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Effect of blade number on the performance of an H-rotor vertical axis wind turbine under low wind speed conditions

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Abstract

Vertical Axis Wind Turbines (VAWTs) have significant potential for small-scale wind energy applications, particularly in regions with low to moderate wind speeds. One of the key design parameters influencing VAWT performance is the number of blades. This study aims to experimentally investigate the effect of blade number on the operational characteristics and aerodynamic efficiency of a laboratory-scale vertical axis wind turbine. Three turbine configurations with 2, 3, and 4 blades were tested, each with a blade height of 25 cm and installed at 45 cm above the ground. Experiments were conducted using an axial fan with a flow straightener in a laboratory setup under wind speeds of 2, 3, 4, and 5 m/s. Measured parameters included rotational speed (RPM), torque, mechanical power, Tip Speed Ratio (TSR), and power coefficient (Cp). The results indicate that the three-bladed turbine exhibits the best overall performance, achieving a maximum power coefficient of 0.37 at a wind speed of 5 m/s and a TSR of approximately 2.2. A relative efficiency analysis confirms that the three-bladed configuration offers the most favorable balance among torque generation, rotational speed, and aerodynamic losses. These findings offer valuable insights for optimizing small-scale VAWT design and enhancing wind energy utilization in low-wind-speed environments.

Keywords:
Blade number, low wind speed, performance, renewable energy, vertical axis wind turbine.

1 Introduction

The increasing global energy demand, accompanied by the depletion of fossil fuel resources and rising greenhouse gas emissions, has accelerated the development of renewable energy technologies [1], [2], [3], [4], [5]. Wind energy is one of the most promising clean energy sources, with significant and sustainable potential, particularly for small-scale and distributed applications [6], [7], [8], [9]. However, in regions with low wind speeds and highly variable wind directions, such as tropical areas and urban environments, the use of conventional wind turbines still faces several limitations.

Vertical Axis Wind Turbines (VAWTs) have emerged as a promising alternative due to their ability to capture wind from all directions without requiring a yaw mechanism, their relatively simple structural configuration, and their strong integration potential at building and laboratory scales. Compared to Horizontal Axis Wind Turbines (HAWTs), VAWTs exhibit more adaptive operational characteristics under unstable flow conditions, making them widely developed for low wind-speed applications [10], [11], [12]. The performance of vertical axis wind turbines is strongly influenced by aerodynamic design parameters, including blade profile, pitch angle, aspect ratio, and number of blades [13], [14], [15].

The number of blades directly determines the rotor solidity, which affects torque generation, rotational speed, and overall energy conversion efficiency [16]. Turbines with fewer blades generally operate at higher Tip Speed Ratios (TSR) and achieve higher power coefficients (Cp); however, they often exhibit limitations in start-up capability and rotational stability [17], [18]. Conversely, increasing the number of blades can enhance initial torque and mechanical stability, but may reduce efficiency due to increased aerodynamic drag and wake interaction between blades. Several previous studies have reported the influence of blade number on VAWT performance through both numerical and experimental approaches [19], [20], [21], [22], [23]. Nevertheless, the results still show considerable variation, primarily due to differences in turbine scale, flow conditions, and geometric configurations employed. Furthermore, strictly controlled laboratory-scale experimental studies remain relatively limited, particularly under low-wind-speed conditions relevant to practical applications in tropical regions. However, most existing studies have focused on moderate to high wind speeds, and systematic experimental investigations of low wind speeds (below 5 m/s) remain scarce. Furthermore, controlled laboratory-scale studies with consistent geometric parameters are needed to isolate the effect of blade number from other variables.

Therefore, this study aims to conduct an experimental investigation on the effect of blade number variation on the aerodynamic performance and power output of a laboratory-scale vertical-axis wind turbine under controlled low wind speed conditions (2-5 m/s).

Three configurations (2, 3, and 4 blades) were tested with identical geometric parameters (rotor diameter = 0.4 m, blade height = 0.25 m, chord length = 0.06 m, NACA 0015 profile) to isolate the influence of blade number. Performance is evaluated by measuring rotational speed, torque, mechanical power, TSR, and power coefficient (Cp). The findings are expected to provide practical guidance for the design of small-scale VAWTs optimized for low-wind-speed applications, particularly in tropical regions where such conditions are prevalent.

2 Research methodology

This study is an experimental investigation conducted at a laboratory scale to analyze the performance of a vertical-axis wind turbine under low wind speed conditions. An experimental approach was selected because it enables direct measurement of turbine performance parameters under controlled conditions representative of real operational environments. The primary focus of this research is to evaluate the influence of blade number configuration on the aerodynamic and mechanical characteristics of a vertical-axis wind turbine, while maintaining all other design parameters and testing conditions constant.

2.1 Design of the vertical axis wind turbine

The wind turbine used in this study is an H-rotor VAWT. The turbine was designed with a modular configuration, allowing the number of blades to be varied without altering the main geometric dimensions or blade material properties. In this approach, blade number is the sole independent variable affecting turbine performance, enabling a focused analysis of the contribution of blade configuration to wind energy conversion efficiency.

2.2 Research variable

This study aims to analyze the effect of blade number variation on the performance of a laboratory-scale wind turbine. The independent variable is blade configuration, with 2, 3, and 4 blades. Turbine performance is evaluated based on the main dependent variables, including rotor rotational speed (RPM), torque, mechanical power output, power coefficient (Cp), an indicator of energy conversion efficiency, and TSR, which represents the operational compatibility between rotor speed and the incoming wind velocity.

To ensure the validity and comparability of the experimental results, several factors were strictly controlled. The inlet wind speed was maintained constant at each testing stage. The geometric dimensions (length, chord, and twist) and material properties of all blades were made identical, with the blade number being the only parameter varied.

All experiments were conducted in a closed laboratory environment to minimize external wind disturbances and fluctuations in ambient conditions. These controls ensure that any observed changes in the dependent variables can be directly attributed to variations in the number of turbine blades.

2.3 Experimental setup and parameters

The experiments were conducted using an artificial wind source in the form of an axial fan equipped with a flow straightener to produce a relatively uniform and stable airflow. The turbine was mounted on a test rig at a height of 45 cm above the floor to minimize boundary layer effects and flow disturbances near the ground surface. Wind speeds were varied to 2, 3, 4, and 5 m/s, representing low-wind conditions. Fig. 1 shows the experimental layout setup.

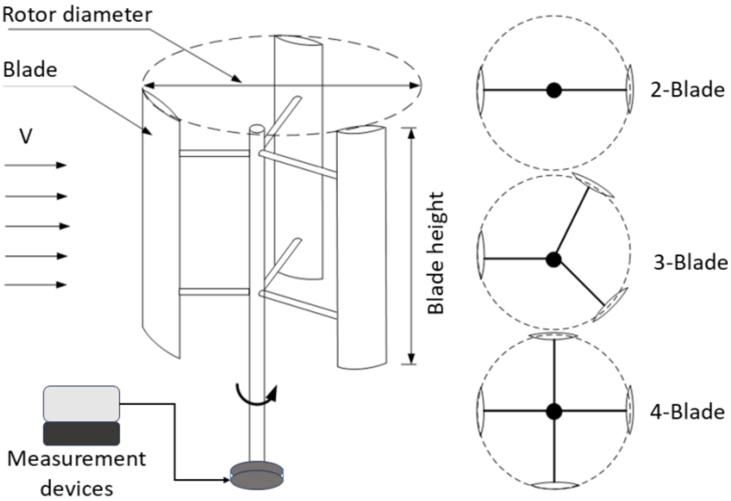

Fig. 1. Experimental setup layout for aerodynamic performance testing of the H-rotor vertical axis wind turbine.

The measurement instruments included a digital anemometer (Lutron AM-4204 range 0.4–30.0 m/s) for wind speed measurement, an optical tachometer (DT-2234C+ range 5-99.9999 rpm) for rotational speed (RPM) measurement, and a rotary torque sensor (Kyowa KPN-20KNCB range 0–5 Nm) for torque measurement. A stopwatch and multimeter were used as supporting instruments during the experiments. The testing procedure began with assembling the turbine according to the blade configuration being evaluated. The wind speed was then adjusted to the desired value and allowed to stabilize. The turbine was operated until steady-state conditions were achieved, indicated by stable rotational speed. RPM and torque data were continuously recorded over a predetermined measurement interval. This procedure was repeated for each wind speed and for all blade-number configurations. To ensure reproducibility and data reliability, each test was conducted at least three times.

The turbine performance parameters were calculated from the experimental data. The mechanical power output of the turbine was determined from the product of torque and rotor angular velocity [24], [25].

The mechanical power was calculated using the Eq. (1):

$$P = \omega T \tag{1}$$

The angular velocity can be calculated as Eq. (2):

$$\omega = \frac{2\pi n}{60} \tag{2}$$

Power coefficient (C_P) can be calculated as Eq. (3):

$$C_P = \frac{P}{\frac{1}{2}\rho A V^3} \tag{3}$$

And the TSR is calculated using the Eq. (4) [26]:

$$\lambda = \frac{\omega R}{V} \tag{4}$$

where T is the torque (Nm); ω is the angular velocity (rad/s); ρ is the air density (kg/m³); A is the rotor swept area (m²); V is the wind speed (m/s); n is the turbine rotational speed (RPM); and R is the rotor radius (m).

Solidity values of each blade (σ_2, σ_3, σ_4) calculated as Eq. (5) [26], where N is the number of blades, c, is the cord's length, and D is the rotor diameter.

$$\sigma = \frac{N\,c}{D} \tag{5}$$

The air density used in Eq. (3) was taken as $\rho = 1.2$ kg/m³, corresponding to the average laboratory conditions of 27°C and 101.3 kPa during the experiments. The rotor swept area is A = 0.10 m², calculated from the rotor diameter (D = 0.4 m) and blade height (H = 0.25 m) given in Table 1. These parameters serve as the primary indicators for evaluating the turbine's efficiency and aerodynamic characteristics.

Table 1. Specifications of the H-rotor type vertical axis wind turbine used in this study

Parameters	Description
Type of turbine	VAWT H-rotor
Blade number	2, 3, and 4
Blade height	0.25 m
Rotor diameter	0.40 m
Material of the blade	PVC material
Blade profile	NACA 0015
Cord length	0.06 m
Pitch angle	0°
Installation level	0.45 m from the floor
Solidity for 2, 3. and 4 blade	0.3. 0.45 and 0.6

2.4 Data analysis

The experimental data were analyzed quantitatively by constructing power coefficient-tip speed ratio (Cp–TSR) curves to determine the turbine's optimum operating condition. In addition, power versus wind speed curves were generated to evaluate the turbine's capability to extract wind energy under various flow conditions. In addition, power versus wind speed curves were generated to evaluate the turbine's capability to extract wind energy under various flow conditions. Fig. 2 shows the experimental workflow flowchart.

A comparative performance analysis among different blade number configurations was conducted to identify the configuration that delivers the best overall performance. The analysis was further supported by aerodynamic interpretation to explain the observed differences in torque characteristics, rotational stability, and energy conversion efficiency during the experiments.

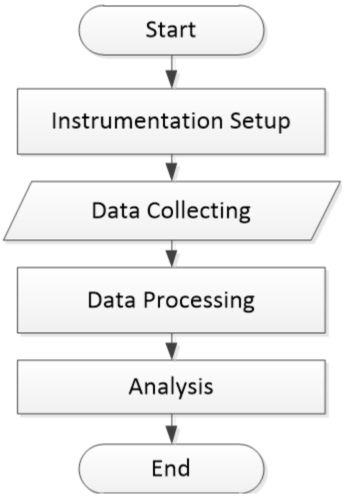

Fig. 2. Experimental workflow flowchart.

3 Results and discussion

3.1 Rotational speed characteristics of the turbine

The experimental results indicate that the rotational speed (RPM) of the vertical-axis wind turbine is strongly influenced by both the number of blades and the wind speed. For all configurations, the RPM increased consistently with increasing wind speed from 2 to 5 m/s. However, clear differences were observed among the various blade number configurations (Fig. 3).

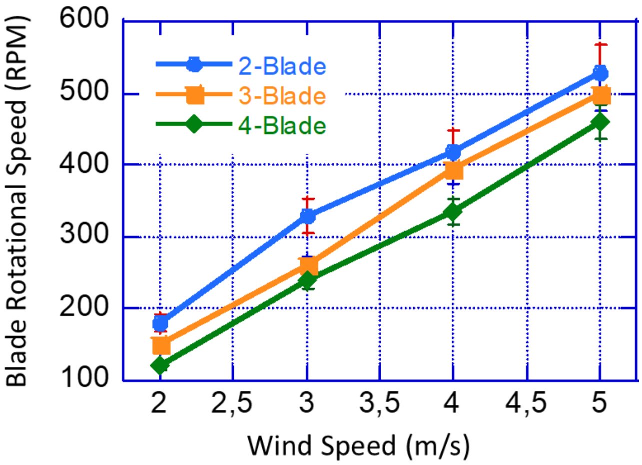

Fig. 3. Turbine rotational speed under different wind speeds (the error bars representing ± one standard deviation).

The turbine with 2 blades produced the highest RPM across all wind speeds. This behavior is attributed to its lower solidity, which allows the rotor to operate at a higher TSR. However, the higher rotational speed is not necessarily accompanied by increased torque, and therefore does not directly represent optimal power performance.

In contrast, the 4-blade configuration exhibited the lowest RPM. Increasing the number of blades increases the surface area interacting with the airflow, resulting in higher aerodynamic drag. Nevertheless, this configuration provides more stable rotational characteristics, particularly at low wind speeds.

The 3-blade configuration demonstrated RPM characteristics intermediate between the 2- and 4-blade configurations, with smaller rotational fluctuations. This condition indicates that the 3-blade configuration achieves a favorable balance between lift and drag forces, thereby supporting more stable aerodynamic performance.

3.2 Torque analysis and start-up capability

Torque is a critical parameter for assessing a wind turbine's start-up capability and operational stability, particularly in low-wind-speed applications. The experimental results indicate that torque increases significantly with the number of blades, as shown in Fig. 4.

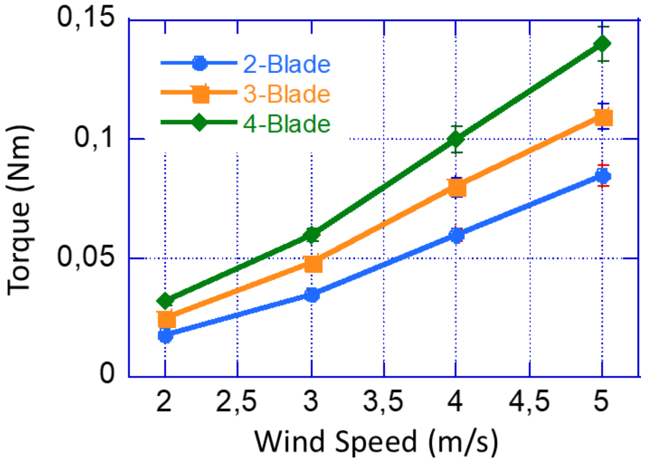

Fig. 4. Generated torque at various wind speeds (the error bars representing ± one standard deviation).

Based on the experimental results, the 4-blade turbine consistently produced the highest torque across the entire wind speed range. This indicates that the increased swept area and higher rotor solidity effectively enhance the turbine’s ability to capture wind energy, while simultaneously providing greater starting torque. This advantage makes the 4-blade configuration particularly suitable for low-wind-speed applications that require reliable self-starting capability.

In contrast, the 2-blade configuration generated the lowest torque. At a wind speed of 2 m/s, the torque was very small and approached the initial inertia threshold, leading to inconsistent rotation. This phenomenon explains the limitations in start-up of turbines with fewer blades. However, at higher wind speeds, the 2-blade turbine achieved higher RPM due to its lower aerodynamic drag.

The 3-blade turbine is optimally positioned, providing sufficient start-up torque to overcome inertia without excessive drag losses. This combination, where torque is adequate for stable operation without sacrificing efficiency at the optimal TSR, supports the conclusion that the three-blade configuration represents the best compromise between start-up performance and maximum operational efficiency.

3.3 Power performance as a function of wind speed

The relationship between mechanical power and wind speed shown in Fig. 5 exhibits a non-linear trend consistent with wind energy theory, in which wind power is proportional to the cube of wind velocity. For all configurations, power increased sharply as wind speed was raised from 2 to 5 m/s.

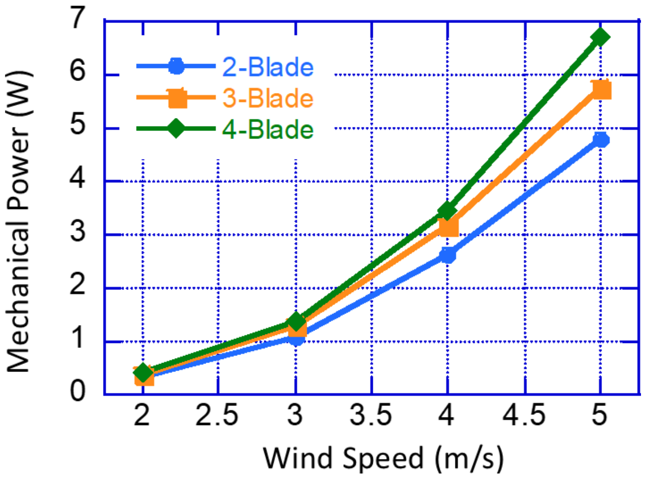

Fig. 5. Mechanical power generated by the blades at various wind speeds (the error bars represent ± one standard deviation).

The experimental results show that the 4-blade turbine consistently generated the highest mechanical power across all wind speed variations. This superiority is primarily attributed to its ability to produce significantly higher torque, which compensates for its relatively lower RPM compared to the other configurations. At a wind speed of 5 m/s, the peak power output was the highest among all tested configurations.

However, a high absolute power output does not automatically indicate optimal energy conversion efficiency. The actual performance must be evaluated through the power coefficient (Cp), which compares the mechanical power output to the available kinetic energy of the wind. The Cp analysis reveals that although the 4-blade configuration excels in torque and absolute power, it is less efficient at converting wind energy than the 3-blade configuration at its optimal TSR.

3.4 Cp–TSR characteristics

The Cp versus TSR curve shown in Fig. 6 provides a more comprehensive representation of the turbine’s aerodynamic performance. The experimental results indicate that each blade number configuration possesses a distinct optimum TSR range.

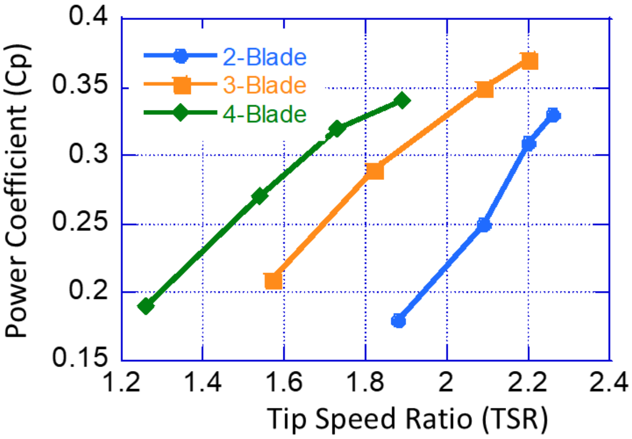

Fig. 6. Power coefficient (Cp) versus TSR for different blade numbers.

Based on the Cp–TSR relationship analysis, the three configurations exhibit significantly different performance characteristics.

The 2-blade turbine achieved its maximum Cp at a relatively high TSR (2.2–2.3); however, its peak efficiency remained the lowest among the tested configurations. This behavior is attributed to large aerodynamic fluctuations resulting from the limited number of blades, which lead to torque pulsations and increased energy losses. Although it can operate at high rotational speeds with low initial resistance, its overall aerodynamic stability is inferior.

The 4-blade turbine operated optimally at a lower TSR range (1.8–1.9). Increased aerodynamic drag and significant wake interactions between blades limited its maximum efficiency. Its main advantage is the generation of high starting torque at very low wind speeds, making it suitable for applications requiring strong self-starting capability.

The 3-blade turbine demonstrated the best overall performance, achieving a maximum Cp of 0.37 at a TSR of 2.2. This result is consistent with values reported in analogous studies on H-rotor Darrieus turbines under low wind speed conditions; for instance, Ali et al. (2024) experimentally obtained a peak Cp of 0.39 for a similar three-bladed configuration [27].

The superior performance of the three-bladed rotor can be explained by its intermediate solidity ($\sigma = 0.45$), which represents an optimal aerodynamic balance. Compared to the two-bladed rotor ($\sigma = 0.30$), which exhibits low torque but high rotational speed, the three-bladed configuration generates higher torque without the excessive drag penalties associated with the four-bladed rotor ($\sigma = 0.60$).

This configuration provides the most balanced aerodynamic condition: more stable blade interaction than the 2-blade configuration and lower overall drag than the 4-blade configuration. As a result, it extracts wind energy more effectively, delivering the highest efficiency while maintaining operational stability.

3.5 Aerodynamic efficiency analysis

To evaluate the relative efficiency of each configuration, the Cp values were normalized with respect to the global maximum Cp (Cp_max = 0.37) obtained from the 3-blade turbine.

Table 2. Relative efficiency of turbines with respect to the maximum Cp for each blade configuration

Wind speed (m/s)	2-Blade (%)	3-Blade (%)	4-Blade (%)
2	48.6	56.8	51.4
3	67.6	78.4	73.0
4	83.8	94.6	86.5
5	89.2	100	91.9

The relative efficiency analysis presented in Table 2 indicates that the 3-blade configuration consistently exhibits the highest efficiency across the entire wind speed range. At a wind speed of 5 m/s, the 3-blade turbine achieved 100% relative efficiency, whereas the 2-blade and 4-blade configurations reached only approximately 89.2% and 91.9%, respectively.

At low wind speeds (2–3 m/s), the efficiency differences among configurations become more pronounced. The 4-blade turbine demonstrates higher efficiency than the 2-blade configuration, indicating its superiority in generating initial torque. However, this efficiency improvement does not surpass that of the 3-blade configuration due to greater aerodynamic losses as shown in Table 3.

This phenomenon highlights a fundamental trade-off between torque and efficiency. Increasing the number of blades enhances energy extraction during the start-up phase, but at higher wind speeds, performance is constrained by increased aerodynamic drag and wake interactions.

Table 3. Experimental data for three-bladed configuration at all tested wind speeds

Wind speed V(m/s)	Rotational speed (RPM)	TSR (λ)	Torque T (Nm)	Power P (W)	Cp
2	150	1.57	0.03	0.39	0.21
3	260	1.82	0.05	1.31	0.29
4	395	2.09	0.08	3.18	0.35
5	500	2.20	0.11	5.76	0.37

3.6 Design and application implications

Based on the results and efficiency analysis, the 3-blade configuration can be concluded as the most optimal design for a laboratory-scale VAWT operating within low to medium wind speed ranges [28]. This configuration offers the best overall performance balance, characterized by high aerodynamic efficiency (Cp), good rotor rotational stability, and reliable start-up capability. The analysis indicates that the 3-blade configuration achieves an optimal balance between lift and drag forces compared to the other configurations.

On the other hand, the 4-blade configuration delivers superior initial torque, making it highly suitable for applications that prioritize power output at very low wind speeds. Meanwhile, the 2-blade configuration, with its lower rotational inertia, can achieve higher RPM and is more appropriate for generator systems designed for specific optimal rotational speeds, albeit at the expense of stability and starting torque. Therefore, the selection of the blade number depends strongly on the wind speed profile and the desired load characteristics [29].

From a policy and practical application perspective, the findings of this study support the strategic implementation of three-bladed vertical-axis wind turbines as a viable solution for decentralized energy generation in low-wind-speed regions, such as coastal areas, rural zones, and remote communities. The balance between efficiency, operational stability, and low-wind start-up capability makes this configuration particularly suitable for off-grid systems and hybrid renewable energy systems. Furthermore, these results may serve as a technical reference for policymakers and energy planners in formulating guidelines for the adoption of small-scale wind turbine technologies, especially in regions with low and fluctuating wind conditions, where conventional horizontal-axis wind turbines are less effective.

4 Conclusions

This study experimentally investigated the effect of blade number on the aerodynamic performance of a laboratory-scale Darrieus vertical-axis wind turbine (H-rotor) under low wind-speed conditions (2–5 m/s). Based on the experimental results and analysis, the main conclusions are: (1) Blade number is a critical design parameter governing VAWT aerodynamic performance. Variations in blade number affected rotational speed, torque, mechanical power, TSR, and power coefficient (Cp), with each configuration showing distinct aerodynamic behavior; (2) The 2-blade configuration produced the highest rotational speed but showed limitations in torque and efficiency. Although capable of operating at higher TSR values, it generated lower torque and lower Cp, especially at low wind speeds, resulting in weaker self-starting capability and larger speed fluctuations; (3) The 4-blade configuration excelled in torque generation and absolute mechanical power output but had lower aerodynamic efficiency. Increasing blade number improved start-up performance and power output, but higher drag and wake interaction limited the maximum Cp. This indicates a trade-off between torque capacity and efficiency, where excessive solidity ($\sigma > 0.45$) gives diminishing returns; (4) The experimentally validated optimal configuration was the 3-blade turbine ($\sigma = 0.45$), which achieved the highest Cp of 0.37 at TSR 2.2. It consistently showed the best balance of torque, rotational speed, and stability across the tested wind-speed range, supporting efficient small-scale deployment; (5) Normalization to the maximum Cp confirmed that increasing blade number does not necessarily improve efficiency. The 3-blade design minimized aerodynamic losses while maintaining adequate start-up capability.

Limitation of this study

This study is limited to laboratory-scale experiments under idealized flow conditions, using only three blade configurations with a fixed chord length and profile (NACA 0015), without statistical replication or quantitative vibration measurements.

Future works

Future work should focus on field validation under turbulent wind conditions and on other parametric studies, including varying blade numbers, chord lengths, and airfoil profiles, as well as quantitative vibration analysis and statistical replication to enhance the generalizability and reliability of the findings.

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