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Review

Wind Turbine Technology Trends

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Abstract: The rise in prices of traditional energy sources, the high dependence of many countries on their import, and the associated need for security of supply have led to large investments in new capacity of wind power plants. Although wind power generation is a mature technology and levelized cost of electricity low, there is still room for its improvement. A review of available literature has indicated that wind turbine development in the coming decade will be based on upscaling wind turbines and minor design improvements. These include further improvements in rotor blade aerodynamics, active control of the rotor blade rotation system, and aerodynamic brakes that will lead to increased power generation efficiency. Improvements in system maintenance and early diagnosis of transmission and power-related faults and blade surface damage will reduce wind turbine downtime and increase system reliability and availability. The manufacture of wind turbines with larger dimensions presents problems of transportation and assembly, which are being addressed by manufacturing the blades from segments. Numerical analysis is increasingly being used both in wind turbine efficiency analysis and in stress and vibration analysis. Direct drive is becoming more competitive with traditional power transmission through a gearbox. The trend in offshore wind farms is to increase the size of wind turbines and to place them farther from the coast and in deeper water, which requires new forms of floating foundations. Due to the different work requirements and more difficult conditions of the marine environment, optimization methods for the construction of offshore substructures are currently being developed. There are plans to use 66-kV cables for power transmission from offshore wind farms instead of the current 33-kV cables. Offshore wind farms can play an important role in the transition to a hydrogen economy. In this context, significant capacity is planned for the production of "green" hydrogen by electrolysis from water. First-generation wind turbines are nearing the end of their service life, so strategies are being developed to repower them, extend their life or dismantle and recycle them.

Keywords: wind turbine; development trend; electricity; renewable energy sources

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1. Introduction

Environmental problems, air pollution and major climate changes are being solved by the use of renewable energy sources, with wind energy playing a leading role. In Europe, this is further accentuated by the difficult procurement of classic sources of energy, oil and natural gas, due to the war in Ukraine and disrupted trade relations with Russia. The technology for using wind energy has made great progress in the last two decades and is now mature. Large investments in the future capacity of wind turbines have also encouraged investment in further improving wind turbine technology to make electricity generation as reliable, efficient and cost-effective as possible.

Due to the pandemic of the COVID-19 virus, there was a delay in the installation of new renewable energy capacity and difficulties in procuring traditional energy sources.

Hence, many countries are rapidly increasing their investments in their own renewable energy sources. In addition to this negative aspect, the COVID-19 pandemic has initiated an analysis of project delays and opportunities to increase productivity and shorten manufacturing times of plant components [1]. Europe, as the world's leading region for wind turbine manufacturing with extensive experience in this field, should continue on the path of wind turbine development and technological improvement. According to IRENA (International Renewable Energy Agency, Masdar City, Abu Dhabi), the total capacity of onshore wind farms is expected to triple by 2030 and quadruple by 2050 [2].

The Russian invasion of Ukraine has led to a sharp increase in the prices of basic products, especially fuel. Security of energy and food supplies is a growing concern in Europe and around the world. From the second half of 2021, energy prices in Europe and the world increased. The situation has also been affected by Russia's decision to suspend gas supplies to some European Union member states. The leaders of the 27 European Union (EU-27) member states have agreed on the need to reduce dependence on Russian fossil fuels and accelerate the transition to renewable energy sources. This could mean shortening the planned dates for the installation of wind turbines, which would lead to a sharp increase in electricity production. In other words, the energy projections for 2030 and 2050 could be realized earlier (Figure 1) [2]. However, this will require a major effort, as 17 GW of new wind energy capacity was installed in Europe in 2021, including 11 GW in the EU-27, which is less than half of the EU's plan to meet its climate and energy targets by 2030.

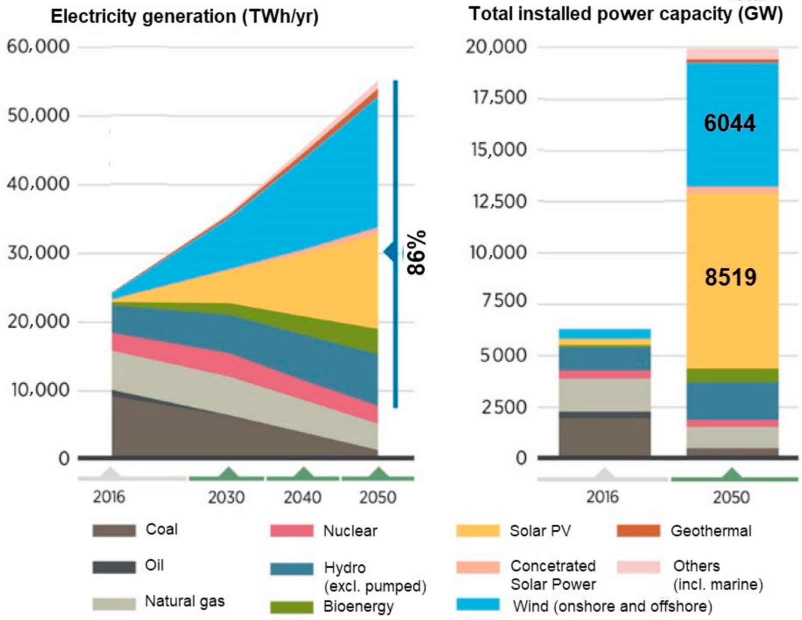

Figure 1. Predictions about the method of power generation [2].

Onshore wind farms account for 81% of new capacity in Europe in 2021, with Sweden, Germany, and Turkey making the largest contributions. In terms of new offshore global wind capacity, 21.1 GW was commissioned 2021, three times more than in 2020, making 2021 the best year in the history of offshore wind. At the same time, China accounted for 80% of the global offshore wind capacity added in 2021. In onshore wind farms, China has overtaken Europe to become the largest onshore wind market, accounting for nearly one-third of the world's installed capacity [2].

The installation of a planned 6044 GW of wind energy can generate more than one-third of the total electricity demand in 2050. This would reduce energy-related carbon emissions by 6.3 gigatons of CO_2, which is more than a quarter of the total emissions reduction potential from renewable energy sources and energy efficiency measures.

At the same time, it is predicted that the price of electricity generated by wind farms will decrease (Table 1), as will investment costs (Table 2) [2].

Table 1. Levelized cost of electricity from wind energy [2].

	2010	**2018**	**2030**	**2050**
Onshore wind ($/kWh)	0.08	0.06	0.03–0.05	0.02–0.03
Offshore wind ($/kWh)	0.16	0.13	0.05–0.09	0.03–0.07

Table 2. Total installation cost * [2].

	2010	**2018**	**2030**	**2050**
Onshore wind ($/kWh)	1913	1497	800–1350	650–1000
Offshore wind ($/kWh)	4572	4353	1700–3200	1400–2800

* IRENA takes inflation into account in levelized cost of electricity and installation cost.

Interest in wind turbine development is evidenced by a large number of articles published in the last two decade. For example, a thematic search of the Web of Science (WoS) database using only the keywords "wind turbine" yields 45,559 published articles in the last 10 years, while the Scopus database contains 61,321 published articles (Figure 2).

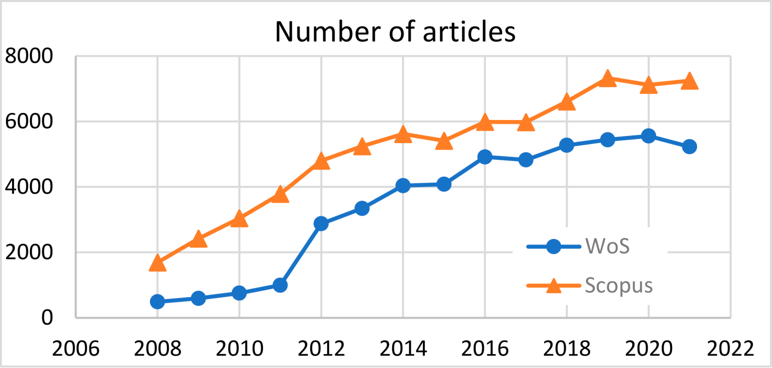

Figure 2. Number of published articles in the WoS and Scopus database (search for the topic "wind turbine").

2. Materials and Methods

The information for conducting the study is based on publications in journals, books, conferences, as well as scientific databases such as Science Direct, Scopus, Google Academic, Google Scholar, and specific topics on websites. This work also uses certain reports and documents published by the European Union (EU Directives, Brussels, Belgium), WindEurope Association and International Renewable Energy Agency (IRENA, Masdar City, Abu Dhabi). Data for which there are no reliable and cited sources are not considered. In analyzing the data from the above sources, the state of the art of wind turbine technology was identified, as well as the areas where research is being conducted to identify opportunities for improvement. Subsequently, the main directions of technological development in the future were determined by synthesizing the identified facts.

3. Discussion

3.1. Onshore Wind Turbine Development

Based on available literature, it was determined that wind turbine development in the coming decade will be based on increasing wind turbine power and thus dimensions, as well as minor design improvements (Figures 3 and 4).

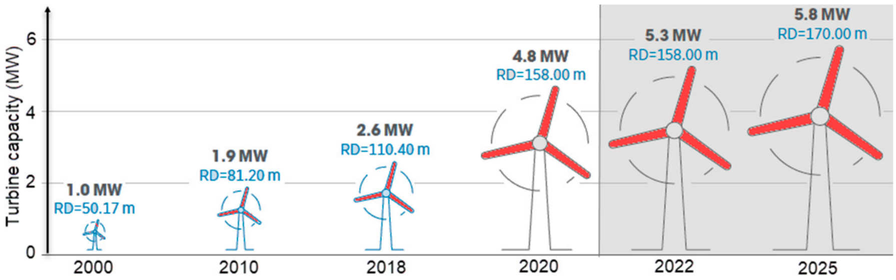

Figure 3. Power and rotor diameters of existing and planned onshore wind farms [2].

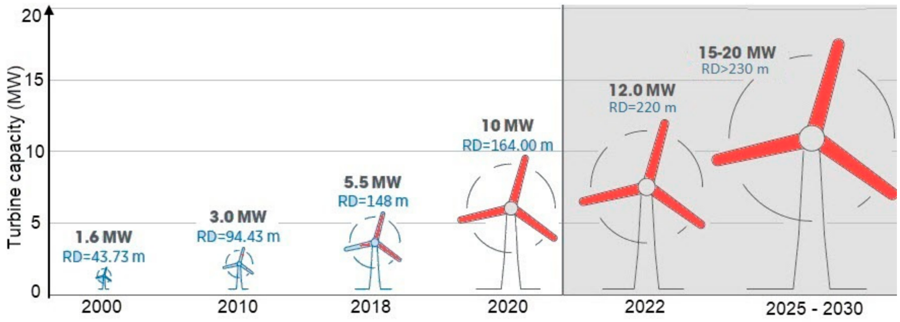

Figure 4. Power and rotor diameters of existing and planned offshore wind farms [2].

These improvements include further enhancements to the rotor blade aerodynamics, wind farm operational management system, and maintenance and fault diagnosis system, resulting in improved wind farm efficiency, reliability, and availability [3]. The power curve of a wind turbine (Figure 5) shows the output power of the turbine at different wind speeds. The annual electricity production of a wind turbine depends, among other things, on two important points on the power curve: the wind speed at which the wind turbine is turned on, and the wind speed at which the wind turbine is turned off, so that there is no excessive stress and damage to the parts of the wind turbine if the wind speed continues to increase.

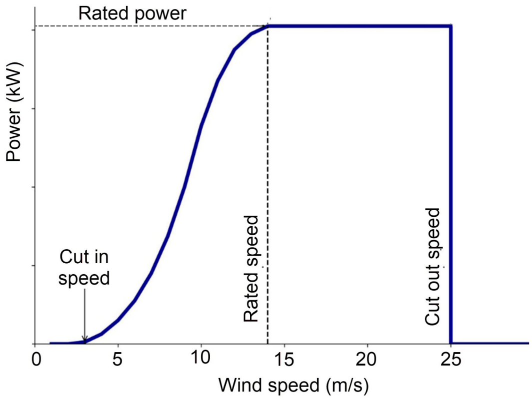

Figure 5. Typical wind turbine power curve.

The lower the cut-in speed and the higher the cut-out speed, the more energy the wind turbine will produce on an annual basis. The development of wind turbines that generate energy at low wind speeds theoretically expands the possibility of constructing wind farms in areas with lower average annual wind speeds. Therefore, we analyze at what electricity price such a wind turbine (e.g., with a capacity of 3.4 MW and a rotor diameter of 208 m) would be competitive in the European electricity system. Although the electricity price of such a power plant is currently 45% higher than that of a conventional onshore wind turbine with the same hub height, it has been shown that this technology could yield more than twice as much as conventional turbines in the future European electricity system in areas where lower wind speeds prevail [4].

Similarly, Figure 5 shows that it is desirable to design wind turbines so that they can still produce electricity in extremely strong winds (shifting the boundary to the right). Even for existing wind turbines, it is possible to improve the power curve of the wind turbine by updating the control system. In doing so, the wind turbine may be subjected to severe vibration and stress on the one hand, but on the other hand, the increase in production energy is significant [5].

Currently, various mechanical and aerodynamic braking systems are implemented to control the overspeed of wind turbines at extreme wind speeds. A recent approach attempts to aerodynamically control the overspeed of wind turbines by placing chord slots (openings). By placing the slots, the pressure distribution on the blade surface is altered and the wind turbine speed is reduced within allowable limits. In this way, the excessive speed of the turbine rotor is effectively reduced without affecting energy production. In the work of Kumar et al. [6], the effects of various slot parameters on the chord, such as the position and length of the slot, on power generation were analyzed and the slot parameters were optimized experimentally and computationally.

3.1.1. Wind Turbine Blades

Advances in technology are leading to improved wind farm performance and reliability and lower component costs. To drive its technological development, the wind energy industry has adopted materials, systems, and products from other sectors, such as sensors from electrical engineering, technologies from aerospace and shipbuilding for rotor blade manufacturing, and from the mining industry for mining technology. As wind energy technology increasingly crosses the boundaries of these sectors, the development of new technologies is needed to drive wind turbine development.

When it comes to rotor blade aerodynamics, numerical analysis can provide useful information. For example, Urbahs et al. [7] used numerical analysis to determine the angle of attack, lift coefficient, and drag-to-lift ratio for the selected blade profile of the “Espero” wind turbine. As a result of calculations and computer simulations, the optimal values of the coefficients for blade variants with and without geometric twist were determined: flow deceleration, ideal power, edge and blade profile losses, and specific blade tip speed ratio.

Applying computational fluid dynamics, Madsen et al. [8] tried to optimize the shape of the blade tip. The performance prediction of aerodynamic design of a blade using Deep Learning method was presented in the work of Du et al. [9]. Two parameterization methods based on geometric relations and neural network are proposed. The methods can generate smooth and complete blade profiles. Overlong blades pose a special problem. The problems of aerodynamics of such blades have been studied by Chetan et al. [10].

Duthe et al. [11] addressed the problem of surface erosion at the leading edge of the rotor blades. This can be a major problem for wind turbine reliability as it leads to reduced performance, unbalanced aerodynamic loads, increased noise emissions, and additional maintenance costs. If not corrected, it leads to deterioration of blade functionality.

The twist angle distribution (TAD) along the blades determines their efficiency in terms of power generation. Since wind blades are usually used in dynamic wind environments where the wind speed varies greatly, it is important to find the optimal TAD for different wind speeds. In their work, Jia et al. [12] present a learning-based method for finding the optimal TAD, which they call RL-TAD. A case study was conducted to validate the proposed method. This study indicates that the method can converge to the optimal TAD three to five times faster than the method based on a genetic algorithm.

The objective of the research of Sohail and Farzaneh [13] was to define a comprehensive mathematical modeling approach based on maximizing the coefficient of power (Cp) to achieve the control of the blade pitch angle and tip speed ratio (TSR), taking into account the detailed power losses in the different parts of the wind turbine. This approach is used to determine the optimal power coefficient of a wind turbine drivetrain for direct drive and gearbox configurations.

A current research topic in the field of wing design is the so-called "intelligent wings", which change their shape depending on the wind conditions. Within this category of wing design, there are numerous approaches, including aerodynamic control surfaces or materials for smart actuators. The goal of the research [14] is to limit end loads and stresses that affect material fatigue or to increase dynamic energy absorption. The research is based on similar concepts in helicopter control and is being conducted by the Wind Energy Research Institutes. These aerodynamic control surfaces include blade tip ailerons, blade pitch control, blade roll, and boundary layer control. More complex blade shapes are possible with the introduction of new shaping technologies and materials. However, the economics of production combined with the difficulty of analyzing a complex design will determine the final blade shape. Leading wind turbine manufacturers are optimizing features such as twist angle, chord length and blade geometry.

Worldwide, the horizontal design of wind turbines with three blades predominates. The blade rotation system is used because of its efficiency, allowable noise level, and durability. Many alternatives to this design have been explored but discarded due to higher cost and lower efficiency. Research [14] shows that greater cost efficiency is achieved by building turbines with a larger rotor diameter. However, this may soon change as the increasing dimensions increase the problem of transportation and assembly, which will impose limits. Systematic minor improvements in the design of rotor blades and other wind turbine assemblies will then become a higher priority.

A wind turbine rotor blade goes through more material fatigue cycles in one year than an airplane wing does in its entire lifetime, so this is the biggest concern of wind turbine manufacturers and operators. Metal is not satisfactory in this regard, so wind turbine blades are made of polyester, epoxy resin reinforced with glass fibers, or fiberglass. Carbon fiber or Kevlar are also used as reinforcing materials to protect against breakage or cracking. The company Enel Green Power is developing an innovative blade made of a special technical fabric [15]. This fabric makes it possible to generate more energy, reduce manufacturing costs and facilitate recycling at the end of the blade's life.

Due to the orthotropic mechanical properties of the composite, the structural properties of the sheet are determined by the orientation of the fibers. In their paper, Torregrosa et al. [16] present the advantages of optimizing the angle of each layer of the composite. They report that the inclined structure increases the critical wind speed for the defined control system and the electrical system by 10%, which contributes to a higher efficiency of the wind turbine.

Composites with glass and carbon fibers are used for the production of wind turbine blades to achieve higher strength, lower weight, and better corrosion resistance. The main problems related to these materials are their availability, biodegradability, risk to human health and the high cost of their production. For this reason, research is being conducted on the possibility of replacing these materials with natural fibers [17,18]. The development of fabrics based on natural fibers for the production of composites is a new technology that can solve the challenge of balanced mechanical properties of composites. In the work of Lamhour et al. [19], alfa and wool fibers were used as reinforcement for the development of four fabrics and low viscosity unsaturated epoxy resin as matrix. The fabrics were fabricated applying the taffeta weaving technique. The vacuum forming process was chosen to obtain the hybrid composite because it offers superior advantages.

The results of static tests of this reinforced composite indicated an enhancement in tensile and flexural strength.

Andoha et al. [20] investigated the suitability of a new composite of bamboo fibers and recycled plastic for the manufacture of wind turbine blades. The percentage of fibers in ten samples ranged from 2.5% to 25%. The results showed that as the percentage of bamboo fibers in the sample increased, the tensile strength and impact fracture also increased. The authors conclude that the composite with 25% bamboo fibers is suitable for wind turbine rotor blades.

Segmentation of rotor blades could speed up the process of manufacturing rotor blade parts, machining and coating to protect the surface. However, segmentation brings challenges in terms of minimizing the common mass, load transfer between segments, and logistics [21,22].

Also worth mentioning is the ability to apply 3D printing technology and simulate wind turbine operation for additional verification and improvement of wind turbine operation [23]. QBlade is an open-source program for wind turbine calculations. It allows users to design rotor blades and calculate the performance and apply it directly in the design and verify the characteristics of the wind turbine through simulation. Other programs used for wind turbine design are FOCUS6, HAWC2, QBlade, Simpack and others.

3.1.2. The Tower

The development of the tower, that is, the foundation that supports the structure of the wind turbine, has changed compared to the first windmills built of wood. Today, the wind turbine tower is usually made of steel to obtain a solid and resistant structure. Another material used for the construction of the tower is concrete, which also meets the necessary requirements of structural integrity, strength and durability. Recently, optimization techniques have been used to maximize load-bearing capacity while reducing material use and cost. During the operation of a wind farm, the tower is subjected to intermittent loads due to changing wind speeds, which can cause some back and forth bending of the tower. To reduce this motion, the frequency of the tower must be balanced with the natural frequency of the other components. Therefore, it is necessary to analyze the relationships between the tower and other components of the wind turbine, such as the rotor, nacelle, and foundation. In addition, the material cost, component manufacturing, assembly, and environmental impact should be considered to select the optimal design [24].

3.1.3. The Drivetrain

The gearbox is the part of the turbine that requires the most maintenance. So, if you remove it, the reliability of the turbine will be increased. It is also the most massive element in the nacelle of the turbine, so removing it will also improve this aspect of the turbine. For this reason, research has been conducted for years to optimize direct-drive turbines [25] to make them more competitive than turbines with gearboxes. This type of power generator has no gearbox and operates at the same speed as the rotor of a wind turbine. These generators are very large and the electrical energy output is converted to a constant frequency and voltage using power electronics. Direct drive, on the other hand, eliminates two-thirds of the conventional drive: gearbox, coupling and high-speed generator. In addition, direct-drive turbines are more practical at higher wind speeds. Until recently, however, the size and price of the generator prevented them from becoming a major competitor to geared turbines. The development of direct-drive turbines and the drop in the price of permanent magnets led to a more affordable and lightweight direct-drive model. It should be remembered that thousands of turbines with gearboxes are in operation and will continue to function for a long time. For this reason, gear technology continues to be refined to reduce costs and increase reliability.

Experts place the two technologies side by side, which can be interpreted in two ways: Either both technologies will evolve until one prevails, or both technologies will find enough users to coexist in the marketplace. Other experts believe that direct-drive technology will prevail over time. They support this with three arguments:

1. The cost of offshore support structures for direct-drive wind turbines is lower because of their lighter mass.
2. While the geared wind turbine has almost reached maximum efficiency, direct drive offers more potential for further enhancement.
3. Direct drive is more efficient at higher wind speeds, as geared wind turbines require additional gear stages, resulting in higher losses in the gearbox. There is also the possibility of a hybrid design, which combines elements of a gearbox and a direct drive [14].

Development has resulted in wind turbine electromagnetic systems containing less copper and being lighter. The rotor contains components that generate a magnetic field and therefore represent rotating poles. There are two types of components that can perform this task: synchronous and asynchronous generators. So-called synchronous generators have simple permanent magnets similar to ordinary horseshoe magnets. In a synchronous generator, the rotor and the magnetic field rotate at the same speed (synchronously). These generators are increasingly used in wind turbines due to their high power density and low mass. The challenges these generators face are demagnetization of the permanent magnets when extreme heat is generated, rendering the generator unusable, and the inability to generate power at a fixed frequency. This is due to the variability of wind speeds and rotation at the same speed. Therefore, these generators require rectifier power converters. An alternative to the synchronous generator is an asynchronous generator. It generates an electric field with the help of additional coils. According to Faraday’s law, electric current and magnetic field always exist together. So a magnetic field can be used to induce an electric current, but a magnetic field can also be created by sending current through the coil. This is exactly what asynchronous generators do. This type of generator requires a special power supply for the magnets, but in return, damage is less and reliability is higher. In addition, fluctuations in rotor speed are much easier to absorb because of the higher degree of damping. The design of the asynchronous generator no longer plays a major role, and permanent magnet synchronous generators are considered the best for wind turbines [26].

3.1.4. The Wind Turbine Control System

The wind turbine control system has the main task of maximizing the energy yield and reducing the structural dynamic loads. This system includes various subsystems, such as:

- System for power and load optimization
- Condition monitoring system
- Ice detection and anti-icing system
- Shadow flicker control system
- Fire suppression system
- Bat protection system
- Lightning detection system
- Oil debris monitoring system.

The system includes various sensors, actuators, cable connections, decentralized controls and special computers and software. Therefore, the design performance of the control system is divided into several functional units. It usually consists of a central computer located at the base of the tower, a control and switch unit in the nacelle, and several decentralized controls. This is where the default values for the functional assembly are generated and the remote monitoring system is connected. In the nacelle control unit the signals from the decentralized controls are processed and the results are transmitted to the central computer via the data bus system. The blade pitch control system, for example, is concentrated in the rotor head. Almost the entire control of the blade pitch, from the acquisition of the wind data to the control of the parameters, is carried out largely autonomously via so-called “pitch boxes”. Control systems are becoming more advanced and efficient, and the influence of environmental factors on system operation is also being analyzed [27]. The control algorithms can be adapted to the specific requirements and the monitoring can be performed in real time.

Improving the performance of a wind farm is a major challenge, especially when it operates under unstable weather conditions. Therefore, it is necessary to install a device that tracks the maximum power output expected from the wind turbine (MPPT). Approaches based on (hill climbing) have been applied to simulate maximum power trackers, but they have limitations in terms of tracking speed and efficiency. Fathy et al. [28] propose the latest efficient Archimedes optimization algorithm (AOA) approach for MPPT simulation. The proposed algorithm adjusts the inverter duty cycle to maximize the output power. Experimental test results confirm the robustness of the proposed approach in achieving the best performance of the wind power system.

It should be noted that the performance of a wind turbine operating under transient conditions decreases with age. Byrne et al. [29] analyzed 13 years of operational data from Vestas wind turbines and concluded that wind turbine performance decreased by about 5% over a 10-year period, and the decrease in performance was not linear.

3.1.5. Repowering a Wind Farm

The capacity of about 38 GW of onshore wind farms in Europe will reach the end of their normal life of 25 years (i.e., 20 years) by 2025 [30]. When they reach the end of the useful life for which they have been granted an operating license, there are three options: extending the useful life, for which new operating licenses must be obtained, decommissioning, or restoring the capacity (repowering). Repowering a wind farm involves replacing old wind turbines with more powerful and efficient new models. Regeneration on average doubles wind farm capacity and triples electricity production. Repowering is particularly effective and important because the oldest (and least efficient) wind farms in Europe are located in places with the best wind conditions, as the first wind farms were built there. State-of-the-art turbines in these locations can produce much more electricity than the existing wind farms.

According to the available data, some large repowering projects are already taking place. One such example is the Windplan Groen project in the Dutch province of Flevoland. In this area, there used to be 98 wind turbines with a total capacity of 168 MW. They are now being replaced by 90 new, more efficient wind turbines. This will increase the capacity of the wind farm to about 500 MW, enough to supply the entire province with electricity. Half of the wind turbines are built by Vestas, including 37 V162–6.2 MW EnVentus wind turbines and eight V126–3.45 MW turbines. The main features of the V162–6.2 turbine are: rotor diameter 162 m, swept area 20,612 m^2, hub height 166 m. Cut-in wind speed is 3 m/s and cut-out wind speed 25 m/s. The carbon footprint is 6.1 g CO2e/kWh and the recycling rate is 88%. At the same time, these are the most powerful turbines in the Netherlands [30]. The other turbines in the project will be supplied by Nordex and General Electric (GE).

The wind farm in Malpica (Spain), underwent an even larger rebuild. The number of turbines decreased from 69 to 7, but the electricity production doubled [30]. Repowering can thus be a very effective measure. However, less than 10% of decommissioned wind turbines are currently being repowered. Slow and complex authorization processes and changing laws discourage operators. Instead, most onshore wind farms that reach 25 (or 20) years of operation receive a license to extend their operation.

Another option is to stop operating wind farms, dismantle them, and recycle them. While concrete and steel can be easily recycled, the composites that make up the rotor blades pose a problem. This problem has been studied by Chen et al. [31], Beauson et al. [32], and Ruane et al. [33]. It should be noted that 9.4 GW of capacity is expected to be decommissioned and retired in Europe over the next five years.

Article 16 of the Renewable Energy Directive requires EU member states to issue permits for new renewable energy projects within 2 years and for repowering within 1 year (this does not take into account deadlines for completing environmental impact assessments or deadlines for resolving legal disputes). Unfortunately, most countries do not adhere to these deadlines. The procedure for issuing permits is too slow and complicated, and the reasons for this are mainly:

- Regulations are complex. There are more and more spatial planning restrictions (e.g., minimum distances from residential buildings, height restrictions for buildings, etc.). Moreover, regulations differ not only from one Member State to another, but also between different regions within the same Member State.
- Unnecessary bureaucracy. Procedures are slow because too many administrative bodies are involved at national, regional and local levels. This multiplies the number of applications utilities must make and the number of procedures that must be strictly followed, increasing costs to utilities and the time it takes to resolve problems.
- Permit-issuing agencies do not have sufficient digital and/or human resources to process the increasing number of permit applications.

According to WindEurope, the waiting time for permits is longest in Croatia (up to 120 months), Greece, Belgium and Switzerland (up to 110 months). The fastest permits are issued in Turkey (8 months), England (26 months), Germany and Romania (30 months). Under Croatian law, investors must use the technology specified in the original permit application, while most European countries allow technology upgrades. A permit issuance time of more than five years means that projects become obsolete before construction begins, while a change in technology would result in the need to apply for a new permit, which in turn would extend the construction period. This situation is expected to change in Croatia with the new Renewable Energy Sources Act starting in 2021. According to this law, the period for issuing permits will be a maximum of two years. While financing for renewable energy projects is widely available, long delays in gaining permits discourage investors from developing projects. Therefore, state governments need to drastically simplify authorization procedures [30].

3.1.6. Wind Turbine Maintenance

Maintenance of wind turbines is extremely important during their lifetime as it ensures reliable operation. The most successful wind farms used reliable wind turbines and followed good operation and maintenance programs.

Some improvements can be expected in this area as well. For example, in the context of wind turbine component condition monitoring (CM), Wang et al. [34] proposed a new multivariate state estimation technique (MSET) to provide early warning of component failure. To improve MSET and make it more flexible, a method for creating a dynamic memory matrix and two CM methods based on real-time residuals for early warning of failure were proposed. When several consecutive residuals exceed the threshold, a failure warning is created. In the long run, the method divides the historical residuals into days and analyzes them using control charts. The proposed method was experimentally verified in two real cases of failures due to overheating of gearbox bearings and generator bearings. The results showed that the method significantly reduces the error in MSET estimation.

Planetary gearbox is a critical component of wind turbines and of great importance for their safety and reliability. Intelligent fault diagnosis system for these gears have achieved some successes based on the availability of a large amount of data. Li et al. [35] proposed a new fault diagnosis method that combines gearbox learning with a dynamic model to determine the health status of planetary gearboxes.

Many other studies and analyses have been conducted and improvements related to wind turbine component maintenance have been proposed [36–39]. Part of the research is related to protection against lightning strikes and detection of damage to blades that have suffered a lightning strike [40–42], since the annual damage in this area is significant. Based on all these findings, a significant increase in the capacity factor of wind turbines is predicted (Table 3).

Table 3. Average capacity factor of wind turbines [2].

	2010	**2018**	**2030**	**2050**
Onshore wind (%)	27	34	30–55	32–58
Offshore wind (%)	38	43	36–58	43–60

According to WindEurope [43], the average capacity factor in 2021 was 23% for onshore wind farms in the EU and 34% for offshore wind farms, which is lower than the global average.

3.2. Offshore Wind Turbine Development

Offshore wind turbine design is challenging due to the wide and complex range of design parameters, as well as varying operational requirements and harsh environmental conditions. The service life of offshore wind turbines is typically 50 years, although the foundations are designed to last longer. The tower must be able to withstand static, dynamic, and cyclic loads and their critical combinations, so proper material fatigue analysis is required [44]. To solve these challenges, various optimization techniques are used. With them, it is possible to obtain optimized parameters for different designs of offshore wind turbines while balancing the effects on energy production and wind turbine lifetime. The work of Chen and Kim [45] gives an overview of the basic principles of various critical optimization techniques and their application in the design process of offshore wind turbines. The work of Sunday and Brennan [46] and Trojnar [47] provides a concise overview of important technical aspects, recent improvements in the design of offshore wind turbines on monopiles, and the challenges of future monopile designs with respect to increasing monopile size and turbine performance. The analysis focuses primarily on foundation-tower connections, damping for monopile structural analysis, modeling of soil-monopile interaction, and corrosion. The calculations performed have confirmed that the displacement of the hybrid monopile is 40–70% lower compared to a standard monopile with similar dimensions. An important part of foundation costs relates to protection against scouring, as drifting of material can lead to instability and collapse of the structure. Research by Fazeres-Ferrados [48] shows that scour protection in foundations is a very challenging area of research that still leaves many questions open.

Numerous other works also address the issue of structural optimization considering structural stresses [49,50], the stresses in large diameter flanges in the primary load path of wind turbine foundations, usually found at the base of turbine towers [51]. The new design of floating hybrid platforms will reduce the cost of the overall system due to faster erection and less amount of steel. The project of floating wind farm “Salamander” of Ocergy in 2021 allowed insights into the technology of substructures.

Increasing the rated power of the wind turbine is one of the most important ways to reduce the cost of electricity generation from offshore wind farms. Manufacturers prefer one larger wind turbine to building several smaller wind turbines for the same output, which lowers the cost per installed kilowatt of power [52].

The largest operating wind turbine in the world is the prototype GE Haliade-X in Rotterdam, which by increasing the output of the generator has a capacity of 13 MW. The practice of increasing the power output of an existing turbine by increasing the generator and drivetrain capacity with the same rotor is common among OEMs (Original Equipment Manufacturer) in offshore wind markets. It is a way to increase the power output of the wind turbine on the same platform without making changes to the blade design. Increasing the output of the generator can produce more power and improve efficiency, but increased material fatigue due to increased loading and reduced life must be carefully considered [53].

The benefits of increasing performance by scaling dimensions are potentially even greater than for land-based turbines. In the work of Papi et al. [54], a critical analysis of the technical implications of upscaling was given, focusing on the aerodynamics of the blades and the stress and elasticity of the structure. The study is based on the reference floating wind turbines NREL 5 MW and IEA 15 MW.

Vibration control of a floating wind turbine becomes increasingly important as the size of the wind turbine increases. Therefore, a new three-branch mooring system for Spar-type floating wind turbines is proposed in the work of Liu et al. [55]. The sway, pitch and yaw motions of the wind turbine in regular and irregular waves are calculated to quantify the performance of the mooring system. In the work of Jahani et al. [56], the main issues related to the structural dynamics of offshore wind turbines were analyzed, including modal alignment, aeroelasticity, hydroelasticity, bottom interaction, mooring cable-float interaction, drivetrain vibration, and others.

Offshore wind turbines can be sized larger because their transportation is not as problematic as onshore wind turbines. Vestas plans to develop a 15 MW wind turbine, with a prototype expected to enter service in 2022. With a rotor diameter of 236 m, this wind turbine will have a larger wind-swept area than any other turbine in operation. Series production is planned for 2024 [53].

Floating wind farms are a major breakthrough in ocean energy technology. Floating foundations offer two important opportunities:

- they provide access to sites with water depths greater than 60 m, and
- they facilitate turbine installation even in intermediate water depths (30–50 m) and could ultimately provide a lower-cost alternative to fixed foundations. In general, floating foundations have environmental benefits compared to fixed foundations because less seabed intervention is required during installation.

Floating wind turbines can be installed far offshore and in deep waters. The shift to offshore will increase the use of offshore wind farms. There are plans to install more floating wind turbines in Southeast Asia, Oceania, and Northern Europe (Figure 6).

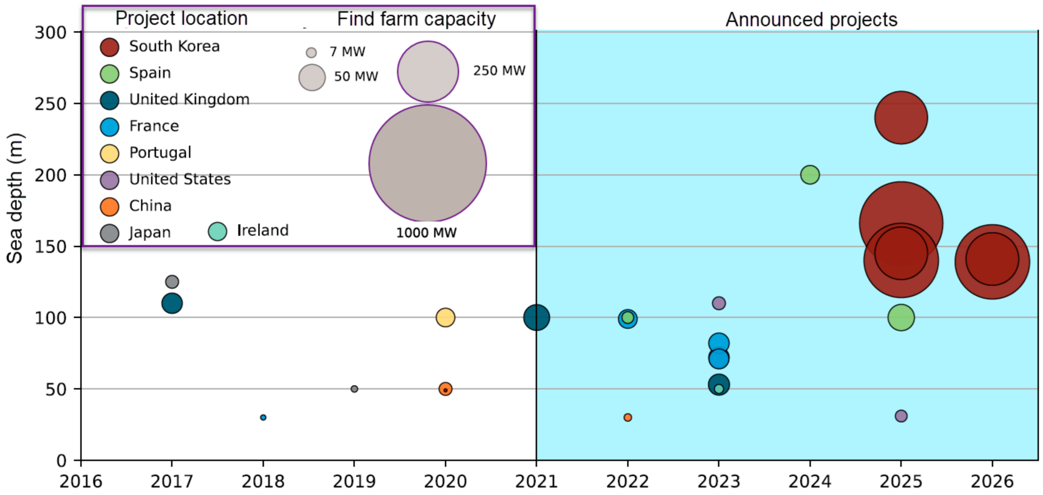

Figure 6. Global floating offshore wind energy projects by depth, country, and project size [53].

The most common foundation type for offshore wind turbines (OWT) is the monopile: a single pile six to eight meters in diameter and 20 to 30 m long below the seabed. It accounts for about 80% of the installed OWT foundations.

Figure 7 shows the technology of offshore wind substructure for future projects. The use of jacket foundations will be more than quadruple in future projects. In addition, the share of monopiles will decrease to 51.6% of the market. This change is due to the fact that projects are planned for deeper waters and increasing manufacturing capabilities for jackets. The share of floating foundations is also increasing. However, the industry's ability to adapt monopiles to deeper waters while maintaining low costs could result in monopiles remaining the dominant foundation type for some time. Based on information about planned projects, gravity foundations will increase their market share because they are better suited to rocky soils where it can be difficult to drive monopiles.

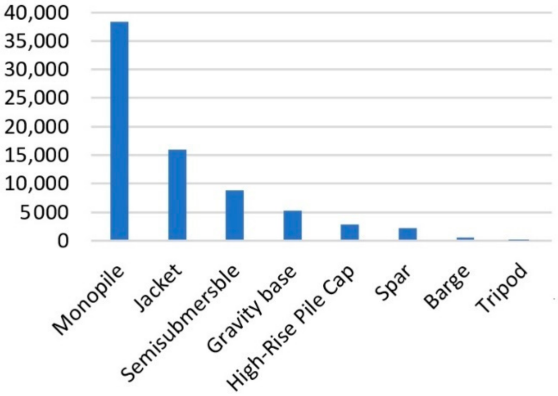

Figure 7. Announced offshore wind foundation types in future projects [53].

Most floating wind farm projects provide for a semi-submersible substructure. The advantage of this type of substructure is a relatively shallow draft and hydrodynamic stability during operation of the wind turbine. This allows for dockside installation and towing to the site without the use of heavy lift vessels.

Figure 8 shows the steady increase in global offshore wind turbine capacity. This continuous growth in rated capacity is one of the factors that has led to a reduction in the cost of offshore wind farms [57]. The significant growth of large offshore wind farms in Europe is also due to improvements in wind turbines and basic structures [58].

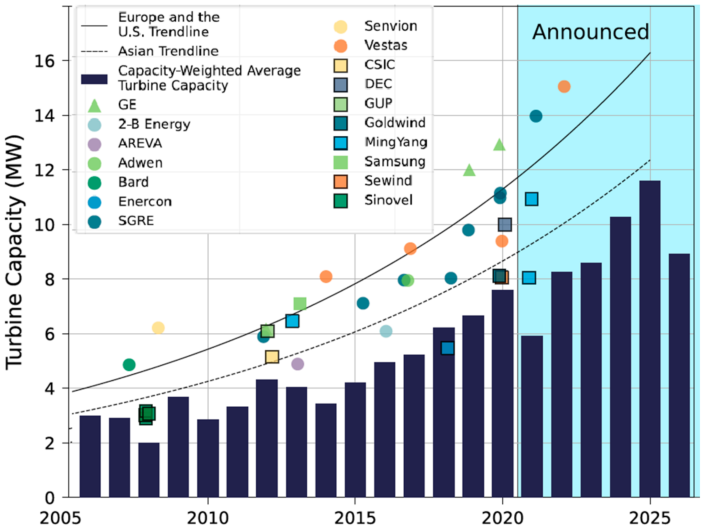

Figure 8. Installed and planned new annual capacities of offshore turbines until 2025 [53].

Figure 9 shows the cumulative deployment of floating offshore wind turbines. Of the 3,688 MW floating offshore wind turbines that will be installed by 2026, most will be located in South Korea (2300 MW), Saudi Arabia (500 MW), Spain (365 MW), and France (132 MW). Other wind farms will be evenly distributed in Europe, some of which are still in the planning phase [53].

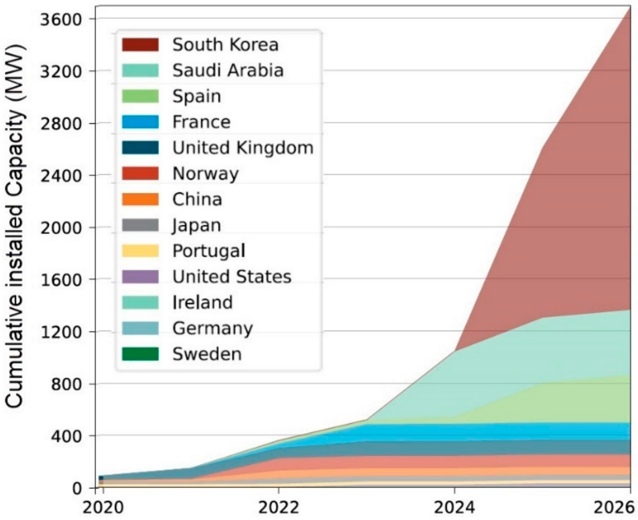

Figure 9. Cumulative floating offshore wind capacity [53].

Wind turbine floating structures must withstand harsh conditions. The combined effects of high winds and waves cause vibration, material fatigue, and severe loads on the elements of the wind turbine. These problems lead to increased maintenance efforts and increase the risk of failures [59].

Therefore, maintenance is very important as it reduces the number of repairs required. Improved maintenance scheduling can reduce costs and increase turbine availability. The possibility of remote maintenance has also developed. This includes remote monitoring, which allows early detection of problems and preventive maintenance. Subsea equipment has also been developed for inspection and repair of components that are difficult to access [53].

Improving and upgrading the power grid is necessary in many countries to accommodate large amounts of renewable energy, including energy from offshore wind farms. Policymakers urgently need to mobilise more public and private investment in secure, smart, and flexible grids that can accommodate an ever-increasing share of renewable energy. Otherwise, the availability of appropriate grid connections, capacity, and transmission lines may be a significant bottleneck to the growth of new utility-scale wind and solar energy projects. Grids need to be comprehensively modernised not only in terms of physical infrastructure, but also in terms of intelligence. The grid in the future energy system is likely to be a data network grafted onto a physical grid, enabling multidirectional energy and information flow with effective and precise controls.

In addition, the development of ports and vessels is accelerating to keep pace with the increasing production of offshore wind turbines and the increase in their dimensions [60].

A sharp increase in offshore wind farm projects leads to a rise in demand for submarine cables. The market is divided into cables connecting an offshore substation to the onshore station and cables connecting adjacent wind turbines and offshore substations. It is estimated that the need for offshore cables in Europe will be about 2000 km per year. In addition, there are efforts to install cables with a voltage of 66 kV, compared to the current 33 kV [53].

The work of Turnbull et al. [61] examines the market trends for offshore technologies in Europe and provides a detailed overview of installed and planned capacity. There is a clear shift from smaller reduction gear turbines to larger direct drive turbines. To investigate the impact of this shift on wind farm reliability, the failure rates of 39 wind farms in Europe and South America with direct drive and geared turbines were analyzed. The analysis revealed several key similarities between the configurations, with the electrical system responsible for the majority of turbine failures in both cases. When considering the total downtime due to failure of all components, the direct drive wind turbine had the highest value, primarily due to the relatively higher downtime associated with the electrical system, generator, and control system. This indicates that further improvements are needed for direct-drive power plants.

It is estimated that the cost of electricity for floating offshore wind turbines will decrease from $160/MWh (2010) to $50–105/MWh (2030), i.e., it can be said that technological progress in the design of floating wind turbines will lead to a significant reduction in costs [2,62]. In this way, the predictions for the year 2050 (Figure 1) could come true that most of the electricity generation will come from wind turbines.

Hydrogen will play a key role in Europe's carbon-neutral economy, as many current scenarios show. Hydrogen produced by electrolysis of electricity from wind turbines is an emerging technology. It could potentially contribute to system flexibility by acting as "seasonal storage" to help integrate various renewable energy sources. Hydrogen contributes to the "sectoral connection" between the electric power system and industry, construction, and transportation. Due to the existence of an extensive gas infrastructure that can be used to transport hydrogen-natural gas mixtures and also converted to transport pure hydrogen, the EU is well positioned to become a leading region in the global hydrogen economy [63]. In its report [2], IRENA forecasts a 19 exajoule increase in the global economic potential of hydrogen from renewable energy sources in total final energy consumption by 2050. This would represent 5% of total final energy consumption, and 16% of the electricity generated would be used for hydrogen production by 2050.

Governments, energy consuming companies (chemical companies, steel producers, etc.), and end users are increasingly interested in offshore wind as an energy source for the production of green hydrogen (produced by electrolysis from renewable energy sources) that can be used in various sectors of the economy (e.g., transportation, heating, industry, grid storage) as a fuel with zero pollutant emissions. Several early-stage global projects are being planned by Shell, RWE, Equinor, Gasunie, Gascade, Ørsted, and Boskalis. These producers plan to install 10 GW of wind power to obtain hydrogen as part of the AquaVentus/AquaDuctus project. Hydrogen can thus play a key role in implementing the EU's offshore renewable energy strategy. The goal is to obtain up to 1 million tons of hydrogen from 2035 [63]. POSCO, as one of the largest South Korean steel producers, plans to use the 1.6 GW Ørsted offshore wind farm to produce the hydrogen needed for further steel production. Neptune Energy's PosHydon project plans to use the produced hydrogen for Dutch utilities Gasunie, Eneco, Noordgastransport and Northern Offshore Gas Transfer. Ørsted's H2RES hydrogen production project will use two 3.6 MW offshore wind turbines at Avedøre Holme to obtain one ton of hydrogen per day for "green" road transport in the urban area of Copenhagen [5].

Finally, it is worth noting that some research has addressed the analysis and improvement of vertical axis wind turbines, although they are very little used compared to horizontal axis wind turbines. In the work of Shouman et al. [64], a modification of Savonius wind turbines is considered. The proposed modification consists of a curtain arrangement with additional fins on the blade. The effect of the proposed modification was predicted by CFD simulation using ANSYS FLUENT software. It was found that the maximum power coefficient of the Savonius rotor with the optimal curtain arrangement (curtain blade lengths 1000 mm and 1150 mm and curtain blade angles 30 and 50) together with the addition of only one fin increased by about 42%.

The rotation induced by the flow through a modified Savonius rotor, in which the blade consists of a semicircular profile and an elliptical shape, is studied in the work of Le et al. [65] using unsteady flow simulations (CFD). The modified rotor provides excellent performance at a tip speed ratio (TSR) of more than 0.8, and the new peak power coefficient Cp is achieved at TSR = 1.4, which is the typical operating condition of wind turbines in urban areas. Thus, their study not only contributes to the basic understanding of the flow mechanism around the rotor, but also suggests a good practical application of this type of rotor for power generation in urban areas. In the work of Tian et al. [66], a new vertical axis wind turbine (VAWT) with side-by-side overlapping Savonius rotors was designed and analyzed. The new VAWT consists of multiple Savonius rotors with a distance between adjacent rotor axes smaller than the rotor diameter. It was found that the new VAWT has an incredible efficiency improvement of 46.95% at TSR = 0.4. The improvement of aerodynamic performance of a Savonius wind turbine using the Taguchi optimization method is addressed by Kaya and Acir [67]. The work of Ahmad et al. [68] addresses the design optimization of a double Darrieus hybrid vertical axis wind turbine. Moreover, Al-Ghriybah et al. [69] analyze the aerodynamics and productivity of a Savonius rotor with additional blades. Although many other papers analyze possible improvements in vertical axis wind turbine design, this approach is not expected to make a significant contribution to power generation.

4. Conclusions

The purpose of this article is to show the development trend of modern wind turbines. The development of wind turbines in the coming decade will be based on increasing the power and thus the size of wind turbines, and on minor improvements in design. These will include improvements in rotor blade aerodynamics, the use of new materials, and the production of segmented rotor blades. Control systems are becoming more sophisticated, enabling real-time control, monitoring, and management of wind turbines. It is expected that the increase in power, dimensions and improvements, which include smart rotor blades and improvements in the aerodynamics of the rotor blades, as well as the expansion of the operating range of the wind farm (cut-on and cut-off points on the power curve) will contribute to a higher efficiency of the wind farm and, consequently, to a lower price for the electricity generated. This will also make it possible to economically install wind turbines in areas with somewhat lower average wind speeds.

The various options for building offshore wind farms will increase electricity generation from renewable energy sources worldwide. Of all the types of offshore wind turbine foundations, monopiles are likely to remain the most common type of foundation, especially in Europe, but floating platforms will also be used more and more, allowing wind turbines to be installed far offshore and in deep waters. Floating foundations not only facilitate turbine placement, but also offer environmental advantages over fixed ground structures.

The development of technology to produce hydrogen by electrolysis from wind energy could contribute to the flexibility of the system, which will facilitate the integration of various renewable energy sources. In this way, the gas grid would be decarbonized.

Although there is ample funding for renewable energy projects and political support for installing more capacity, authorization processes have proven to be a critical bottleneck to accelerating the installation of new capacity. Since the slow issuance of permits leads to increased costs for the investor and great uncertainty, there is a risk that investment in new wind turbine capacity will be deterred.

New ways of recycling and disposing of rotor blades will help reduce the environmental impact of wind turbines and create a more beautiful image of wind turbine implementation in nature.

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Nomenclature

AOA	Archimedes optimization algorithm
CFD	Computer fluid dynamics
CM	Condition monitoring
COVID 19	Coronavirus disease
C_p	The coefficient of power
EU	European Union
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
MPPT	Maximum power point tracking
MSET	Multivariate state estimation technique
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
OWT	Offshore wind turbines
RL-TAD	The optimal twist angle distribution
TAD	The twist angle distribution
TSR	Tip speed ratio
VAWT	Vertical axis wind turbine
WoS	Web of Science

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