

AERODYNAMIC CHARACTERIZATION OF A HELICAL DARRIEUS-TYPE VERTICAL WIND TURBINE USING CFD SIMULATION

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Abstract- This research conducts a comprehensive computational evaluation of the aerodynamic behavior of a three-blade helical Vertical Axis Wind Turbine (VAWT) of the Darrieus type. Using geometric modeling in SolidWorks and CFD simulations in ANSYS CFX, the turbine's behavior was evaluated under Wind Speeds (WSs) of 2, 4, and 8 m/s. Special attention was given to the influence of the Tip Speed Ratio (TSR), Power Coefficient (C_p), torque, angular velocity, and pressure distribution. The blade geometry was designed using symmetric airfoils similar to the NACA 0012 profile, widely used in vertical turbines due to their low drag coefficient and aerodynamic stability. The results obtained show representative values for power output, torque, angular velocity, and C_p , validating the methodology implemented for energy quantification in distributed generation applications. Furthermore, the study highlights the usefulness of Computational Fluid Dynamics (CFD) modeling as a predictive tool in the design for the development and improvement of wind turbines intended for urban settings, where airflow patterns tend to be irregular and constantly changing.

Keywords: Computational Fluid Dynamic, Wind Turbine, Rigid Body, Simulation, Power Coefficient.

1. INTRODUCTION

H-type Darrieus turbines represent an evolution of the traditional curved-blade design of VAWTs, preserving key advantages such as omnidirectional operation and reduced visual impact, while enhancing structural robustness through the use of straight, symmetric blades. A notable variant within this category is the helical configuration, in which the blades are twisted along their longitudinal axis. This design enables a more uniform torque distribution, reduces mechanical vibrations, and improves wind capture under turbulent flow conditions. These characteristics have contributed to the growing popularity of helical

VAWTs in small-scale residential and industrial applications, where their simple construction, smoother operation, and ease of integration in confined or variable-wind environments offer significant advantages [1, 2].

The increasing demand for sustainable energy solutions in urban environments has boosted interest in VAWTs suitable for rooftop installation. Studies such as He et al. [3] and Rezaeiha, et al. [4] highlight the efficiency of these configurations under irregular wind conditions. Additionally, Ciuperca [5] demonstrates that helical rooftop configurations yield better energy capture at low speeds, supporting their implementation on buildings such as the parking lot rooftop of the Autonomous University of the Caribbean.

The installation of a VAWT on the rooftop of the Autonomous University of the Caribbean presents an innovative and sustainable approach to diversifying the institution's energy matrix. This prefeasibility study aims to assess the technical conditions necessary to harness the available wind resources in the urban area of Barranquilla, with the goal of powering low-consumption systems such as the parking gate barriers and other auxiliary functions. VAWTs are particularly well-suited for urban environments due to their ability to operate efficiently in turbulent, low-speed wind conditions, as well as their compact and quiet design. This initiative would not only contribute to reducing the university's carbon footprint but also serve as an educational and research model to promote awareness and adoption of renewable energy within the academic community.

The NACA 0012 airfoil, employed in this study, is one of the most widely used profiles in H-type VAWT blade design due to its symmetrical shape, favorable aerodynamic performance at negative angles of attack, and ease of manufacturing. The use of symmetric blades also minimizes torsional moments on the turbine shaft, allowing for lighter structures with fewer moving parts,

which in turn reduces maintenance requirements and improves overall system reliability [6, 7]. Compared to asymmetric profiles such as the NACA 4412, the NACA 0012 provides greater structural stability and easier manufacturing [8, 9].

The implementation of CFD simulations in the analysis of these VAWTs provides a powerful tool for predicting aerodynamic behavior under realistic operating conditions. Through CFD, key performance parameters such as the C_p , TSR, and flow distribution can be evaluated without the need for physical prototypes. This approach has been validated in numerous studies and is increasingly recognized as a cost-effective and accessible methodology for the development of decentralized energy technologies, particularly in urban or complex terrain settings where wind conditions are highly variable [10, 11].

Magnetic levitation systems have been proposed for VAWTs to reduce friction and allow operation at lower wind speeds, improving durability and efficiency in urban settings [12]. Recent research emphasizes structural optimization for VAWTs, using lightweight materials and innovative supports to enhance reliability and reduce maintenance [13]. CFD-based design and optimization remain key for VAWTs, enabling accurate aerodynamic predictions and cost-effective development without physical prototypes [14]. The main objective of this research is to establish a methodology for simulating VAWTs by comparing the lift and drag coefficients of well-known NACA airfoils and applying CFD-based modeling. This approach aims to predict the aerodynamic behavior and determine the C_p as a function of the turbine's TSR, providing a reliable framework for performance evaluation and design optimization.

2. PREPROCESSING SIMULATION

2.1. Geometric Design of the Turbine

The turbine model was developed using SolidWorks, structured around a VAWT design featuring three helical blades in an H-type configuration. The turbine features a total height of 1210 mm and a diameter of 830 mm, resulting in an approximate swept area of $A \approx 1 \text{ m}^2$. The design incorporates three helical blades symmetrically distributed at 120° intervals around the vertical axis, as illustrated in Figure 1.

To ensure structural integrity and facilitate integration with an electric generator, the distance between the upper and lower support disks was carefully defined. Each disk is connected to the blades via three rigid support arms, providing enhanced stability and minimizing deformation under operational loads. The central shaft was designed with bearing supports at both ends to reduce friction and mechanical wear, while the blade tips were connected using straight, rigid arms to maintain alignment and structural efficiency. Figure 2 presents an analysis of the lift coefficient (C_l) behavior in relation to the drag coefficient (C_d), both of which are widely used in the aerodynamic evaluation of VAWTs.

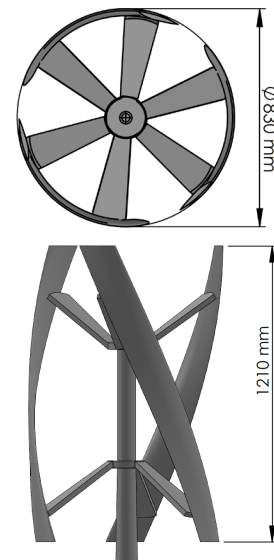


Figure 1. Turbine dimensions

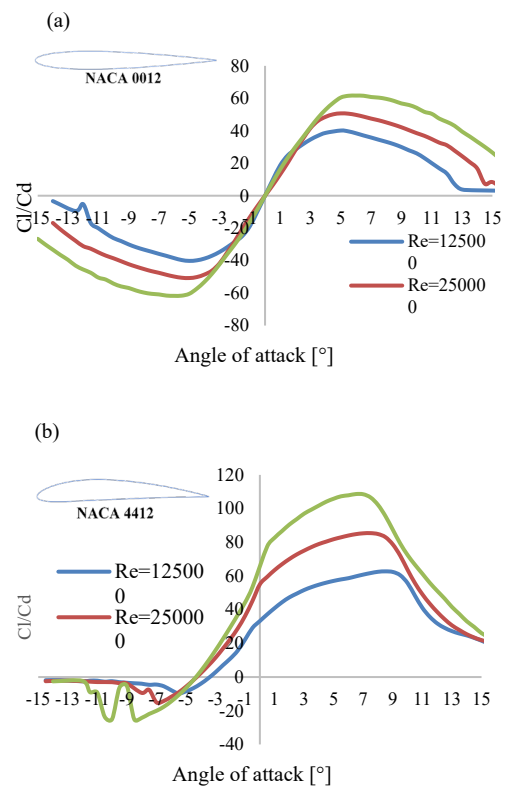


Figure 2. C_l/C_d NACA profile, a) NACA 0012, b) NACA 4412

The C_l/C_m comparison in Figure 2 indicates that the NACA 4412 airfoil demonstrates a more efficient utilization of lift forces compared to the NACA 0012. The angles of attack that yield optimal lift performance range from -3° to 7° for the NACA 4412, with 7° being the most favorable. For the NACA 0012, the optimal range is between 0° and 5° , with 5° being the most recommended. Due to its symmetrical geometry, the NACA 0012 exhibits similar performance for negative angles of attack, which suggests it can more effectively harness wind energy during its rotational motion around a typical vertical-axis of VAWT operation.

Additionally, in the Figure 3, the moment coefficient (C_m) analysis reveals that the NACA 4412 exhibits higher values in the negative Y -axis, indicating significant instability for VAWT applications. In contrast, the NACA 0012 shows greater stability, with C_m values remaining closer to zero across varying angles of attack. This characteristic is particularly relevant, as the symmetrical design of the NACA 0012 simplifies both its manufacturing and installation processes, making it a more practical choice for VAWT systems [15, 16].

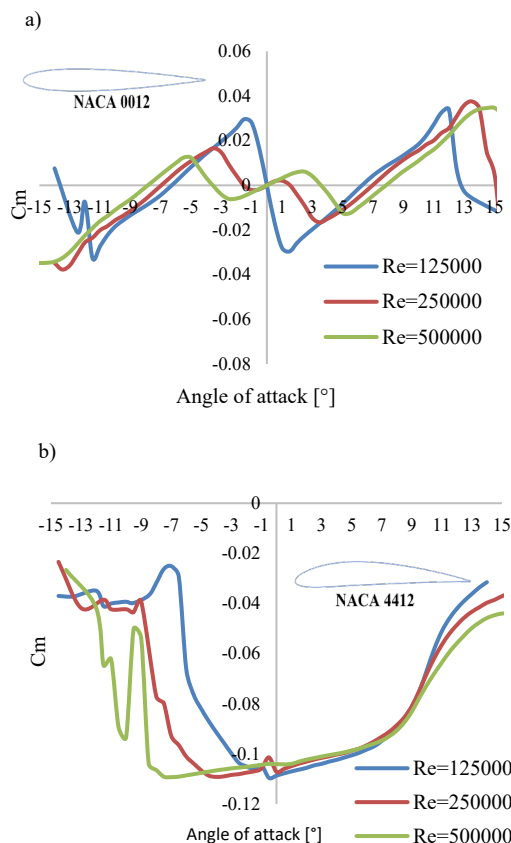


Figure 3. C_m NACA profile, a) NACA 0012, b) NACA 4412

This configuration aims to maximize structural efficiency without compromising the airflow efficiency characteristics of the system. The distribution of the blades was oriented to maintain a perpendicular angle of incidence relative to the incoming wind, in accordance with the lift-based operating principal characteristic of Darrius turbines [17]. Once the CAD model was finalized, it was exported to the ANSYS environment to proceed with the preprocessing stage for CFD simulation.

2.2. CFD Simulation Setup and Volumetric Meshing

The numerical simulation was conducted using ANSYS CFX, with the turbine model imported directly from SolidWorks. An unstructured tetrahedral mesh was generated, with refinement prioritized in the rotor region to accurately capture the effects of turbulent flow around the blades. The computational domain was divided into two main regions: an internal rotating subdomain containing the rotor, and an external stationary domain

representing the surrounding fluid environment. The interface between these regions was defined using a rotating frame of reference model, which allows for the simulation of rotational effects without requiring a dynamic mesh. The boundary conditions applied to the simulation are illustrated in Figure 4.

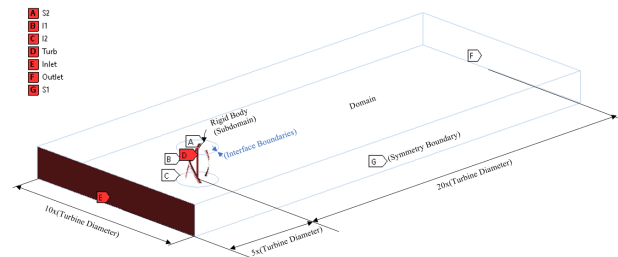


Figure 4. Boundary conditions

The computational domain was sized to ensure accurate aerodynamic predictions and minimize boundary effects. As shown in Figure 4, the inlet and outlet were placed at 10x Turbine Diameter and 20x Turbine Diameter from the rotor, with lateral boundaries at 5x Turbine Diameter. These distances follow established guidelines that keep C_p variation below 1%, supporting mesh-independent results [18,19]. Symmetry conditions were applied to reduce computational cost, and interface boundaries coupled the rotating and stationary regions. This setup guarantees proper flow development and prevents artificial blockage, providing reliable C_p -TSR curves under high-quality simulation standards.

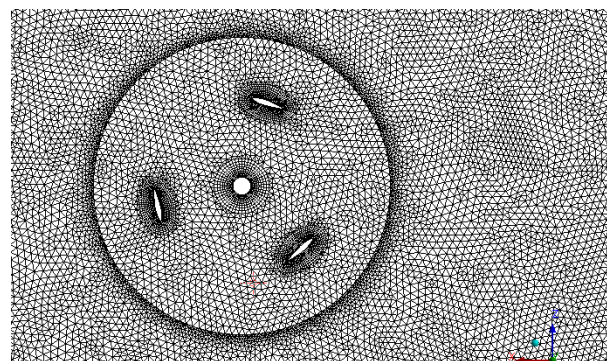


Figure 5. Detailed turbine meshing

The global mesh employed a hybrid approach: structured hexahedral cells were used in the far-field region of the control domain, while unstructured tetrahedral cells were applied near the rotor, where flow behavior is more complex. This configuration enabled more precise resolution of boundary layers along the blade surfaces and better capture of velocity gradients in the wake region. Figure 5 shows the detailed turbine meshing.

To ensure reliable aerodynamic predictions, a mesh sensitivity analysis was conducted by progressively refining the grid, increasing both element count and quality. The results showed that doubling the node density produced variations in the C_p below 3%, which meets standard criteria for mesh independence in wind turbine CFD studies. According to Rezaeiha et al. [4] and Wang et

al. [20], deviations under 5% are considered acceptable; therefore, the achieved stability confirms that the selected mesh provides accurate and consistent results without unnecessary computational cost.

Regarding the simulation setup, the following boundary conditions were applied:

- Inlet: Constant WS for 2, 4, and 8 m/s.
- Outlet: Ambient pressure (1 atm = 101325 Pa) and temperature of 300 K.
- Lateral boundaries: Symmetry condition.
- Rotor walls: Smooth surfaces with a no-slip condition.
- Initial condition: Unsteady (transient) flow, with torque and angular velocity monitored throughout the simulation.
- 20 boundary layers on the turbine blade walls

The simulation was carried out as a transient analysis with a time step of 0.01 seconds. Torque and angular velocity were monitored for each WS scenario, enabling a dynamic assessment of the turbine’s rotational behavior. Air was modeled as an incompressible, isothermal fluid with a standard density of 1.293 kg/m³. The estimated Reynolds number for the test conditions ranged from 1.2×10⁵ to 5×10⁵, which is appropriate for analyzing flow behavior in the transitional to turbulent regime. The *k-ω* turbulence governing model based on shear stress transport was employed due to its superior performance in predicting flow separation and handling pressure gradients near curved surfaces, offering greater accuracy than the traditional *k-ε* model for this type of geometry [21].

3. RESULTS AND DISCUSSION

3.1. Flow Behavior Around the Turbine

The velocity contours obtained from ANSYS CFX for the three inlet conditions illustrate how the airflow accelerates as it passes between the helical blades, generating low-pressure zones on the leading surfaces. This pressure distribution is responsible for inducing the lift force that drives the rotational motion of the rotor. Figures 6a through 6c show a progressive increase in flow magnitude as WS rises, resulting in stronger pressure gradients and improved aerodynamic efficiency under moderate wind conditions. At these speeds, the Reynolds number is sufficiently high to activate effective lift mechanisms without triggering premature flow separation. Additionally, the NACA 0012 airfoil demonstrates optimal performance within mid-range angles of attack and wind velocities, which aligns well with the simulated environment. At lower WSs, the flow lacks sufficient energy to maintain a stable aerodynamic envelope, while at higher speeds, dynamic stall and flow separation effects begin to limit performance [22].

3.2. Torque Behavior

The torque vs. time graphs for each wind condition exhibit the typical oscillatory pattern of vertical axis turbines, caused by periodic variations in the angle of attack as the rotor spins (Figure 7).

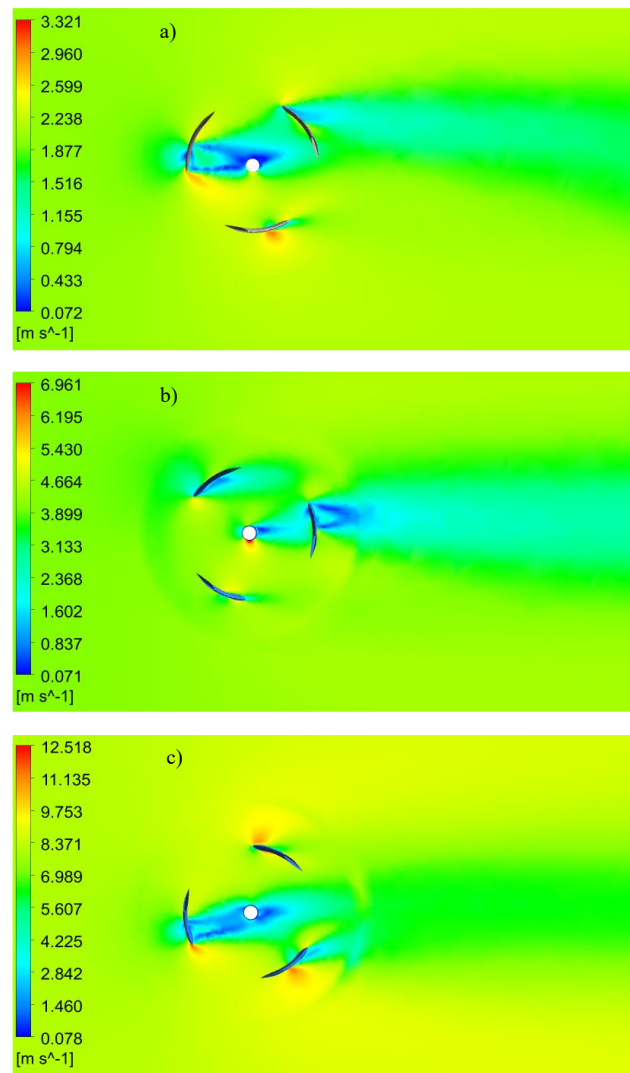


Figure 6. Velocity profile in m/s at: a) 2, b) 4, c) 8

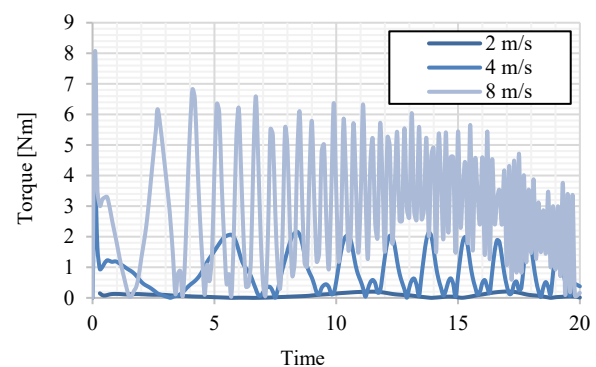


Figure 7. Simulated torque behavior

At an average WS in the range of 2 m/s, the average torque is approximately 0.021 Nm. This value increases significantly to 0.87 Nm at 4 m/s, and reaches 2.91 Nm at 8 m/s, although the latter is influenced by aerodynamic stall and flow separation effects. These results are illustrated in Figure 7.

3.3. Angular Velocity of the Turbine

The angular velocity graphs reveal a stabilization trend after the initial 20 seconds of simulation. The turbine reaches an average angular velocity of 7.88 rad/s at 2 m/s, 16.05 rad/s at 4 m/s, and 36.9 rad/s at 8 m/s, demonstrating a proportional response to increasing wind resource availability. Figure 8 shows the simulated angular velocity behavior.

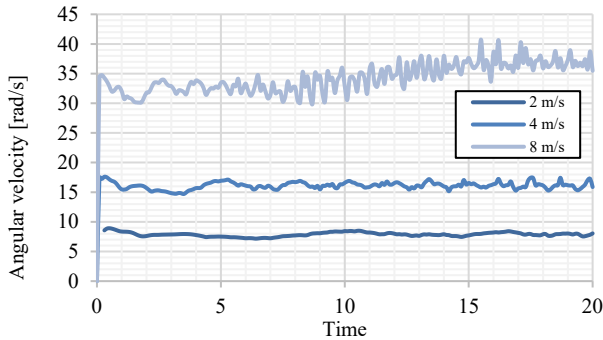


Figure 8. Simulated angular velocity behavior

3.4. Power Output of the Turbine

The following Equation (1) was used to estimate the effective power obtained (P):

$$P = T \cdot \omega \quad (1)$$

where, T is the average torque in Nm and ω is the average angular velocity in rad/s. The resulting power ranged from 0.2 W at 2 m/s reaching a maximum of 108.5 W at 10 m/s, as shown in Figure 9.

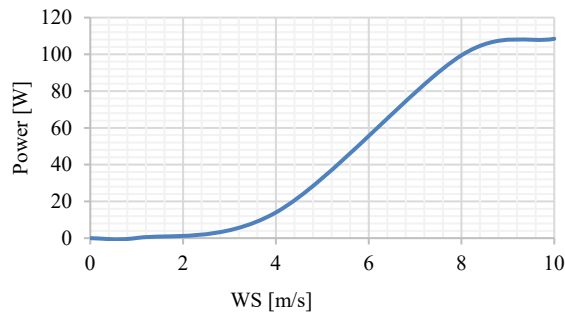


Figure 9. Power generated vs WS

3.5. Obtaining C_p and TSR

To assess the turbine's aerodynamic efficiency, the C_p was determined using the following expression:

$$C_p = \frac{P}{\frac{1}{2} \rho A v^3} \quad (2)$$

where, the air density $\rho = 1.225 \text{ kg/m}^3$, the WS is v , and $A = 1.00286 \text{ m}^2$. The TSR was also computed as:

$$TSR = \frac{\omega r}{v} \quad (3)$$

where, $r = 0.41456 \text{ m}$ is the turbine radius. The C_p values reached a maximum of 0.13 at 1 m/s and increased progressively with WS, peaking at 0.346 at 4 m/s. The relationship between C_p and TSR is illustrated in Figure 10. This confirms a steady improvement in efficiency within the studied WS range.

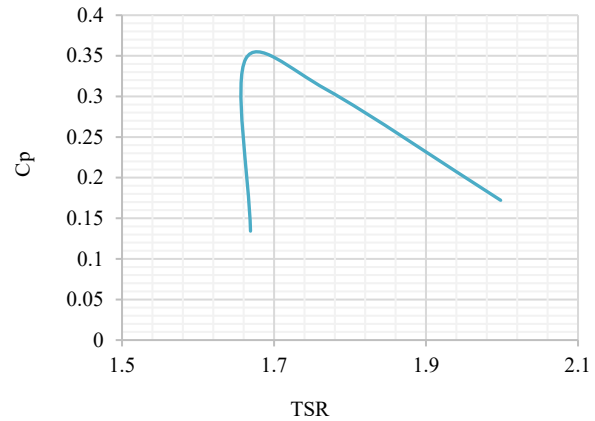


Figure 10. C_p vs TSR

The maximum $C_p = 0.346$ at 4 m/s falls within the range reported by Rezaeiha, et al. [4], who simulated a helical VAWT reaching C_p values near 0.35 under comparable conditions [19]. Similarly, Lanzafame, et al. [23] documented C_p values for similar configurations. These results support the validity of our CFD approach.

4. CONCLUSIONS

This study effectively confirmed the aerodynamic characteristics of a helical blade VAWT using CFD simulations, providing valuable insights into its performance under various WS regimes. The main findings are summarized as follows:

- The helical H-type geometry promotes a more stable torque distribution, particularly at 8 m/s, where an average torque of 2.91 Nm was achieved-significantly higher than the values observed at 2 and 4 m/s.
- The C_p reached a maximum of 0.346 at 4 m/s, representing the highest efficiency within the studied WS range. The corresponding useful power output peaked at 99.5 W, which is characteristic of lightweight turbines designed for low-scale energy applications.
- The TSR remained within the range of 1.66 to 2.01, aligning with expected values for this type of geometry and highlighting the importance of adapting the drivetrain to variable operating conditions.
- The CFD methodology proved to be reliable, as evidenced by the consistency of the results and the realistic physical behavior observed in the simulations. This establishes a solid foundation for future optimization studies, whether through the variation of airfoil profiles or the integration of active control mechanisms.
- Furthermore, the selection of the NACA 0012 airfoil contributed to ensuring dynamic stability of the rotor, providing predictable behavior under varying urban wind conditions. Its symmetric geometry also facilitates manufacturing and installation. In future work, a comparative experimental analysis is proposed in the rooftop setting of the Autonomous University of the Caribbean, where long-term wind data is available from the on-site meteorological station.

NOMENCLATURES

1. Acronyms

CFD	Computational Fluid Dynamics
TSR	Tip Speed Ratio
VAWT	Vertical Axis Wind Turbine
WS	Wind Speed

2. Symbols / Parameters

A :	Swept area
C_p :	Power coefficient
C_l :	Lift coefficient
C_d :	Drag coefficient
C_m :	Moment coefficient
P :	Power obtained
T :	Torque
ω :	Angular velocity
ρ :	Density
r :	The turbine radius
v :	wind speed

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