounding or path changes on the route of the cables, increasing considerably the total cost or length. Significant public, state, and federal investment has been devoted to these projects all over the world to incentivize wind energy development [66,67]. For instance, in Texas between 2008 and 2013, public investment was applied to build more than 3700 km of transmission lines to bring wind power from west Texas to the large urban areas in the east of the state [44,45]. The Competitive Renewable Energy Zones (CREZ) infrastructure ended up costing more than seven billion dollars [68] and has been credited with making Texas the state in the US with the highest installed capacity of wind energy [51,52]. In Germany, public investment in transmission infrastructure to bring wind power from the north to the interior and south areas has led to some of the largest construction projects in Europe. For instance, SuedLink will be the longest underground high-power transmission line in the world, with a length of 700 km. The project will have a cost of 10 billion dollars and will bring wind power from the north to large industrial and consumption areas in Bavaria, in the south.

2.3. Environmental Movement and Wind Energy

Several events during the last part of the 1960s contributed to the development of a widespread societal environmental moment [69–71]. These events coalesced in the Spring of 1970 in the first Earth Day, congregating 20 million citizens across different cities in the US. The idea was to force environmental issues into the national political agenda [72,73]. As a result, during the 1970s, the US Congress created the Environmental Protection Agency and promulgated a significant number of federal environmental laws and regulations [72,74]. These events also brought concerns about conservation and sustainability to the forefront of social conscience, leading to the creation of community-based organizations geared to environmental protection [70,75]. Renewable energy was considered as beneficial by these movements and government organizations promoting sustainability and avoiding pollution [76,77].

However, since during the 1970s wind and solar technology were in initial R&D stages and not able to significantly contribute, more pressing environmental concerns took priority [20,25]. It was not until the 1990s that wind energy started to mature, significantly expanding all over the world and becoming financially competitive with hydrocarbons in the generation of electricity [19]. Concerns about climate change linked to the anthropogenic emissions of greenhouse gases brought renewable energy, particularly wind, to the forefront of the attention of environmental scientists and stakeholders. Diverse UN conferences on climate change highlighted the need to decarbonize electricity generation and the need to significantly increase renewable energy generation as a means to achieve this goal [28,33]. Since 2010, wind energy has considerably increased its competitiveness with hydrocarbon electricity generation. Since 2015, in many locations of the world, wind offers the lowest kWh price, even lower than natural gas. Environmental sustainability and financial competitiveness have made wind energy as one of the main strategies to curb climate change.

Although wind energy has significant sustainability benefits, environmental organizations, communities, and stakeholders have pointed out some challenges for this technology. Some social opposition to wind has arisen considering these concerns [78–80]. An important sustainability challenge facing wind energy is its potential impact on local wildlife, particularly birds and bats [81,82]. Other potentially negative impacts involve visual and noise pollution, causing social opposition from local communities [83]. Some studies have indicated that large wind farms have the potential to reduce moisture in the soil, decrease

the soil's organic carbon [84], and increase the temperature in the wind farm area, as well as downstream from the facility [84,85]. This may be concerning considering agricultural use in the vicinity of wind farms [84]. However, other research has generated contradictory results, indicating that wind farms contribute to increased agricultural yields in neighboring areas [86]. Therefore, additional research is required to validate findings and ascertain if mitigation measures are required [84,85]. Other challenges in wind energy sustainability relate to the end of life of wind turbines, particularly the blades and electronic equipment. Many mature wind energy markets, such as Germany and the US, are struggling to find adequate disposal solutions for this equipment. Blades are especially difficult to sustainably dispose of due to their composition and size [87].

The impact of this technology on wildlife is a concern among wind developers, governments, communities, environmental groups, and stakeholders. Considering the rotor's high speeds and turbulence, it has been documented that birds and bats have suffered impacts with blades, causing injuries and deaths. This has led to more stringent requirements on impact assessment studies for wind farms and their potential impact on local wildlife, birds, migratory birds, and bats [88,89]. Several planned wind farms have been modified and or even cancelled when they may potentially interfere with the normal paths of migratory species or affect the habitats of bats and birds. Wind farm operators are evaluating diverse alternatives to reduce and eliminate the risks caused by the equipment to these species [90]. Developers are using special paint colors or paint patterns to make equipment more distinctive for flying fauna, allowing them to change their path and avoid collisions [82,91]. Airborne detection systems, such as radar, are being deployed in many facilities to stop equipment when flocks of birds approach the wind farm. Other approaches have been explored, such as making the wind farm area less attractive to bird prey by tilling the soil in the vicinity of turbine towers, resulting in a collisions reduction between 75% and 100%. For bat-mortality reduction, the use of ultrasonic countermeasures to discourage them from approaching wind farms has proven successful. Technical and design solutions continue to be explored to reduce and eliminate bird and bat mortality from wind turbines [92,93].

All birds' deaths caused by anthropogenic causes are tragic and should be reduced and completely eliminated. However, when evaluating the main bird mortality causes from human activity is important to develop an adequate perspective and assess the relevance of each factor impacting wildlife. Air pollution is considered the highest risk for birds, impacting egg formation and the successful breeding of adult birds. Air pollution increases bird acute mortality, reduces fertility, and affects the quality of the eggs, reducing egg size and causing shell degradation, with reduced thickness and impaired nutrition for embryos. Other causes of the high incidence of bird mortality due to human activity are bird strikes to windows, strikes to buildings, and cats. Previous research has indicated that these three combined causes may account for 99% of bird mortalities, with wind turbines contributing less than 0.1% [94–96]. However, it has been indicated that bird deaths at wind turbines have an impact on high-conservation-value species. The wind industry continues actively looking for solutions to reduce bird mortality due to wind turbine operation [97–99].

The main renewable energy generation capability in many global locations comes from hydropower, generating close to 20% of the planet's electricity requirements [100]. However, in many countries the potential to grow this resource is limited and wind energy has gained ground, becoming the faster growing new electricity generation source in numerous locations [101]. Hydropower growth presents significant challenges. Most adequate locations have been already occupied by dams. Water volumes are limited due to drought conditions and construction costs are significantly higher than other renewable energy technologies [102]. Furthermore, new hydropower displaces existing communities and significantly affects agriculture in downstream locations [103,104]. New hydropower generally requires much more area than wind farms and locations cannot continue being used for their previous applications [105]. Furthermore, in tropical locations dams cover with water large vegetation areas. This causes environmentally valuable forests to be lost while the submerged decomposing organic matter generates a high volume of green-

house gases, decreasing the environmental value of the projects [106,107]. In the future, hydropower growth appears to be limited by these challenges.

3. Evolution on Name Plate Capacity, Size, Height, and Rotor Diameter

Wind turbines are installed normally in close proximity to each other, creating large clusters in the form of wind farms. Furthermore, developers are continuously looking for new approaches to increase the size and equipment proximity of wind farms due to the significant synergetic benefits that this provides. An important factor on maximizing area utilization for wind farms is the limited availability of optimal locations for wind harvesting [108]. These locations need to have good wind resource availability while simultaneously having access to consumer electric markets and limiting disruption to other activities. The transmission of electricity to large cities or industrial installations is performed through a high-voltage grid, which is expensive to install and operate. Therefore, minimizing the distance of each wind turbine to these transmission lines decreases installation costs and transmission losses [64]. Additionally, to reduce social opposition to these projects it is important to decrease the potential interference of the area usage with other residential, commercial, or industrial activities. In Germany, for instance, the availability of areas for wind farms was reduced when the buffers between these facilities and urban areas were significantly increased [109,110]. These factors raise the density of wind turbines per area, increasing the number of wind turbines per farm, and reducing their separation. Additionally, decreasing the distances between turbines minimizes the required length of the transmission cables running to farm transformers, lowering installation costs [108,111].

However, the turbulent wakes created by the rotating blades are a constraint to minimizing the separation between wind turbines. These wakes create a powerful interaction between each turbine and its neighbors, reducing the wind speed availability for equipment in the downstream direction. Equipment proximity creates additional complexities, as several wakes may merge before actually affecting downstream equipment, further reducing wind speed availability [112,113]. In each location, wind has diverse characteristics in terms of speed and direction. As wind direction changes, the rotor adjusts itself to remain always perpendicular to the wind direction, periodically changing the downstream equipment affected by the wakes. This increases enormously the difficulty to assess and optimize wind farms [114].

In the last decade, the name plate capacity, height, and rotor size of wind turbines have grown significantly to increase wind energy harvesting. As a collateral effect, turbulent wakes have intensified, pushing wind farm developers to further separate equipment, increasing the occupied areas. However, considering that most wind energy is generated at wind-speed-dominant wind directions, in some locations, separation in crosswind directions may be much smaller than dominant wind separation. Figure 3 showcases the exponential increase for the rotor diameter, hub height, and name plate capacity of wind turbines installed in the US [115]. The average indicated in the main vertical axis for all three figures is calculated considering the wind turbines installed in the US during each individual year. The maximum, indicated in the secondary vertical axis and represented by an orange line, is calculated from the highest value from all wind turbines installed in each year in the US. For instance, Figure 3a indicates that the average rotor diameter for 2015 is 102.42 m while the maximum value is 125 m, considering the different ranges indicated in the vertical primary and secondary axis.

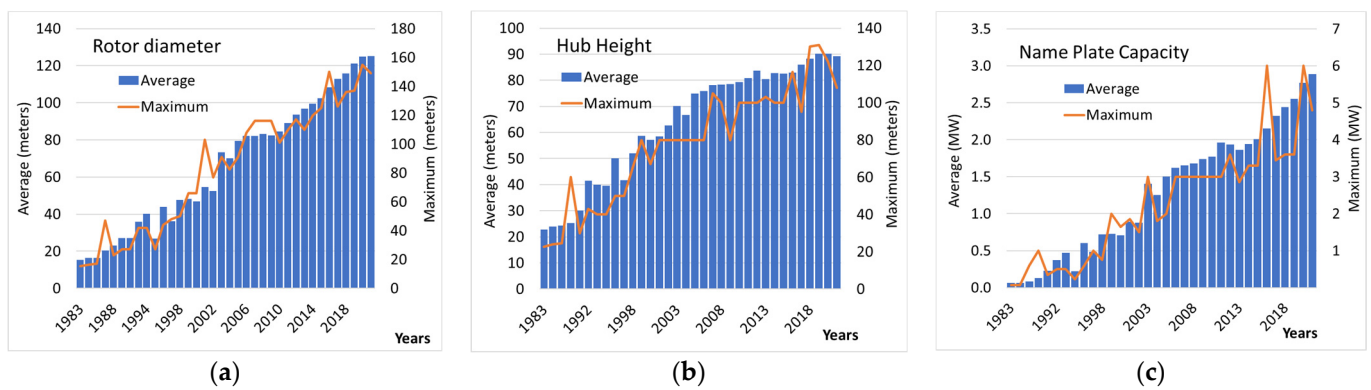


Figure 3. Wind turbine growth over time considering: (a) rotor diameter (b), hub height, and (c) name plate capacity.

The wind farm capacity factor (CF) will continue to improve in the future as technology advances, developing larger and more efficient equipment, maximizing wind site extraction, and optimizing wind farm layouts. Figure 4 showcases the exponential increase of CF over the last 20 years in Texas from data provided by the Electric Reliability Council of Texas (ERCOT) [108,116]. As indicated by ERCOT, when required, all wind speeds were evaluated at wind turbine hub height. All wind farms installed in 1999 had a yearly average CF lower than 0.25, while five years later, 60% of wind farms installed that year had a CF higher than 0.35. By 2014, 77% of wind farms installed that year had a CF higher than 0.4 and 33% higher than 0.45. Furthermore, a higher than 0.5 CF was achieved by 5% of wind farms installed in 2015 and by 14% of the ones inaugurated in 2016. The previous analysis illustrates the impact of technology advancement in equipment performance. However, it is important to highlight that the siting of the wind farm and the wind conditions in the location have a significant impact in energy generation. Lower wind speeds impact wind energy generation and therefore reduces the CF. Furthermore, considering that wind speeds are subject to inter-year variability, years with lower-than-average wind speeds will significantly impact the CF for the equipment.

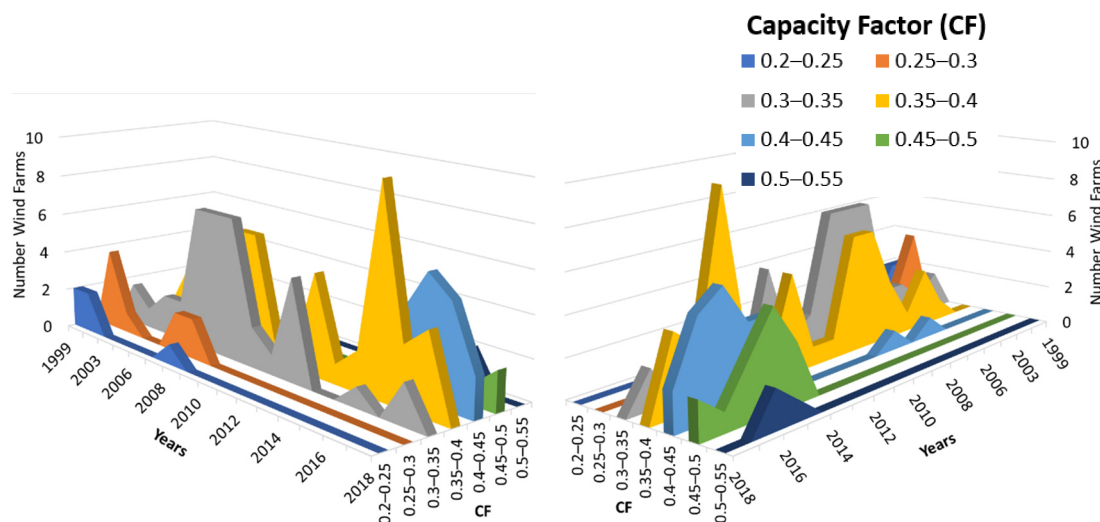


Figure 4. Yearly average capacity factor (CF) of wind farms in Texas according to the installation year, from 1999 to 2018.

As wind turbine installed capacity continues to grow all over the world, challenges presented by bigger wind farms containing larger wind turbines will continue to be addressed by applying the factors reviewed in this paper. Figure 5 presents the growth of wind power installed capacity all over the world over the last 10 years [117]. Figure 3a

indicates the growth divided by continents, showing that in 2020, Asia, Europe, and North America account for almost 93% of all wind power installed capacity. Africa accounts for less than 1% and Central America and the Caribbean account for less than 0.3%. This provides insight into the potential growth of wind energy in these continents, where very large wind-speed-potential areas are available. Evaluating Figure 3b, the geographical imbalance of installed wind energy is further validated, with the top 10 countries in the world accounting for more than 83% of all installed wind capacity. The top two countries in the list, China and the US, account for almost 55% of all installed capacity. This showcases the growth opportunities for wind energy in many nations that still have low wind turbine presence and possess a very significant potential [118].

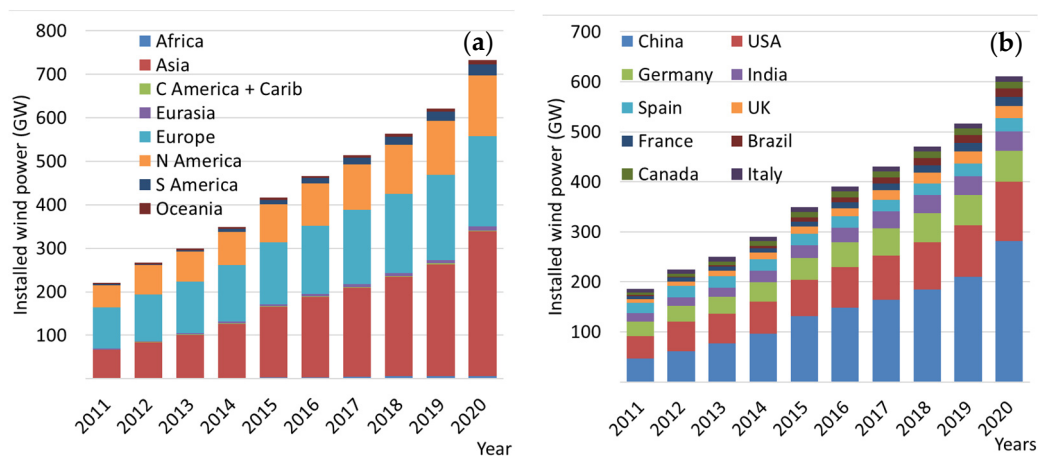


Figure 5. Installed global wind power capacity in GW: (a) divided by continents, (b) divided by the top ten countries for 2020.

4. Improvements on Control Algorithms, Layout Optimization, and Site Assessments

As the technology matures in the wind energy field, different techniques have been employed to enhance the performance of wind turbines. During the last several decades, wind-energy-related technologies have made significant advances in the field. Since the 19th century when the first wind turbine models emerged across different countries in the Northern Hemisphere, wind turbine characteristics, designs, and control algorithms have been advanced with the main purpose of maximizing their performances. From simple designs consisting of two blades to modern turbines generating significant energy output, efficiency improvements in this field have been made possible through the application of diverse methods. Thus, wind turbines have become more cost-effective, reliable, and currently possess a greater lifespan. The areas of innovation in the wind energy field have been multiple; however, in this section, we will concentrate on the improvements that have been influenced by control algorithms, layout optimization, and site assessments.

The political, social, and environmental changes in the 1970s gave rise to the ‘new’ interest in wind energy and steered the successful growth of commercial wind turbines. Although control algorithms, layout optimization, and site assessments are crucial in the development and design process of wind farms, the major implementation of these concepts has been relatively new. Furthermore, the success or failure of these three fields in wind farm development and operations are closely related. If one of them does not perform its functions accordingly, it can impact the performance of the other two.

An important stage in the development of wind farm projects is the feasibility study and assessment of the designated site. An accurate assessment of wind resources is decisive on the prosperity of wind farms [119]. This stage has been a fundamental stage in wind farm design processes ever since the first pioneers, who pushed the modern development of wind energy technology in Denmark, developed the first models about 50 years ago. The following factors need to be considered for site selection [64,120,121]:

- (a) Meteorological Factors: wind speed, wind direction, average wind speed, wind speed standard deviation, wind speed turbulence, temperature, air pressure, humidity, flow inclination, and seasonal trends;
- (b) Physical Factors: orographic conditions, surface roughness, land use, high altitudes, and presence of obstacles;
- (c) Environmental Factors: noise pollution, wildlife and habitats, proximity to cities, airports, or forested areas;
- (d) Economic Factors: easiness of transportation to the site, land cost, distance to electrical grid, and high altitudes.

Throughout the last century, the size of wind farms, the height of wind turbines, and the amount of wind turbines installed at a given wind farm have increased due to technological advancements and cost reduction. The first set of methods employed in the 20th century for site selection were traditional and based on calculations and formulas derived from the site selection factors discussed above. Assessments would focus on the performance of technical and feasibility analyses for achieving the highest possible efficiency at wind farms by concentrating on the estimation of power output; electricity generating costs; cost, value, and uncertainty assessments; and capital investments for installed capacities [122–124]. In the past two decades, the application of geographic information systems (GISs) and remote sensing (RS) techniques have become part of the most popular methods for site selections. The analysis of geographic data allows for a better comprehension of datasets, and the constraints and relationships between different variables. The Environmental Systems Research Institute (ESRI) has indicated that GISs have contributed to the advancement of energy generation and delivery as well as generating new perspectives on the assessment of these energy resources. GISs have made available the creation of high-resolution wind deployment models, the visualization of sites' physical characteristics, the determination of the most favorable locations for wind farms, and an analysis of terrain, economic development at the potential site, and forecasting models. On the other hand, RS methods are successfully employed as well. Light–sound detection and light–sound ranging are employed for wind farm site selection because of their contributions in reducing complexity and uncertainty [121].

The success and implementation of the first installed wind turbines brought up the different efficiency conflicts arising at wind farms to target the power degradation factors in the multiple installed wind turbine arrays. The first computer models were employed to address this issue and for the future engineering and economic planning of wind farm layouts [125]. The Viterna method, developed in 1981 by NASA scientists, became the most common type of method employed in the prediction of wind turbine performance, increasing the efficiency of wind turbine output, and is still employed today, remaining a valuable tool in site assessment according to the Environmental Protection Agency (EPA). Nevertheless, the next approaches and applications of layout optimization would be further studied until the 1990s, with the implementation of modern computational techniques to determine the optimum layout of wind turbines on real wind farm sites. Such programs would implement planning and natural constraints like wind speed, wind direction, site distribution, site topography, or wake effects [126]. An important concept that surged in this field is the wind farm layout optimization problem (WLOP), which focuses on the correct positioning of wind turbines in a wind farm with the main purpose of minimizing wake effects and maximizing power production [127]. As a result, finding optimal solutions leads to greater energy generation and higher profits. Today, wind farm layout optimization concentrates on four main targets: maximizing power generation, minimizing cost, minimizing the wake effect, and minimizing loads.

During the mid-1990s, Mosetti et al. [128] established the concept for wind farm layout optimization by developing the first approach utilizing computational optimization and employing a genetic algorithm (GA) approach, which has been the most common type of algorithm employed for wind farm layout optimization problems ever since [129]. This approach consisted of employing chromosomal strings to represent turbine position and

generate a discretized grid solution space. Currently, the incorporation of data mining, neural networks, and the potential of artificial intelligence (AI) and machine learning (ML) approaches have created new methods for layout optimization, such as particle swarm optimization, mixed-integer optimization, extended-pattern-search multi-agent systems, and others. Some of the most recent algorithms developed for solving the different optimization functions are discussed below (Table 1).

Efficiency improvements in wind farms are achieved by the correct execution of wind farm control strategies and algorithms. Today, these algorithms are essential in wind farms' daily operations. During the 1980s, the development of the first control algorithms utilizing different assumptions about the process and the multiple performance and robustness criteria for single-input single-output (SISO) and multiple-input multiple-output (MIMO) systems appeared. At the same time, linear time-invariant (LTI) systems emerged, using parameters that were assumed to be known and incorporating frequency and time domains to facilitate control system designs. In the 1990s, the modern control theory of wind turbines would concentrate on addressing the issues of setting boundaries and limits for torque and power, minimizing fatigue, and maximizing energy production [147]. In the current century, the focus has been on the development of efficient and reliable control algorithms that allow the generation of energy at a more affordable rate by operating wind turbines near their optimum power efficiency while lessening fatigue loads [148]. PI Historian has become one of the most important applications involved in the collection, visualization, storage, and analysis of historical, real-time, and predictive data for any operational or business process. The function of PI Historian in wind farm operation control includes archiving all necessary information related to wind farm operations and processing control data in their computer platforms [149,150]. Although other components are also important in the operations control network, PI Historian's availability of past data is fundamental for the analysis or implementation of any new system development. Therefore, any new methods can be later incorporated into any substation in the control network, such as PI controller, which is utilized in wind farms for an optimal control system and an effective pitch control/pitch reference signal [150].

Table 1. Optimization functions and methods employed for wind farm layout.

Methods Used	Machine Learning (2007—Present)	Reinforcement Learning (2010—Present)	Enhanced Learning (2006—Present)	Multi-Objective Optimization (2002—Present)	Artificial Neural Networks (1998—Present)
Advantage	Increases performance of WF by addressing prediction and maintenance issues [130]. Forecasts reduced wind speeds for wake simulation purposes [131]. Can lessen prediction errors [132]. Loads are estimated by surrogate models and simulation is performed repeatedly [133]. Capable of solving complex optimization problems by training pre-simulated models. Can work with gradient-based optimizations [133].	Utilized for nonlinear control problems. Can improve some parameters of WF control [134]. Performs actions in a defined order to measure a common reward needed to update the knowledge of other units [135].	Provide efficient solutions for the WFLO problem by the implementation of search techniques. Thus, optimizing the location of wind turbines to max. expected power output [136].	Flexibility on layout design facilitates WF design and future maintenance. Attention is given to achieving high energy efficiency and maximum power output while minimizing different constraints [137]. Allows the creation of different WF layouts in a single run [138].	Effective in predicting power generation and mitigating the influence of wake effect [139]. Provides some of the most accurate predictions for wind conditions [140].
Disadvantage	Strongly rely on computer science to be utilized. Are more demanding than statistical methods [141]. Accuracy may vary when used to predict wind speed [142]. More rigid methods, deeply biased, and strongly rely on selected variables to provide accurate results [143].	Finds optimal solution through trial and error. However, the learning process can be expensive and may harm the equipment [144]. No proper benchmarking for its applications compared to other approaches. Its discussion has been limited and potential has not been fully utilized [145].	It has not been widely technique employed.	Solutions obtained may be hard to implement and the process may be long [146].	Requires substantial amounts of data. Performance fluctuates based on feature selection [143].
Application	Maximizing power generation, minimizing costs, minimizing wake effect, and minimizing loads.	Maximizing power generation and minimizing costs.	Maximizing power generation.	Maximizing power generation, minimizing costs, minimizing wake effect, and minimizing loads.	Maximizing power generation, minimizing costs, minimizing wake effect, and minimizing loads.

5. Changes in the Size of Wind Farms and Their Social Acceptance

Onshore wind farms are arrays of wind turbines installed in an area to harvest onshore wind energy. Onshore wind farms differ in size and layout, varying from small numbers of wind turbines to several hundred wind turbines spread through spacious areas. Over the last several decades, onshore wind farm layouts have evolved as the sizes and name plate capacities of wind turbines have increased [151]. For example, the first European wind farm started its operation in 1983 with only five wind turbines, which had a 15 kW name plate capacity and a less than 11 m rotor diameter. The latest onshore wind farms normally have more than 100 large wind turbines. Figure 6 shows an onshore wind farm with 144 wind turbines, which started its operation in 2017–2019. As the hub heights and rotor diameters of wind turbines increase, interference caused by the wakes of other turbines, the so-called wake effect, becomes a critical factor in the wind farm operation and layout design. The separation between wind turbines within the same wind farm continues to increase to reduce wake interference [152].

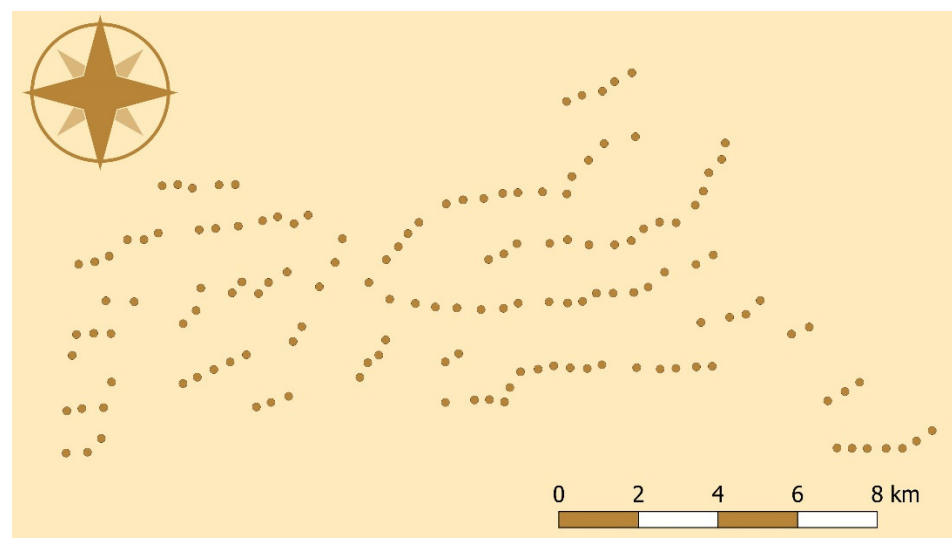
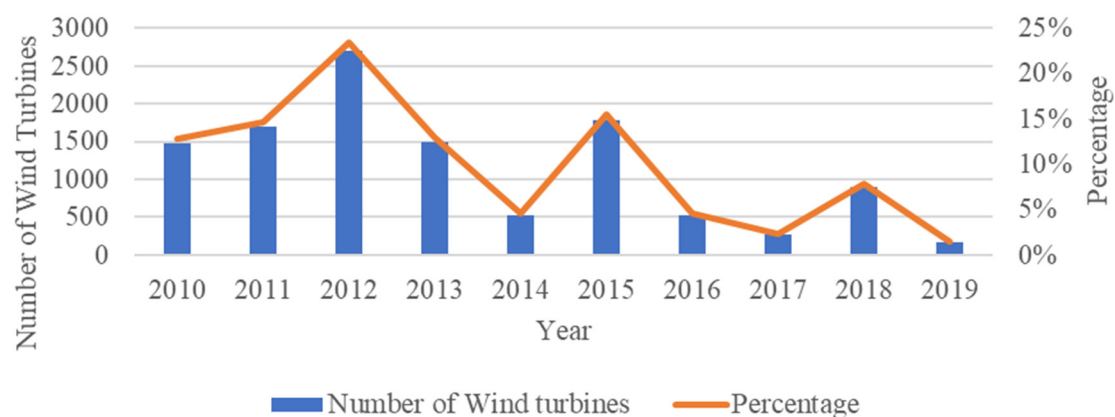


Figure 6. A wind farm with 144 wind turbines started operation in 2017–2019 in Texas.

Studies of wake effects are useful when designing large wind farms because they have a major impact on power generation. In a large wind farm, the interaction between the wakes of nearby wind turbines influences the wind farm's overall efficiency and operation. Due to the wake effect, the actual energy generation of an onshore wind farm can be considerably lower than the estimated energy production [153]. As a result, it is necessary to review the changes in the layouts of commercial onshore wind farms. Various researchers have studied the historical patterns of wind turbines in each country, as well as the reasons for the patterns and spacing of wind turbines. As the sizes of wind turbines increase, the areas of land needed to install an array of these large wind turbines also increase dramatically. For instance, there were a total of 11,559 new wind turbines installed in Texas, consisting of 169 new wind farms between 2010 and 2019, as shown in Table 2. However, during the same time frame (2010 to 2019), the number of new wind turbines installed every year showed a reducing trend, as shown in Figure 7. One of the main reasons is the reduction in available lands for wind farm development.

Table 2. Wind turbines and wind farms installed in Texas (2010 to 2019).

Wind Speed Category (at 50 m Height)	Number of New Wind Turbine Installed	Number of New Wind Farms	Areas of New Wind Farms (km ²)
0–12.5 mph	713	15	979.84
12.6–14.3 mph	4004	66	3470.83
14.4–15.7 mph	2630	40	2326.73
15.8–16.8 mph	4212	48	3708.76
Total	11,559	169	10,486.17

**Figure 7.** Number of wind turbines installed each year in Texas between 2010 and 2019.

In the last several decades, as wind energy experienced a rapid development, it also enjoyed the endorsement from most of society as a clean and renewable form of energy source. However, when more and more wind turbines were installed in the last several decades, the distances between large wind turbines and residential areas decreased. Wind energy development has started to be met with suspicion and even opposition in recent years from some in the public sector, especially among those residents whose houses, properties, or communities are near the wind farms [154,155]. Several major factors have been identified that were associated with the skepticism, including noise impact [156–158], visual impact [159,160], depreciation of property value [161–163], safety impact [164–167], landscape beauty [168–170], and damage to wildlife [26,171,172]. These factors, together with less available land, may be related to the reduction of the number of new wind turbines installed every year, as shown in Figure 7.

6. Future of Onshore Wind Energy

Several paths are being explored in regards to the future continuous growth of wind energy. Relevant research areas are being developed to expand, explore, and further advance avenues to reduce the carbon footprint through wind energy penetration. In the next decade, equipment and technological advances will bring larger and more efficient onshore wind turbines, capable of extracting much more power [173]. Wind farm location will be an important criterion in wind expansion, both for new and previously untapped areas (greenfield) and the repowering of current wind farms [174]. Equipment selection for each wind farm, generation–consumption balance, newer materials for wind turbines, and sustainable disposable are some of the topics that will need to be explored for wind energy to achieve full maturity [87].

The placement of new equipment plays a pivotal role in the growth of wind energy. Equipment may be installed on greenfield locations where there are currently no wind farms, and in place of existing wind farms. Both alternatives are complex and require sophisticated technical and financial analysis [175]. Furthermore, on the placement selection process the accessibility of consumption areas should be evaluated. Additionally, the

development of new markets that are demanding electricity should be considered in the analysis [176]. As countries continue developing their economies, intensive pressures will be asserted on their electricity generation and distribution systems. Regulations on the use of land are of paramount importance on determining the feasibility of a wind project. The Federal Aviation Administration, for instance, has set up limits on the maximum height of structures that may interfere with aerial navigation, potentially impacting the installation of advanced wind turbines attempting to tap into stronger high-altitude winds [177]. Natural protected areas or aquifer recharge zones may impact new wind farms or the expansion of current installations. Social opposition from local communities plays a very important role in the success of wind projects, with many projects delayed or completely scrapped in light of strong local opposition. It has been recognized that strong communication with local authorities and communities plays a significant role in overcoming these potential obstacles [80,178].

As wind turbines become larger and taller, technological issues in transportation, installation, maintenance, and safety have created concern among stakeholders. Transporting extremely large blades or very heavy towers and nacelles have strained logistic partners [179]. Traditionally, trucks have been used for transportation of this equipment, but as wind turbines become larger, route planning, permits, and the blockage of traffic have become challenging. Routes with narrow segments, low bridges, or steep curves have become unfeasible trails for longer turbine blades. Furthermore, the heavy loads may exceed many roads' tolerances, creating a complex routing scenario. This has shifted the transportation of newer wind turbines to railways, which are able to accommodate longer and heavier loads. Many companies have developed new technologies to accommodate these parts in rail carts. However, this further limits the reach of new wind technology to locations currently served by cargo trains [80,180]. Furthermore, as bigger wind turbines require larger separation between equipment, to reduce the negative interference of turbulent wakes, internal roads on wind farms will be impacted. These internal roads, normally narrow and unpaved, will need to accommodate the transportation of longer and heavier equipment from the main highway or railway junction to the location of each wind turbine, increasing the cost and technical requirements [181].

Identifying locations that, in addition to optimal wind speeds and interconnection with the grid, are able to satisfy these constraints can be extremely challenging. Furthermore, since wind energy has been in development in the United States for more than 30 years and in Texas for more than 20 years, many prime wind locations are already occupied by older wind farms [115]. Considering that the first wind farms were able to select the best locations, it is possible to assume that available locations over time have been progressively less desirable. If prime locations for wind farms are becoming scarce, it is important to consider how optimal the harvesting that current installations are able to provide will be. This present state of affairs should be evaluated by considering that wind turbines were designed to have an average lifespan of 20 years, after which the unrecoverable performance loss becomes very significant and the power output, when compared with current equipment, is several times smaller. Operators at this stage normally need to decide on the future of these older wind farms occupying prime spots for wind energy: closure, repowering, or run-to-fail [108,182,183].

Recently it has become clear that one important challenge for the expansion of the wind industry is the development of sustainable end-of-life systems for wind equipment. Growing public concern has been highlighted by news reports, which is most acute in mature wind markets, such as Germany, California, and Texas, where the first-installed wind turbines are starting to reach the end of their useful production life. One distressing fact is that the issue will grow in the near future, as surging numbers of wind turbines become decommissioned [87,184,185]. Concerning news has been reported in regards to some of the first-installed wind farms being allowed to perform in a run-to-fail mode, leaving older equipment in operation until they fall apart, as the original developers have gone out of business or are not able to remove the equipment [182,186]. It had been the

prevailing assumption that older wind turbines will have a salvage value that will cover decommissioning, which has proven to be unrealistic. Many jurisdictions now require wind farms to incorporate end-of-life regulations in their permits and bonded contracts. A number of their components have complex reuse or recycle challenges, leaving unpalatable alternatives, such as landfilling or incineration, which have detrimental social connotations and negative environmental impacts [187,188].

Another challenge for the continuous growth of wind energy is the significant asynchronous nature of wind energy generation and electricity consumption in many locations. This makes increasing wind participation on national electric grids more challenging. Electricity consumption is low during the night and starts increasing at sunrise, with peaks at late-afternoon times when the population arrives home after work [189,190]. In the US, electricity consumption peaks around 5 PM. However, in many locations, onshore wind has a low daytime generation, with the highest production times after midnight when consumption collapses [116]. This has caused national grid operations to require energy generation backups to supplement the grid when wind dies down. These backup sources are normally natural gas or coal, considering their great flexibilities for ramping generation up and down. This is a critical challenge for wind energy growth [191,192]. Unless alternative methods are devised, wind energy increases may signify keeping all hydrocarbon electricity generation sources available, and possibly even growing them. This reduces environmental benefits from wind energy and causes price increases to consumers. Currently, several European countries are experiencing record electricity costs [193–195].

Energy storage offers a solution for the required backup power for renewables. During low-consumption–high-generation periods, storage systems can be replenished to be used when usage increases at low-wind-speed times. Several alternatives are currently under evaluation [196,197]. Grid energy storage includes systems capable of accumulating large quantities of energy through chemical, mechanical, or physical processes. Large battery banks have been implemented in some wind farms to test this concept, with positive results [198]. Other systems are experimenting with the use of pressurized air in underground caverns or underwater containers. Optimization of these large-scale energy storage systems will aid in further advancing wind energy penetration in the electric grid [199]. Decentralized storage systems in the form of domestic or industrial batteries are additionally being considered. One alternative that offers strong synergetic possibilities is the use of the batteries in electric vehicles (EV) for this purpose [200,201]. It is expected that EVs will grow exponentially in the next 10–20 years. Governments, companies, and organizations all over the world are promoting this strategic transportation shift to reduce the pollution caused by traditional fuels [202]. Considering that each vehicle will integrate a battery, which will be unused when the vehicle is parked, it is possible, through the use of smart chargers, to replenish batteries during the nights when consumption and prices are low and wind energy is high [140]. During the day, the EV can provide the grid with electricity at high-consumption and high-cost times. The EV owner would obtain a profit under these circumstances, which will aid in paying the vehicle acquisition price. The EV owner will be able to set a minimum level of battery charge for its system to avoid being stranded [197,203,204].

New technologies, such as intensive data processing, the increased use of telecommunications, internet of things growth, and electric vehicles, will substantially increase energy requirements in the near future. The transition to EVs may increase energy consumption by as much as 40–50%, putting additional stress on the electric grid [205]. Wind energy growth will help offset these energy increases and satisfy growing electricity demand. The synergy between equipment with batteries (EVs, for instance) and wind energy would allow for wind energy to have a much more robust growth perspective to satisfy growing global electricity requirements.

7. Conclusions

The use of wind to aid in performing human activities can be traced to antiquity. Its use to mill grain, pump water, and power ships was fundamental in the success of diverse civilizations. The modern use of wind to generate electricity has seen an uneven development during the 20th century, with diverse events incentivizing its development. The installation of large numbers of industrial wind turbines in the 1970s and 1980s was propelled, in most part, by concerns about disruptions caused by oil's political instability and wind's environmental benefits. Diverse factors, among them government support, technological advances, and increased environmental concerns, brought wind energy to the forefront of the renewable energy revolution over the last 30 years. Increasingly larger wind farms, both in the number and size of their equipment, have been installed in locations all over the world. Learning curves have improved wind energy harvesting dramatically, making, in recent times, the kWh from wind the lowest-cost option in many locations. This has generated a cycle of growth in the wind energy sector, with progressive numbers of global markets introducing or expanding this industry.

Wind provides a significant number of environmental and economic benefits. It has been designated as one of the main strategies to curb climate change, one of the most serious threats to human development. Compared with traditional electricity generation, it generates almost no air pollution. Furthermore, as transportation switches to EVs, electricity from wind has the potential to provide a double benefit by curbing both the electricity generation and transportation air pollution problems. As technology evolves, the cost of wind energy has plummeted in many markets, providing additional incentives for growth in this industry, both in numbers of turbines and in their sizes. There are significant challenges for wind energy sustainability, which are being actively addressed by researchers, developers, and the industry. Among these challenges are social opposition caused by the visual or noise impacts of the equipment or wildlife repercussions. As onshore wind continues to grow in mature markets, the installations of newer facilities and the placement of transmission lines closer to communities have increased social opposition. Diverse measures have been taken to ameliorate these issues and potentially eliminate them in the future. Measures to camouflage equipment to avoid visual or noise impacts, procedures to protect wildlife, and undergrounding transmission lines are some examples of actions taken in this regard.

The future of wind energy will involve its expansion into a significant number of world locations, with ever-growing wind turbines and larger wind farms. As the price of electricity for wind continues to decrease, financial support for this activity increases. Public opinion backing wind continues to be mostly strong due to the challenges presented by climate change and the measures taken from the industry to address social opposition. However, to achieve the continuous development of wind energy, a number of challenges should continue to be addressed in the future. The sustainable disposal of removed equipment after their end-of-life cycle is a pressing concern and significant research is being performed on this topic. Overcoming the asynchronous nature of wind generation and electricity consumption without requiring natural gas or coal reserve generation is an additional priority. The use of energy storage systems offers attractive potential in this area. The decentralized use of EVs to store electricity, and later on sell to the electric grid, is a strong synergistic opportunity for these two advancing technologically upcoming industrial segments.

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