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REVIEW ARTICLE

Current Developments and Prospects as Composite Materials for Wind Turbine Blades

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ABSTRACT

With the global shift towards renewable energy sources, the wind energy industry has seen remarkable advancements in recent years. One of the key development areas has been the materials used for wind turbine blades. The integration of advanced composite materials has played a pivotal role in enhancing these blades' performance, efficiency, and durability. This review aims to explore the recent advances and future perspectives of composite materials for wind energy turbine blades. Recent advances in composite materials have significantly improved the performance and durability of wind energy turbine blades, enabling the development of larger and more efficient turbines. The use of advanced composite materials, such as carbon fiber reinforced polymers (CFRP) and glass fiber reinforced polymers (GFRP), has led to increased structural integrity, reduced weight, and improved fatigue resistance. Moreover, researchers are exploring new composite material combinations, such as hybrid CFRP-GFRP and basalt fiber reinforced polymers (BFRP), to further enhance properties like impact resistance and corrosion protection. Future perspectives include the development of smart composites with integrated sensors and self-healing capabilities, as well as the use of 3D printing technology to create complex composite structures with tailored properties. These advancements have the potential to enable the development of even larger and more efficient wind turbines, ultimately driving down the cost of wind energy and increasing its share in the global energy mix. In this study, the historical development of composite materials in the production of wind energy turbine blades is reviewed. Specifically, the work is focused on the composite materials used for manufacturing wind energy blades and the level of penetration of composites in the rotor and blades while mentioning some recent developments in composite selection, design, and structure and focusing on the characterization and testing of composite parts. Finally, a novel approach for improving the reliability, life, and sustainability of wind energy blades is highlighted, mentioning opportunities for future research in the area of wind energy composite materials.

***Keywords**: - carbon fiber reinforced polymers, composite materials, smart composite, 3d printing technology, turbine blades, wind energy.*

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1. Introduction

To reduce the effects of climate change on the natural world, there has been a major push over the past decade to identify cleaner and more efficient renewable alternatives for energy generation. In this sense, we can mention wind energy, which is one of the fastest-growing forms of electric power production, accounting for more than one million gigawatt-hours annually. This trend has been instrumental in spurring a great deal of activity aimed at the development of alternative designs for wind turbine rotors, drivetrains, and support structures. Great attention has been addressed toward the industry that makes the blades of these wind turbines, willing to improve their properties, taking advantage of the materials used as well as the geometric distribution of the reinforcements in the structural configuration[1], [2]. Wind turbines are structures consisting of blades that are affected by the wind and therefore rotate around the center (Figure 1). In most cases, they are made of composite materials that have high strength-to-weight and fatigue properties[3].

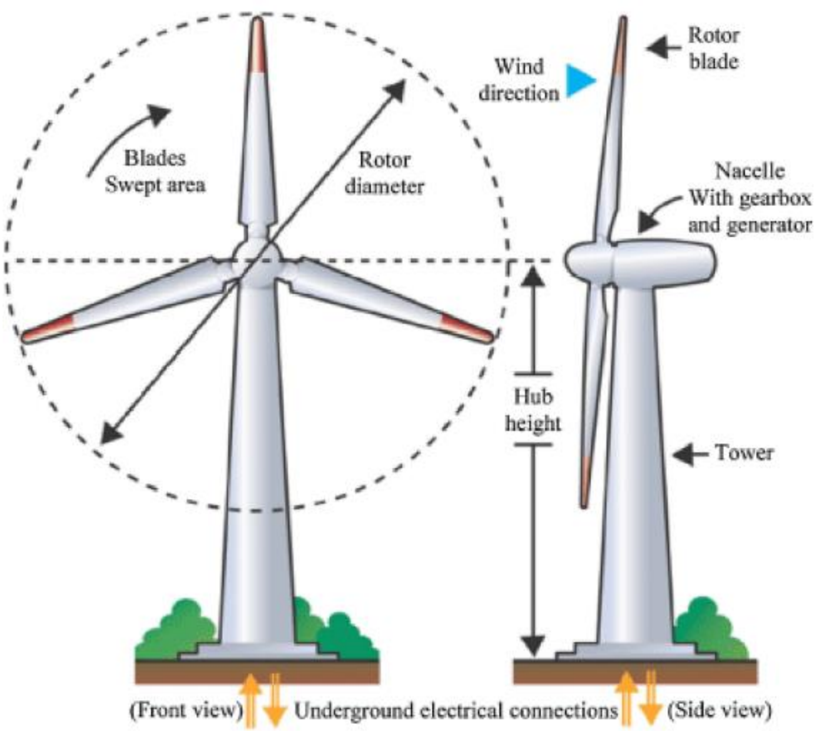

Figure 1. Wind turbines at different views[4].

The low weight, variety of designs, ease of processing and assembly, and ideal geometric properties for transitioning to modern aerodynamics are common features of wind turbine blades. Additionally, another reason why power generation at the top of wind energy turbines is effective is that in this region, the wind is more continuous, and powerful, and flow changes are minimal, making windings in the windings common[4]. The wind energy sector is growing fast, and efforts to increase power output and reduce energy costs are constant. In this scenario, wind energy has become concentrated in both onshore and offshore large wind turbines. Up to now, some of the largest wind turbines have already been achieved, up to 7.5 MW. As shown in Figure 2, the power increase of wind turbines increases the size of the blades and the supporting structure, increasing the height of the towers and the amount of concrete needed. Furthermore, smaller wind turbines are being replaced by larger ones to harness more wind power, but this leads to more complex wind farm development and increased transportation and installation costs. For this reason, the sector is rapidly moving towards higher MW wind turbines with larger diameters and lighter structures[5]. One way to achieve these goals is through the use of lightweight but durable composite materials, which can save up to 80 to 100% of the weight of the turbine and make blade manufacturing easier[6].

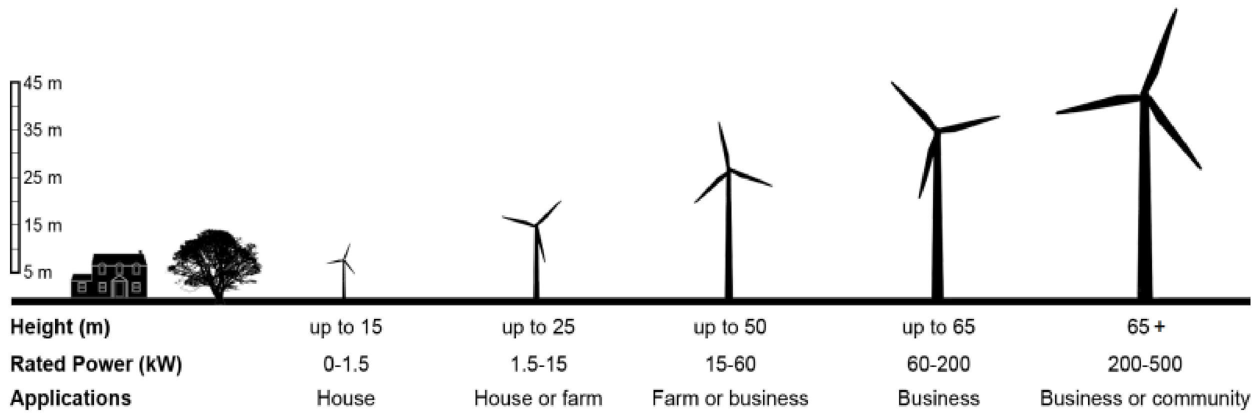

Figure 2. Wind turbine dimensions and rated power outputs as a function of various applications [7].

The wind blades are the most important components in a wind turbine because their structure deeply affects many extremely difficult design problems, including aerodynamics, unsteady dynamics, aeroelasticity, and optimal design. The growth of the global wind energy market in terms of annual installed capacity per year and the increases in both the power demand and national objectives are placing continuous stress on the supply chain. However, the high cost of a wind turbine is a significant barrier to the widespread exploitation of wind power[7]. The blade is typically the structural component of the wind turbine with the highest mass and spans over the largest volume, estimates of the relative contributions of the total blade material cost to the total blade cost typically exceed 50%. With the expected cost of CO_2 emissions levying a premium on its alternates, the increased consumption of wind energy will require an increase in the level of research, development testing, and nonrenewable resources used for these materials[8].

The structure of wind turbines has undergone some alterations due to the rapid improvements in material technology. The primary benefit of that variance was a decrease in wind turbine pricing. As is well known, a variety of materials are employed in wind turbine structures. Wind turbine materials are affected by a variety of factors, including mechanical equipment, fatigue resistance, corrosion resistance, breaking toughness, stiffness, weight, and appearance. This characteristic has led to the widespread usage of materials like composite in wind constructions in recent times. Blades in wind structures are undoubtedly a significant factor in system performance. The evolution of that component in the past related to the materials used in its design, which ranged from cloth to wood and sheet metal, but in the last year composite material has been implemented by all turbine makers. Dimensions and numbers of that component vary based on the strength of the turbine. However, about design specifications, that vital component of wind turbines needs to be thoroughly understood (Figure 3).

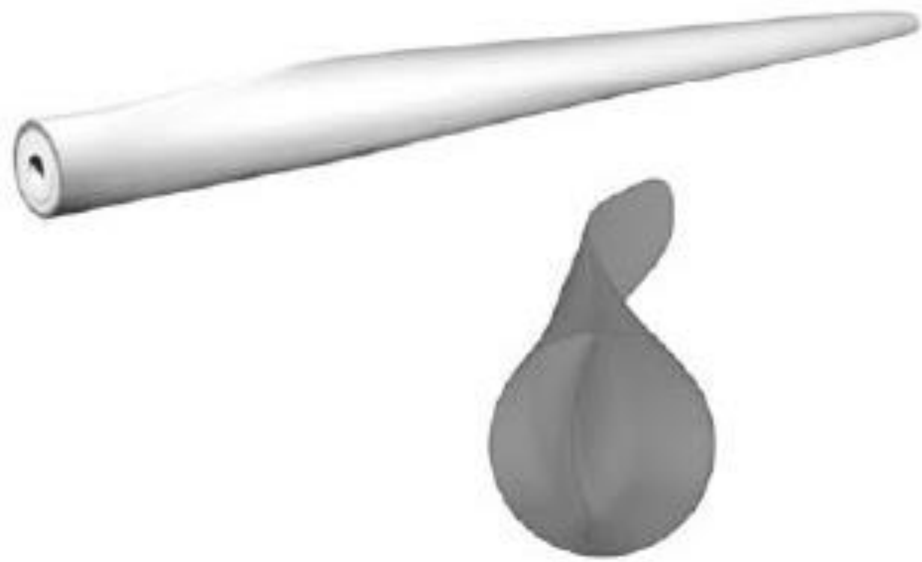

Figure 3 Blade profile [9].

Figure 4 shows a segment of a blade at radius r along with the corresponding angles, forces, and velocities. W represents the relative wind vector at radius r. It is the sum of the rotating component u T and the axial component u P. The air swirl velocity, r ν Ω, and the velocity owing to the motion of the blades, r Ω, add up to the rotational component. The wake effect, or retardation, caused by the blades reduces the axial velocity u P by a component Va 0, where V0 is the upstream undisturbed wind speed. The rotational and axial interference factors are denoted by the terms ά and ά, respectively[9]. The symbols a, q, and f represent the angle of attack, the pitch of the blade, and the relative wind angle to the rotational plane, respectively. As a result, the lift and drag forces are directed perpendicularly and parallel to the relative wind, as indicated by the symbols L and D.

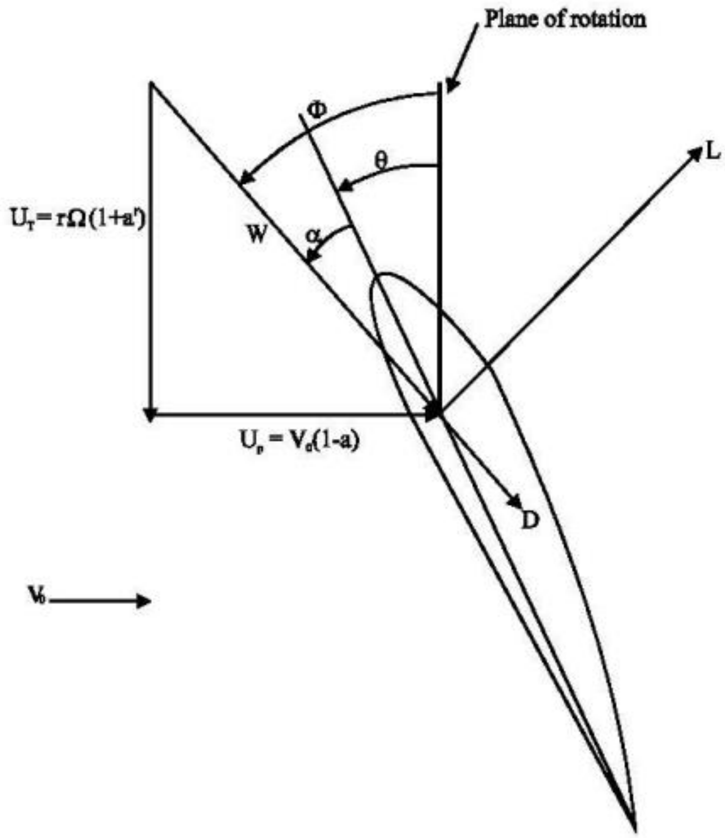

Figure 4. Blade element force velocity diagram [9].

Fatigue is a significant issue that affects the construction and functionality of wind turbines. The large number of rotations that happen at relatively low-stress magnitudes gradually shortens the lifespan of most components. Centrifugal and gravitational loads are mostly to blame for the components that show the highest percentage of fatigue failure (50%) in turbine blades. Additional factors that contribute to fatigue damage include tower shadow, turbulence, wind shear, and interference from turbines upwind. It is challenging to assess how each of these parameters affects the rotor, and a lot of study is being done to get a better understanding. Taking into account all of those aspects, the use of composite materials in wind blades has been chosen as the explanation in that instructive study. Unfortunately, these benefits are hindered by some inherent drawbacks. The first, and possibly most important, is that the mechanical load-bearing capability of glass-fiber-reinforced polymer (GFRP) is generally inadequate at the type of utilization where wind blades are subjected. Additionally, under fatigue conditions, which are important for wind blades, GFRP does not perform optimally. Furthermore, the matrix can deteriorate if the temperature and humidity are not environmentally regulated, thereby decreasing the material's long-term mechanical properties. Decrement of mechanical properties of laminates is responsible for the short-term function of the material. The reinforcement that the glass fibers provide is also restricted by the glass fibers' brittleness. Therefore, the performance of GFRP wind blades may inhibit the continuous upscaling of the wind turbine. In other words, it will limit the use of GFRP wind blades. Recent years have witnessed a significant surge in the utilization of composite materials, particularly carbon fiber-reinforced polymers (CFRP) and glass fiber-reinforced polymers (GFRP), in the manufacturing of wind turbine blades. These advanced composites have proven instrumental in enhancing the structural integrity, reducing the overall weight, and improving the fatigue resistance of the turbine blades. As a result, larger and more efficient turbines have become a reality, contributing to the overall growth of the wind energy sector[10].

Moreover, ongoing research and development endeavors within the industry have focused on the exploration of novel composite material combinations to further augment the properties of wind turbine blades. Hybrid composite materials, such as combinations of CFRP and GFRP, have shown promising results in enhancing impact resistance and corrosion protection. Additionally, the introduction of basalt fiber reinforced polymers (BFRP) as a viable alternative composite has garnered attention for its potential to further fortify the structural characteristics of turbine blades.

Looking ahead, the future perspectives of composite materials for wind energy turbine blades paint a compelling picture of innovation and progress. Foremost among these is the development of smart composites, equipped with integrated sensors and self-healing capabilities. Such advancements hold the promise of proactive maintenance, real-time structural monitoring, and an extended service life for wind turbine blades[11]. The culmination of these recent advances and future perspectives in composite materials has the potential to catalyze the development of even larger and more efficient wind turbines. Ultimately, this trajectory stands to drive down the overall cost of wind energy production, making it a more competitive and sustainable energy source globally[12].

2. Historical Development of Composite Materials in Wind Energy Turbine Blades

As shown in Figure 5, the development of wind blade materials is a monument to the industry's unwavering quest for sustainability and efficiency in wind power. This essay has a historical viewpoint, charting the development of materials that have fueled the improvement of technology in wind turbines. In the Beginning, because it was readily available and simple to make, wood was the main material used to make blades in the early days of wind generation. However, shortcomings in durability and strength fueled the search for substitutes. Mid-Century Transition, Steel and aluminum began to replace wind turbines as they became larger and more powerful in the middle of the 20th century. Although these materials were stronger, their weight and corrosion resistance presented problems. Revolution Composite, A significant change occurred in the late 20th century with the advent of composite materials, especially fiberglass reinforced with epoxy resin. This was a game-changer because it combined strength, flexibility, and reduced weight to enable bigger, more effective blades. Present-day Innovations Advanced composites, such as carbon fiber, are used in modern wind blades to improve strength-to-weight ratios. The current endeavor entails investigating bio-based materials and recyclable composites, which are in line with modern sustainability objectives. The wind blade materials' historical course reflects the industry's dedication to innovation. Every period has enhanced wind energy's sustainability and efficiency, from wood to sophisticated composites[13], [14].

Figure 5. Historical development of wind turbine blade materials. a) Wood turbine blade, b) Steel and aluminum turbine blade, and c) Composite material wind turbine blade.

The historical development of composite materials dates back and is marked by many research studies undertaken over the years. In many scientific and engineering disciplines of the present, including those related to wind energy, the renewed emphasis on improving efficiency and performing an environment-friendly approach draws much attention to composite materials and structures. The application of composite materials in different sizes of wind turbine blades is one of the attractive growth areas. The large growth in the length scale of the wind energy blade design over the past years led to significant challenges in manufacturing, transportation, maintenance, and even recyclability. Such large-scale requirements come up with the use of highly efficient and reliable, possibly lightweight, materials and manufacturing processes[15]. The technical history of composite wind turbine blade construction is roughly associated with the history of the wind energy industry[16].

Polymer composites have been utilized extensively to increase the loading capacity, stiffness, and strength-to-weight of structures compared with conventional materials such as steel and aluminum alloys. Wind energy is one of the fastest-growing sectors of today's renewable energy market due to its economic, environmental, and energy security benefits. This favorable trend encouraged wind energy blade designers to focus on the use of composite materials in ever-larger blades, even at the earliest stages of development, despite their higher initial costs. Polymer composites are now widely and almost exclusively used to fabricate wind energy turbine blades which typically have a length of the order of tens of meters[17]. The historical development of composite materials in wind energy turbine blades has been a significant technological revolution within the field of renewable energy. The early 1990s saw wind turbine blades predominantly constructed from aluminum or fiberglass, materials that had their limitations in terms of durability and efficiency. However, the introduction of composite materials such as carbon fiber-reinforced polymers (CFRP) and glass fiber-reinforced polymers (GFRP) has transformed the industry [16]. The adoption of composite materials marked a turning point, offering a range of benefits including improved strength-to-weight ratios, corrosion resistance, and enhanced fatigue life. These characteristics have paved the way for the design of larger and more efficient blades, enabling wind turbine technology to evolve. Today, modern wind turbines boast blades that span over 100 meters in length, revolutionizing the landscape of renewable energy production[18]. The utilization of composite materials in wind energy turbine blades has not only facilitated the increase in size and complexity of the blades but has also played a pivotal role in elevating the overall efficiency and effectiveness of wind turbines. The incorporation of these advanced materials has led to enhanced performance, increased energy production, and reduced costs, subsequently making wind energy a more sustainable and cost-effective alternative to traditional fossil fuels[10]. When considering the historical development of composite materials in wind energy turbine blades, it is essential to acknowledge the role that these materials have played in driving forward the renewable energy sector. The shift toward composites has propelled the wind industry into new realms of innovation, allowing for the continuous development of larger turbines and more efficient energy production systems. This progression has significantly contributed to the global effort to reduce greenhouse gas emissions and combat climate change[19]. As the demand for clean and renewable energy continues to rise, the historical advancement of composite materials in wind energy turbine blades remains an integral aspect of the renewable energy landscape. The ongoing research and development within this field are crucial for further maximizing the potential of wind energy as a sustainable and reliable source of power for the future[20].

3. Key Properties and Requirements of Composite Materials for Wind Energy Turbine Blades

Composite materials have been widely used in WET blades due to their lightweight ratio, tailored material properties, and decreased manufacturing costs, which are essential in increasing the WET size. From the point of development potentiality, the glass fiber-reinforced polymer (GFRP) has long been the most popular composite for WET blades due to its excellence in electrical insulation, shape design, and excellent strength-to-weight ratio. With the growth of WET size, design speed is also increasing, which leads to a shorter blade life. For wind energy turbines, carbon fiber-reinforced polymer (CFRP) materials, as well as carbon powder-reinforced polymer matrix, give good results in fatigue behavior and stiffness of the WET blade materials[21]. Lately, the hybrid FRP, which has the distinct advantages of every observed material, including reduced cost and vibration damping, has caught widespread notice due to its exclusive application in WET blades. In general, many structural elements are applied to decrease the vibroacoustic of WET blades, like sandwich structures. Meanwhile, the recently developed functional fiber-reinforced FRP with thermal self-sensing capability is also investigated to solve some problems in the WET blade. Taking all the above into account, using composite materials in the WET blade can significantly change the blade's properties, including decreasing the blade cost, improving the fatigue life, and simplifying the blade inspection, allowing for easier access to the internal elements of the blades[22].

Composite materials have revolutionized the way we harness wind energy, particularly in the design and construction of turbine blades for wind farms. The drive for more efficient, durable, and cost-effective wind turbines has led to the increasing use of composite materials, which offer a host of key properties and requirements crucial to their performance in this demanding application[23]. One of the primary reasons for the widespread adoption of composite materials in wind energy turbine blades is their exceptional strength-to-weight ratio. These materials are typically formed by combining a polymer matrix with reinforcing fibers such as fiberglass or carbon fiber. This results in turbine blades that are not only lightweight but also possess the necessary strength to withstand the mechanical forces exerted by the wind[24]. In addition to the high strength-to-weight ratio, composite materials used in wind turbine blades must exhibit high stiffness to ensure their structural integrity and efficient energy conversion. This stiffness is vital for maintaining the aerodynamic profile of the blades and optimizing their performance in converting wind energy into rotational motion. Furthermore, toughness and impact resistance are fundamental properties that enable turbine blades to withstand various environmental conditions, including strong winds, hail, and other potential sources of impact[25].

Table 1. Tensile and fatigue properties of unidirectional flax/polyester and E-glass/polyester composites[26].

	Property		Flax	E-glass	Flax/E-glass
Physical	Fibre volume fraction	%	30.9	42.8	
	Density	$g\ cm^{-3}$	1.31	1.79	0.732
Tensile	Composite stiffness	GPa	23.4	36.9	0.634
	Composite specific stiffness	$GPa/g\ cm^{-3}$	17.9	20.6	0.869
	Effective fibre stiffness[a]	GPa	67.6	81.6	0.828
	Composite strength	MPa	277	826	0.335
	Composite specific strength	$MPa/g\ cm^{-3}$	213	461	0.462
	Effective fibre strength[a]	MPa	883	1920	0.460
	Composite failure strain	%	1.70	1.90	0.895
Physical	Fibre volume fraction	%	26.9	30.0	0.897
	Density	$g\ cm^{-3}$	1.29	1.64	0.787
Fatigue ($R = 0.1$)	Single cycle strength	MPa	236	567	0.416
	Fatigue strength at 10^6 cycles	MPa	115	204	0.564

As shown in Table 1, Fatigue resistance is another crucial requirement for composite materials in wind turbine blades. As these blades are subjected to constant cyclic loading over their operational lifespan, they must be able to resist damage accumulation and maintain their structural integrity. The ability of the composite material to withstand fatigue is crucial to ensuring the long-term reliability and safety of wind turbines[27]. Moreover, resistance to environmental degradation is essential for the longevity of wind turbine blades. Exposure to ultraviolet (UV) radiation, moisture, and thermal cycling can degrade the performance of composite materials over time. Therefore, these materials must be specifically formulated and engineered to resist degradation and maintain their properties over the entire service life of the turbine blades[28]. A low coefficient of thermal expansion is also an important requirement for composite materials used in wind turbine blades. This property is critical for minimizing stress concentrations and ensuring the smooth rotation of the turbine blades, particularly during temperature variations. By maintaining a low coefficient of thermal expansion, composite materials can reduce the risk of structural damage and operational issues associated with thermal cycling. The selection of suitable composite materials for wind turbine blades is influenced by various factors, including the specific blade design, operating conditions, and intended lifespan. It is essential to tailor the properties of the composite materials to match the environmental and mechanical demands placed on the turbine blades during their operational life[29].

4. Types of Composite Materials for Wind Turbine Blades

The utilization of composite materials in airplanes, helicopters, and other aerospace applications was the pioneering field that made these new materials well known. For aircraft manufacture, the lightness of composite materials is critical. The consequences of utilizing these materials in huge sections, as in wind energy turbine blades, are as much or maybe even more crucial. These materials might also revolutionize one issue linked with processed materials like rusts, specific ratios like weight to energy, etc. The results obtained in the fatigue area prove that wind energy blades can be a more appropriate industrial sector for composite materials marketing than the aircraft industry currently is. These materials transmit damage, are composed of natural fibers, and can also be recycled material, fulfilling two requirements currently under consideration for materials in the year 2020[30]. In the last decades, the use of composite materials has been increasing in various sectors. Composite materials have unique properties that cannot be found in traditional materials such as metals, mainly due to the combination of constituents and the generation of new materials with defined microstructures. The mechanical and physical properties of composite materials depend on the geometric characteristics of their constituents, and many times the composite is represented as a function of these constituents. There are different types of composite materials produced to obtain specific properties, and the combination of different constituents with different compositions can lead to additional properties in the resulting composite materials. Each type of composite material offers its unique combination of properties, with the identification of the most suitable types of materials for each application promoting key aspects regarding both technical features and the value associated with the component[31]. Composite materials began to be used in the construction of wind turbine blades due to the great reduction in weight, and consequently in the operational costs of the wind turbines, in addition to the high specific strength and stiffness. The concept of specific strength and stiffness is the maximum stress and strain that the material can withstand before breaking, which is the relationship between the mechanical properties and the density of the material, respectively. The synergy of using fiber reinforcement and polymer resin means that very high specific strength and stiffness values can be achieved while offering the advantage of tailoring many other properties to suit the nature of the intended load-carrying function. This allows the weight and mass of wind turbine blades to be reduced by 50-60%, resulting in lower costs, and easier handling and installation. Furthermore, composite materials prevent operation and equipment breakdowns, induce low accentuation levels, improve the aerodynamic and electrical properties of the blades, and reduce the noise produced by the wind turbine[32]. Wind energy has become an increasingly popular source of renewable energy worldwide, with wind turbine blades playing a crucial role in harnessing this valuable resource. These large blades are subject to tremendous forces and must be able to withstand the harsh conditions of wind energy generation. To meet these demanding requirements, composite materials are the go-to choice for constructing wind turbine blades. This review will explore the various types of composite materials used in wind turbine blades and the key considerations when choosing the right material for the job[33].

Glass fiber reinforced polymers (GFRP) are one of the most common composite materials used in wind turbine blades. They are known for their exceptional strength and relatively low cost, making them a popular choice for smaller or mid-sized turbines. GFRP blades are lighter than traditional materials such as steel, which contributes to reduced overall weight and improved energy efficiency. This results in lower manufacturing and transportation costs, making GFRP an attractive option for wind turbine manufacturers. Fiber-reinforced polymer composites, and especially glass fiber-reinforced polymer composites (GFRP), are currently the most commonly used materials in the manufacturing of blades in the wind energy sector. As compared to the early designs for wind turbine blades in the 1980s, competition and research in the sector led to cheaper and more reliable designs, since the performance of any new blade can and should be checked with developments in designs, materials, concepts, failures, etc[34].

Carbon fiber reinforced polymers (CFRP) offer a higher strength-to-weight ratio compared to GFRP. This makes them an ideal choice for larger turbines that require stronger, lighter blades to maximize energy output. The superior mechanical properties of CFRP blades allow for longer and more slender blade designs, effectively capturing more wind energy and increasing overall turbine performance. While CFRP blades may incur higher manufacturing costs, their advantages in performance and efficiency make them a compelling option for large-scale wind energy projects [35].

Hybrid composites represent a blend of GFRP and CFRP, combining the best attributes of both materials. By leveraging the cost-effectiveness of GFRP and the high performance of CFRP, hybrid composites offer an attractive middle ground for wind turbine blade construction. These materials provide enhanced mechanical properties, allowing for greater design flexibility and improved overall blade performance. Additionally, the use of hybrid composites can potentially reduce manufacturing costs without compromising on quality, making them a promising choice for a wide range of wind energy applications[36].

Natural Fiber Reinforced Polymer Composite, Mostly glass and carbon fiber-reinforced plastics (i.e., GFRP and CFRP, respectively) have been used for the production of large-scale wind turbine rotor blades. The use of glass and carbon fiber is no longer attractive to rotor blade manufacturers because the cost of these materials is high and the use of these materials causes environmental hazards. These attributes of synthetic fibers stimulate researchers to develop alternative materials for wind turbine rotor blades. The wind turbine indeed becomes the central part of the energy generation but problems come when all those wind turbines need to be replaced. The currently used materials glass, Kevlar, and carbon are non-biodegradable. For the prevention of this large waste, research efforts have been made to develop biodegradable materials. The next generation's best materials will be lingo cellulose-based natural fiber-reinforced materials. Plant fibers offer several economical, technical, and ecological advantages over synthetic fibers in reinforcing polymer composites. Due to the relative abundance, low cost of raw material, low density, high specific properties, and positive environmental profile of plant fibers like flax, hemp, coir, abaca, alpaca, bamboo, and jute; they have been marketed as prospective substitutes to traditional composite reinforcements, specifically E-glass. As 87% of the 8.7 million tonnes global fiber-reinforced plastic (FRP) market is based on E-glass composites (GFRPs)[37]. Natural fibers and their composites have a great opportunity for development and market capture. Besides, recent advancements in nanomaterials and **3D printing** have sparked new possibilities for enhancing the properties and longevity of wind turbine blades. Nanomaterials, such as carbon nanotubes and graphene, offer remarkable improvements in strength, stiffness, and fatigue resistance, presenting exciting opportunities for next-generation wind turbine blade construction. Additionally, 3D printing technologies enable the production of intricate blade designs with optimized internal structures, leading to improved mechanical performance and overall turbine efficiency[38]. The integration of 3D printing technology into the production of composite structures is poised to revolutionize the industry. This innovation allows for the creation of complex, intricate geometries that can be tailored to exhibit specific mechanical properties. The use of 3D printing technology also presents opportunities for cost-effective manufacturing and customization, thereby contributing to the overall affordability and accessibility of wind energy technologies[39].

5. Manufacturing Processes for Composite Materials in Wind Energy Turbine Blades

In specific production techniques, it is common to use thermoset matrix polymers such as polyester (UP), epoxy (Ep), and vinyl ester (VE) because of their long-term properties, corrosion resistance, high-temperature resistance, good mechanical properties, and low cost of production materials. Additionally, the usage of thermoplastics, which are highly preferred in today's composite materials, is also increasing due to the ease of recycling and reuse. Cooling, as one of the significant parts of the whole process, is the next process of dealing with many problems in composite materials, which are of great importance in the manufacture of wind turbine blades and whose improvement continues. Closed chamber and vacuum systems, commonly preferred components of cooling systems, reduce the time of process control and mechanical properties. The main factor to be considered here is the controller variable in the flow of air on the composite material and the heat transfer[40]. In most of the literature on wind turbine blades, processing-induced effects are added to the static and fatigue loads experienced by the blade. The existing factor to be calculated in most of the literature is during the newly prepared blades. Innovative procedures have been developed for blade manufacturing and for reducing the maintenance costs of wind turbines. The use of automatic manufacturing and robotic handling, based on current specifications, can further reduce manufacturing costs and work times. The combination of intelligent manufacturing, thermal robotic manufacturing, resin-based manufacturing, and automatic lay-up of composite factory-based 3D technology will contribute to the development of this field[41]. In recent years, attention has been drawn to the use of pultrusion in the manufacturing of wind rotor blades (Figure 6). Pultrusion is a continuous composite manufacturing process that is already available in the composites sector, using on a commercial scale, different composite fibers such as carbon fiber, natural fibers, and glass fibers. Also, this process still needs to be improved on a larger scale, mainly for the manufacturing of rotor blades. The main advantage of pultrusion, as compared to composites used in blades, can vary according to the design and purpose of the composites. Some composites offer positive benefits in terms of properties and performance. In a rotor blade, for instance, constraints such as operational conditions and service time can preempt certain alternatives. Consequently, the choice of composites is important in defining the blade considering its physical and mechanical properties[42]. Furthermore, pultrusion is a continuous manufacturing process that has gained prominence in the production of composite materials for wind turbine blades. Pultrusion involves pulling continuous fibers through a resin bath and then through a heated die to shape the composite material into the desired form. This continuous process allows for the efficient production of long and complex shapes, which are integral for constructing the aerodynamic and structurally resilient profiles required for wind turbine blades. Pultruded composite materials offer exceptional strength-to-weight ratios and can be tailored to meet specific performance requirements, making them a valuable option for turbine blade construction[43].

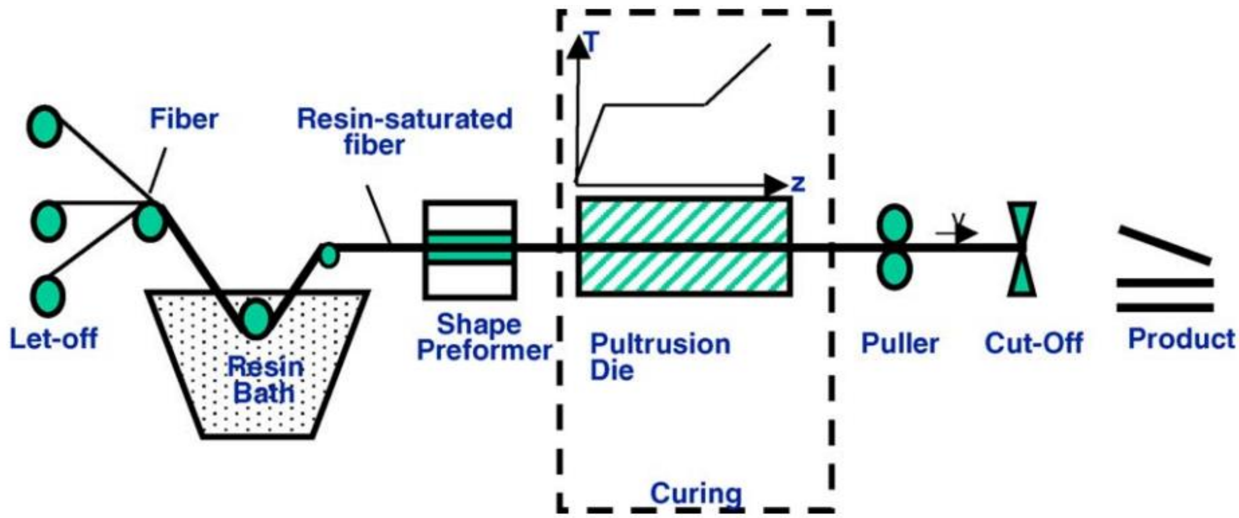

Figure 6 Schematic of the pultrusion process for fabrication of thermosetting matrix composites[44].

The use of composite materials in wind energy turbine blades has revolutionized the manufacturing processes in the renewable energy sector. Composites offer a unique combination of strength, lightweight properties, and versatility, making them an ideal choice for constructing large wind turbine blades. To meet the growing global demand for clean energy, manufacturers have been leveraging a variety of advanced manufacturing processes to produce high-performance composite materials for wind turbine blades[45]. As shown in Figure 7, one of the most widely used methods for manufacturing composite materials in wind turbine blades is the vacuum-assisted resin transfer molding (VARTM) process. VARTM involves infusing a resin into a fiber reinforcement while under vacuum conditions. This method allows for precise control over the fiber orientation and resin distribution within the composite material. The ability to control these parameters is crucial for optimizing the mechanical properties of the blades, ensuring that they can withstand the harsh environmental conditions they are exposed to while maintaining efficient energy production[46].

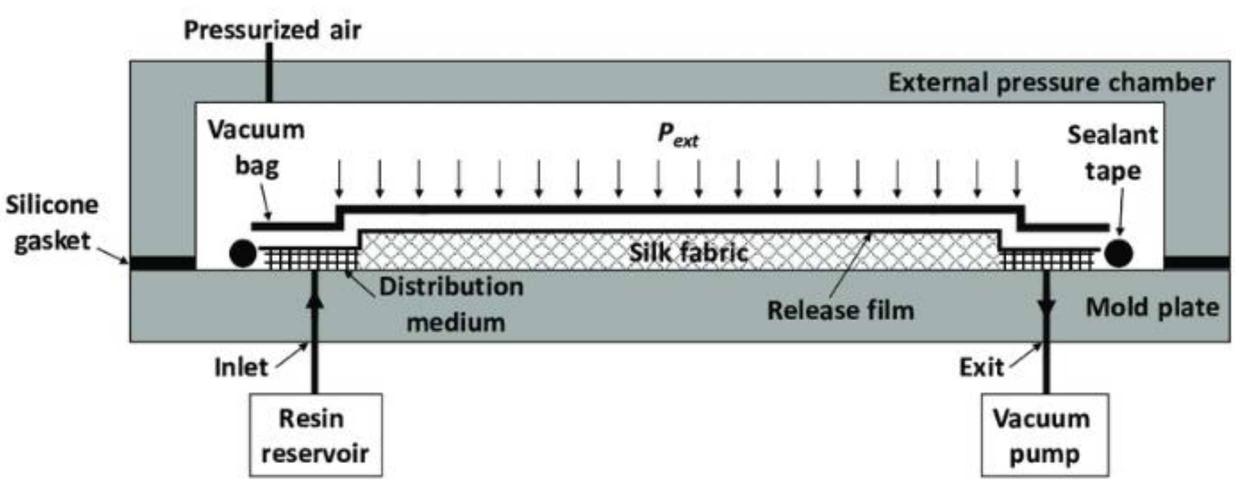

Figure 7. Vacuum-assisted resin transfer molding (VARTM) manufacturing process of composite materials in wind turbine blades[46].

In addition to VARTM, autoclave molding (Figure 8) is another essential manufacturing process for composite materials in wind turbine blades. Autoclave molding utilizes high pressure and heat to cure the composite material, resulting in a high-strength and lightweight blade. The application of high pressure and heat during the curing process ensures the proper consolidation of the composite materials, leading to the formation of a durable and structurally sound blade. This method is known for producing components with exceptional mechanical properties, making it well-suited for the demanding requirements of wind turbine blade construction[47].

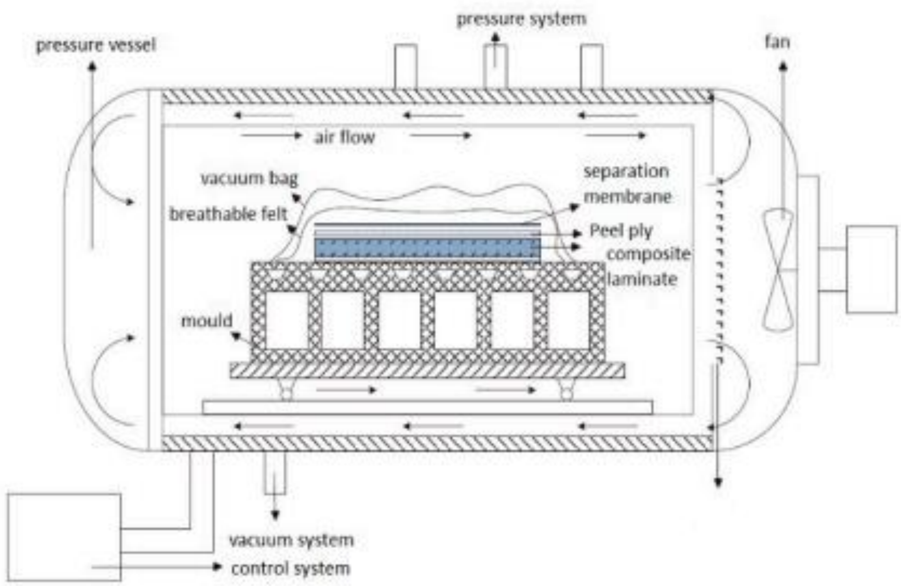

Figure 8. Composite autoclave molding process principle[48].

The integration of these advanced manufacturing processes for composite materials has significantly enhanced the capabilities of wind energy turbine blade production. The precise control over fiber orientation and resin distribution provided by VARTM, the high-strength properties achieved through autoclave molding, and the efficient production of complex shapes using pultrusion have collectively contributed to the development of durable, lightweight, and aerodynamically optimized wind turbine blades[49].

6. Performance Evaluation and Testing Methods for Composite Materials in Wind Energy Turbine Blades

Wind turbine blade materials have evolved from wood to composites. The versatile properties of composite materials make them an attractive option for wind turbine blade manufacturing. The modern wind energy industry is continuously building even larger wind towers, operating in increasingly aggressive environmental and loading conditions. This makes more robust aerodynamics and structural designs essential to the operability and sustainability of wind power technology[50]. The wind energy industry has been taking significant leaps in recent years in terms of novel blade and turbine designs. It is producing larger offshore wind farms and large land-based monopole-supported towers operating under extreme environmental conditions and huge fatigue loads. The goal is to eventually offer advanced yet reliable designs that do not need extensive reinforcement or retrofitting[51]. The material and mechanical tests applied to novel wind turbine blade designs or materials are crucial. They ensure the practice of energy production, quality of materials and structure, load endurance, microscopic and macroscopic characterization of the material, and time-dependent behavior in unfavorable environmental conditions. These tests also help in innovating large composite wind structures, making them reliable to provide the required investment and re-licensing guarantees[52].

The performance of a typical wind turbine blade is closely associated with many properties, including flexural and tensile strength, stiffness, fatigue strength, fatigue life, and toughness properties. These properties deteriorate during the service life of a wind turbine, most frequently attributing to environmental effects, such as the damage mechanisms caused by temperature effects, UV radiation, rain, and insects[53]. The traditional approach of experimental determination of properties is a time-consuming endeavor for the manufacturer. Determination of the combined material properties, especially necessary mechanical properties that can insert requirements on the performance in service, could be an even more complex challenge. However, most testing methods require advanced equipment and are not easy to implement after a wind turbine is at the installed site, introducing the need for remote or in situ testing methods. The most effective way to establish experimental values of composite material properties is to evaluate them during the design, optimization, and certification phases of the blade. The resulting perceived advantages are immense for all concerned parties—the wind farm owner, the blade O&M team, and, not least, the composite material supplier[54].

This review study aims to explain the impact behavior of composites and to compare the results of different testing methods, potential advantages, and disadvantages related to these methods. Strain energy release of the tested types of composites is another issue. Highly promising investigations have been made using testing methods, primarily optical methods. The advantages of these methods include the ability to assess composite behavior, with the ability to monitor variables and obtain full-field strain distributions. The drop-weight impact, three-point bending, compact tension, and circular patch tests on glass, natural fiber/epoxy, carbon/epoxy, and hybrid composites have been tested to assess impact response and damage resistance. The results have been evaluated visually and using non-destructive testing methods. The influence of fiber-reinforced composites on their behavior is interesting; therefore, another aim is to investigate these composites from the point of view of strain energy release[55]. The work is thus aimed at evaluating the performance and pair static-dynamic testing of the following types of composites, which are frequently used when constructing wind turbines: glass/epoxy, natural fiber/epoxy, carbon/epoxy, and their hybrid counterparts. It is important to compare these testing methods - from the point of view of insensitivity or sensitivity - relative to the type of applied composite. To determine the ways these composites behave, their strain energy release is calculated using a compact tension test, and their resulting results are compared. We aim to compare insensitivity or sensitivity to evaluate the dispersion field coefficients (Ak, from k = 1 to k = 11) and the global field of the following tested composites subjected to the same specimen loading level characteristic. The results of static tests - optical methods or NDE techniques - and drop-weight tests seem to be not altogether in comparative agreement[56].

The use of composite materials in wind energy turbine blades has become increasingly prevalent, owing to their lightweight, high strength, and corrosion resistance. However, ensuring the reliability and efficiency of these composite materials requires comprehensive performance evaluation and testing methods. Various testing approaches are employed to assess the mechanical properties, resistance to fatigue and impact damage, and overall performance of the composite materials. These evaluations play a crucial role in enhancing the safety and longevity of wind turbine blades in the renewable energy sector[57]. One of the primary testing methods used for composite materials in wind energy turbine blades is static testing. This method involves applying a constant load to the material to evaluate its response under specific conditions. By subjecting the composite material to controlled loads, engineers can assess its deformation, stress distribution, and ultimate strength. Static testing provides valuable insights into the material's behavior under normal operating conditions and aids in determining its structural integrity and load-bearing capacity[58]. In addition to static testing, dynamic testing is instrumental in evaluating the response of composite materials to varying loads and environmental conditions. Dynamic testing involves subjecting the material to cyclic loads, simulating real-world conditions experienced by wind turbine blades during operation. Through dynamic testing, engineers can analyze the material's fatigue behavior, assess its ability to endure prolonged cyclic loading and identify potential failure modes. This method is essential for understanding the long-term performance of composite materials in wind energy applications[59]. Moreover, impact testing plays a pivotal role in assessing the resilience of composite materials in wind turbine blades. Wind turbine blades are susceptible to impact from debris, hail, and other environmental factors, making it imperative to evaluate their resistance to sudden impact loads. Impact testing allows engineers to measure the material's ability to withstand sudden force and detect any signs of damage or delamination. By subjecting the composite material to controlled impact loads, its durability and damage tolerance can be effectively determined, contributing to the overall safety and reliability of wind turbine blades[60]. Tension-torsion testing represents another critical evaluation method for composite materials in wind energy turbine blades. This testing approach involves applying both tension and torsion loads to the material to assess its mechanical properties under combined stress conditions. By subjecting the material to simultaneous tension and torsion, engineers can accurately characterize its strength, stiffness, and torsional behavior. This comprehensive testing method provides valuable data for understanding how composite materials in wind turbine blades perform under complex loading scenarios, contributing to their enhanced design and structural optimization[61]. In addition to physical testing methods, non-destructive testing (NDT) techniques such as ultrasonic testing and acoustic emission testing are integral for detecting defects and damage within composite materials. These non-invasive testing methods allow for the thorough inspection of wind turbine blade components without causing any structural impairment. By utilizing ultrasonic waves and acoustic emission monitoring, engineers can identify internal flaws, delamination, and material discontinuities, facilitating the early detection of potential defects and ensuring the overall integrity of wind turbine blade materials[62]. Lastly, computational modeling and simulation tools play a crucial role in predicting the behavior of composite materials in wind energy turbine blades. Through advanced modeling techniques, engineers can simulate the material's response to various environmental conditions, loads, and stresses. Computational modeling allows for the optimization of wind turbine blade designs and the prediction of material performance, ultimately leading to enhanced reliability and efficiency in renewable energy applications[63].

7. Challenges and Limitations of Composite Materials in Wind Energy Turbine Blades

Wind turbine blades often fail due to low-velocity damage, such as coating cracking, local delamination, core shear, and disbanding resulting from aging effects like erosion, rain, and thermal cycling. Composite materials are ideal for use in the wind energy industry due to their high strength-to-weight ratio. Carbon/glass-based composite materials, such as poly or epoxy, are generally stronger, inexpensive, and compatible with any wind turbine blade design[64]. The adoption of composite materials in wind energy turbine blades has presented both opportunities and challenges for the renewable energy industry. While composite materials offer advantages such as lightweight and high strength, some significant challenges and limitations have hindered their widespread adoption[65]. The production of wind energy has recently increased worldwide due to the rising concern for climate change and interest in renewable energy production. Locally, businesses and local authorities are implementing wind energy farms to finance economic development and diversification within rural areas. The main interests with wind energy technology are the low levels of air and water pollutants, water consumption, land use, and disturbance to natural beauty. The composite materials widely used for the design and manufacture of wind turbine blades are based on epoxy-reinforced fiberglass and epoxy-reinforced carbon fiber. These components of composite materials cannot be recycled and are an environmental concern. The recycling of polymer matrices reinforced with other types of fibers hardly exists[66].

One of the primary challenges facing composite materials in wind energy turbine blades is the high cost of production. The use of composite materials can account for up to 30% of the total blade cost, making it a significant factor in the overall economics of wind energy projects. This has implications for the affordability and scalability of wind energy, especially in the context of competing with traditional energy sources[67]. Moreover, composite blades are prone to delamination and damage from fatigue. Delamination occurs when the layers of composite materials separate, leading to structural weaknesses and compromising the integrity of the blades. Fatigue damage, caused by cyclic loading and environmental factors, can significantly reduce the lifespan of composite blades and result in increased maintenance costs. Addressing these issues is crucial for ensuring the long-term reliability and performance of wind turbine blades[68]. In addition to performance concerns, the environmental impact of composite materials must be taken into consideration. Despite being lightweight, the high stiffness and density of composite materials can make them challenging to repair and recycle. This poses environmental concerns regarding the disposal and end-of-life management of wind turbine blades. As the renewable energy sector seeks to minimize its environmental footprint, the limited recyclability of composite materials presents a significant obstacle[69]. Furthermore, the limited availability of raw materials and supply chain disruptions can hinder the widespread adoption of composite blades. The dependency on specific raw materials and complex manufacturing processes increases the vulnerability of the supply chain, leading to potential delays and uncertainties in production. These challenges underscore the importance of diversifying the material supply chain and exploring alternative composite formulations to enhance the resilience of the wind energy industry[70]. Addressing the challenges and limitations of composite materials in wind energy turbine blades requires a multi-faceted approach. Research and development efforts aimed at improving manufacturing techniques, enhancing material durability, and developing advanced recycling methods are essential to overcome these obstacles. Additionally, fostering collaboration between industry stakeholders and policymakers can facilitate the innovation and standardization necessary for the sustainable deployment of composite blades in wind energy applications[71].

8. Recent Advances in Composite Materials for Wind Energy Turbine Blades

The knowledge about material aging and scattering across wind turbine blades and their potential impact on blade performance is important, and many researchers around the world are working on this subject. This review reports and discusses the most recent contributions found in the literature on different types of composite materials and coatings (epoxy, poly, and silicone) suitable for wind turbine blade applications. These materials show significant potential for optimizing the aging of materials in wind turbine blades, thus enhancing their lifetime remarkably. There is also potential to integrate these materials in situ during the blade construction process[64]. The technical aspects presented in this work represent state-of-the-art, but they also encourage the development of new manufacturing concepts and likely the attachment and assembling of the blades during their lay-up or after construction, but still in the factory[72]. In recent years, the wind energy industry has experienced substantial growth, driven by advancements in composite materials used for turbine blades. These developments have not only improved the efficiency and durability of wind turbines but have also contributed to the overall sustainability of renewable energy sources. The introduction of new composite materials, such as carbon fiber-reinforced polymers (CFRP) and glass fiber-reinforced polymers (GFRP), has revolutionized the design and manufacturing of wind turbine blades[45].
One of the most notable impacts of these new materials is the ability to produce longer and lighter blades. By utilizing CFRP and GFRP, manufacturers have been able to extend the length of turbine blades, thereby increasing the swept area and consequently enhancing the energy capture capabilities of wind turbines. The lightweight nature of these composite materials has also resulted in reduced material usage, contributing to more sustainable and cost-effective blade production [73]. Moreover, researchers and engineers have been exploring innovative composite designs to further optimize the performance of wind turbine blades. Techniques such as 3D printing have enabled the creation of complex, aerodynamically superior blade designs that were previously unattainable using traditional manufacturing methods. This development has paved the way for the production of customized blade shapes tailored to specific wind conditions, ultimately maximizing energy extraction from the wind[74]. Furthermore, the integration of hybrid composites, combining different types of reinforcing fibers, has been instrumental in enhancing the structural integrity and fatigue resistance of turbine blades. This has led to an extended lifespan of the blades and minimized maintenance requirements, contributing to improved overall operational efficiency[36].

The advancements in composite materials have also had a significant impact on the cost competitiveness of wind energy. With the increased energy capture and reduced material usage enabled by these materials, the levelized cost of electricity (LCOE) from wind power has substantially decreased, making it more competitive with traditional fossil fuel-based energy sources. As a result, the continued growth of wind energy has become increasingly attractive not only from an environmental standpoint but also from an economic perspective[75]. The adoption of these advanced composite materials and designs has positioned wind energy as a crucial player in the global transition toward renewable energy. As countries seek to reduce their carbon footprints and mitigate the effects of climate change, the use of composite materials in wind turbine blades plays a pivotal role in driving the growth of sustainable energy generation. With ongoing research and development in this field, it is expected that further improvements in composite materials and blade designs will continue to enhance the performance and cost-effectiveness of wind energy, further solidifying its position as a prominent source of clean, renewable power[76].

9. Nanotechnology Applications in Composite Materials for Wind Energy Turbine Blades

Wind energy is one of the most important renewable energies which can provide electricity around the world. The growth of wind energy has promoted the development of wind turbine blades. However, with the larger blade-wind energy converter, the loads on the blades also become higher, resulting in more frequent and more destructive failures. Consequently, this increases the operating cost and decreases the competitiveness of the whole wind unit. Nanotechnology has a fast-growing influence on many industrial materials, especially the composites. The use of carbon nanofibers, carbon nanotubes, graphene oxides, and other carbon-based nano-reinforcements in the composites can significantly enhance the mechanical properties of the composites, and reduce the moisture absorption, brittleness, and manufacturing time[77]. Nanotechnology has the potential to revolutionize many materials systems. Certain properties of electrical, thermal, and mechanical can be significantly enhanced in advanced composites developed with the use of nanotechnology. It was applied to the field of wind technology and particularly to composite materials for the realization of wind turbine blades. As a result, new manufacturing technologies were invented and specifically adapted to products that have the use of modular carbon-based nano-reinforcement in a composite, which are characterized by good mechanical and thermal properties and can be efficiently used in structural parts particularly suited for use in the wind industry sector[78]. Nanotechnology is revolutionizing the world of wind energy by offering innovative solutions for turbine blade design and performance. With the incorporation of nanomaterials into composite materials, wind turbine blades can achieve enhanced mechanical, thermal, and electrical properties, ultimately contributing to improved efficiency and durability[79]. One of the key advantages of integrating nanotechnology into composite materials for wind turbine blades is the ability to significantly improve the strength-to-weight ratio. Nanoparticles such as carbon nanotubes, graphene, and Nano clay play a crucial role in reinforcing the composite matrix, thereby increasing the overall strength of the material while keeping it lightweight. This improvement in strength-to-weight ratio allows for the design of blades that are not only stronger and more durable but also lighter, enabling them to operate at higher speeds and endure harsh environmental conditions[80] The incorporation of nanomaterials contributes to the enhancement of fatigue resistance in composite materials. Wind turbine blades are subject to repetitive loading and unloading forces due to wind dynamics, which can lead to fatigue-related issues over time. By integrating nanoparticles, the composite materials can exhibit improved fatigue resistance, prolonging the lifespan of the blades and reducing the need for frequent maintenance and replacement[81]. In addition to mechanical properties, nanotechnology also has a significant impact on the thermal conductivity of composite materials. Through the addition of nanomaterials, the thermal conductivity of the composites can be enhanced, allowing for better heat dissipation during operation. This improvement in thermal management can contribute to the overall efficiency of wind turbine blades, especially in high-stress operating conditions[82]. Furthermore, nanotechnology enables the development of self-healing composite materials for wind turbine blades. Nanomaterials can be engineered to facilitate self-repair mechanisms within the composite matrix, allowing the material to autonomously heal cracks and damages that may occur during operation. This self-healing capability not only reduces maintenance costs but also minimizes downtime, ultimately leading to increased operational efficiency and cost savings for wind energy producers[83]. By leveraging nanotechnology in the design and manufacturing of wind turbine blades, manufacturers can optimize the overall performance of the blades, increase energy efficiency, and ultimately reduce the overall cost of energy production. The potential for nanotechnology to revolutionize composite materials for wind turbine blades represents a significant step forward in the ongoing pursuit of sustainable and renewable energy solutions[84].

10. Future Perspectives and Emerging Trends in Composite Materials for Wind Energy Turbine Blades

The wind energy industry has been experiencing a notable transformation with the increasing utilization of advanced composite materials for wind turbine blades. This shift is primarily fueled by the pursuit of enhanced efficiency, cost reduction, and improved durability within the sector. Additionally, a marked emphasis on the adoption of novel materials and innovative design strategies has been observed, signifying the advent of new trends in composite materials for wind energy turbine blades[85]. One of the prominent emerging trends includes the incorporation of recycled carbon fiber into the production of wind turbine blades. The utilization of recycled materials not only aligns with sustainable practices but also presents a viable solution for reducing the environmental impact of composite manufacturing processes. This trend contributes to the industry's commitment to environmental responsibility while concurrently addressing the demand for durable and cost-effective materials[86]. Another compelling development is the utilization of 3D-printed composites in the manufacturing of wind turbine blades. The application of 3D printing technology in the production of composite materials offers unparalleled flexibility in design and material composition, enabling the creation of intricate and optimized structures tailored to specific performance requirements. This trend represents a significant leap forward in the customization and production of turbine blades, with the potential to enhance overall performance and efficiency [87]. Likewise, a growing trend is observed in the use of hybrid materials, combining carbon fiber with other types of fibers such as glass or natural fibers. This approach aims to leverage the unique properties of different fibers to create composite materials with enhanced strength, flexibility, and reduced weight. By blending various fibers, manufacturers can tailor the characteristics of the composite materials to meet the specific demands of wind turbine applications, thereby optimizing the overall performance and longevity of the blades[88].

In tandem with material advancements, an increasing focus is directed toward the design optimization of blade geometries and shapes to harness the capabilities of advanced composite materials effectively. The synergy between advanced materials and optimized blade designs holds the potential to elevate energy yields while concurrently reducing maintenance requirements. This holistic approach underscores the industry's commitment to maximizing the efficiency and longevity of wind turbine systems through meticulous attention to both material selection and structural design[89]. Looking ahead, the integration of emerging trends in composite materials for wind energy turbine blades is poised to revolutionize the landscape of the wind energy industry. The convergence of recycled materials, 3D printing technologies, hybrid material compositions, and optimized designs underscores a pivotal shift towards sustainable, high-performance wind turbine solutions. As these innovations continue to unfold, they are expected to drive substantial improvements in energy production, cost-effectiveness, and environmental sustainability within the wind energy sector[90].

Conclusions

The historical development of composite materials in wind energy turbine blades has revolutionized the renewable energy industry, paving the way for larger, more efficient, and cost-effective wind turbines. The incorporation of advanced materials such as CFRP and GFRP has propelled the industry forward, contributing to a more sustainable and environmentally friendly energy landscape. As technology continues to evolve, the role of composite materials in wind energy turbine blades will remain critical for the ongoing advancement of renewable energy solutions. The selection of composite materials for wind turbine blades is a critical decision that directly impacts the performance, cost, and sustainability of wind energy projects. While GFRP, CFRP, and hybrid composites continue to dominate the market, ongoing research and development in nanomaterials and 3D printing are reshaping the landscape of wind turbine blade construction. As the demand for clean energy grows, the continued advancement of composite materials will play a pivotal role in driving the efficiency and viability of wind energy generation for years to come. The manufacturing processes for composite materials in wind energy turbine blades play a pivotal role in enabling the production of high-performance blades that are essential for the efficient generation of renewable energy. By leveraging a combination of traditional manufacturing techniques and advanced technologies, manufacturers can meet the stringent demands of the wind energy industry, thereby contributing to the continued growth of clean and sustainable energy sources. With ongoing advancements in composite manufacturing, the future of wind energy holds the promise of even more efficient and reliable turbine blades. Comprehensive performance evaluation and testing methods for composite materials in wind energy turbine blades are essential for ensuring their reliability, safety, and longevity. By employing a combination of static testing, dynamic testing, impact testing, tension-torsion testing, non-destructive testing techniques, as well as computational modeling and simulation tools, engineers can effectively assess the mechanical properties, durability, and overall performance of composite materials in wind turbine blades. These testing methods are instrumental in advancing the development of renewable energy technologies and promoting sustainable energy production for the future.

Recent advances in composite materials for wind energy turbine blades have brought about significant improvements in efficiency, durability, and sustainability. The adoption of carbon fiber-reinforced polymers, glass fiber-reinforced polymers, and innovative composite designs have propelled the wind energy industry towards greater competitiveness with traditional energy sources and has accelerated the global shift towards sustainable energy production. The incorporation of nanotechnology in composite materials for wind turbine blades offers a promising pathway toward achieving higher performance, durability, and efficiency in wind energy generation. With ongoing research and development in this field, the potential for nanotechnology to reshape the future of wind energy is both exciting and impactful. The incorporation of composite materials, specifically CFRP and GFRP, in wind energy turbine blades presents a compelling case for the advancement of sustainability and environmental responsibility within the renewable energy sector. Through their improved durability, reduced weight, recyclability, and enhanced aerodynamic properties, composite materials have the potential to significantly reduce the environmental impact of wind energy production while increasing its overall sustainability. As the demand for renewable energy sources continues to grow, the pivotal role of composite materials in driving the sustainability of wind energy cannot be overstated. The ongoing evolution of composite materials for wind energy turbine blades reflects a dynamic and progressive trajectory within the wind energy industry. The amalgamation of novel materials and innovative design paradigms heralds a future characterized by heightened efficiency, reduced costs, and increased durability, marking a transformative phase in the development of wind turbine technologies.

Authorship contribution statement

Dawit Teseema Ebissa: Conceptualization, Writing – original draft, Investigation & Validation. Molla Asmare Alemu: Conceptualization, Validation, Supervision, Writing – review & editing.

Declarations

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