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“A COMPREHENSIVE REVIEW ON WIND TURBINE TECHNOLOGY: DESIGN, AERODYNAMICS, STRUCTURAL ANALYSIS, AND FUTURE PERSPECTIVES”

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ABSTRACT

Wind energy has emerged as one of the most promising renewable energy sources due to increasing global energy demand, depletion of fossil fuels, and environmental concerns such as climate change. This paper presents a comprehensive review of wind turbine technology, focusing on aerodynamic performance, structural behavior, design evolution, and computational analysis techniques. The study highlights the historical development of wind turbines, from early windmills to modern multi-megawatt systems, and discusses recent advancements in horizontal-axis and vertical-axis wind turbines. The review emphasizes the influence of blade characteristics, surface roughness, turbulence, and environmental conditions on turbine efficiency and performance. Special attention is given to computational approaches such as Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD), which are widely used to evaluate stress distribution, deformation, and aerodynamic behavior. Additionally, emerging areas such as additive manufacturing, structural health monitoring (SHM), hybrid turbine configurations, and building-integrated wind energy systems are discussed. The findings indicate that turbine performance is strongly dependent on aerodynamic optimization, material selection, and structural integrity. While horizontal-axis turbines dominate large-scale applications, vertical-axis turbines are gaining attention for urban and low-wind environments. This review provides a consolidated understanding of current research trends and identifies critical challenges and opportunities for future advancements in wind energy systems.

Keywords: Wind Energy, Wind Turbine Review, Horizontal Axis Wind Turbine (HAWT), Vertical Axis Wind Turbine (VAWT), Finite Element Analysis (FEA), Aerodynamics, Structural Analysis, Renewable Energy, CFD, Structural Health Monitoring (SHM).

I. INTRODUCTION

The development of nations or countries are driven by the energy, energy resources, method of harnessing energy, utilizing energy and policies regarding energies. In last decades the consumption of energy raises rapidly because of raising rate of development and consumption, but conventional energy resources are limited, they cannot be fulfilling the raising demand of this energy in future, so we should shift our dependency from conventional sources of energies to the renewable sources of energies wind energy is most readily source of energy and it has no limitation of use and availability.

Over the past four decades, the depletion of fossil and nuclear resources, rising oil prices, and the challenges of global warming and climate change have significantly accelerated the demand for alternative, clean energy sources. Among

these, wind power has emerged as one of the most sustainable options from economic, social, and environmental perspectives, as demonstrated by its rapidly expanding installed capacity over the last two decades [1-4].

The year 2020 marked a milestone for the global wind industry, recording its strongest growth in history with a 53% annual increase. Despite disruptions to supply chains and project execution caused by the pandemic, more than 93 GW of new wind capacity was added, raising global cumulative capacity to 743 GW. This expansion contributes to an annual reduction of approximately 1.1 billion tons of CO₂ emissions. Onshore wind capacity alone grew by 59% compared to 2019, reaching 86.9 GW, with China and the United States dominating the market. Together, these two countries increased their market share by 15%, accounting for 76% of global onshore installations. Over the past decade, global wind power capacity has nearly quadrupled, establishing wind as one of the most competitive and reliable renewable energy sources worldwide [5, 6].

Technological innovation and economies of scale further reinforced wind energy’s global competitiveness in 2020. Investments in offshore wind reached approximately USD 330 billion, surpassing 2019 levels. The sector demonstrated resilience to pandemic-related disruptions, supported by the longer timelines typically required for offshore projects (Global Wind Report, 2021).

As illustrated in Figure 1 and Table 1, the global distribution of wind energy by year, along with the breakdown between onshore and offshore contributions and country rankings, highlights the sector’s development trends. Particularly after 1995, advancements in turbine capacity and rotor diameter became increasingly evident, with early kilowatt-scale turbines giving way to megawatt-scale wind power plants.

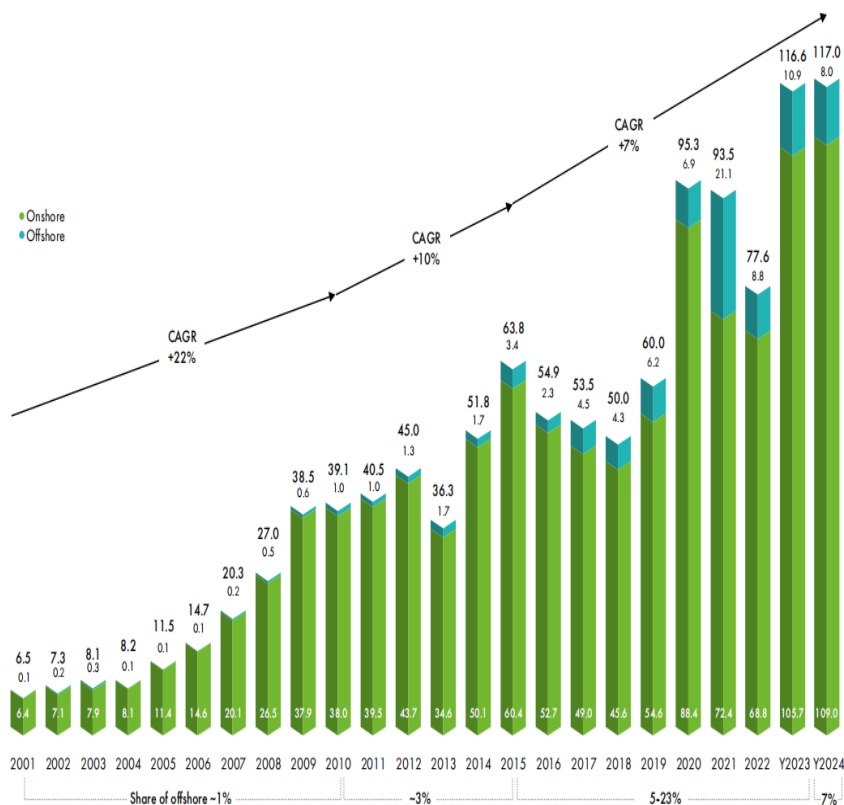


Fig. 1. Historic development of total installations.

At present, wind power plants have achieved capacities of up to 6 MW. In parallel with this growth, turbine rotor diameters have also expanded significantly. The average rotor diameter, which was approximately 20 meters in the 1980s, increased to nearly 100 meters by the 2000s. Today, turbines with rotor diameters of around 150 meters are in operation [3]. Looking ahead, it is expected that even larger turbine structures will be developed in the near Future.

Table 1. Leading countries and new capacity changes for 2020.

Country/Region	2020	New Capacity 2020	2019	2018
China*	290'000	52'000	237'029	209'529
United States	122'328	16'895	105'433	96'363
Germany	62'784	1'427	61'357	59'313
India	38'625	1'096	37'529	35'129
Spain	27'446	1'638	25'808	23'494
United Kingdom	24'167	652	23'515	20'743
France*	17'949	1303	16'646	15'313
Brazil	18'010	2'558	15'452	14'707
Canada	13'588	175	13'413	12'816
Italy*	10'850	280	10'512	9'958
Turkey	9'305	1'249	8'056	7'369
Rest of the World*	110'000	14'000	96'035	84'814
Total*	744'000	93'000	650'785	589'547

At present, wind power plants have achieved capacities of up to 6 MW. In parallel with this growth, turbine rotor diameters have also expanded significantly. As shown in Figure 1-2, the average rotor diameter, which was approximately 20 meters in the 1980s, increased to nearly 100 meters by the 2000s. Today, turbines with rotor diameters of around 150 meters are in operation [4]. Looking ahead, it is expected that even larger turbine structures will be developed in the near future. India's wind energy sector has experienced significant progress, with 3.4 GW of new capacity added in 2024—the highest annual addition since 2017—bringing the total installed capacity to 48.16 GW. Most of these new projects were concentrated in the states of Gujarat, Karnataka, and Tamil Nadu. With energy demand rising due to rapid industrialization and urban growth, wind power is expected to play a central role in achieving India's clean energy targets of 500 GW of non-fossil capacity by 2030 and net-zero emissions by 2070. To align with this vision, annual wind capacity additions of around 10 GW will be essential to firmly establish wind energy as a pillar of the country's decarbonization efforts.

According to the National Electricity Plan (2022–2032), India's installed wind capacity is projected to reach 73 GW by 2026–2027 and further expand to 122 GW by 2031–2032. However, maintaining this growth trajectory will require substantial investments, upgraded grid infrastructure, regulatory streamlining, and continued technological advancements.

Wind turbines operate by converting the kinetic energy of moving air into mechanical energy. In modern applications, this mechanical energy is primarily used to generate electricity, in which case the system is referred to as a wind generator. When the energy is used directly for mechanical tasks, such as grinding or pumping, the system functions as a windmill. In wind generators, airflow causes the rotor blades to spin, which in turn rotates a shaft connected to a generator. Through electromagnetic induction, this rotational motion is transformed into electrical power. Electricity generation from wind turbines now ranges from kilowatt-scale systems to multi-megawatt installations. Typically, turbines are capable of harnessing 20–40% of the available wind energy, with performance largely dependent on blade efficiency. Advances in turbine technology have led to significant improvements in both size and output capacity, a trend that continues to evolve. The actual energy production is influenced by several factors, including rotor radius, wind speed, and blade design. The turbine can be classified by various ways like on the basis of axis of turbine rotor most commonly applicable. The horizontal axis wind turbine and Vertical Axis wind turbine. The horizontal axis wind turbine are commonly design wind turbine today, i.e. the axis of rotation is parallel to the ground. Horizontal axis turbines are classified according to rotor direction, rotor control, number of blades. And the detail classification of windmills is given below Figure 2. The wind mills are generally classified according to their axes of rotation, it can

also be classified in terms of revolution, Power, and Number of Blades [33].

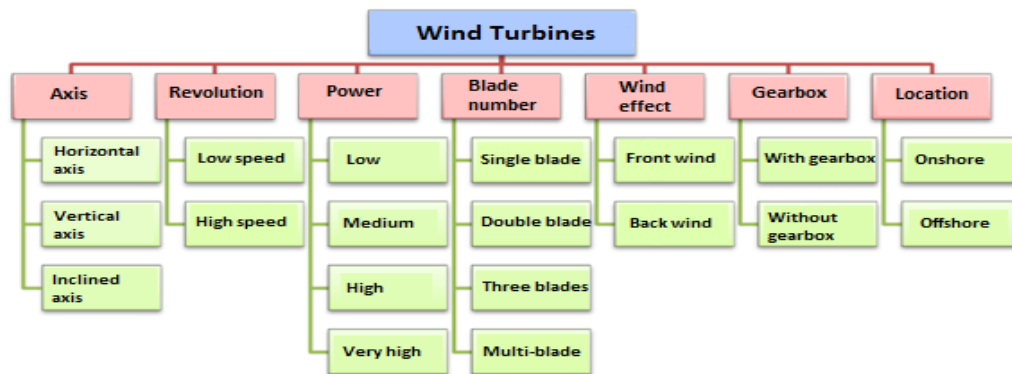


Fig. 2. Wind turbine classification, source.

II. LITERATURE REVIEW

The impact of blade surface roughness because of dust accumulation on wind turbine effectiveness has also been investigated experimentally. Since energy generation costs are closely linked to turbine output, which in turn depends on blade characteristics, the degradation of blade surface smoothness presents a significant operational concern. In one study, the performance of a 300-kW stall-regulated horizontal-axis turbine was analyzed under varying levels of surface roughness caused by accumulated dust. The mechanisms of dust deposition, its progression with turbine operating period, and the influence of roughness intensity on aerodynamic efficiency were systematically examined. Specific attention was given to the leading-edge region of the blades, where roughness areas ranging from 5% to 20% of the chord length were tested. Additionally, experiments were extended to a 100kW pitch-regulated turbine and compared against a stall-regulated turbine of the same capacity. The findings demonstrated that dust accumulation significantly alters blade aerodynamics and reduces performance, with the extent of efficiency loss depending on turbine type and roughness distribution [9].

The issue of aerodynamic noise generation in wind turbines has been studied extensively to better understand its sources and characteristics. In one experimental investigation, acoustic field measurements were performed on a three-bladed wind turbine with a rotor diameter of 58 m to identify dominant noise sources, particularly trailing edge noise. A large horizontal microphone array was deployed one rotor diameter upwind of the turbine to capture noise distribution across the rotor plane and individual blades, while turbine operating parameters were recorded in parallel. More than 100 measurements were conducted under wind speeds ranging from 6 to 10 m/s, with one blade cleaned, another tripped, and the third left untreated to assess the effect of surface roughness. Results revealed that nearly all ground-level noise was generated during the downward motion of the blades, with the outer blade regions—excluding the tips—being the primary sources. The noise levels were found to scale with the fifth power of local flow speed, consistent with trailing edge noise theory. Comparative analysis showed that the tripped blade was significantly noisier than the others, while narrowband spectral analysis confirmed that broadband trailing edge noise rather than bluntness noise dominated the emission. These findings provide strong experimental evidence that trailing edge noise remains the principal source of aerodynamic sound in modern horizontal-axis wind turbines [10].

Computational modeling has also been advanced for the study of vertical-axis wind turbines (VAWTs). A notable contribution introduced a new aerodynamic model based on the double-multiple streamtube concept, enhanced to account for rotors with blades following oval trajectories at variable setting angles. This model was applied to analyze the performance of the Variable-Geometry Oval-Trajectory (VGOT) Darrieus turbine, an innovative concept proposed for extra-large wind power plants. To capture the unique geometric characteristics of the VGOT configuration, three novel non-dimensional performance parameters were defined: the equivalent power coefficient, the equivalent solidity

coefficient, and the trajectory efficiency. Numerical simulations conducted across several rotor configurations and varying wind scenarios demonstrated the model's capability to evaluate aerodynamic behavior and performance trends of complex VAWT geometries [11].

The influence of forest environments on wind flow characteristics and turbine siting has also been investigated through experimental modeling. In one study, bidimensional forest clear-cuts oriented perpendicular to the wind direction were simulated in a wind tunnel using foam models to represent forest canopies. Particle Image Velocimetry (PIV) was employed to capture boundary layer displacement and the formation of cavity shear layers at canopy height, which generated strong velocity gradients, turbulence intensities, and wind gusts. Extreme wind conditions were analyzed using extreme value methods applied to the PIV data. Results indicated that, compared to forest-free conditions, turbulence intensity increased by 4–9%, wind energy availability was reduced by 5–20%, and extreme wind speeds were elevated by 15–30%. The findings were further interpreted in relation to the IEC 61400-1 standard for turbine siting, suggesting that the rotor clearance from the ground should be at least twice the forest height to mitigate adverse shear layer effects. This research highlights the importance of accounting for forest canopy aerodynamics in the technical feasibility and safety of wind turbine installations [12]. Long-term wind measurement programs have played an essential role in assessing wind resource variability and its impact on turbine performance. A comprehensive study was conducted on a 300 kW Nord-tank stall-regulated horizontal-axis wind turbine installed at the Hurghada Wind Energy Technology Centre's test station. The research included detailed documentation of experimental setups and long-term wind speed records for Hurghada city over the period 1973–2001. Wind speeds and directions were measured at multiple mast heights of 10 m, 24.5 m, and 31 m, with data acquisition beginning in 1986. Measurements were recorded at a 2 Hz scanning rate and stored as one-hour averages, alongside monthly statistical analyses. The findings indicated that variations of $\pm 10\%$ in the annual mean wind speed around the long-term average corresponded to a natural variability of $\pm 25\%$ in the available wind energy. The study further examined the influence of wind variability on the power curve of wind turbines in the Hurghada farm, emphasizing the importance of long-term site-specific measurements in the accurate prediction of wind farm performance [13]. In recent years, renewable energy generation in urban environments has attracted growing attention due to its proximity to end users. Among the various approaches, building-integrated wind turbines (BIWTs) have been proposed as a viable solution, though their adoption has been limited by both technical and architectural constraints. To address these challenges, one study revisited the Sistan-type windmill, recognized as one of the earliest drag-based wind energy converters, and explored its modern adaptation for building integration. The analysis demonstrated that design improvements could enhance the theoretical efficiency of drag force rotors to approximately 48% under conservative estimates and up to 61% under optimistic assumptions. Furthermore, scale model experiments achieved efficiencies exceeding 40%, confirming the feasibility of the concept. The study also discussed architectural integration strategies by comparing the proposed design with existing BIWT types, thereby highlighting the potential of drag-based systems as an effective and aesthetically adaptable solution for urban renewable energy generation [14]. Comprehensive reviews of wind turbine blade design have provided valuable insights into both theoretical and practical aspects of aerodynamic performance. One such review examined the state-of-the-art in blade design, encompassing theoretical maximum efficiency, propulsion mechanisms, and practical efficiency limits. The analysis emphasized the predominance of horizontal-axis wind turbines (HAWTs) in modern applications, reflecting their aerodynamic advantages over alternative configurations. Detailed discussions were presented on key aerodynamic design principles, including blade geometry, aerofoil selection, and optimization of attack angles to maximize performance. Furthermore, the review addressed the wide range of design loads acting on blades, such as aerodynamic forces, gravitational effects, centrifugal and gyroscopic loads, as well as operational stresses. Together, these findings provided a holistic framework for understanding the critical design considerations that govern the performance, reliability, and structural integrity of wind turbine blades [16].

The increasing global adoption of wind energy as a renewable source has been supported by significant technological maturity in terms of design, infrastructure, and cost competitiveness. However, the performance and long-term reliability of wind turbine systems remain strongly dependent on factors such as aerodynamic efficiency, material selection, and structural integrity. To address these aspects, the role of Structural Health Monitoring (SHM) has been emphasized as a critical tool for real-time evaluation of turbine performance. Recent studies have further explored the integration of smart materials within SHM systems, which not only enhance monitoring capabilities but also serve as

micro-energy harvesters. Despite these advancements, the application of SHM in tropical regions such as Malaysia remains limited, particularly with respect to the use of biocomposite materials in turbine blades. Research has also highlighted issues related to Vertical-Axis Wind Turbines (VAWTs), material performance under humid climates, and the development of effective micro-harvesting strategies. Collectively, these studies underline the need for further work on material adaptation, SHM integration, and energy harvesting in order to advance wind energy utilization under region-specific conditions and support the promotion of sustainable green technologies [17]. The Persian or Sistan windmill, regarded as one of the earliest wind energy devices, utilized a vertical axis with six blades partially enclosed within a shroud that exposed only half of the rotor to the wind. Historically, its efficiency ranged between 5% and 14%, rendering it unsuitable for practical application in modern energy systems. Nevertheless, the underlying concept has regained attention due to its potential for building integration. Recent investigations revisited this traditional design to assess its adaptability and performance under improved configurations. Exploratory studies demonstrated promising results, leading to a series of controlled experiments at Southampton University with a scaled model (0.6 m diameter, 0.5 m height). These experiments, incorporating advanced measurement and data acquisition systems, examined multiple geometrical variations. Findings indicated that a gap between the blade and axis is crucial for proper operation, while optimized geometries yielded efficiencies in the range of 40–50%, comparable to those of modern Darrieus-type Vertical Axis Wind Turbines (VAWTs) at blade-to-wind speed ratios of 0.82–1.8. The results suggest that the modified resistance-type VAWT holds potential for further development and could provide a viable pathway for innovative applications in urban and architectural contexts.[18]. Vertical Axis Wind Turbines (VAWTs) offer several advantages over Horizontal Axis Wind Turbines (HAWTs), particularly in their adaptability to turbulent wind flows and urban environments. Despite these benefits, the widespread adoption of VAWTs has been limited by inherent drawbacks, notably their relatively low efficiency and poor self-starting capability, especially in the case of lift-type VAWTs. Unlike HAWTs, VAWT blades do not consistently generate positive torque throughout operation, which restricts performance. To address these challenges, a range of innovative design modifications have been proposed, including variations in rotor configurations and blade profiles. A key focus of recent research has been on flow augmentation systems, which aim to enhance the power coefficient (CP) by optimizing airflow around the turbine. Such augmentation systems have demonstrated the potential to increase maximum power output by up to 9–10%, primarily through mechanisms that increase upwind velocity and reduce negative torque. Furthermore, the integration of flow augmentation devices into building structures has been highlighted as a promising approach for urban wind energy applications, aligning turbine performance improvements with architectural functionality [16]. With the inevitable depletion of nonrenewable energy resources such as fossil fuels, oil, and natural gas, the need for alternative and sustainable energy sources has become increasingly critical. Among various non-conventional methods of power generation, wind energy has proven to be both effective and reliable. Considering specific geographical attributes, research highlights that vertical axis windmills (VAWTs) can offer efficient solutions for electricity generation, particularly in regions with variable wind conditions. The focus of this study is on the design and fabrication of a VAWT capable of operating at low wind speeds, thereby addressing one of the key limitations of traditional wind turbine systems and extending their applicability to a wider range of environments [20]. Additive manufacturing has recently gained attention as a promising technique for fabricating complex three-dimensional components with efficiency and precision. In this context, cross-axis wind turbine (CAWT) blades and components were produced using fusion deposition modeling (FDM) with Acrylonitrile Butadiene Styrene (ABS) material. The process involved developing 3D CAD models, converting them into .STL format, and processing them through “Slicer” freeware to generate G-code files for automated 3D printing. The fabricated components were assembled into a CAWT and evaluated in an open-jet wind tunnel at wind velocities ranging from 4–10 m/s. Results demonstrated that the coefficient of power (C_p) increased gradually with tip speed ratio (λ), attaining a maximum value of 0.02385 at $\lambda \approx 1.20$ and $V_a = 10$ m/s. These findings highlight the potential of 3D-printed turbine components in the development of small-scale wind energy systems [19]. The historical evolution of the lift-type vertical axis wind turbine (VAWT) is traced back to its origin in the early 1930s, though significant development did not occur until the 1970s when researchers in Canada and the USA revisited the design for electricity generation. During this period, a variety of curved-bladed VAWTs were tested, while parallel efforts in the UK focused on developing the straight-bladed VAWT. However, throughout the 1990s, VAWT research and development declined due to the increasing dominance of the horizontal axis wind turbine (HAWT) in the commercial wind energy sector. More recently, literature suggests a revival of VAWT technology, particularly in the context of offshore floating wind turbine applications, with ongoing

attempts to commercialize these systems. This renewed interest highlights the potential of VAWTs in specialized applications where their unique structural and aerodynamic characteristics can be advantageous [20].

Airflow behavior in mountainous terrain is significantly influenced by the terrain profile and surface.

III. ANALYSIS

A. Finite Element Analysis

Finite Element Analysis (FEA) is a computational technique used to obtain approximate solutions for boundary value problems. It is based on the Finite Element Method (FEM), a numerical approach that divides complex structures into smaller, manageable elements. FEA allows engineers to model a design in a computer environment and analyze it under specific conditions to determine responses such as stress, strain, deformation, deflection, natural frequencies, mode shapes, and temperature distributions.

The principle of FEA can be illustrated with a simple analogy. Consider measuring the perimeter of a circle without using the standard formula. The circle can be divided into several equal segments, as depicted in Figure 1. By connecting the start and endpoints of each segment with straight lines, the lengths of these lines can be measured and summed to approximate the perimeter. This approach mirrors the FEA concept, where a complex geometry is discretized into smaller elements, enabling approximate but accurate solutions to otherwise difficult problems.

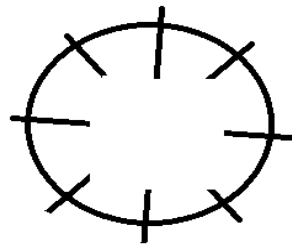


Fig. 3. The circle divided into small equal segments

Dividing a circle into only a few segments, such as four, results in a poor approximation of its perimeter. Increasing the number of segments improves accuracy, but also requires more computation time. This trade-off between accuracy and computational effort is a fundamental principle of the Finite Element Method and is the reason why FEA is inherently an approximate method.

FEA was initially developed for high-stakes applications in the aerospace and nuclear industries, where structural safety is critical. Today, it is widely used across engineering disciplines, including the design and evaluation of even relatively simple products.

In FEA, a structure or component is divided into a finite number of elements, which are small regions with predefined shapes such as triangles, quadrilaterals, tetrahedrons, or hexahedrons. Each element is governed by equations that describe its response to applied loads, and the collective responses of all elements are assembled to predict the overall behavior of the complete model. This enables simulation of real-world loading conditions, allowing engineers to assess and optimize designs for both new products and existing systems.

A wide range of commercial FEA software packages is available for engineering analysis. Most Computer-Aided Engineering (CAE) software offers multiple modules tailored to different types of analyses, allowing users to select the module best suited to their specific requirements. Some organizations rely on a single software package, while others may use multiple CAE tools or even develop customized versions of commercial software to meet specialized needs.

IV. CONCLUSION

This review highlights the rapid evolution and growing importance of wind energy as a sustainable and clean power source. The analysis of existing literature reveals that wind turbine performance is governed by a combination of aerodynamic efficiency, structural strength, and environmental conditions. Horizontal-axis wind turbines (HAWTs) continue to dominate large-scale energy production due to their higher efficiency and maturity of technology, whereas vertical-axis wind turbines (VAWTs) offer promising solutions for urban and low-wind-speed applications due to their omni-directional capability and compact design.

The study also demonstrates that factors such as blade surface roughness, turbulence intensity, wake effects, and terrain conditions significantly influence turbine performance. Structural analysis using Finite Element Analysis (FEA) has proven to be an effective tool for evaluating deformation, stress distribution, and failure-prone regions in turbine blades, ensuring safe and optimized designs.

Furthermore, recent advancements in computational modeling, additive manufacturing, and hybrid turbine configurations have opened new avenues for improving efficiency and reducing costs. However, challenges such as low efficiency of VAWTs, aerodynamic noise, structural fatigue, and site-specific variability still require further investigation. Overall, the integration of advanced materials, intelligent monitoring systems, and optimized design approaches is essential to enhance the reliability and efficiency of wind energy systems. This review consolidates existing knowledge and provides a foundation for future research and development in wind turbine technology.

V. FUTURE PROSPECTS

The future of wind energy technology is highly promising, driven by continuous innovation and increasing global demand for clean energy. Several key directions can be identified for future research and development:

- Development of lightweight, high-strength composite materials and bio-composites for turbine blades to improve durability, fatigue resistance, and efficiency.
- Integration of sensors, IoT, and smart materials for real-time monitoring, predictive maintenance, and fault detection in wind turbines.
- Combining wind turbines with solar, wave, or energy storage systems to enhance overall energy reliability and efficiency.
- Adoption of advanced manufacturing techniques for rapid prototyping, complex blade geometries, and cost-effective production of turbine components.

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