Innovations in Blade Design for Enhancing Wind Turbine Efficiency: A Review of Aerodynamic, Structural, and Material Advancements

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Abstract – *This paper reviews the most significant aerodynamic, structural, and material advances in wind turbine blades. If the market is to be more sustainable, wind turbine efficiency becomes an important consideration. The article highlights the aerodynamic innovations that refine blades to optimize performance and capture more energy in higher lift-to-drag ratios. The structural advancement is based on high-end design techniques for high performance in extreme conditions to eliminate maintenance costs. Then there are the material improvements, such as lightweight, robust composites that make for longer blades with the ability to capture more energy without compromising strength. This multidimensional approach is, overall, crucial to widespread utilization of wind as a sustainable and affordable energy source against the backdrop of increasing energy needs.*

Keywords: *Wind Turbine Efficiency, Aerodynamic Optimization, Structural Integrity, Material Innovations, Lift-to-Drag Ratio, Sustainable Energy*

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I. Introduction

The innovations in the blade technology for optimizing wind turbine efficiency became all the more important given rising demand for green power worldwide. Wind is an important renewable source of energy, and aerodynamic tuning of the blades of wind turbines can help optimize energy capture and storage. This review outlines the many aerodynamic, structural, and material technologies used to enhance the efficiency of wind turbine blades.

Aerodynamic improvements look to optimize the blade's form and efficiency so as not to lose wind energy. These innovations are fundamental to optimizing the lift-to-drag ratio, which directly affects the overall efficiency of wind turbines. Additionally, the structural improvement involves adopting advanced design and analysis techniques to make turbine blades more resilient and functionally reliable so they can withstand severe environmental environments with low-cost maintenance [1]. Along with aerodynamic and structural innovations, materials science makes a significant contribution to the efficiency of the blades of wind turbines. The advent of lighter, more resilient alloys means longer blades that can take on more energy while maintaining strength. Such material improvements are critical to increasing the deployment of wind as a stable and cost-effective source of energy when demand for energy continues to increase [2].

II. Blade Design of Wind Turbines

The design of the blade is one of the most important elements in wind turbine performance and efficiency. Properly constructed blades can capture as much energy as possible from wind and maintain structural integrity against various operational stresses.

II.1. Importance of Blade Design

Aerodynamic performance, efficiency, and longevity are all influenced by the shape of wind turbine blades. There's a good degree of energy to be harnessed by blades that have proper shape, length, and materials.

II.2. Key Factors in Blade Design

The wind turbine blades are influenced by several variables:

- *Aerodynamics*: A blade design must offer the greatest lift and lowest drag. That's the key to harvesting the most energy from the wind.
- *Material Selection*: Materials must be selected based on strength-to-weight and fatigue characteristics. Composites are usually utilized as they have good performance properties [3].
- *Length & Width*: Blade length determines how much wind power can be harvested. But long blades come with risks in terms of both stress and weight, so advanced structural design is needed to lower the risk.
- *Twist and Pitch*: Blades can be designed with a twist or pitch that optimizes performance across a range of wind speeds. This flexibility maintains efficiency in uncertain environments [4].

II.3. Advances in Blade Design

The latest efforts have been on:

- Variable Geometry: There are some modern designs that allow blades to adjust pitch or shape to match wind direction, increasing efficiency and safety.
- Computational Modeling: Powerful computer software tools are available that allow engineers to calculate aerodynamic performance at different operating conditions. Computational Fluid Dynamics (CFD) simulations are typically used to calculate flow at the blades [5].
- Blades Engineered for Decommissioning: There is now a growing focus on creating blades that can be easily broken down and recycled at the end of their useful lives in a sustainable manner for the wind energy industry [6].

II.4. Challenges in Blade Design

The major problems that arise during blade design are:

- *Fatigue Load Management*: Blades of wind turbines receive cyclic loadings, which can result in fatigue failure over time. The prevention and mitigation of these failure modes are critical to longevity [7].
- *Environmental Impact*: The manufacturing and disposal of turbine blades imposes the risk of environmental pollution. Designers are now exploring eco-friendly materials and processes [6]

The blade design plays an important role in ensuring wind turbines operate and maintain optimal performance. New technologies and research continue to assist in improving blade efficiency, as well as reducing fatigue and environmental impacts. Maintaining attention to these areas will be the key as demand for renewable energy rises.

III. Aerodynamic Advancements in Wind Turbine Blade Design

Following is a breakdown of several major blade innovations, such as optimizing airfoil shape, modifying blade tip, leading-edge tubercles, and the influence of blade length and swept area.

III.1. Airfoil Shape Optimization

The shape of the airfoil is an essential factor for high aerodynamics in blades. Several techniques, especially neural network-based approaches, have been tried to predict airfoil behavior. It is common to use the Class Shape Transformation approach, which allows Chebyshev polynomials to be used to parameterize the surface geometry of the airfoil to perform design sprints. The optimizations often target reducing drag as much as possible with respect to different operational conditions, thereby greatly increasing the energetic performance of wind turbine blades [8]. Moreover, with the right computational techniques, like reduced-order models (ROMs), we can predict the aerodynamic performance of shapes effectively. The combination of two-dimensional and three-dimensional CFD models allows a wide analysis and optimal shapes to effectively perform under realistic flow conditions [9].

III.2. Blade Tip Modifications for Improved Efficiency

Altering the blade tip geometry is a very efficient way to mitigate vortex shedding and thus drag. Tip optimization usually entails blade tips with winglets or other aerodynamic modifications to eliminate the vortices in the blade tips. All these upgrades result in better lift-to-drag ratios, which boost the overall performance of the rotor system. The addition of vortex generators (VGs) could be used to actively control flow separation, increasing the productivity of adapted blade tips [10].

III.3. Leading-edge Tubercles and Passive Flow Control

Leading-edge tubercles are a novel design feature that optimizes blade aerodynamics for different operating conditions. These wavelike fins on the leading edge of the airfoil prevent stalls by facilitating better airflow attachment at low speeds and with high angles of attack. This effect is useful, especially for the blades of wind turbines, where one can maintain energy capture during turbulent wind flow. Passive flow control techniques using leading-edge tubercles have been shown to dramatically improve the wind energy conversion performance and reduce operating noise [11].

III.4. Impact of Blade Length and Swept Area on Energy Capture

The length of blades and the area swept are important to wind turbines' energy capture performance. The longer the blades, the more wind is caught and the more swept area one receives, and therefore the more energy is created. But longer blades also can pose structural problems and costs in terms of material, so length and structural integrity should be balanced. Research and modeling have revealed that long blades are critical for high performance and low wind shear and turbulence to minimize their harm [10].

These aerodynamic blade designs, in short, demonstrate the continuing development of technologies for higher efficiency and effectiveness of energy capture. Design efficiency techniques, innovations in structure, and principles of aerodynamics are the core of blade technology for many future sectors of renewable energy production.

IV. Structural Innovations in Wind Turbine Blades

Enhanced strength, fatigue resistance, and performance of wind turbine blades depend on structural enhancements. New research has emphasized many aspects of these developments, such as optimization via finite element analysis (FEA) or the influence of blade flexibility.

IV.1. Load-bearing Capacity and Fatigue Resistance

The wind turbine blades are also subject to immense force while in use that can cause them to wear and break if they aren't managed well. The blades must remain structurally sound because larger blades and their capacities increase the bending moments, which should transfer to the hub [12]. Evidence has also shown that using materials such as glass fiber reinforced polymer (GFRP) composites increases the fatigue life and load-bearing ability of wind turbine blades [13]. The materials are specially engineered to absorb the massive bending effects of the environment (windstorms and heavy rainfall).

IV.2. Use of FEA for Structural Optimization

FEA is a key design and optimization tool for wind turbine blades. It makes it possible to model real-world loads and simulate blade behavior under a variety of conditions. Engineers can use FEA to detect the highest stress points on the blade surface and accordingly distribute material at the best possible rates for better performance [14]. For example, FEA has been used to model the structural behavior of blades under various loads, and the results are improved design for safety and cost effectiveness.

IV.3. Blade Flexibility and Impact on Performance and Durability

It is the correct ratio of rigidity and flex in wind turbine blades that makes the blade work best. Increased flexibility also results in greater energy recovery as blades respond to the dynamic conditions of the wind [15]. Yet too much flexibility risks structural failure in extreme situations. This combination of extensibility and stiffness needs to be carefully adapted to deliver as much performance as possible. Blades' flexibility in response to the forces of wind means they can continue to function efficiently without the danger of becoming fatigue prone as time goes on.

In short, more improved load-bearing capacity, fatigue resistance, and structural design using techniques like FEA is needed to build better, more efficient wind turbine blades. Additionally, controlling blade flexes is important for blade performance and field life.

V. Material Advancements in Blade Manufacturing

Material innovations for blades have received significant focus in the area of application needs for enhanced performance and efficiency, particularly in the aerospace and renewable energy sectors. In this section, we review the key advances in lightweight composites, the use of carbon fiber and thermoplastics, and how to mitigate degradation and maintain high performance over time.

V.1. Lightweight Composite Materials for Enhanced Strength-to-Weight Ratio

In blade construction, lightweight composite materials became the must-have for superior strength-to-weight ratios. The aerospace and energy markets are chasing these materials in the interest of performance and fuel economy. Composites provide the possibility to retain structure at the cost of weight minimization, especially important in space applications where every gram of weight matters [16].

Such composites typically combine several materials (fibers, resins, etc.) to have certain mechanical characteristics. This is one of the biggest advantages of light-weight composites for blade fabrication:

- *High Performance: They possess a higher* mechanical strength than standard materials, and blades perform better at high temperatures.
- *Corrosion Resistance*: Most lightweight composites are highly resistant to corrosion, giving parts a longer lifespan.
- *Design Flexibility*: Composites are produced in a manner that allows complex geometric designs with enhanced aerodynamics and cost-efficiency [17].

V.2. Carbon Fiber and Thermoplastic for Blade Manufacturing Process

Due to their properties, carbon fiber and thermoplastic composites are also becoming more common in blade manufacturing. Carbon fiber reinforced polymers (CFRPs) have been developed with great strength and rigidity, but they are lightweight [18]. The use of these materials in blade construction benefits many different ways:

- *Superior Durability*: CFRPs are highly fatigue resistant, so they're perfect for high cycle uses in wind turbine blades and aircraft [19].
- *Thermoplastic Uses*: When thermoplastics can be used in conjunction with carbon fibers, they can create lighter, tougher blades. They are less costly, and they can be reworked and recycled or reused, which is another great green design benefit.
- *Value for Money*: Carbon fiber may be costly at the beginning, but its long-term resiliency and lower costs of upkeep are often worth it for high-performance use [20].

V.3. Material Degradation and Long-term Performance

Material loss is a major issue in blade manufacturing, particularly when working in high ambient temperature environments, such as wind turbines and jet engines. Key recommendations to prevent degradation and increase the performance over the long term are:

- *Stable Coatings*: Using durable protective coatings can protect blades against elements such as UV rays, moisture, and corrosion. This can make the blades more durable [21].
- *Regular Maintenance and Inspection*: Establishing regular maintenance schedules and using inspection technologies such as non-destructive testing helps identify potential fatigue or material breakdown so that blades continue to operate effectively throughout the duration that was planned [22].
- *Material Research and Development*: Continuous R&D aims to discover new materials and composites that are resistant to degradation. Such includes studying nanotechnology and biomimetic structures that mimic nature's remedies for improved material endurance [23].

These materials and engineering improvements enhance the performance of blades as well as other industry-wide sustainability and eco-friendly efforts.

Using these improvements, producers can ensure that their blades remain agile and resilient against changing market needs.

VI. Latest Aerodynamic, Structural and Material Innovations for Wind Turbine Blade Design: Industry Contributions

Design innovations have improved efficiency and performance in wind turbine blades, a huge part of which has come from the design of the blades. These are six such past cases sorted by aerodynamic, structural and material improvements and listed companies responsible for the innovations.

VI.1. Aerodynamic Improvements

- *Gamesa*: It's one of the first to use a customized airfoil shape for their wind turbine blades, which has made it far more efficient to capture energy. They are designed to decrease drag and maximize performance with variable wind conditions, making wind power an increasingly attractive fuel [24].
- *Vestas Wind Systems*: Vestas has invented variable-pitch turbine blades, maximizing wind-extracted energy. They can adjust the angle of the blades according to the actual wind strength, ensuring optimal performance and higher production of overall energy [1].

VI.2. Structural Developments

- *GE Renewable Energy:* The blades on the Haliade-X offshore wind turbine are the longest and most complex in the world, using structural concepts such as segmented blades. This makes it much easier to transport and install bigger blades that capture and save more energy [25].
- *LM Wind Power:* A maker of bend-twist-coupled blades, LM Wind Power is known for designs that twist while bending, so the mechanical stress will be removed, and blades can be longer and lighter. This shape strengthens the blades in strength and efficiency to harvest wind energy [26].

VI.3. Material Innovations

- *TPI Composites, Inc.:* This company has pioneered the use of cutting-edge composites to develop robust and lightweight wind turbine blades. These designs work by improving the strength-to-weight ratio, which allows for longer blades that deliver more wind energy without adding too much weight to the entire turbine [27].
- *Arkema*: Arkema has been committed to manufacturing recyclable blades for wind turbines and putting sustainability into the design. This move is to improve the life of blades and still ensure a low impact performance, in line with the industry's commitments to sustainable energy [28].

These examples illustrate how companies have applied aerodynamic, structural and material technology to optimize wind turbine blade design, making wind energy systems more efficient and cost-effective.

VII. Literature Review of Aerodynamic, Structural and Material Innovations in Wind Turbine Blade Design

The number of papers retrieved from publications (2019-2024) on aerodynamic, structural and material advances in wind turbine blade design is summarized in Figure 1.

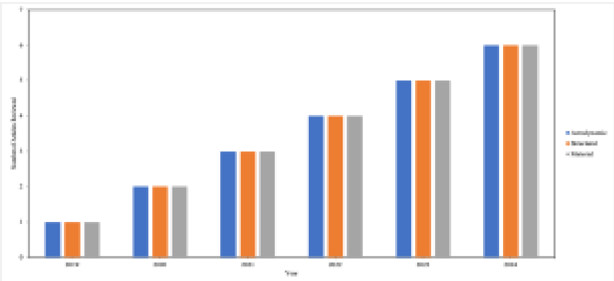

Figure 1. Articles reviewed (2019-2024) for aerodynamic, structural and material advancements in wind turbine blade design

VII.1. Aerodynamic Characteristics Underlying Contemporary Wind Turbine Blade Efficiency

Table 1 presents the quantitative distribution of the number of reviewed papers on aerodynamic advancements in wind turbine blade design and their publishers.

Table 1. Number of articles from different publishers reviewed for aerodynamic advancements in wind turbine blade design.

Publisher	***Number of Articles Reviewed***
EAWE	2
IOP Publishing	2
Karagandy University	2
MDPI	2
Sage Journals	2
Wiley	2
DergiPark Akademik	1
Elsevier	1
Extrica	1
Heliyon	1
IEEE	1
IntechOpen	1
Semarak Ilmu Publishing	1
Springer	1
UTP Press	1
Total	**21**

In the study by Madsen et al. (2019), an aerodynamic shape optimization of a 10 MW wind turbine was done using a high-fidelity CFD approach, targeting blade planform, cross-sectional shapes, and airfoil profiles. The optimization strategies were a 3D adjoint style approach, which allowed for a tremendous performance improvement due to the lower relative thickness and new airfoil design that increased turbine performance by 1.44-fold [29]. By contrast, Li et al. (2020) examined the aerodynamic and aeroelastic behavior of bendable wind turbine blades during regular erratic flows, including wind shear, tower shadow, and yawed flows. Their work stressed the need to model these nonlinearities to anticipate performance fluctuations and improve turbine stability and efficiency [30]. Tanasheva et al. (2020) experimented with revolving cylinders, studying the Magnus effect to enhance lift force and efficiency of turbines, especially at lower wind speeds. They found the best possible cylinder spacing for best aerodynamic efficiency, which indicates its suitability for smaller wind turbines for small-scale power generation [31].

Wu et al. (2021) examined the effects of VGs on the turbulence zone between the blades of wind turbines in an effort to suppress flow separation to increase aerodynamics. They found that VGs also helped reduce flow separation and therefore enhance lift, drag, and efficiency, which is extremely important for optimizing energy capture [32]. By contrast, Barlas et al. (2021) were focused on aeroelastic design optimization of tip extensions on a 10 MW wind turbine, using surrogate models to achieve increased performance without increasing the loads. They found an 8% increase in their energy generation per year, demonstrating the ability of optimized tip extensions to reduce aerodynamic stresses during turbulence [33]. Zhang et al. (2021) conducted aerodynamic topology optimization of blade tip geometries, introducing convex-concave-convex geometry that decreased separation of flow and loss of pressure at the blade tips. This new tip design increased aerodynamic performance through the reduction of drag and greater airflow at the blade's surface [34].

Chavan et al. (2022) looked at aerodynamic performance using leading-edge tubercles modeled on humpback whale flippers. They showed that tubercles helped with lift-to-drag ratios, to as much as 8.5 (compared with 1.7 for standard blades), especially at low wind speeds [35]. McKegney et al. (2022) also looked at leading edge tubercles, doing wind tunnel testing on a NACA-0021 aircraft. They concluded that tubercles had 115% higher post-stall lift and significantly lower induced drag, suggesting major improvements under different wind loads [36]. In comparison, Jayanarasimhan and Subramani-Mahalakshmi (2022) opted for flow control devices, in particular VGs, that enhanced aerodynamic efficiency by postponing stalls and maximizing lift. They stressed that the placement and configuration of VGs would be highly beneficial to maximize the production of power [37].

Horcas et al. (2022) focused on curved tips with various aerodynamic simulations for horizontal axis wind turbine blades. Whereas simpler algorithms like the blade element momentum (BEM) could not accommodate the complexity caused by tip curvature, more sophisticated algorithms like the blade-resolved Navier-Stokes solver could model unsteady dynamics, particularly when under deep stall [38]. By contrast, Abbas et al. (2023) focused on trailing edge flaps, adding aero-servo-elastic designs to accommodate large blades. They reported a 21% reduction in blade tip deflection and a 1.3% reduction in levelized cost of energy (LCOE), further proof-of-concept of the economical and performance benefits of flap-based controls [39]. Xu et al. (2023) optimized the aerodynamic efficiency of wind turbine blades using the new CSA-KJ4412 airfoil. Their research had significant results in lift-to-drag ratio and pressure distribution, optimizing power output through adhesive flow and anti-stall over a wide range of angles [40].

Abdalkarem et al. (2023) compared trailing edge wedge tails (WTs) to fish wedge tails (FWTs) on the NACA 0021 airfoil and found FWTs provided superior lift/glide ratios compared with traditional Gurney flaps. The authors did CFD simulations and achieved maximum efficiency with 2.5% tail height and 1% airfoil length, which enhanced aerodynamic efficiency by more than 31% [41]. Tokul and Kurt (2023) compared the NACA 2414 and the NACA 6409 airfoils for small horizontal axis wind turbines (HAWTs) and concluded that the NACA 6409 achieved higher lift-to-drag and distribution of pressure ratios at a Reynolds number of $1x10^6$ [42], which makes the aircraft more efficient. Ahmadi et al. (2023) studied the installation of winglets on NACA 0012 airfoil blades and determined that this change at 15° of attack minimized drag and increased torque, resulting in better performance [43].

Erwin et al. (2024) looked at the effect of turbulators on the NACA S1046 airfoil and, by CFD simulations, demonstrated how turbulators delayed flow separation, enhancing lift-to-drag ratios in low angles of attack. They concluded that turbulators at 40–50% chord length provided the best lift, which means improved efficiency in vertical wind turbines [44]. Koca and Genç (2024) examined the effect of partial flexibility on a cambered airfoil and found that a flexible membrane on the suction side prevented bubbles of laminar separation and aerodynamic noise. Increasing the flow profile in the post-stall region also resulted in improved aerodynamic performance and decreased structural vibrations that are important for a long-life turbine [45]. Schaffarczyk et al. (2024) created a 60% thick airfoil that eschewed computations and experiments to demonstrate dramatic performance gains in the root area of wind turbine blades. They also applied aerodynamic devices like VGs and gurney flaps that increased lift and decreased drag in thicker airfoils, filling a technological need in blade design [46].

The paper by Solombrino et al. (2024), focused on the structure and aerodynamics of flatback airfoils and swallowtail add-ons. They found flatback airfoils had better structural integrity but added a drag penalty. Swallowtail design reduced this drag with aerodynamic efficiency and derived structural benefits [47]. Dyusembaeva et al. (2024) tested combinatorial blades with a spinning cylinder and fixed blade arrangement. Mathematical calculations showed a 0-degree angle as the most aerodynamic, with the highest lift coefficient at 10 and the lowest drag coefficient at 4.5; the best energy yield [48]. Akheel et al. (2024) studied camber and thickness adjustments to small wind turbines' airfoil. They changed this to add 6.7% power and 20.47% more energy per year, thanks to a higher lift-to-drag ratio [49].

VII.2. The Impact of FEA on Structural Optimization and Efficiency in Wind Turbine Blade Design

The quantitative distribution of the number of reviewed articles cited on the structural advances in wind turbine blade design and their publishers can be found in Table 2.

Table 2. Number of articles from different publishers reviewed for structural advancements in wind turbine blade design.

Publisher	***Number of Articles Reviewed***
MDPI	5
EAWE	2
IEEE	2
Springer	2
ARC	1
ASME	1
Elsevier	1
Emerald	1
IJSREM	1
IOP Publishing	1
JAZ	1
PTMTS	1
Sage Journals	1
Turin Polytechnic University in Tashkent	1
Total	**21**

Anderson et al. (2019) tuned a 13-meter blade on a wind turbine through the application of high-resolution multidisciplinary modeling, cutting off-axis matrix stress by 18–60% but increasing blade deflection. This emphasized the balance between stress reduction and stiffness to enhance the efficiency of the turbine [50]. Muyan and Coker (2020) studied the bending behavior of a 5-meter composite blade flap-wise, edgewise, and under combined loads. They found critical failure points and observed that combined loads caused less damage than flap-wise loading, improving the buckling strength of the blade [51]. Iori (2020) optimized a DTU 10MW blade configuration with non-linear transient loads using the Nested Analysis and Design (NAND) vs. Simultaneous Analysis and Design (SAND) approaches. Both designs came up with 1.89x lighter designs than the original, and SAND provides better computational performance [52].

Rustamov (2021) used FEA to improve the design of a 9-meter-long composite blade, mainly by manipulating the properties and shapes of the materials. The study showed that weight savings without structural collapse were achieved by employing a carbon/glass hybrid material, delivering increased strength and efficiency of energy harvesting [53]. Özkan and Genç (2021) also applied FEA in combination with the NSGA-II algorithm and fluid structure interaction (FSI) models to perform multi-objective optimization of micro-wind turbine blades. They concentrated on mass reduction, and their research showed weight loss of up to 14.3% at the expense of increased manufacturing expenses [54]. Tian et al. (2021) used FEA and a genetic algorithm to optimize the structural strength and durability of a blade for a wind turbine. Their work focused on weight reduction and pushed up the natural frequency of the blade, so it didn't resonate, leading to a 15% weight reduction [55].

Song et al. (2022) optimized internal structure of large-scale offshore blades to reduce weight by 9.88% while complying with all structural specifications. The team used aerodynamic simulations and a variable density topology optimization strategy to improve the bending resistance and aerodynamic performance [56]. Dellaroza et al. (2022) used a surrogate-based optimization algorithm to optimize the stacking sequence of laminated composites and improve power coefficients by adding stiffness to the blade. They showed that bend-twist coupling influence accounted for the crucial role of bend-twist coupling in passive pitch angle regulation, and material layup orientation had important implications for turbine efficiency [57]. Camarena et al. (2022), streamlined land-based wind turbine blades focused on transportability and durability. It also showed that novel constructions such as downwind configurations and heavy-tow carbon fiber would allow the carrying of larger blades at massive mass savings [58].

Raičević et al. (2022) were mostly focused on how wind velocity effects stress and deformation of composite blades using FEA to pinpoint critical stress points and provide design recommendations to optimize structural integrity and reduce manufacturing cost. This analysis provided essential clues as to how shear and normal stresses caused the deformations, which were critical to ensuring blades could be maintained in operation [59]. By contrast, Batay et al. (2023) addressed a joint optimization scheme of CFD and FEA to optimize aero-structural design. They demonstrated both enhanced power generation potential (6.78%) and reduced weight of the blades (42.22%) in order to reduce manufacturing costs and preserve structure integrity [60]. Ghoneam et al. (2023) investigated the dynamic life and fatigue life of vertical-axis wind turbine (VAWT) composite blades using dynamic analysis using FEA. They discovered that optimized blade design sustained the least amount of damage with dynamic loading; hence, composite materials play a vital role in optimizing blade performance [61].

Yamina et al. (2023) focused on a 61.5-meter blade that was designed to operate at high wind speeds. Using COMSOL Multiphysics for fine-grained simulation and FEA, stress distribution was assessed, and critical Von Mises stresses were determined to be predictive of structural integrity under gravitational and centrifugal loads [62]. Instead, Chandana and Radha (2023) employed experimental procedures for evaluation of rotor blades from glass fiber epoxy coated with natural fibers. By performing mechanical testing and simulations with the help of SOLID WORKS and ANSYS FLUENT, they had shown that the composite material had a significant increase in mechanical and aerodynamic properties, providing performance far beyond conventional materials [63]. Zhang et al. (2023) used a novel airfoil optimization approach based on a Kriging surrogate model and CFD to enhance the aerodynamic and structural efficiency of offshore wind turbines. They found reduced torsion angles and higher lift-to-drag ratios for the optimization of airfoils integrated into the blade [64].

Kim and Cho (2024) looked at using graphene platelets (GPLs) as nanofillers for wind turbine blades in order to improve the mechanical properties and lower the cost. Their finite element calculations showed that GPL-reinforced blades were more robust and lighter than traditional fiberglass blades, providing higher energy conversion efficiency and less construction cost for support girders [65]. By contrast, Nezzar et al. (2024) involved the structure optimization of a glass/epoxy composite blade for miniaturized VAWTs. They created an optimal structure for the ply thickness and orientation modeling, which saved 59% weight over an aluminum blade and met safety requirements, demonstrating the possibilities of composites for better performance and rigidity [66]. Batay et al. (2024) adopted a much more comprehensive approach, combining aerodynamic shape optimization with FEA to reduce drag and structural mass in wind turbine blades and other aerodynamic devices. They employed coupled solvers using a one-way coupling scheme to study how to optimize aerodynamic and structural models at the same time, increasing efficiency [67].

In their second paper, Kim and Cho (2024) demonstrated that FEA could be used to design and build graphene platelet-reinforced composite (GPLRC) wind turbine blades to improve structural strength and save weight. The results showed that gratings armed with GPLs produced better performance, measured by less deflection and stress, than conventional fibers such as glass fiber and carbon nanotubes (CNTs), showing significant improvement in strength and energy recovery [68]. On the other hand, Ivanyna et al. (2024) focused on stress analysis and eigenfrequency measurement of composite blades made of glass-reinforced vinyl ester and PVC foam. They showed how the dynamic behavior of the blade under multiple operating scenarios was crucial for determining structural integrity, leading to an overall description of stress distribution and vibrational characteristics that could affect operational reliability [69]. Prakesh et al. (2024) simulated and optimized in CATIA and ANSYS, addressing the design and material selection for the blade profile to increase efficiency and minimize cost. Their optimization process brought out the most optimal combination of design features and materials, ultimately resulting in more rugged and cost-effective wind turbine blades [70].

VII.3. Material Innovations Evolving Efficiency and Lower Costs for Wind Turbine Blades

Table 3 provides a quantitative breakdown of the total number of reviewed articles related to the material advances in wind turbine blade design and publishers.

Table 3. Number of articles from different publishers reviewed for material advancements in wind turbine blade design.

Publisher	***Number of Articles Reviewed***
MDPI	6
Elsevier	4
Taylor $ Francis	2
Wiley	2
AIChE	1
AIP Publishing	1
ASME	1
IEEE	1
Osti.gov	1
Sage Journals	1
YRPI	1
Total	**21**

Panduranga, Alamoudi, and Ferrah (2019) studied high-performance composites that were coated with electro-spun polymer nanofibers and experienced 150% improvement in fracture toughness and 33% improvement in delamination resistance. These improvements were made without sacrificing other mechanical characteristics of the blades, which allowed them to be used in larger turbines and to be more long-lasting [71]. Rather, Cognet et al. (2020) developed a universal scaling algorithm to select the right soft materials for flexible blades, with a 35% increase in harvested power compared to traditional rigid blades. The result was a weight reduction of 5% to 20% that in turn increased efficiency and saved material costs [72]. Sellitto et al. (2020) was dedicated to OneShot Blade® technology, which eliminated the adhesive requirement in fiberglass blade manufacturing. The invention meant less labor time and expense while also making the blades better structurally and tolerably damaged [73].

Kasagepongsan and Suchat (2021) investigated epoxy resin nanocomposites reinforced with modified epoxidized natural rubber fibers and glass fibers, which were also more mechanically robust and weather resistant during accelerated aging tests. Their findings of a 35% increase in tensile strength following UVB exposure at 168 hours and the field application confirmed with a tree wind turbine of 5 kW to demonstrate the potential of their engineered composites to operate in the wild [74]. Conversely, Andoh et al. (2021) created a composite of bamboo fiber and recycled HDPE to address the double problem of increased material costs and environmental responsibility. They discovered that composites comprising 25% bamboo fiber had better tensile and impact strength, supporting the performance advantages of using natural fibers in wind turbine composites [75]. Johansen et al. (2021) explored nanofabricated graphene-coated materials that dramatically improved the anti-erosion properties of wind turbine blades. Their paper also showed that graphene-coated coatings had 13-fold longer lifetimes compared to the non-coated coatings, which decreased maintenance costs and increased blade life [76].

Samuel et al. (2022) focused on improving a natural fiber hybrid reinforced composite (PxGyEz) with pineapple leaf fiber and synthetic fibers. This study was able to provide significant gains in tensile strength (95.31 MPa) and flexural strength (92.82 MPa) with a significant weight saving of 64% on a simulated 5 MW wind turbine blade, showing eco-friendly materials are viable candidates for clean wind energy [77]. Rather, the research by Liu et al. (2022) evaluated polyethylene terephthalate (PET) foam for the replacement of older types of foams, such as polyvinyl chloride (PVC) and styrene-acrylonitrile (SAN), in blades for wind turbines. Their results found that PET foam was mechanically more effective, more thermally stable, and more cost-effective, as well as 100% recyclable, further underscoring its utility as a renewable substitute [78]. In the work of Saadeh et al. (2022), they tested self-healing features in glass fiber-reinforced epoxy nanocomposites for the blades of wind turbines. In it, we have shown that incorporation of CNTs made them much stronger, increased their strength up to 10 times, and showed extremely fast stress recovery in the healed material, which points towards the use of self-healing devices to make wind energy more maintenance-efficient and long-lasting [79].

Ganesh et al. (2022) examined the mechanical qualities of carbon fiber, fiberglass, aluminum, wood, and more. It used ANSYS computation modeling to simulate under various conditions and found carbon fibers were better for larger blades due to strength and fatigue resistance and fiberglass composites for smaller blades [6]. In contrast, Mdallal et al. (2023) stressed the sustainability of using sustainable products like reinforced plastics and bamboo composites. These studies emphasized sustainability and highlighted corrosion-proof coatings as a key factor in increasing turbine efficiency while overcoming such issues as quality inspection and testing for durability [80]. Ennis et al. (2023) focused on the economic benefits of pultruded composites, highlighting mechanical efficiency and lower prices due to pultrusion production. This experiment demonstrated a 17% improvement in design strength over conventional technology, establishing the feasibility of light, powerful turbine blades [81].

Cardoso et al. (2023) explored jute fiber reinforced epoxy composites as a sustainable substitute for synthetic fibers and reported that their mechanical properties could be utilized in low-wind-speed applications. They used Classical Laminate Theory and Extended Bredt-Batho Shear Flow Theory to test the strength of the composites, with good results including torsional stiffness of 1873.6 N m^2 and flexural rigidity of 1.45×10^6 N m^2 [82]. Conversely, Carron et al. (2023) focused on large-scale additive manufacturing, specifically polymer-based material extrusion, which worked well for wind turbine hulks. As they saw, the efficiency of core materials would directly drive down manufacturing costs without sacrificing performance and enable cost-efficient manufacturing [83]. Mishnaevsky et al. (2023) had designed a bio-inspired structure with bio-inspired adhesives to provide wind turbine blades with higher strength and recycling. Their new adhesive design solved interface degeneration problems seen in traditional blades with a dual-mechanism design that integrated mechanical interlocking and chemical attachment. This study, in addition to ensuring better adhesive joint strength, enabled possible blade parts to be isolated for reuse and thus was sustainable [84].

This study, published by Muhammed et al. (2024), evaluated E-glass fiber infused with SiO2-Al2O3-TiO2 montmorillonite in AW 106 epoxy for tensile strength, hardness, and fatigue resistance of blades of wind turbines. The mechanical performance of this nanocomposite exhibited excellent quality; Al2O3 at 1% concentration was optimal in performance, potentially enabling a more robust blade [85]. Thakur and Kumar (2024) reported on new bio-derived resins and composites for reusable wind turbine blades by focusing on additive manufacturing to improve the recyclability and minimize environmental impact. But structural integrity and scalability problems emerged [86]. In the meantime, Pender et al. (2024) tested natural fibers such as flax and hemp, showing that they minimized the environmental impact of wind turbines by reducing Global Warming Potential (GWP) and stiffening them. Furthermore, recycling practices such as cement kiln co-processing were considered good at lifecycle environmental reduction [87].

In the article by Quesada-Bedoya et al. (2024), the researchers looked at bioinspired manufacturing options, particularly roto-molding along with polyurethane casting. They aimed to solve environmental problems and manufacturing challenges and found that this approach markedly improved energy capture and inertia, improving the overall performance and profitability of blades for small wind turbines [88]. Kim and Cho (2024), on the other hand, investigated the integration of GPLs into the blades of wind turbines and found a major improvement in mechanical parameters (static bending, free vibration, and torsion). It turned out that blades coated with GPLs were more robust and lighter than standard fiberglass components, leading to a lower cost of construction and better energy production [89]. Finally, Papadakis and Condaxakis (2024) tested a passively governed wind turbine blade design with GFRP composites. They also found that plane-spaced GFRP laminates increased blade flex and aerodynamics for a better, more efficient design [90].

VII.4. General Contributions in Wind Turbine

Berboucha et al. (2017) suggested a wind turbine that would use Permanent Magnet Synchronous Generators (PMSG) and a 5-level diode-clamped inverter, with a focus on fuzzy logic control to control rotational speed under wind conditions. Their results revealed less total harmonic distortion (THD) and more dynamic range, evidence that good control algorithms improve power quality and efficiency [91]. Riyadh et al. (2017), using CFD calculations and inverse BEM methods, investigated the aerodynamic performance of the NREL Phase II rotor using S809 blade profiles. Their findings showed the need for precise pressure distribution and torque prediction to maximize power delivery, though they lacked the ability to simulate deep stall [92]. Saidi et al. (2018) was devoted to assessing sensor-based and sensorless Maximum Power Point Tracking (MPPT) for PMSG. The method of estimating wind speed showed improved system stability and mechanical stress reduction and effectively maximized power extraction [93].

Ebrahimi et al. (2018) studied the best-fit design of a hybrid microgrid comprising solar, wind, diesel, and grid for Kish Island, bringing a 34% renewable share, as well as the dynamics of energy trade-offs and carbon savings [94]. Saidi et al. (2019) focused on a fuzzy logic-based direct voltage control (DVC) system for a PWM rectifier coupled to a PMSG in a variable-speed wind power system that provides high load- and wind-strength-related stability with a low THD of 2.25% [95]. Ahmed et al. (2019) compared Proportional-Integral (PI) and fuzzy PI controllers for vector control of a Doubly Fed Induction Generator (DFIG) in variable-speed wind turbines, showing that the fuzzy controller was more robust and flexible under parametric variations [96].

Douvi et al. (2021) analyzed rain’s aerodynamic performance on HAWTs in computational models. They showed that the rainfall significantly reduced the efficiency of turbines, and power coefficients dropped by up to 23.9% at high Liquid Water Content (LWC), due to more aerodynamic drag and water film formation [97]. Kouadria and Debbache (2022), on the other hand, studied the structural behavior of wind blades with and without power control. They discovered that power control slowed blade tip deflection by 64 percent at high wind speeds, reducing stress and extending blade life. They focused on the importance of composite material and structural design to maximize endurance and performance [98]. Meanwhile, Zemali et al. (2022) used an Adaptive Neuro-Fuzzy Inference System (ANFIS) for fault detection and isolation in wind turbine drive trains. Their diagnostic method was successful at identifying defects under artificial conditions, which illustrates how intelligent systems can preserve stability [99].

Sithole et al. (2023) performed a predictive analysis of small wind turbine applications in South Africa and found Prototype 3 most efficient at low wind speeds (39.5 W at its peak power in Soweto) and predicted improvements along the coast (such as Gqeberha) [100]. Dahmani et al. (2023) built a bootstrap-aggregated neural network (BANN) to forecast global horizontal irradiance

(GHI) globally in Tamanrasset, Algeria, and had a correlation coefficient of 0.9580, showing its usefulness in the prediction of solar energy [101]. The second article, by Sithole et al. (2023), focused on optimizing small wind turbine blades by BEM Theory (BEMT) and CFD. It revealed that a 7-blade prototype produced maximum power of 39.5 W at 4.2 km/h wind speed, and that optimized blade geometry and pitch angles resulted in improved efficiency [102].

VIII. Conclusions

The study on developments in blade design for boosting wind turbine efficiency underlines the significant advancements in aerodynamic, structural, and material technologies that are vital for the future of renewable energy production. The research underlines that improving the aerodynamic geometry of wind turbine blades is crucial for optimum energy extraction. Innovations in this field concentrate on increasing the lift-to-drag ratio, which directly improves the overall efficiency of wind turbines. Structural advances are emphasized as vital for assuring the longevity and operational dependability of turbine blades. These advances enable blades to survive harsh weather conditions while lowering maintenance expenses, ultimately boosting their lifetime and performance. The article emphasizes the essential importance of material improvements in blade design. The development of lightweight and durable materials permits the production of longer blades that can catch more energy without sacrificing structural integrity. This is necessary for the greater acceptance of wind energy as a dependable energy source. Overall, the article highlights the necessity of a diverse approach to blade design advances. By combining aerodynamic, structural, and material developments, the efficiency of wind turbines may be greatly enhanced, helping the shift to sustainable energy sources in response to rising worldwide energy needs. In conclusion, the ongoing advancement of wind turbine blade technology is crucial for boosting energy absorption and conversion efficiency, eventually contributing to the sustainability of renewable energy systems.

IX. Challenges and Future Directions

There are many issues related to the blade design of wind turbines that should be solved to make it efficient and sustainable. Here are the following challenges and potential research-and-development areas:

IX.1. Challenges in Blade Design

- *Environmental Impact*: The manufacture and disposal of turbine blades pose severe environmental concerns, i.e., pollution. Design needs to look for alternative materials and processes that reduce these effects.
- *Fatigue Load Management*: Blades in wind turbines can fatigue after a specific period under a periodic loading. It is essential to know and control these failure modes to make the blades last.
- *Material Degradation*: Degradation of material used in manufacturing blades poses a big problem, especially when used in environments that require high temperatures and environmental pressure. This will require ongoing work on materials that don’t degrade over time and perform better.

IX.2. Future Directions

- *New Material Research:* Future work will need to involve the development of new materials and composites that are intrinsically degradable. This includes looking into nanotechnology and biomimetic designs that mimic nature’s solutions for greater material resilience.
- *Durable Protective Coatings:* By applying hardened protective coatings, blades can be protected from exposure to UV radiation, moisture, and corrosive agents. Advanced coatings could have dramatic effects on turbine blades.
- *Sustainability Programs:* As demand for renewable energy expands, the need exists for innovation to drive efficiency, in addition to overall sustainability programs. This includes creating sustainable manufacturing techniques and materials that minimize industrial emissions.
- *Interdisciplinary Collaboration:* Future innovations in blade design will require cross-disciplinary input from engineers, material scientists, and environmental specialists. This collaborative model can yield breakthrough solutions to the many challenges that wind turbine blade design faces.

Declaration

- The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.
- The authors declare that this article has not been published before and is not in the process of being published in any other journal.

- The authors confirmed that the paper was free of plagiarism.

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