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Simulation of the Influence of Wind Speed on the Power Output of a Vertical Axis Wind Turbine

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Abstract
This study aims to analyze the effect of varying wind speeds on the power output generated by a Vertical Axis Wind Turbine (VAWT). This type of turbine holds great potential for harnessing wind energy in both urban and rural areas, particularly due to its ability to operate under fluctuating wind directions. The methodology employed is numerical simulation based on Computational Fluid Dynamics (CFD), which models fluid flow around the turbine rotor at wind speeds ranging from 2 m/s to 12 m/s. Key parameters analyzed include power coefficient (Cp), torque, and mechanical power output. The simulation results indicate a nonlinear relationship between wind speed and power output, where increasing wind speed significantly enhances power up to a certain optimum point, beyond which turbulence and energy losses become more dominant. These findings provide a foundation for optimizing VAWT design and selecting suitable installation sites according to local wind conditions. This research also supports the development of sustainable and environmentally friendly renewable energy technologies, particularly for small- to medium-scale applications.

1. Introduction

The growing global emphasis on environmentally friendly and sustainable energy sources has accelerated advancements in wind energy technologies. Among the various turbine designs available, the Vertical Axis Wind Turbine (VAWT) offers distinct advantages, particularly in regions characterized by low wind speeds and turbulent airflow, such as urban and suburban environments. Unlike Horizontal Axis Wind Turbines (HAWT), VAWTs do not rely on a wind-direction tracking system, enabling them to harvest energy from winds coming from any direction and making them highly suitable for small-scale local installations (Calautit, 2024; Pandele et al., 2025).

Wind speed is a fundamental variable that directly influences the operational efficiency of any wind turbine system. Understanding how variations in wind speed affect VAWT performance is essential for optimizing turbine geometry and determining the most suitable installation locations. Although experimental approaches have provided valuable insights in this field, computational simulations have emerged as a more flexible and cost-effective alternative for exploring aerodynamic behavior under varying wind conditions.

This study applies Computational Fluid Dynamics (CFD) to investigate airflow interactions around a VAWT rotor operating at wind speeds between 2 m/s and 12 m/s. The study evaluates key performance indicators such as mechanical torque, power output, and power coefficient (Cp), with the aim of uncovering the complex and nonlinear relationships between wind speed and turbine efficiency. Ultimately, the findings of this research are expected to contribute to improved VAWT design strategies and support the integration of renewable energy solutions in locations with moderate wind availability.

2. Method

This study employs a computational approach to evaluate how variations in wind speed affect the performance of a Vertical Axis Wind Turbine (VAWT) (Wilberforce & Alaswad, 2023; . The analysis is carried out using Computational Fluid Dynamics (CFD), which enables the simulation of fluid behavior around a three-bladed straight-blade Darrieus rotor— a configuration commonly used in small- to medium-scale wind energy applications.

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The overall workflow of the simulation is illustrated in the flowchart (Figure 1). In the initial stage, a three-dimensional model of the turbine is created using Computer-Aided Design (CAD) software. The geometry is then imported into a CFD environment (such as ANSYS Fluent or OpenFOAM), where domain discretization (meshing) and boundary condition assignments are performed. The computational domain adopts a horizontal cylindrical shape with the rotor positioned at its center. A structured hexahedral mesh is utilized, featuring local refinement around the blade surfaces to enhance resolution in critical flow regions.

Simulations are conducted under steady-state conditions for wind speeds of 2, 4, 6, 8, 10, and 12 meters per second, all under standard atmospheric pressure and temperature at sea level. To accurately capture flow-separation phenomena, turbulent wake behavior, and near-blade aerodynamic interactions, the Shear Stress Transport (SST) k–ω turbulence model is employed.

The primary output parameters analyzed include torque, power output, power coefficient (Cp), pressure contours, and streamline flow patterns. The Cp value is computed as the ratio of mechanical power output to the kinetic energy of the incoming wind. By comparing performance metrics across various wind speeds, the study aims to identify the nonlinear operational behavior of the turbine and determine its optimal operating range.

Validation of the simulation results is conducted by comparing them with findings from existing literature, with particular emphasis on maximum Cp values and observed flow structures under comparable operating conditions.

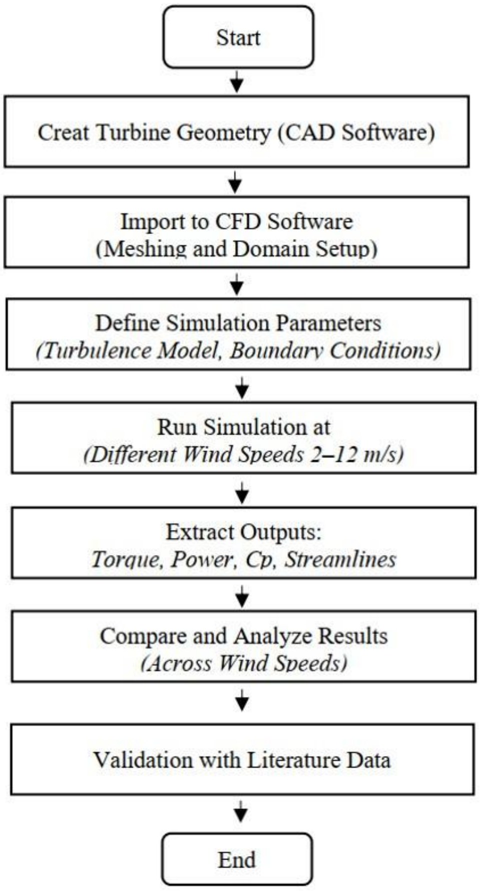


Figure 1. Flowchart of the CFD-Based Research Methodology for the Simulation of a Vertical Axis Wind Turbine (VAWT).

3. Result and Discussion

This section presents the key findings obtained from the Computational Fluid Dynamics (CFD) simulations conducted on a Vertical Axis Wind Turbine (VAWT) under various wind-speed conditions. The evaluation focuses on three primary performance parameters: torque, mechanical power output, and power coefficient (Cp). The results are displayed through graphical visualizations and streamline plots, followed by a critical discussion that contextualizes the findings within the framework of existing scientific literature (Olowe et al., 2024; Rahman et al., 2025).

3.1. Effect of Wind Speed on Power Output and Efficiency

Numerical simulations were performed at wind-speed levels of 2, 4, 6, 8, 10, and 12 meters per second. The mechanical power generated exhibited a nonlinear upward trend with increasing wind speed, consistent with the theoretical relationship that wind power is proportional to the cube of wind speed ($P \propto v^3$). A summary of the computed torque, power output, and power coefficient (Cp) for each wind-speed condition is presented in Table 1.

Table 1. Performance of the Vertical Axis Wind Turbine (VAWT) at Various Wind Speeds (Simulation Results)?

Kecepatan (m/s)	Torsi (Nm)	Daya Keluaran (W)	Koefisien Daya (Cp)
2	0,04	1,2	0,078
4	0,22	6,6	0,115
6	0,63	18,9	0,148
8	1,10	33,0	0,181
10	1,62	48,6	0,189
12	2,10	63,0	0,182

The power coefficient (Cp) exhibited a consistent increase as wind speed increased, reaching its peak value of 0.189 at a wind speed of 10 m/s. Beyond this point—specifically at 12 m/s—a slight decrease in Cp was observed. This pattern aligns with the findings reported by Karimian and Abdolahifar (2020), who noted that Darrieus-type vertical axis wind turbines typically achieve their highest aerodynamic efficiency at moderate wind speeds, after which the performance declines due to intensified wake formation and flow-separation effects.

Figure 1. Power Coefficient (Cp) as a Function of Wind Speed

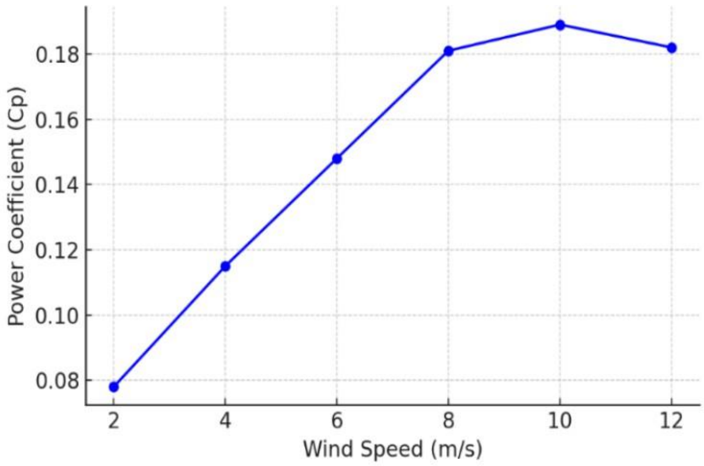
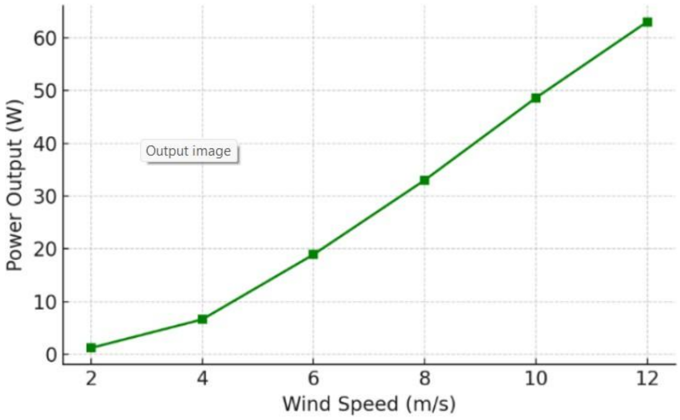


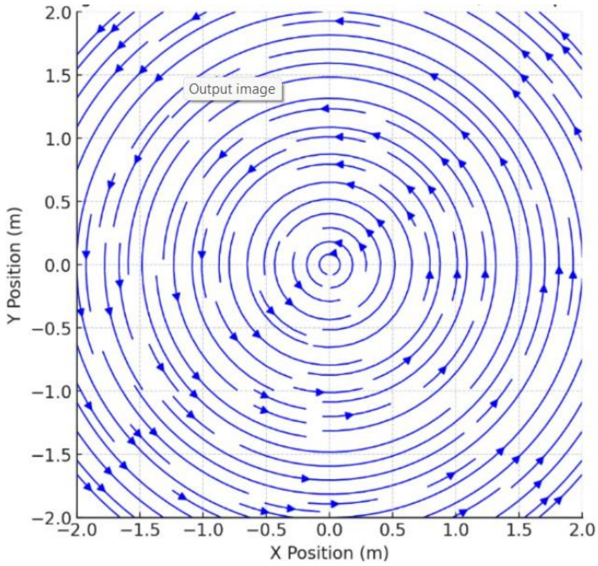
Figure 2. Power Output as a Function of Wind Speed



3.2. Streamline Visualization and Flow Behavior

To gain a deeper understanding of the aerodynamic performance of the turbine, an analysis of the streamline contours was conducted at various wind-speed conditions (Firoozi et al., 2024; Ke et al., 2022). This visualization serves as a qualitative indicator of key flow phenomena, including boundary-layer separation, vortex formation, and wake development (Yang et al., 2023; Shi et al., 2023)

Figure 3. Streamline Visualization of the VAWT at a Wind Speed of 10 m/s



At a wind speed of 10 m/s, the airflow on the upstream side of the rotor appears well-structured and largely laminar, indicating an efficient aerodynamic interaction between the incoming wind and the turbine blades. In contrast, a significant wake effect is observed on the downstream side, characterized by vortex shedding and increased turbulence, particularly near the blade's trailing region. These disturbances are consistent with the reduction in Cp recorded at a wind speed of 12 m/s, where flow instability leads to a decline in overall aerodynamic effectiveness.

Similar aerodynamic behavior was also documented by Li et al. (2016), who identified the development of asymmetric wake structures and blade-tip vortex phenomena in their three-dimensional CFD investigation of straight-bladed VAWTs. Such turbulent characteristics not only diminish power extraction but may also generate unsteady aerodynamic forces on the rotor, potentially affecting structural reliability (Li et al., 2022; Wei & Dabiri, 2023).

3.3. Comparison with Previous Studies

The performance pattern observed in this research is highly consistent with findings reported in earlier studies. For example, Watanabe et al. (2023) demonstrated that small-scale Vertical Axis Wind Turbines equipped with blade-performance enhancement components were capable of achieving Cp values ranging from 0.17 to 0.21. Likewise, Gao et al. (2022) noted that although aerodynamic refinement can increase Cp, the improvement remains effective only up to a certain wind-speed threshold—beyond which unstable flow phenomena begin to diminish turbine efficiency. The simulation results obtained in the present study fall within the performance range established by the literature, thereby reinforcing the conclusion that moderate wind speeds—approximately 10 m/s—represent the most optimal operating condition for VAWTs (Davis et al., 2022). At higher wind speeds, the benefits of increased kinetic energy progressively diminish due to the intensification of aerodynamic losses (Song et al., 2025; Zhang et al., 2025). This highlights the importance of carefully optimized blade design and thorough assessment of local wind conditions when planning turbine installations (Lakdhar et al., 2025; Li et al., 2025).

4. Conclusion

This study investigated how variations in wind speed influence the aerodynamic efficiency of a Vertical Axis Wind Turbine (VAWT) using a Computational Fluid Dynamics (CFD) approach. The key performance indicators analyzed included torque, mechanical power output, and the power coefficient (Cp), across a wind-speed range of 2 m/s to 12 m/s. The simulation results revealed a nonlinear growth in torque and power output as wind speed increased, which is consistent with the theoretical cubic relationship between wind power and wind speed ($P \propto v^3$). Meanwhile, the Cp value increased gradually and reached a peak of 0.189 at a wind speed of 10 m/s, before showing a slight decline at 12 m/s—likely attributable to intensified turbulence and wake formation in the downstream region of the rotor. The streamline visualizations reinforced these findings by clearly depicting flow separation and vortex formation at higher wind speeds, both of which are known contributors to reduced aerodynamic efficiency. Collectively, the results suggest that the optimal performance range of the turbine lies around 10 m/s. This conclusion aligns well with previous literature and provides meaningful insights for refining VAWT design and planning installation strategies that account for local wind conditions. For future research, it is recommended to focus on structural load assessment, real-time (transient) flow modeling, or blade-shape optimization to further enhance turbine performance under more complex environmental scenarios.

Author Contributions

The author conceptualized the research framework and defined the scope of the study. The turbine model and computational domain were designed and developed, followed by the configuration of the numerical setup and boundary conditions for CFD simulation. The author conducted the simulations, extracted and processed the performance data, and carried out the visualization and interpretation of the results. The manuscript was written and revised by the author, including the integration of relevant literature and the development of the discussion and conclusions.

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Declaration of Conflicting Interests

The author affirms that the research was conducted with full academic independence, without any influence from external parties that could compromise the integrity of the study. Throughout the entire process beginning from the conceptual development, computational simulation, data interpretation, and manuscript preparation the author did not receive financial, commercial, institutional, or personal benefits that could be perceived as a source of conflict. Accordingly, the author confirms that there are no competing interests that could have affected the objectivity, validity, or presentation of the findings reported in this article.

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