STATE OF THE ART OF CONVENTIONAL WIND TURBINES DEVELOPMENT

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Abstract - The present paper aims to analyze the development of the wind turbines during the past decade and to put it in the context of the environmental changes that took place in the past years. Artificial intelligence, genetic algorithms and machine learning may increase energy production and ensure predictive maintenance of wind turbines. Implementing artificial intelligence at the level of wind turbine control systems, brings a lot of benefits. The main advantages are related to the reduced data analysis time; standardized data labeling; increased performance and reduced maintenance costs. Another alternative for detecting and determining the need for repairs could be machine learning, which can reduce downtime and extend the life of the turbine. The efficiency of blade pitch and durability of vertical axis wind turbines may increase with the use of genetic algorithms. Analysis of system errors and multiple key parameters facilitates maintenance and reduces operating costs. These advanced control methods for both horizontal axis and vertical axis wind turbines increase efficiency, provide optimized system parameters and control designs as output. 3D printing technology could be used for the production of wind turbine components, in this way a reduction of carbon dioxide emissions can be achieved. Environmentally friendly materials such as polylactic acid could be used to make parts. Advanced materials may reduce the mass of turbine components making the transport and installation much easier. This makes wind turbines a sustainable and environmentally friendly power generation device. In addition to these advantages, transportation costs are also reduced because it no longer requires large transport vehicles and traffic disruption.

Keywords: Wind Turbines, Horizontal Axis Wind Turbine, Vertical Axis Wind Turbine, Artificial intelligence, Recyclable, Plant-Based Material, 3D printing

1. Introduction

Climate changes are becoming a huge challenge for all technological sectors, due to the direct impact of the manufacturing industry on the global temperature by releasing numerous poisonous gases and toxic substances resulting in the process [1,2,3]. All factors that are directly or indirectly involved in industry, research, government or environmental activists are looking for and developing methods for a greener planet and a better and more sustainable future [4]. The main directions of development in the energy field are wind energy, solar energy, thermal energy and hybrid energy [5]. Since ancient times, wind energy has been utilized by humans for different household chores such as grinding grain and pumping water [6]. About three centuries ago a wind turbine was used to generate electricity [7]. Over time, turbines have evolved technologically, and in the last 20 years they have experienced exponential development [8,9]. Global energy demand continues to grow, creating an urgent need for cleaner and more sustainable solutions to mitigate the environmental impact of greenhouse gas emissions from traditional power plants [10]. The dependence on fossil fuels can be reduced by using wind energy because it is a clean and sustainable alternative to reducing environmental pollution [11]. Electrical energy is obtained by transforming the movement of the wind turbine into rotational movement, this movement is amplified and transmitted to the generator. They can be classified according to several criteria, but the main classification criterion is the way the rotor is

https://doi.org/10.17683/ijomam/issue19

mounted, there are two types of rotor placement, horizontal and vertical. Large-scale turbines have the rotor positioned horizontally and are called horizontal axis wind turbines (HWAT), they have made significant progress in development, which has led to a decrease in the cost of production and maintenance. On the other hand, turbines with a vertical axis, which are also called vertical axis turbines, although they are being studied, researched and there is a desire to be developed, they have not made significant progress [12]. The demand for sustainable and economically viable energy sources has increased due to growing environmental concerns, especially global warming [13,14]. The use of wind energy is increasing due to its minimal environmental impact, making it one of the most promising sustainable energy resources available today. The development of control algorithms that balance efficiency and reliability is becoming increasingly complex due to the increasing size and flexibility of wind turbines [15]. Monitoring wind parameters such as speed and direction, expanding energy storage capacity, and updating regulations are essential to increasing energy generation capacity. Electricity generated from wind energy has a low impact on increasing land surface temperatures compared to climate projections for the 21st century [16].

The visual appearance of wind farms is perceived as negative by some residents of nearby settlements, and the noise produced can affect human health, causing sleep problems and headaches [17]. Birds and bats can be struck by turbines and die, leading to habitat destruction, raising concerns for already declining populations [18]. To reduce or avoid the extent of damage to wildlife populations, a study should be carried out before choosing a wind farm location to assess the potential impacts [19].

1.1 Wind Turbines

The kinetic energy of the wind is converted into electrical energy by means of wind turbines. During this operation, a gearbox or a hydraulic transmission system is used to increase the rotational motion of the blades. At the output of the transmission, a shaft is connected to the generator via a coupling, which transmits the amplified rotational motion [20].

Table 1 shows the classification of wind turbines according to the main characteristics: construction, axis, type, location, number of blades and power range. Turbine power output data has been collected from several sources that sell wind turbines on the market. Power output increases with each passing year and the table may not be 100% accurate due to the rapid evolution of technology.

Table 1. Wind Turbine Classification [21]

Wind Turbine	Construction	Axis	Type	Site	Number of blades	Power range
Classification	Conventional	Horizontal	Upwind	Onshore/ Offshore	1 up to 5	20W up to 26 MW
			Downwind			
		Vertical	Darrieus		2 up to 7	40W up to 750 kW
			Savonius			
			H-shape blades			
			Helix shape blades			
	Unconventional	Horizontal	Twin-bladed rotor	Onshore/ Offshore	Multiples	5kW up to 1MW
			Downwind rotor			
			Ducted rotor			
			Co-axial, multi-rotor			
			Counter-rotating			
			Furling tail and twisting blades			
		Vertical	Gorlov		Multiples	30 W up to 65 kW
			Enclosed blades			
			Revolving			
			O-wind turbine			
		Bladeless	Solid state wind generator		None	100 W up to 1kW
			Vortex			
			Piezoelectric			
		Aerial	Airborne wind turbine		Multiples/ None	100 kW up to 10 MW

1.2 Horizontal Axis Wind Turbine

Horizontal axis wind turbines are the most widely used for producing electricity from renewable resources, namely wind. Their use to such a large extent is due to the amount of wind energy that they can capture and transform into electricity. In general, these turbines are grouped in the form of wind farms, of course there are also turbines that are not part of these parks. These single units usually serve small communities or private entities (household consumers). Depending on their size, they can be located both in open areas such as shores and agricultural land, but also in isolated areas such as high, hilly mountain areas, where there is still no electricity grid. Horizontal axis wind turbines can be classified by size, how the rotor is positioned relative to the wind direction, and by the area in which they are located. Figure 1 shows the two types of horizontal axis wind turbines. The upwind turbine has the rotor positioned at the top of the tower, attached to the nacelle and facing against the wind. This turbine model is not widely used due to its inflexible design and problems related to the mounting distance from the tower. The downwind turbine has the rotor positioned in the direction of the wind and connected to the nacelle.

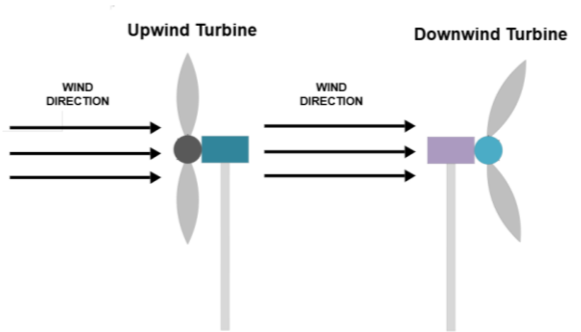

Figure 1: Upwind and Downwind Turbines

Large turbines are located in coastal areas or even offshore, but also in hilly or plain areas, far from settlements in order not to disturb residents with the noise they produce or the visual appearance, because they do not integrate into the landscape [22]. Turbines in coastal areas have developed more in terms of anchoring methods and protection of creatures that live near the shores. There are several concerns about the impact of these locations on the reproductive cycle of creatures. Thus, attempts are being made to develop turbine models that do not interfere with the evolution of populations or with the disturbance of sea currents due to the processes used to consume excess energy [23]. Turbines located in hilly and plain areas have experienced technological advances in terms of control systems and blade manufacturing technology. In the case of these installations, a series of problems related to the disturbance of bird populations due to collisions with the blades have arisen. There have been several deaths among birds that have unbalanced the food chain to a certain extent, for a certain period [24]. However, there is no clear evidence regarding the degree of damage to bird populations and other living things. There are several studies that support this negative impact that wind turbines have, but they do not provide a quantitative assessment of the number of individuals of those species that have been affected. Considering that the location of the turbines does not take up much space, the land around them can be used for agriculture or for raising domestic animals [25]. The location of turbines away from inhabited areas is also done for safety reasons. Due to the size of the masses and the moving components, in unfavorable, extreme or even normal weather conditions, turbines can fail [26]. These failures, if they occur, are due to strong winds that can dislocate or break the nacelle, blades and tower. In such a scenario, if they were located near inhabited areas, they could cause significant damage, even loss of life [27].

Small turbines produce less energy and have a smaller number of components and fewer control systems. Their placement is much easier because they are reduced in size, are easy to transport, and do not involve high precision in the positioning of components during installation [28]. Figure 2 shows the main components that can be found in the construction of a wind turbine are foundation, tower, nacelle and rotor. The foundation is the main component that ensures the support and balance of the tower. Before the foundation is made, the soil composition is studied to find out if it is suitable for the location of the turbine [29,30]. After the geological study, in case of a favorable result, excavations are carried out and the construction of resistance elements is carried out, by reinforcing the foundation. The tower is fixed to the foundation, which is usually made of reinforced concrete or steel, depending on the size of the turbine. Inside the tower there is an access ladder that provides access to nacelle. The height of the tower varies from one turbine model to another, depending on the size of the rotor. The nacelle is the element that houses the following equipment: input shaft, coupling 1, speed multiplier, output shaft from the multiplier, coupling 2, generator, in addition there are a series of auxiliary devices that deal with cooling, processing and transmitting data from the sensors [31].

The nacelle orientation system is the connecting element between the tower and the nacelle. It orients the nacelle in the direction of the wind. There are two main types of mechanisms that produce the reduction of the nacelle: toothed gear driven by an electric motor and hydraulic system. There are several constructive types of speed multipliers (also known as gearboxes) that are used: continuously variable, planetary type, helical and worm. The main materials from which the gearboxes are made are high-quality alloys, cast aluminum, stainless steel, etc. The role of the multiplier is to increase the input speed to an optimal operating speed of the generator. In general, the operating speeds of the generator are between 1500-3000 rpm to generate sufficient energy at a frequency appropriate for transmitting energy to the network [32].

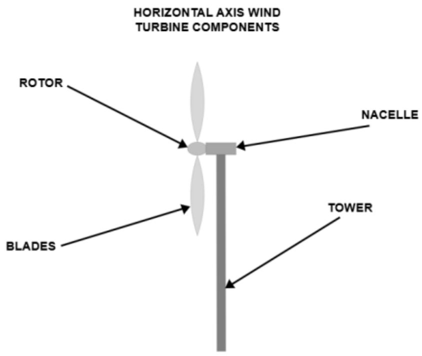

Figure 2: Horizontal axis wind turbine components

To transfer power from the turbine rotor to the generator, hydrostatic transmission is also used, which has the advantage of a small size and an efficiency comparable to that of gearboxes. Hydrostatic transmissions are much more durable over time, unlike gearing which wears out much more often and requires maintenance, which also implies high maintenance costs. Another advantage of these transmissions is their high precision and robustness. The generator converts the motion transmitted by the output shaft of the gearbox into electricity. Its operating principle is based on Faraday's law of the principle of electromagnetic induction. Inside it are copper coils that pass through a magnetic field as the rotor rotates, producing an electric current. Along with this, a frequency converter is also used to ensure the necessary frequency of 50Hz, for the electrical network [33]. The wind turbine is the assembly formed by the hub and blades. This is connected to the nacelle by means of the hub that is fixed on the input shaft in the nacelle. Inside the hub is the blade orientation system, which connects the hub to the turbine blades. This system is formed by a mechanism that is hydraulically operated, which changes the angle of attack of the blades. The blades are the elements due to which the rotational movement of the rotor occurs under the action of the wind. Both in small horizontal axis wind turbines and in medium or large ones, a number of 2-3 blades are generally mounted. It was found that the optimal number of blades for a turbine to produce energy with a power factor close to the Bentz limit should be between 3-5 blades. The materials used to manufacture the blades are wood-epoxy or fiberglass-reinforced polyester. The production process of the blades also involves negative repercussions on the environment through the carbon footprint it leaves [34]. The decommissioning of turbines at the end of their operating cycle raises problems regarding the recycling and reuse of the materials used for the construction of the turbines. In this regard, considerable efforts are being made to find solutions for the reuse of the remaining materials after decommissioning. These materials are used in the construction industry to make cement and could be used in the automotive industry to build chassis and other elements. Although some solutions have been found, the problem of recycling the blades has not yet been fully resolved. Research is currently undertaken on the materials that could be used to make the blades. Promoting the concepts of recycling, reusing materials obtained from the decommissioning of wind turbines and equipment from other industries such as automotive, and energy, helps to develop environmental awareness [35]. Today, 85-90% of a dismantled wind turbine is recycled and reused in the circular economy. Figure 3 shows a history of wind turbine decommissioning in the United States. As can be seen, 2015 was the year in which the most wind turbines were decommissioned. Most of the wind turbines decommissioned were first- and second-generation models, which are much smaller than those currently in operation. New onshore wind turbines in the United States had an average capacity of 3.4 megawatts (MW) in 2023, with an average height of 103 meters [36].

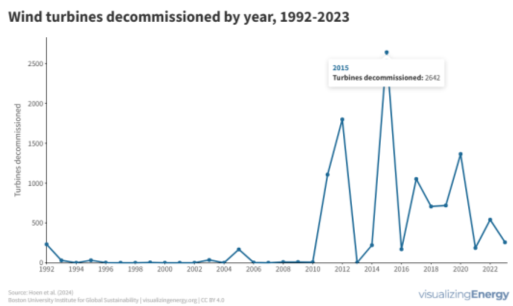

Figure 3: Wind turbine decommissioning [36]

The principle underlying the transformation of wind energy into electrical energy is based on elements related to the rotation of the earth, the Coriolis force and the way in which the earth's surface heats up [37]. The factors mentioned above influence the movement of air masses, and as is well known, wind is generated by moving air masses. They have different temperatures, and since cold air, which has higher pressure, tends to move into areas of warm, low-pressure air, the movement called wind occurs [38].

Table 2. The advantages and disadvantages of a horizontal axis wind turbine [22,39]

Advantages	Disadvantages
✓ High power output	× Large in sizes
✓ Tall tower	× High weight
✓ High efficiency	× Hard to relocate
✓ High reliability	× Difficult to install
✓ Self-starting	× Noisy in operation
✓ Stabile	× Difficult to maintain
✓ Damage control system	

1.3 Vertical Axis Wind Turbine

The vertical axis wind turbine is a device used for the same purpose as the HWAT, but with a different rotor layout. This construction variant is capable of transforming a smaller amount of wind energy, which gives it lower efficiency. Its structure is much lighter due to the reduced number of components it has. There are four main subtypes of vertical axis turbines, and these are: Savon, Darrieus, H-rotor, Helix. In addition, there are a series of models obtained by combining these subtypes to increase efficiency [40]. The components that make up the turbine structure are foundation, anchors, rotor, shaft, generator, brake, bearing. Depending on the subtype they belong to, securing it to the ground or other surface is done by attaching it to the foundation through support and anchoring it with straps. The rotor is arranged vertically, and the blades are attached to it with the help of a support. The blades have an aerodynamic profile, which allows them to capture wind energy regardless of the wind direction. Due to the shapes of these turbines, they do not require wind direction orientation systems or an angle of attack orientation system. For extreme weather situations, they are equipped with a brake to block the rotational movement of the turbine. Their overall dimensions may vary from one construction variant to another but are smaller than horizontal axis turbines. They are used in different geographical areas where there is wind potential, either to produce energy for a single user or for a community. They are also found in wind farms alongside horizontal axis turbines. Due to their relatively small size, they can be installed between or near large turbines, and since they can operate in turbulent wind conditions, they are not affected by the turbulence created by large wind generators. The materials from which the blades are made can be diverse (wood, metal, carbon, etc.). Given their arrangement, the forces acting on the blades are much lower, which gives them greater resistance to breakage, unlike the other type of turbine [41].

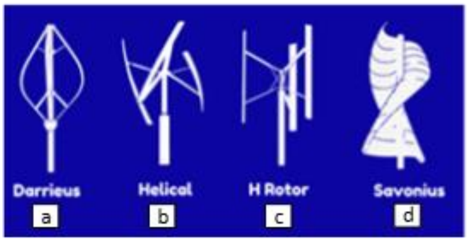

Figure 4: Subtypes of vertical axis wind turbines [41]

The Savonius rotor shown in figure 4.d, is a type of vertical axis wind turbine characterized by its relatively massive, drag-driven design. It is known as a drag rotor because the entire rotor surface provides wind resistance and is essentially pushed by the wind. Drag limits the speed and power of the rotor, which gives it the lowest efficiency of all small wind turbines. The amount of electrical energy is much lower than that of other small turbines. The Darrieus turbine shown in figure 4.a, has a shape similar to an eggbeater with curved airfoil blades arranged vertically around a central axis. The working principle is based on the lift created when the wind blows over the inclined blades. In terms of power generation, lift-based rotors are more efficient than thrust-based rotors because they can spin faster than the wind. The Darrieus rotor has a number of derivative designs, including disc, helix, and straight-bladed H-rotors. These can convert up to 40% of the available wind energy due to their thin blades and aerodynamic efficiency, approaching Bentz's maximum theoretical efficiency of 59%. The H-blade rotor shown in figure 4.c, does not have the curved blade configuration of the classic model, but rather straight blades. This subtype of vertical axis wind turbine has a larger surface area facing the wind and, theoretically, produces more energy compared to other blade designs. Helical rotors, shown in figure 4.b, are the second most well-known design that uses lift to spin the blades. The design is characterized by curved blades that form a propeller shape or spiral around a vertical shaft, which allows the turbine to capture wind from different directions without the need for steering mechanisms in the direction of the wind [42].

Table 3. The advantages and disadvantages of a vertical axis wind turbine [22,40]

Advantages	Disadvantages
✓ Small dimensions	× Produce less energy
✓ Gusty and steady winds operation	× Lower efficiency
✓ Fewer structural parts	× Limited scalability
✓ Lighter tower	× Requires a higher wind speed to start rotating
✓ No orientation system	× Prone to fatigue and stress
✓ Omni directional	× Threat to birds and bats
✓ Low production cost	
✓ Quieter	

1.4 HAWT versus VAWT – A Short Literature Analysis

A comparative study was carried out in [43], between the two major types of turbines (HAWT and VAWT), focuses on key design parameters such as lift/displacement ratio, peak speed ratio, power coefficient and torque coefficient. The study reveals that horizontal axis turbines (HAWT), especially three-blade models, are suitable for large-scale operations, while vertical axis turbines (VAWT) are used for small-scale applications (isolated areas, private entities or companies) in areas with turbulent winds. and lower noise requirements. Among the aspects considered in the work, the advantages of VAWT were highlighted. Low noise, transportation and construction costs and the ability to harness wind energy from all directions even in turbulent wind conditions. In terms of rotor design evolution, vertical axis wind turbines benefit from a new approach to hybrid rotors (Savonius-Darrieus) that address the problem of self-starting (Darrieus) and low efficiency (Savonius), making them efficient at low wind speeds.

Comparing the two main types of wind turbines in terms of design, advantages, disadvantages, applications and efficiency. Horizontal axis wind turbines (HAWTs) have an efficiency of over 70%, making them cost-effective for both large and small energy projects [44]. On the other hand, vertical axis wind turbines (VAWTs) have an efficiency of up to 50–60%, making them suitable for urban environments due to their ability to operate at low wind speeds, regardless of wind direction [45]. Methodologies applied to large turbines could be used to improve the performance of small turbines. To improve the performance of small wind turbines, the following elements must be considered: evaluation of the blade element momentum, study of the noise generated and its impact on the area where the turbines are located, improvement of computational tools for design, micro location and simulation [46].

According to [47,48], vertical axis wind turbines (VAWT's) are a growing option, versatile, compact and do not require wind orientation due to technological improvements that increase power generation with a smaller footprint. The significant progress in terms of efficiency, given that they operate in diverse wind conditions, offering an optimistic outlook for the development of the wind energy industry. The aerodynamic design of the blades is crucial, especially at low wind speeds, to extracting as much energy as possible in those conditions.

[49] highlights recent progress in improving VAWTs and emphasizes the need for improved designs of HAWTs. The strengths of vertical axis wind turbines (VAWTs) are their simple design, operation in turbulent wind without a wind direction guidance system. Despite this, their lower efficiency remains a challenge. Modification of the rotor design, blade shape, angle, edges and the use of counter-rotating rotors can match the efficiency of horizontal axis wind turbines (HAWTs). Directing the airflow using guidance vanes or diffusers could improve energy production. The main obstacles are related to technological limitations, environmental factors, location and wind conditions.

Unsteady flows around Darrieus and Savonius rotors were analyzed in [50], using computational fluid dynamics (CFD) simulations to study the flow patterns, aerodynamic performance and the development of rotor shapes. The analysis resulted in improved power coefficients at increased airflow speed and reduced blade stiffness of Darrieus rotors, changing the optimal operating range. Regarding Savonius rotors, the results highlighted higher energy efficiency of rotors with fewer blades. A strong influence on the performance of Darrieus rotors was observed at low airflow speeds that generate dynamic blocking effects. The authors emphasized that rotor efficiency depends on factors such as airflow characteristics, blade design and operating conditions. Through the study, they intended to apply advanced transition models and develop tools for 3D simulations of complex rotor designs to increase turbine accuracy.

2. Tendencies in development of Wind Turbines

2.1 Artificial Intelligence (AI) and Control Algorithms

The renewable energy industry has recently joined the ranks of industries that have seen rapid growth due to the use and exploitation of the full potential of artificial intelligence (AI) and machine learning [51]. The wind energy industry produces large amounts of data, obtained from sensors and monitoring systems, which AI can analyze to predict trends and address performance issues. There are barriers to integrating AI into wind power systems related to the collection of data from multiple wind farms, as companies consider the data proprietary and are reluctant to share it. Lack of data sharing delays the development and refinement of AI algorithms because it makes it difficult to benchmark industry problems, delaying progress in optimizing energy production and reducing defects [52]. Using artificial intelligence as a tool for predicting and assessing potential problems does not provide a direct solution to the problems but supports the industry in making informed decisions. Even though AI can accurately predict potential incidents, it has limitations and is not foolproof. In addition, the absence of standardized data labeling and event tracking creates challenges in data processing and analysis [53]. Disparate data transformation makes it difficult to obtain meaningful information about specific events during turbine operation in a short time. AI can reduce data analysis time, enable standardized data labeling, increase performance and reduce maintenance costs by providing more accurate and efficient information about turbine operation [54]. An effective solution to determine the need for repairs or replacement of components is the installation of condition monitoring systems (CMS). These systems use sensors and signal processing tools to monitor turbine components, analyzing signals such as vibration, sound, voltage and temperature [55]. Turbine performance can be optimized by applying machine learning to the control and monitoring system (CMS). Downtime can be reduced, and turbine life can be extended through predictive maintenance. Based on the data collected and correlated by machine learning, the timing and opportunity to perform predictive maintenance or other unforeseen repairs can be determined. Using data collected from multiple control and monitoring systems over a longer period to train algorithms can improve understanding of problems that may arise in the system [56]. According to [57], improving efficiency and decreasing the use of the drive system for wind direction orientation as well as angle of attack adjustment can be achieved by using artificial intelligence and hybrid techniques. Maximum power point tracking and neural network controllers can be used to forecast wind conditions. Classical controllers, PI/PID, have limited performance in wind turbine systems, but the use of AI algorithms can optimize them, improving responsiveness and reducing problems such as overshoot. Fuzzy logic, compared to classical controllers, allows for more efficient management of system uncertainties, providing faster responses. Robustness and adaptability to different operating conditions can be increased by applying artificial intelligence to fuzzy controllers. By using a genetic algorithm, the optimal blade pitch kinematics can be determined for different operating conditions, increasing the efficiency and durability of vertical axis wind turbines. This hypothesis is also validated by the authors in [58], who applied a genetic algorithm to a turbine model they created, and the experimental results indicated a three-fold increase in power factor and a 77% reduction in load fluctuations. To address the limitations of traditional momentum theory that lead to inaccurate force predictions, MIT engineers have developed a new physics-based model. Inaccurate force predictions lead to failures at high speeds or extreme angles. They claim that the model predicts airflow around wind turbines and propeller blades with great accuracy, even under extreme conditions, and provides precise information that could improve rotor design and optimize wind farm operations. Real-time adjustment of turbine parameters allows for maximizing power output while ensuring operational safety [59]. Artificial intelligence can be used to achieve desired results in a shorter period and to provide specific solutions for each wind farm based on historical event data.

2.2 Recyclable, Plant-Based Materials

Wind turbines could be improved by using advanced materials such as carbon fiber composites and metal alloys [60]. Strong but lightweight materials offer numerous advantages. They are easier to transport and install, reduce stress on the wind turbine's supporting structure, are more wear-resistant, and make the blades lighter, allowing them to spin faster with the same wind force [61]. Along with advanced materials, the assembly process can also be improved. Transportation can be simplified by dividing the turbine blades into segments, while the towers can be assembled on site using methods such as spiral welding or 3D printing. These improvements reduce costs and allow construction in more remote locations [62]. The use of new, more environmentally friendly materials for blades, towers, and other structural elements can improve efficiency and reduce turbine mass in large, medium, and small-scale horizontal axis wind turbines (HAWTs). It supports the rapid expansion of wind energy by improving performance indicators such as energy efficiency, power coefficient, blade mass and design constraints [63]. 3D printing technology plays a major role in promoting sustainable development goals in the wind energy sector, making significant contributions to energy recovery and reducing carbon dioxide emissions. Using this technology to manufacture wind turbine parts can reduce CO_2 emissions by up to 25% compared to conventional production [64]. Methods for manufacturing complex shaped blades on a large scale are currently being studied. The blades are fabricated using additive techniques such as fused deposition modeling (FDM), continuous fiber reinforcement (CFR), stereolithography (SLA), and large-scale additive manufacturing (LSAM). The materials used to make the parts include thermoplastic composites, epoxy resins, and fiber-reinforced polymers. Each of these are tested in terms of mechanical resistance, durability and environmental impact. Additive technologies can be used to produce wind turbine blades because they increase their cost-effectiveness, customization, and structural optimization. However, there are challenges that need to be addressed, such as material limitations, surface quality, dimensional constraints, and structural integrity [65]. In an investigation, two scenarios were taken into consideration, for a 3D printed horizontal axis wind turbine with a conical spiral design (the turbine with and without a casing). The results showed that adding a casing significantly improved efficiency by 28.11% and power output increased by 10.16%, especially at peak speeds greater than 3.27 [66]. Another study showed promising results in terms of the performance of a small 3-blade wind turbine designed for research and teaching purposes, obtained through 3D printing. The material from which the rotor was made is PLA with a gyroid filling structure. During the design verification, it was found that the shape of the blades is accurate, but geometry verification and surface polishing are still needed. Although the test results showed that the blades have static strength and aerodynamic performance, additional load calculations are still needed [67]. The poor performance of wind energy conversion systems at low wind speeds is addressed in [68]. The authors propose a 100 W micro wind turbine as a solution to generate energy efficiently in such low wind conditions. The micro wind turbine has blades made of 3D printed polylactic acid (PLA). The PLA-based wind blade performs better than traditional ABS blades in terms of stress, deformation and efficiency at low wind speeds. The manufacturing costs of the blades are lower, and the material can be reused after the blades are no longer used.

3. Conclusions

The energy sector is in a state of continuous expansion and development, using all the technological innovations of today to increase energy production. The main types of wind turbines have been improved over time, increasing their efficiency. Even though horizontal axis wind turbines are the most widely used for large-scale energy production, small vertical axis turbines are seeing an increase in interest for their use in urban, rural and remote areas due to their size and the advantage of not requiring high wind speeds or complex guidance systems. The main trends observed are in the application of artificial intelligence, genetic algorithms, machine learning in the field of wind energy for optimizing energy production and for predictive maintenance. Another trend is the use of environmentally friendly materials for the construction of wind turbines. Trends and performance issues could be predicted by artificial intelligence (AI) due to the large amounts of data that can be analyzed. To integrate AI into wind energy systems, some barriers related to collecting data from multiple wind farms must be overcome. Companies must agree to data sharing, labeling standardization and event tracking. The major advantages that AI brings are: it reduces data analysis time, enables standardized data labeling, increases performance and reduces maintenance costs. Turbine wind direction orientation and angle of attack adjustment could have more efficient controllers due to AI optimization algorithms. Understanding system problems by using machine learning (ML) algorithms to analyze historical data obtained by condition monitoring systems from other turbines will become easier. ML can determine the need for component repairs or replacement, reducing downtime and extending turbine life. Genetic algorithms may increase the blade tilting efficiency and durability of vertical axis wind turbines. Advanced materials could facilitate transportation and installation, prevent corrosion, reduce stress and lighten the structure of wind turbines. A significant contribution to the production of wind turbine components and the reduction of carbon dioxide emissions can be achieved through 3D printing technology. Better research is still needed to meet all the requirements related to strength, surface quality, etc.

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