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Review Article

Reviewing the enhancement optimum performance characteristics of horizontal axis wind turbine blades using add-on of suitable aerodynamic properties

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ABSTRACT

Standard horizontal-axis wind turbine blades are characterized by operational noise and low power output. Therefore, it is crucial to integrate mechanical components within the wind turbines to enhance their peak power output while simultaneously reducing their noise emissions. This article reviews enhancing optimum performance characteristics of horizontal axis wind turbine blades using various geometrical inbuilt Add-On mechanical devices of suitable aerodynamic properties. Evaluation of torque, thrust, and blades' aerodynamic properties, which enhance efficiency, were investigated to understand the performance of aerodynamic add-ons on rotor blades. The current work showed that adding aerodynamic add-ons to wind turbine blades can improve the performance and efficiency of the blades, as well as increase the power output of the blades. This study also considered the performance and efficiency of blades in turbulence and high wind speeds. Various turbulence-inbuilt models of numerical fluid dynamics modules were investigated and analyzed to predict the motion surrounding the horizontal axis wind turbine. Numerical outputs showed that Add-Ons on horizontal wind turbine significantly enhances the efficiency and performance with expected reduced noise.

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INTRODUCTION

The nation's population and industrialization expansion are expanding continuously, and this is leading to an increase in energy demand [1]. The Energy Information Administration estimates that between 2008 and 2035, household and commercial energy requirements will increase at annual average rates of 1.10% and 1.50%, respectively [1]. Energy consumption around the globe is anticipated to rise by 56% from 2010 levels to 2040 levels, reaching 820 quadrillion BTUs [2]. The main cause of greenhouse dioxide pollutants in the atmosphere is the extensive use of

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non-renewable energy [3]. Additionally, using fossil fuels directly contributes to the problem of global warming by emitting greenhouse gases including CO2, CH4, N2O, and others [3,4].

Due to increased environmental consciousness, a decline in the use of conventional fuels, tight environmental regulations, and the need for clean energy sources has astutely increased drastically [5-7]. In terms of emerging technologies, wind energy appears to be one of the more well-liked because of its relatively low cost and quick global expansion [8]. From 298,601 MW in 2013 to 600,000 MW at the end of 2018, it is predicted that the quantity of wind energy installed globally will reach 817,000 MW by 2021 [2].

Figure 1 shows that the operational green energy output in 2025 increased by about 50.22 GW, which is somewhat less than the operational green energy output in 2010. This is based on updated statistics from the World Wind Energy Association. After record numbers in 2015 and 2014, the operational green energy output in 2020 reached the third-highest operational level annually. However, since the development of wind power generation technology at the start of the early 1900s, the slow growth in the market rate of 9.1% was revealed [2]. In 2021, the percentage share of Countries in the Worldwide Wind Energy market contributed most to the energy produced via wind turbines (Fig. 2) [2]. However, Figure 3 is the biggest wind generator that was introduced between 2000 and 2020 were presented. Wind turbine blades have grown from tens of meters to hundreds of meters (220 m), or almost 2.75 times the Airbus A380's wingspan (79.8 m). Now, a typical wind turbine's overall height is 260 m, or around 80% of the height of the Eiffel Tower (Fig. 3) and 26% of the atmospheric boundary layer's standard height (Hs = 1000 m). The height of wind turbines has doubled in the past 10 years, rising from 13 percent Hs in 2000 to 26 percent Hs in 2020 [9].

Wind turbine technology has been assessed through several evaluations. Various methodologies were sated and utilized in examining flow-control devices to optimize wind turbine performance [10]. In 2018, [11] offered an overview of the different blade design methodologies for horizontal

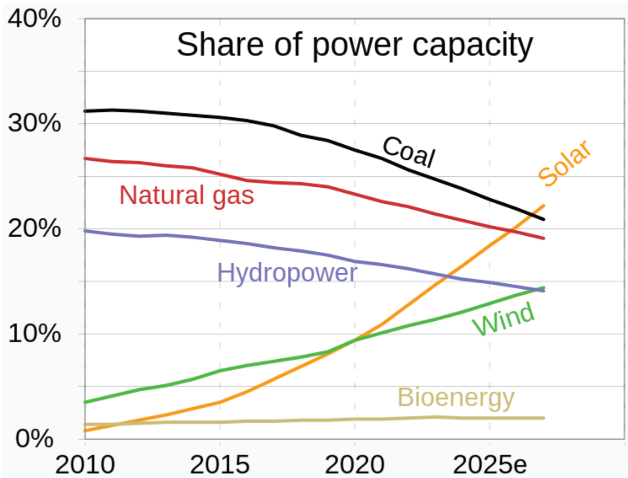

Figure 1. Different renewable energy power capacity sources [From Khlaifat et al. [2], with permission from AIMSpress Energy Journal].

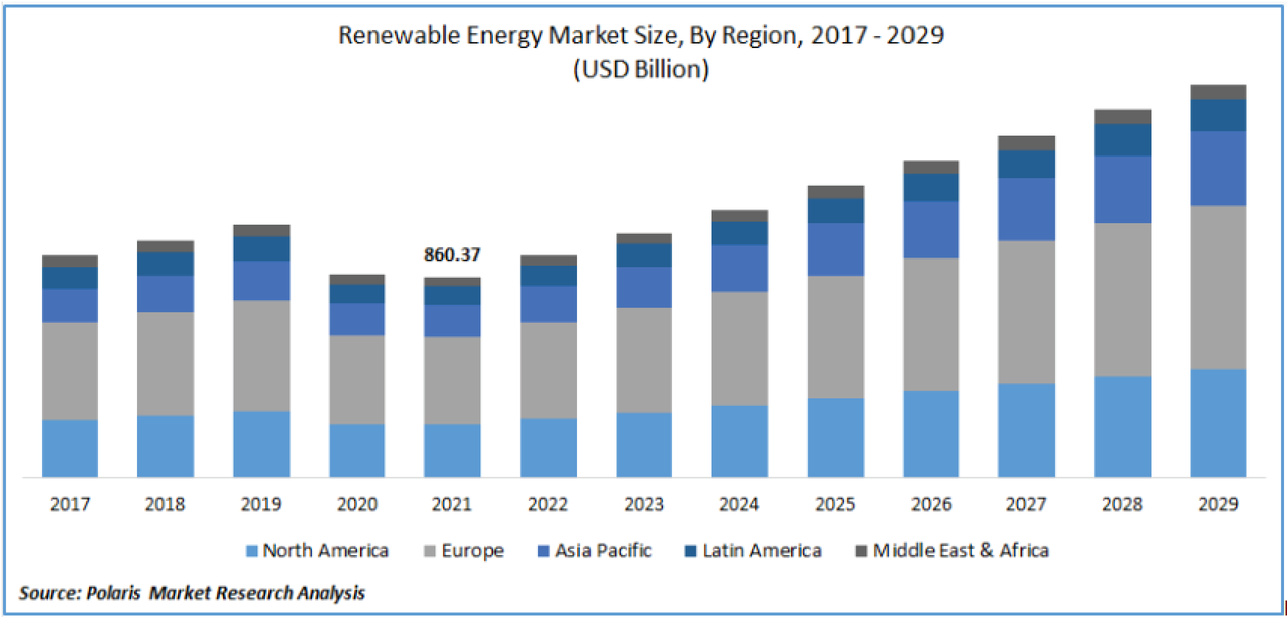

Figure 2. The percentage share of countries in the worldwide wind energy market at the end of 2029 [From Khlaifat et al. [2], with permission from AIMSpress Energy Journal].

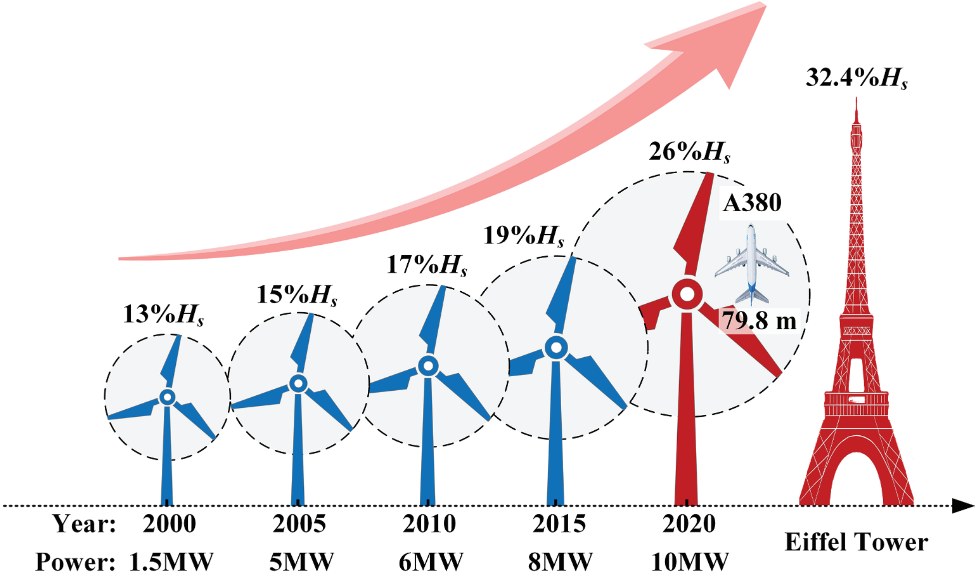

Figure 3. Trends in the advancement of contemporary wind turbines [From Gao et al. [9], with permission from Elsevier].

axis wind turbines. The discussion focused on trends and upcoming challenges in this field, as well as methods for enhancing efficiency and monitoring progress. [12,13] explored various airfoil characteristics of wind turbine horizontal-axis add-on designs. The effects of varying fluid dynamics techniques on performance were also examined. The goal of the study is to draw attention to the sensitive variables that have impacts on the aerodynamic performance of horizontal-axis wind turbine blades. The amount of energy produced is greatly affected by undermining any fundamental operating parameters of the wind turbine. The quantity of energy produced can be significantly increased by optimizing the operating parameters of wind turbine designs. Discussions include the geometry of the wind turbine blade, the wind power distribution and tip speed ratio, and the arrangement of the airfoil. Atmospheric circumstances (wind data models) are also covered. Nevertheless, this study examined the corresponding aerodynamic properties of different criteria that influence the performances of horizontal-axis turbine blades. The various turbulence models were also emphasized, along with application in computational fluid dynamics modeling to examine the horizontal wind turbine's aerodynamic properties.

ENHANCING FACTOR AND AERODYNAMIC CHARACTERISTICS FOR THE WIND TURBINE BLADE'S PERFORMANCE

A traditional horizontal axis wind turbine (HAWT) can produce noise and is vulnerable to wind turbulence [13]. The aerodynamic characteristics of HAWT are affected by several factors, including the effect of air density and wind blade form. To maximize energy output, the wind turbine must be able to scale up its capacity. Therefore, it's critical to comprehend the key operational factors that influence the performances of wind turbines when preparing for the anticipated power output.

Aerodynamic properties describe the way wind turbine blades interact with the air, which implies how well they work. Airfoil configuration, which describes the form and arrangement of a wind turbine blade's surfaces, forms the basic element in defining the aerodynamic properties of the blade. To increase the aerodynamic performance of wind turbines, which eventually improves power production and capacity factor, multi-element configurations have been researched. Typically, an airfoil's aerodynamic properties are assessed by examining its lift and drag coefficients as well as its stall behavior [14]. [15] described airfoil as the cross-sectional shape of an object whose motion through a gas is capable of generating significant lift, such as a wing, a sail, or the blades of a propeller, rotor, or turbine. In short, a perpendicular cut through an aircraft's wing, crossing both the leading and trailing edges, reveals the cross-sectional shape of the wing, which is known as an aerofoil. When solid bodies move through a fluid it produces aerodynamic forces. The component of this force perpendicular to the relative freestream velocity is called lift. The component parallel to the relative freestream velocity is called drag. An airfoil is a streamlined shape that is capable of generating significantly more lift than drag.

Although wind energy can offer nearly constant and stable power, it can be challenging to use this energy efficiently. The Betz coefficient is the first restriction on the production of electricity using wind turbines [16,17]. Bet's law gives the criterion of the amount of accessible wind kinetic energy that can be collected by a wind turbine. According to this regulation, the efficiency of wind turbines is limited to roughly 59.3%. The aerodynamic efficiency of

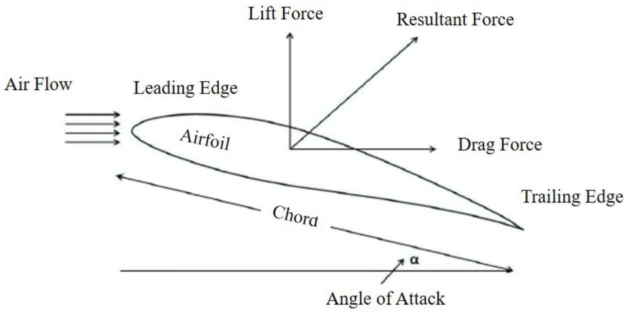

Figure 4. Forces acting on an airfoil [From Ebrahimi and Movahhedi [16], with permission from Elsevier].

wind turbine blade profiles is significantly impacted by elements that cannot be avoided, such as surface roughness brought on by contamination, erosion, and icing, as well as design considerations (such as the angle of attack) [15]. Investigations into wind-turbine performances remain a difficult and dynamic area of study since there are many pertinent parameters [18].

The wind turbine blade's angle of attack is one of the most important design parameters for industrial wind turbines as shown in Figure 4, which has undergone extensive research for a variety of turbine blade profiles. As one of the goals of this study, it is now necessary to investigate the aerodynamic properties of wind turbines to ascertain the lift-to-drag ratio of the blade. This is an illustration of the lift-to-drag force ratio on the blade geometry as shown in Figure 4. According to [16], the lift force and the drag force are given by Equ.1 and Equ.2 respectively.

$$F_L = 0.5\rho C_L A_L V^2 \,[16] \tag{1}$$

$$F_D = 0.5\rho C_D A_D V^2 \,[16] \tag{2}$$

Here, ρ is the density of air, A_L is the projected wing area, A_D is the rotor blade's cross-sectional area and V is the velocity of the oncoming airstream, while C_L and C_D are the lift and the drag coefficients respectively. The lift-to-drag ratio is defined as C_L/C_D and is mostly used as an indicator of efficiency [16].

Note that Equations 1 and 2 are not predictive. Knowledge of C_L and C_D is required to find F_L and F_D but until experiments or computer simulations for the specific airfoil under consideration have been done, the two coefficients are unknown. The design of the turbine blade will, however, dictate the type of airfoil. Research indicates that increasing the Reynolds number can postpone stall behavior [18]. Consequently, the investigations were conducted within the parameter range of $Re = 10^6 \leq Re\ 3 \times 10^7$ and angles of attack $0° \leq \alpha \leq 25°$. Reynolds number (Re) is a non-dimensional number that is used to represent the scale-down model and to anticipate the behavior of the fluid in various situations [19,20]. The Reynolds number is named after Osborne Reynolds, an Irishman who used pipe flow to introduce die to forecast various flow patterns. The ratio of inertial force to viscous force is known as the Reynolds number (Re). The Reynolds number used in this study is given by Equation 3 where c is the chord length and μ is the dynamic viscosity of air.

$$Re = \frac{\rho V c}{\mu} \,[16] \tag{3}$$

A wind turbine blade's surface configuration, which determines how aerodynamically efficient it is, is referred to as airfoil configuration in the literature. The performance of horizontal-axis wind turbines is influenced by structural design and the airfoil shape of the blade [21,22]. The flow acting on the blade surface significantly impacts the aerodynamic performance of wind turbines. [23] investigated the aerodynamic forces, such as lift and drag, operating on the surface of an airfoil under various boundary layer circumstances. They discovered that the performance of the airfoil was considerably impacted by the presence of a turbulent boundary layer. The wind turbine blade's overall efficiency was diminished as a result of the turbulent boundary layer's higher drag and decreased lift. The article emphasizes how critical boundary layer management is for enhancing HAWT blade performance. It implies that the negative impacts of turbulent boundary layers can be reduced by optimizing the surface quality, airfoil profile, and blade angle of attack, leading to improved turbine performance and better energy collection. Also, to assess the pitching moment operating on the blade surface and the flow over the blade surface, [24] conducted experimental studies of the airfoil surface flow of a horizontal axis wind turbine.

The effectiveness of the wind turbine depends on the airfoil used, which takes into account parameters such as blade aerodynamic performance, blade quality, and manufacturing complexity [25]. The choice of the most aerodynamic airfoil is necessary for the design of wind turbine blades [26]. [27] conducted aerodynamic study of the three airfoils NACA4412, NACA0009, and NACA 23012. Among the three airfoils considered, NACA4412 has a relative camber of 4 percent, a maximum camber position of 0.41 at the length of the chord, and a relative thickness of 12%. The typical symmetrical airfoil NACA0009 has a relative thickness of 9%. Regarding NACA 23012, the first value indicates that the airfoil's maximum relative camber is 2/100, or 2 percent, and the second digit 3, or 3/20, or 15 percent, shows the position of the maximum relative camber concerning the chord length. The airfoil's simple arc and relative thickness of 12 percent are indicated by the last three digits. Utilizing Profili software, the results for the three airfoils were determined, and the maximum lift-to-drag ratio and ideal attack angle for each were computed. The NACA4412 airfoil has a theoretically greater aerodynamic performance over the other two, as evidenced by its lift-to-drag ratio of 110.2929 at an attack angle of =6°. [28] looked into how dimples affected the NACA 642e014A airfoil at standard Reynolds numbers. They discovered that dimples could enhance viscous drag while decreasing pressure drag. They also stressed how the angle of attack has a significant impact on the favorable impact (lift) that dimples have on the airfoil.

[29] investigated how the performance of wind turbine blades is affected by inserting a micro-cylinder in front of the leading edge. By modifying the airflow around the turbine blades, the study seeks to increase the turbine's power production efficiency. To assess the impact of the micro-cylinder on several performance metrics, including power coefficient, torque coefficient, and blade loading, the researchers ran numerical simulations and experimental experiments. They looked into the effect of the micro-position cylinder and size on these variables. The results imply that the micro-presence cylinder can enhance the wind turbine's aerodynamic capabilities. With the addition of the micro-cylinder, it was noticed that the power coefficient increased, indicating increased power generation efficiency. Additionally improved were the torque coefficient and blade loading, suggesting improved wind energy consumption. By positioning a microplate in front of the blade's leading edge, the results are verified [29,30]

[30] investigated ways to make horizontal wind turbine blades more efficient. To maximize performance, the authors suggest a design strategy that includes several airfoil sections and gates. Multiple airfoil sections along the length of the blade, according to the researchers, can lessen the impacts of flow separation and boost aerodynamic performance as a whole. The blade can more effectively adapt to changing wind conditions, minimizing turbulence and boosting power output, by carefully choosing and mixing airfoil designs. The study also introduces the idea of fences in addition to various airfoil sections. These are little objects positioned on the surface of the blade to regulate airflow and lessen turbulence's negative consequences. The efficiency of the blade can be enhanced and drag can be decreased by using fences to reroute the airflow and prevent it from splitting.

[31] demonstrated the potential of using riblets to reduce drag on big wind turbine blades. Small, parallel grooves called riblets can be used to alter the direction of airflow. The study focuses on analyzing various riblet designs and application approaches to ascertain how well they can reduce drag. The impact of riblets on the productivity of wind turbine blades was analyzed using computational simulations and wind tunnel testing. They looked at numerous riblet geometries, including varying depths, shapes, and spacings of grooves. They also looked into whether applying riblets to the entire blade surface or just certain areas would have an impact. Riblets can indeed lessen the drag on wind turbine blades, according to the research. It was dependent on variables like wind speed and flow conditions to determine the ideal riblet geometry. The study also demonstrated that applying riblets to the whole blade surface as opposed to just a few selected areas resulted in a higher reduction in drag.

[32] analyzed the flow behavior around various airfoil designs with varying degrees of concavity using computational fluid dynamics (CFD) simulations. They contrasted the concave airfoils' performance parameters with those of traditional flat and convex airfoils, including lift, drag, and power coefficient. Concave airfoils can increase lift-to-drag ratio and power production efficiency compared to flat and convex airfoils, according to the study's findings. Concave blades provide smoother airflow over their surfaces, which lowers drag and increases lift. This results in higher power output and enhanced turbine efficiency. The best concavity depth that maximized the blade's power coefficient was also discovered by the researchers. The highest performance was shown by airfoils with intermediate amounts of concavity; excessive concavity caused flow separation and a reduced lift. The study focuses on the possible advantages of using concave airfoil shapes for making wind turbine blades. Concave airfoils can help boost power production and energy capture, making wind energy systems more effective and commercially viable.

[33] examined the effects of various angles of attack on the wind turbine's aerodynamic performance and effectiveness. The researchers examined the flow parameters around the wind turbine blade at various angles of attack using CFD simulations. They looked at how variables including lift, drag, power coefficient, and flow separation changed with the angle of attack. According to the study's findings, the wind turbine blade's aerodynamic performance is substantially influenced by the angle of attack. Within a specific range, raising the angle of attack causes the lift and power coefficient to increase, which improves the turbine's ability to generate power. Beyond a certain angle, however, flow separation takes place, which reduces performance and increases drag. To maximize power output while minimizing drag and flow separation, the study emphasizes the need to maximize the angle of attack for wind turbine blades. The efficiency and performance of horizontal axis wind turbines can be increased by carefully choosing the right angle of attack, according to designers and operators of wind turbines.

Effect of Aerodynamic Add-on, on Horizontal Wind Turbine Blade

The performance of a wind turbine blade is affected by the aerodynamic add-on, also known as a winglet, and is reliant on a variety of variables, including the size and shape of the winglets, the wind speed, and the design of the wind turbine [34,35]. However, winglets can generally be a very efficient approach to boost wind turbine performance. The geometrical characteristics of a winglet are shown in Figure 5. To enhance the performance of wind turbines, several activities that may be divided into passive and active flow control methods have been established [36]. Increasing the lift-to-drag ratio and postponing the stall phenomenon in

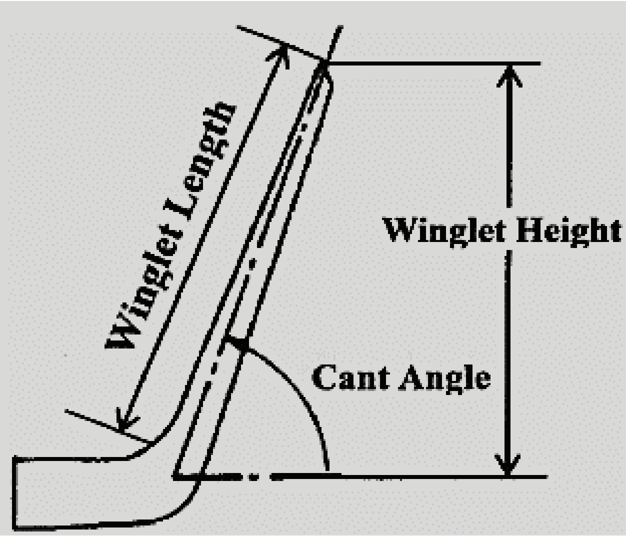

Figure 5. Geometrical parameters of a winglet [From Khaled et al. [37], with permission from Elsevier].

rotor blades are two common actions based on this concept without using external energy (the passive flow control method). Some of these tactics include the use of fusion winglets, adopting blade grooves, taking into account slots on the leading edge of the blades, installing trailing edge flaps, and taking into account riblets or vortex generators (VGs) on the surface of the blades.

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[38] examined the potential for using bionic blades in wind turbines. Bird wings are renowned for their excellent aerodynamic efficiency, and bionic blades are made to resemble their structure and shape. According to the study, bionic blades can greatly boost wind turbine performance, with a maximum power output increase of 14%. The simulation's findings demonstrated that the lift-to-drag ratio of bionic blades is higher than that of conventional blades. A multi-objective design optimization research is introduced by [39] to look into the use of bladelets, or tiny wings-like structures, on the tips of wind turbine blades. The authors create entire blade plus bladelet configurations for a three-blade propeller-type wind turbine using a 3D flow-field analysis and multi-objective restricted shape design optimization. The findings demonstrate that bladelets can boost the wind turbine rotor's power output by more than 4% with little loss in thrust force. The impacts of winglets on the fluid and structural performance of wind turbine blades are examined [40]. The flow around a wind turbine blade with and without a winglet is simulated by the authors using a computational fluid dynamics (CFD) code. According to the findings, the winglet decreases the tip vortex, increasing the blade's lift and power production. The authors claim that the winglet raises structural loads on the blade, these loads can be reduced by utilizing a stronger material or thickening the blade. When compared to a standard blade, the structural analysis for the blade with the winglet follows a similar pattern as shown in Figure 6.

The fusion winglet is a novel accessory made to increase the turbine's effectiveness and power-generating potential [41-42]. The main goal of the [43] study is to assess the turbine's performance using numerical models and experimental experiments. To compare the aerodynamic performance of the turbine with and without the fusion winglet, the researchers used computational fluid dynamics (CFD) simulations. To validate the CFD results, additional wind tunnel tests were done. The study's findings show that the fusion winglet greatly raises the performance of the turbine. It efficiently captures and reroutes the incoming wind flow, increasing the overall power output. The fusion winglet increases the turbine's aerodynamic efficiency by assisting in the reduction of tip vortices [44]. simulates the flow

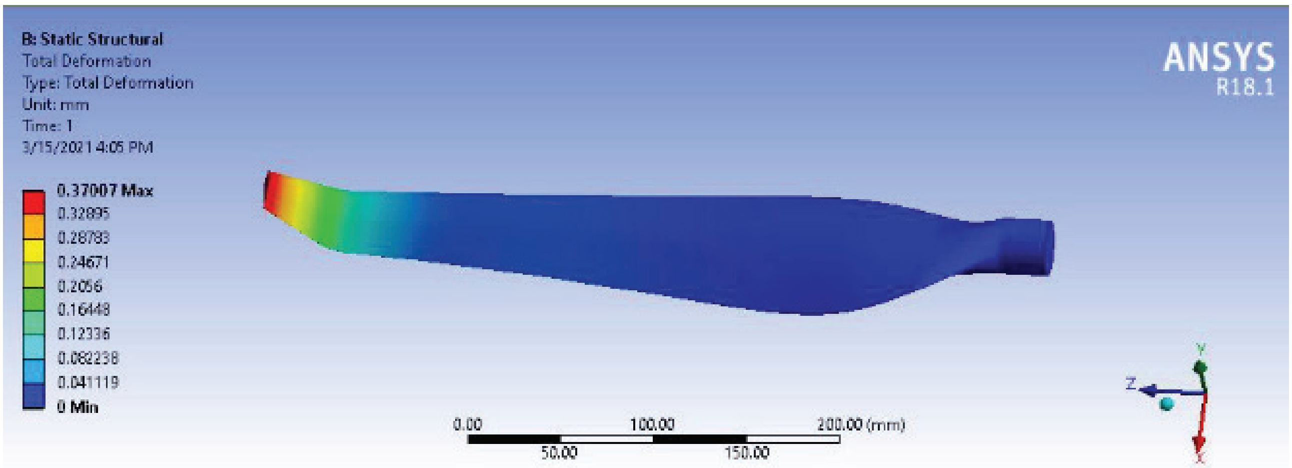

Figure 6. The deformation and stress distribution with winglet [From Reddy et al. [39], with permission from Elsevier].

around a HAWT with various chord distributions, twist, and winglets arrangements using a computational fluid dynamics (CFD) code. According to the findings, winglets have less of an effect on the power production of the HAWT than chord distribution and twist. It is discovered that a linear distribution and an exponential twist are the best options for chord twists. The HAWT's power output is increased by up to 10% with the inclusion of winglets. [45] experiment in 2019 to determine how winglet and pitch changes affect a horizontal axis wind turbine's performance (HAWT). In a wind tunnel, an experimental examination was carried out. With and without winglets, as well as at various pitch angles, the HAWT was evaluated. The outcomes of the experimental study demonstrated that the HAWT's performance can be enhanced by winglets and pitch changes. The power output of the HAWT was boosted by the winglets by up to 10%, and by the pitch changes by up to 5%. The impact of winglets on the stall characteristics of wind turbine blades with horizontal axes is studied by [46]. The flow around a baseline blade and a winglet blade is simulated by the authors using computational fluid dynamics (CFD). They discovered that for both low and high turbulence intensities, the winglet can postpone stall by up to 15 degrees. Additionally, the winglet lowers the lift coefficient at the stall while raising the drag coefficient. The authors did not, however, make the case that the winglet's ability to delay stall is a key benefit and that it may be exploited to increase the safety and dependability of wind turbines.

To enhance the performance of a model-scale wind turbine, [47] introduced the usage of winglets optimization. The performance of the turbine is examined by the authors using computational fluid dynamics (CFD) in conjunction with wind tunnel testing. They discovered that the ideal winglet shape can boost a turbine's power production by as much as 7.8%. To minimize the quantity of CFD simulations necessary to optimize the winglet shape, the scientists developed a Kriging surrogate model. Kriging is a statistical technique for building a model of a function from a small set of data points. This enables the authors to rapidly and effectively test a variety of winglet forms and identify the most effective one. The authors performed wind tunnel testing to validate the CFD models' outcomes. The optimized winglet shape delivered a power output that was within 1% of the CFD projections, according to wind tunnel testing. Using a lifting line vortex particle approach, [48] study the impact of winglets and blade sweep on the aerodynamic performance of wind turbine blades using LVLPM which stands for Level-set-based Volume of Fluid (VOF) and Level Set methods with Piecewise Linear Interface Calculation (PLIC) interface tracking. (LVLPM). The LVLPM is a numerical technique for resolving the incompressible, inviscid flow Euler equations. The rectangular winglet and the triangular winglet are the two types of winglets that the authors take into consideration. Three alternative blade sweep angles 0 degrees, 15 degrees, and 30 degrees are also taken into account. The study's findings demonstrate that wind turbine blade aerodynamic performance can be enhanced by both winglets and blade sweep. The swept blade, triangular winglet, and rectangular winglet all boost performance to varying degrees. Performance is more affected by winglet type than by blade sweep angle. The performance of horizontal axis wind turbine (HAWTs) winglet geometry is studied by [49]. The flow around a HAWT with and without winglets is simulated by the authors using computational fluid dynamics (CFD). They take various winglet heights, cant angles, and shapes. The study's findings indicate that winglets can boost HAWT performance by up to 6%.

The Wind Turbine Blade's Design

Depending on the design, different wind turbines have different numbers of blades [50]. Due to its system efficiency, stability, and economic viability, the 3-bladed upwind horizontal wind turbine is currently the most widely used modern wind turbine design. Major parts make up a horizontal rotor blade. The distribution, engine, and controllers are housed in the skyscraper, which also houses the core and provides structural support for the power station. The local grid, which transmits maximum torque from the blade to the engine, is made up of the gearbox and mechanical braking system [51]. According to [52] the generator transforms mechanical energy into electrical energy using electromagnetic components. The rotary component, meanwhile, collects wind energy and transforms it into mechanical power. The hub-mounted blade portion of the rotor is contained within it. Wind turbine blades are made from a variety of materials, including particulate and S-glass [53,54]. Many studies have shown that reducing the weight of a blade component will reduce sustainable competitive advantage. The dynamic aero-structural constraint of this decrease should be observed, and balance difficulties must be taken into account in the design [55,56].

Figure 7 shows how the chord length of the wing and the distribution of twist angle (θ_t) along the blade are key design elements that determine the appearance of the wind turbine and the cant angle (θ_r). The cant angle is also a key design parameter that has a significant effect on the performance of the blade. Turbine blades are typically angled at a specific angle, known as the cant angle, relative to the central axis of the turbine. Figure 8 illustrates how discrete radial stations along the blade were used to define the geometry of the blade. The angle between the local wing and the aerodynamic tips has been referred to as the chord, c(r), and the twist angle, β(r), to characterize the shape of the blade while (θ_p) is the cant angle.

The determination of the airfoil chord length distribution along the wind turbine blade is one of the most important design elements. Although there are alternative methods for determining the chord length, the Betz optimization hypothesis is the most straightforward and offers close approximations of the span length for the airfoil section [57]. When discounting failure from the tip

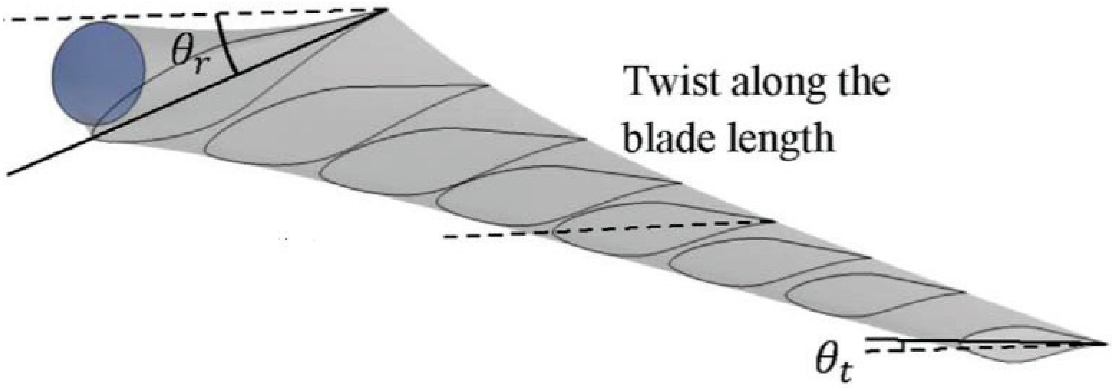

Figure 7. Schematic of wind turbine blade [From Khlaifat et al. [2], with permission from AIMSpress Energy Journal].

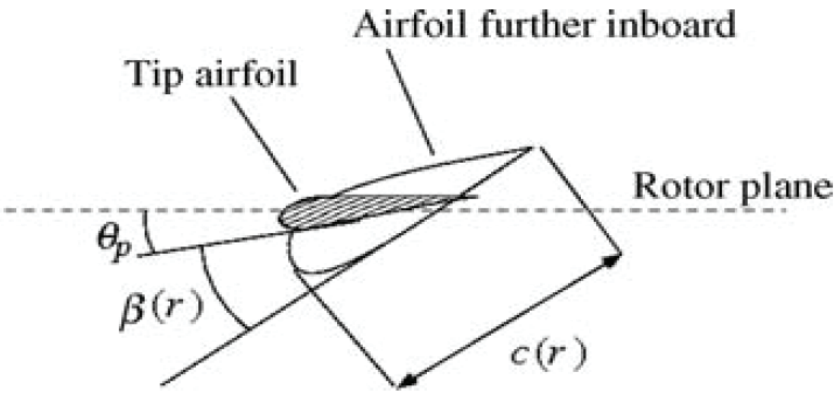

Figure 8. Sketch showing twist angle, chord length and pitch angle on a blade [From Khlaifat et al. [2], with permission from AIMSpress Energy Journal].

and drag, this method comes close to the ideal blade span length, which has a 7–9 tip velocity ratio. This approach is occasionally inaccurate because of low tip velocities, blade portions that are close to the axle, and high-drag aerosol sections [58]. The base, semi, and end of the rotor blade are the three key components that are separated based on the structural and aerodynamic functions. The greater chord length should be at the base area due to mechanical loads, whilst the thin airfoil sections will be at the end region area. As a result, the required starting torque is generated close to the base, while the majority of the output torque is generated close to the end [59].

Changes to the angular position and span lengths spread along the edges have been the focus of research on optimizing the wind turbine's shape from an aerodynamic standpoint. A specific location's wind capacity is determined using a wind dataset, and the aim of the optimization is to increase that location's yearly energy output [60]. The new efficiency of constant wind turbine velocities utilizing the regularization of an angular degree of twist contour and chord pattern method was researched by [54,58]. They concluded that when developing an ideal blade employing new regularization for air velocities increasing from 4-7 m/s, there's a substantial increase in yearly power output. Based on wind speed, the turbine of such a 301kW wind turbine horizontal axis was designed with the aid of the Blade Element Momentum hypothesis (BEM) [61]. Regarding its maximum power coefficient and easy manufacturing, the results identified the ideal shape for a wind turbine. By choosing, organizing, and linking the best turbine blade model for an Arabic situational analysis, [62] increased the AEP for areas with low wind speeds. In 2018, [63] used a gradient-based optimization approach to optimize the geometry of a wind turbine utilizing Blade Element Momentum (BEM). [64] carry out numerical analysis of a wind turbine, the researchers evaluated the efficiency of the shape optimization. According to their research, optimizing the distribution of chords boosted wind turbine output by 3.7% at rated velocity (10 m/s), while mean output was higher by 1.2% for all air velocities.

Table 1. Considerations in designing the tip speed ratio of wind turbine blade [2,69]

Tip speed ratio	Lower (λ about 1, 2)	Higher (λ > 10)
Drive system	conventional wind turbines	prototypes that have one or two blades
Shearing force	High	Low
	Low	Gain direct proportion to the rotational speed.
Performances	Decreases considerably below five because of the spinning wake caused by heavy loads.	Increasingly negligible after eight.
Airfoil	Basic	Crucial
Blade profile	Large	Significantly narrow
Vibration	Gain to the seventh power	Nearly

Aerodynamic Energy and Tip Speed Ratio (TSR)

The voltage curve displays the wind turbine's energy output current for each air velocity. The ability to estimate wind computational efficiency is essential for improving network management and incorporating wind energy into power networks [65]. The cut-in velocity is the lowest wind speed needed to produce useable electricity, and the generator is shut off at the cut-out wind velocity for technical safety operation, to avoid damage from exceedingly high generator loads [66]. Among the techniques utilized to improve the HAWT's aerodynamic performance in various wind velocities is lowering the cut-in wind velocity. For example, [67] utilizing a computational approach, a power station windmill with improved start-up efficiency at low wind speeds was created. This served to minimize the cut-in wind velocity and created an improved mix of lift-to-drag ratios. In comparison to the experimental data, this was validated.

One important design parameter that influences the calculation of various design parameters for the ideal rotor size is the tip speed ratio [20]. The ratio of the rotor blade's velocity to the relative wind speed is known as the tip speed ratio. Any modifications to the tip speed ratio will have an impact on the wind turbine's aerodynamic design [20]. As a result, a rotor blade design operating in reasonably strong winds will produce less torque in light winds. Additionally, this rotor's operation in high wind speeds will make cut-in speed and self-starting challenges worse [68,69]. Table 1 demonstrates that when choosing a tip speed ratio, it is important to consider the design of several characteristics, including the drive system, shearing force and performances, airflow properties, and vibration [69,70]. The sound pollution will practically increase to the seventh power if the tip velocity ratio increases [71]. To produce an effective energy transition, the tip speed ratio for a contemporary multiple-blade wind generator should be between six and nine, and between nine and 10 for a double-blade wind generator [72].

The two main variables that can be changed to affect HAWT performance are tilt direction (pitch angle) and generating power [55]. To follow the generator torque control system's maximum power point, the rotor speed will change accordingly. In contrast, the steady output power in the pitch-regulated system will come from managing the wind input torque. The direction in the pitch-regulated differential velocities of a horizontal wind turbine, controlling the appropriate blade pitch angle and optimal tip speed ratio will provide the ideal current, particularly because the optimum power factor is correlated with specific wind velocities [2,72].

Computational Fluid Dynamic Techniques

The lifespan of the wind turbine is significantly impacted by external factors like wind speed and direction [2,73]. For accurate findings, it is crucial to comprehend the turbulence model, which models the aerodynamics of wind flow around a wind turbine. Various turbulent theories for all flow of conservation equations will be covered in this part. Regarding every fluid flow column in CFD approaches, the momentum and mass equations as well as the turbulence equations are solved using the finite element method. This section may be divided into subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

As yet, no single theory has been able to accurately predict all of the physical attributes of turbulence flow. In the turbulent flow of wind turbines, several models are used, including Direct Numerical Simulation (DNS), Reynolds Averaged Navier-Stroke (RANS), and Large Eddy Simulation (LES). The most accurate turbulence solution is DNS. However, the necessary computation time and expense are quite significant [74,75]. RANS is the most widely used model for resolving Navier-Stokes equations [76,77]. The mathematical principle behind the computation approach of the Navier-Stokes equation is based on the Reynolds decomposition, which separates the fluid into a fluctuating part and an averaged part [77].

To solve the RANS equation, many turbulence models are employed. First, the turbulent dissipation rate (ε) parameter and the turbulent kinetic energy (k) parameter are both solved in the k-ε turbulence model series to determine the eddy viscosity. Launder and Sharma [78], described the widely used standard k-ε which performs poorly for flow simulations that include separation phenomena, such as circulation across a wind generator at elevated wind velocity. To achieve the Renormalization Group, standard k-ε has undergone yet another upgrade and change (RNG) k-ε and Realizable k-ε turbulent theories [79]. The transport equation is the same for both models as conventional k-ε for turbulent kinetic energy (k) and dissipation rate (ε). However, these models differ according to how they generate and calculate turbulent viscosity. Using statistics, the renormalization group theory was employed to resolve the RNG k-ε turbulence theory. The RNG k-ε turbulent features alterations that are distinct from normal k-ε, such as those that take the effect of spinning on vortex swirling into account. The RNG k-ε is seems to be more accurate and capable of forecasting separating fluid processes than typical k-ε [80]. The realizable k-ε model is advised for turning bodies because the results may be superior to those of normal k-ε for whirling flow issues under certain Reynolds numbers [7,79].

The k-ω turbulent theory is another RANS that is frequently employed to simulate movement around wind turbines [81]. Because of vortex tube has a negative surface tension in some situations, the k-ω model is more accurate than a regular k-ε model, allowing the pathway to be incorporated without any need for further dampening mechanism [82]. However, k-ω is still difficult to implement for some flows because of the open stream borders constraint. According to [83,84] k-ω Shear Stress Transport (SST) is a sophisticated turbulence model that combines the benefits of the k-ω and k-ε turbulence models. Consequently, where the boundary layer's innermost portion is utilized in the k-ω models and then gradually switched to k-ε in the outer layers of the wake region and the free shear layer, as a result, the blending functions are related to the translation between the two models. The adjustment of vortex fluidity, which takes into account the impact of turbulent boundary load transfer, has additional benefit to this model. Different k-ω Shear Stress Transport (SST) changes had been made to enhance spinning and laminar shapes [85,86].

The mathematical simulations used for wind turbine design under operational conditions influence the parametric study of flow around the wind turbine. Numerous turbulent theories have been employed in the literature section to test various computational methods against experimental results. For instance, to investigate the unstable RANS and DES theory, [29] and [87] employed NREL Phase VI CFDs sailing with a moving grid. The analysis discovered that the thrust force and moment values did not match the results of the experiments. However, utilizing DES significantly reduced the wind turbine's unstable flow.

Using a computer modeling of NREL Phase VI, [88] investigated k-ω SST and transition SST. With experimental work, the results showed that transition SST had superior capabilities than k-ω SST. Another study by [52] examined the impact of relatively close grid modification on the wind turbine's airflow capabilities. Eight scenarios of the NREL Phase VI theories using the k-ω SST and transition SST turbulent theories were evaluated for a near-wall grid. For forecasting thrust forces and pressure coefficients, different wind speeds are taken into account. The thrust values in the test findings did not correlate well with the k-ω SST thrust force results. The k-ω SST model generally overestimates how well the wind turbine will operate. However, notably in the inboard zones, the transition SST performances deviate from the k-ω SST theory, but the results are consistent with the experimental data. The flow surrounding the wind turbine and the dynamic behavior of the wake are studied using k-ω turbulence models. Three wind turbines were fully studied by [89] using various k-ε turbulent theories, and the findings were contrasted. These demonstrated that the modified k- ε agrees with earlier experimental measurements more favorably than the normal k-ε. Various researchers assessed the accuracy of turbulent theories used to forecast wind turbine efficiency. [90] used two RANS models to compute the NREL Phase VI: k-ω, k-ω SST. When evaluating k-ω, the k-ω SST turbulent model performs better when calculating the turbulent kinetic energy value. [90] looked at the accuracy of projecting the NREL Phase VI wind turbine using RANS and 12 turbulence models. When tested against experimental findings, all RANS numerical key performance coefficients at low-velocity ratios showed a good result. Although realizable k-ε highlighted rather decent outcomes, k-ω SST produced the worst simulation results at high tip speed ratios.

The influence of various RANS turbulent theories, including Spalart-Allmaras, k-ω SST, and transition SST on calculating the aerodynamic properties surrounding the NREL Phase VI turbine blade was studied by [91]. Their findings showed that transition SST can trap the laminar divergence ripples near the top of the airfoil and turbine blade. As a result of accurate predictions of the boundary layer's transition region, the findings of the k-ω SST transformation phase closely match scientific results. Two distinct relatively close approaches of high and low Reynolds numbers were used in an examination of the use of RANS turbulent models to forecast the numerical performance of several advanced country wind turbines [92]. Spalart-Allmaras and k-ε RNG, were the RANS models used in the high Reynolds number model, whereas k-ω SST and k-ω were the models utilized in the low Reynolds number model. Under low wind ranges, all four models could accurately predict the wave energy airflow characteristics. More discrepancies between the models became apparent as the wind speeds rose, and the high Reynolds model outperformed the low Reynolds model in terms of output. When wind speed increases, it is advised to use the RNG k-ε turbulence model because of the swirl effect that was taken into account with wall function corrections [92-95].

As a result of its ability to balance precision and computational expense, RANS has become the most widely used method. Although standard k-ε is well-liked and frequently employed, it performs poorly in simulations of flows that exhibit separation phenomena, including energy turbines operating at very strong wind speeds. The RNG k-ε is more accurate than average in predicting the separation flow of standard k-ε. When compared to ordinary k-ε, the realizable k-ε model gives better results for swirling flow issues under particular Reynolds numbers and is hence advised for spinning elements. Even though k-ω is a straightforward model for wind turbines, its implementation is limited by how sensitive it is to flows with unrestricted stream boundaries. To improve rotation and streamline curvature, k-ω Shear Stress Transport (SST) has been used to solve flow issues with wind energy. During the change transition, SST models are more accurate than traditional RANS turbulent models because they can handle the laminar-turbulent transition, which is where the separation and stall events occur.

CONCLUSION AND CHALLENGES

The writers suggested incorporating environmental factors into blade design as a potential future research path. There is a paucity of data from wind turbine experiments to verify CFD models. Therefore, realistic wind speed circumstances should be used in any future CFD modeling study. The aerodynamic properties of conventional and flatback airfoils, specifically, are still in need of more study, according to the scientists. When utilizing wind turbine technology, several difficulties arise, such as intense industry competitiveness, the accuracy of wind measurement devices, maintenance and operational issues, and problems with electricity and grid distribution. There are a variety of ways to enhance the wind forecasting equipment and control system. The aerodynamics of wind turbines have been studied for more than 200 years, with earlier research mostly concentrating on problems and solutions through experimental techniques. Due to the expense and complexity, 3D simulation work is still in its infancy and requires numerous simplifications.

The study investigates how different aerodynamic accessories affect the efficiency of horizontal axis wind turbine (HAWT) blades. The aim is to evaluate the contribution of various add-ons to the performance and efficiency of HAWTs. The use of winglets, serrations, and vortex generators among other aerodynamic additions was also taken into consideration. Each of these add-ons tries to improve the lift, control flow separation, and reduce the drag of the turbine blades to improve their aerodynamic performance. According to the review, adding aerodynamic accessories can improve the performance of HAWT blades. The lift-to-drag ratio can be increased and flow separation can be delayed with the use of vortex generators. Winglets decrease the development of tip vortices, reducing power losses and increasing efficiency. The performance improvements achieved with these aerodynamic add-ons vary depending on factors such as wind speed, turbine size, and blade design. Therefore, choosing the best add-on for a particular turbine setup requires significant thought and optimization. The accuracy of the HAWT CFD simulation depends on the use of the appropriate turbulence models, also a really helpful tool for estimating airflow efficiency. The majority of recent numerical research is to improve the precision of CFD models in forecasting aerodynamic performance. They achieve this by running simulation trials to overcome time and financial constraints.

The review concludes that adding aerodynamic add-ons to HAWT blades can improve performance qualities such as increased electricity generation, enhanced efficiency, and reduced fatigue loads on the turbine structure. However, the review does not provide a detailed cost-benefit analysis of adding winglets to wind turbines. While winglets can provide benefits such as increased efficiency and power output, the cost of manufacturing and installing winglets can be significant and should be considered in any cost-benefit analysis.

NOMENCLATURE

BTU	British Units
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Nitrogen oxide
CFD	Computational Fluids Dynamics
HAWT	Horizontal Axis Wind Turbine
Re	Reynolds Number
F_L	Lift Force
F_D	Drag Force
ρ	Density of air
A_L	Projected wing area
A_D	Rotor blade's cross-sectional area
C_L	Coefficient of Lift
C_D	Coefficient of Drag
V	Velocity of the oncoming airstream
c	Chord length
μ	Dynamic viscosity of air.
NACA	National Advisory Committee for Aeronautics
VG	Vortex generators
3D	Three Dimensional (xyz Coordinate)
LVLPM	Level-set-based Volume of Fluid (VOF)
PLIC	Piecewise Linear Interface Calculation
BEM	Blade Element Momentum
TSR	Tip Speed Ratio
DNS	Direct Numerical Simulation
RANS	Reynolds Averaged Navier-Stroke
LES	Large Eddy Simulation
SST	Shear Stress Transport
NREL	National Renewable Energy Laboratory
RNG	Reynolds-averaged Navier-Stokes equation

AUTHORSHIP CONTRIBUTIONS

Oluwaseyi O. Alabi: Writing- Original draft preparation, Investigation and Editing. **Oyetunde Adeoye Adeaga**: Conceptualization, Visualization, Methodology, Editing. **Ademola A. Dare:** Supervision and Validation, Reviewing

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest concerning the publication of this paper.

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ETHICS

There are no ethical issues with the publication of this manuscript.

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