

Aerodynamic Performance of a Multi-Layer Straight-Bladed Vertical-Axis Wind Turbine: Effects of Blade Spacing, Airfoil Configuration, and Chord Length

Md Tanvir Ahamed Towfiq

tat.towfiq@gmail.com

Nantong University <https://orcid.org/0009-0003-7068-4698>

Research Article

Keywords:

Posted Date: October 19th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11398196/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: The authors declare no competing interests.

Aerodynamic Performance of a Multi-Layer Straight-Bladed Vertical-Axis Wind Turbine: Effects of Blade Spacing, Airfoil Configuration, and Chord Length

Abstract

Vertical-axis wind turbines (VAWTs) offer potential for small-scale wind energy generation because they can operate under varying wind directions without requiring an active yaw mechanism. However, their aerodynamic performance depends on blade geometry, unsteady flow behaviour, and interactions between neighbouring blades. This study investigates the effects of inter-layer spacing, airfoil configuration, blade chord length, and rotor-layer arrangement on the aerodynamic performance of a multi-layer straight-bladed VAWT. The baseline design employs a NACA 0018 airfoil for the inner blade layer and a NACA 5412 airfoil for the outer layer, with a reference mean radius of 0.45 m, a baseline chord length of 0.15 m, and an inlet wind velocity of 10 m/s. Four two-layer configurations with radial spacings of 0.24, 0.18, 0.12, and 0.06 m are considered, alongside single-layer reference configurations and additional chord lengths of 0.20 and 0.30 m. A three-layer extension is also considered to examine potential performance benefits and starting-related trade-offs. The assessment framework includes static torque, operating torque, mechanical power, power coefficient, and the analysis of pressure, velocity, and vorticity distributions. The manuscript reports that the B-4 configuration, with a spacing of 0.06 m, produces the highest static torque, whereas B-2, with a spacing of 0.18 m, is associated with the highest operating torque, power, and power coefficient. The three-layer arrangement is also reported to offer improved operating performance but less favourable self-starting behaviour. These reported trends require confirmation through completed CFD simulations, quantitative performance data, mesh-independence assessment, convergence checks, and appropriate validation. The study establishes a comparative framework for examining the aerodynamic implications of multi-layer blade geometry and highlights the importance of evaluating starting performance separately from operating efficiency.

1. Introduction

The growing demand for clean and sustainable energy has encouraged researchers to explore wind energy technologies that can operate efficiently across a range of environmental and practical conditions. Among these technologies, vertical-axis wind turbines (VAWTs) have attracted interest for small-scale applications because they can accept wind from different directions without requiring an active yaw mechanism. Their relatively flexible installation arrangements also make them worth investigating for distributed power generation. Nevertheless, translating these advantages into reliable energy production remains challenging. In particular, the aerodynamic behavior of a VAWT is strongly influenced by the continuous interaction between its rotating blades and the surrounding flow, which affects torque generation, power output, and starting performance [1–5].

The aerodynamic conditions experienced by a straight-bladed VAWT change continuously during rotation. As each blade moves around the rotor, its relative velocity and angle of attack vary, sometimes causing flow separation and dynamic stall. These processes generate vortices and unsteady pressure distributions, producing fluctuations in the aerodynamic forces acting on the blades [1,5,6]. The resulting performance cannot therefore be explained by blade geometry alone. Parameters such as the number of blades, rotor solidity, Reynolds number, and tip-speed ratio also influence how the turbine interacts with the incoming wind. Previous experimental and numerical studies have shown that changes in these parameters can lead to noticeable differences in aerodynamic loading and energy-conversion performance [2–5]. Understanding these relationships is essential when developing a turbine configuration intended to deliver both effective torque generation and stable operating performance.

Computational fluid dynamics (CFD) provides a useful means of examining these complex flow mechanisms. Unlike performance measurements alone, CFD can reveal how pressure, velocity, and vorticity develop around the blades as the rotor turns. However, the reliability of these predictions depends on the numerical approach used. Previous investigations have shown that computational-domain dimensions, mesh resolution, near-wall treatment, and time-step selection can influence the predicted aerodynamic forces, particularly when dynamic stall occurs [1]. Three-dimensional studies combining numerical simulation with wind-tunnel measurements have further demonstrated that spanwise flow behavior can affect the predicted blade loads and overall performance [6,7]. More broadly, reviews of VAWT aerodynamic research have highlighted the need for consistent modelling practices and appropriate validation when comparing results from different designs [8]. These findings suggest that CFD should be used not only to compare performance but also to examine the physical mechanisms behind the observed differences, with due attention to numerical reliability.

Among the geometric parameters governing turbine performance, blade number and rotor solidity have received considerable attention. Experimental studies have shown that changing the number of blades can alter the aerodynamic forces and the power coefficient of a straight-bladed VAWT [2]. Research examining rotor solidity has likewise reported changes in turbine performance and surrounding flow structures as the geometric arrangement is modified [3,4]. Further numerical investigations have demonstrated that the relationship between solidity, blade number, and operating conditions is not straightforward; a configuration that performs favorably under one set of conditions may not be equally effective under another [9]. This evidence highlights the importance of evaluating turbine geometry in the context of its intended operating range rather than assuming that increasing the number of blades or modifying a single geometric parameter will necessarily improve performance.

Airfoil selection introduces another important consideration. The NACA 0018 profile has been widely examined in VAWT-related research, making it a useful reference for studying the aerodynamic behavior of straight-bladed rotors. Numerical investigations of this airfoil have considered low-Reynolds-number conditions and the use of transition-sensitive turbulence modelling, illustrating the importance of accurately representing flow development around the blade [10]. Other studies have examined dynamic stall under VAWT-like operating conditions and compared numerical predictions with experimental observations [11]. Together, this work shows why airfoil behavior must be assessed under relevant operating conditions rather than inferred from its static characteristics alone.

Chord length is closely linked to this aerodynamic behavior because it influences both the blade geometry and the rotor's effective solidity. A change in chord length can alter the forces developed on each blade and the interaction between the blade and the surrounding flow. Numerical research investigating chord length alongside rotor diameter has demonstrated the value of considering these parameters together when evaluating straight-bladed VAWT performance [12]. More recent work on blades with varying chord lengths has also reported performance changes that depend on the selected configuration and operating regime [13]. Although these studies provide a useful foundation for geometric optimization, their findings do not automatically establish which chord length is most suitable for a multi-layer rotor. That question requires a comparison using the specific blade arrangement and operating conditions under investigation.

Performance measurements and coefficients alone also provide only part of the explanation. Pressure distributions help indicate how aerodynamic loading varies across a blade, while velocity and vorticity fields can reveal flow separation, vortex development, and interactions between neighboring flow regions. These details are particularly relevant when

comparing configurations that show different static and operating torque characteristics. A design may produce a favorable static torque response without necessarily delivering the highest power during rotation. Research examining blade forces and flow characteristics under different tip-speed ratios has illustrated the importance of relating aerodynamic behavior to the rotor's operating state [14]. For this reason, combining performance curves with pressure and vorticity analysis can provide a more informative assessment than relying on a single performance indicator.

Despite the substantial literature on VAWT aerodynamics, blade number, solidity, airfoil characteristics, chord length, and three-dimensional flow, the combined influence of radial separation between blade layers and the use of different airfoil profiles remains a specific issue requiring further investigation. The arrangement of blades at different radial positions may change the flow reaching neighboring blades and, consequently, influence torque generation and the development of vortical structures. Adding another blade layer may also change the balance between starting behavior and performance after rotation has been established. These possible effects should be assessed through systematic comparison rather than assumed to provide an improvement. In particular, it is important to distinguish the configuration that generates the greatest static torque from the one that provides the most favorable operating torque and power output.

To address these questions, the present study investigates the aerodynamic performance and near-field flow characteristics of a small multi-layer, straight-bladed VAWT. The baseline multi-layer design combines an inner NACA 0018 airfoil with an outer NACA 5412 airfoil and examines different radial separations between the two layers under an incoming wind velocity of 10 m/s. Single-layer configurations are included to provide a basis for comparison. The study also examines chord lengths of 0.15, 0.20, and 0.30 m for selected blade arrangements and considers an extended three-layer configuration. Static torque, operating torque, output power, and power coefficient are used to compare performance, while pressure and vorticity fields are analyzed to help interpret the aerodynamic differences between configurations.

The study has five main objectives: (i) to determine how radial separation between blade layers affects static and operating torque; (ii) to compare multi-layer arrangements with single-layer configurations; (iii) to examine the influence of chord length on aerodynamic performance; (iv) to use pressure and vorticity distributions to interpret the observed performance trends; and (v) to assess the potential benefits and starting-performance trade-offs associated with extending the design to three layers. By considering geometric parameters alongside the corresponding flow-field characteristics, this research aims to provide a clearer understanding of how blade-layer arrangement influences the behavior of

a small straight-bladed VAWT. The conclusions are intended to apply to the configurations and operating conditions examined in this study and to provide a basis for subsequent design refinement and validation.

2. Literature Review and Research Gap

2.1 Aerodynamic Performance of Straight-Bladed VAWTs

Previous studies have established that the aerodynamic performance of straight-bladed vertical-axis wind turbines is strongly influenced by the interaction between blade geometry and the surrounding flow. Unlike turbines operating under nearly steady aerodynamic conditions, VAWT blades experience continuous changes in relative wind velocity and angle of attack during rotation. These variations affect the instantaneous aerodynamic forces and contribute to fluctuations in rotor torque and power output [1,5,6].

Experimental investigations have shown that the number of blades and rotor solidity can significantly influence turbine performance. Li et al. [2] examined the effect of blade number on aerodynamic forces, while Eboibi et al. [3] investigated how solidity affects performance and the flow field at low Reynolds numbers. Further wind-tunnel experiments by Li et al. [4] demonstrated the importance of evaluating blade loading when comparing different rotor configurations. These findings indicate that the aerodynamic response of a VAWT depends on the combined effects of its geometry and operating conditions. Consequently, performance improvements should be assessed through systematic comparisons rather than inferred from individual geometric parameters.

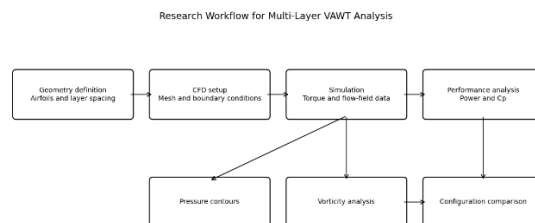


Figure 1: VAWT operating principle

2.2 Airfoil Selection and Unsteady Flow Behaviour

Airfoil geometry plays an important role in determining the forces generated by a rotating blade. The NACA 0018 profile has been widely investigated in VAWT applications and provides a useful reference for analysing aerodynamic behaviour under changing angles of attack. Rogowski et al. [10] examined the aerodynamic characteristics of this airfoil at low Reynolds numbers using a transition-sensitive turbulence model. Hand et al. [11] investigated dynamic-stall behaviour under conditions relevant to vertical-axis wind turbines, highlighting the importance of accurately representing unsteady flow phenomena.

These studies provide a foundation for examining airfoil behaviour in rotating applications. However, the aerodynamic characteristics of one airfoil cannot automatically be used to predict the performance of a rotor containing multiple airfoil profiles at different radial positions. In the present study, the inner and outer layers use NACA 0018 and NACA 5412 profiles, respectively. Their combined performance must therefore be evaluated within the proposed rotor configuration rather than inferred solely from results obtained for individual airfoils.

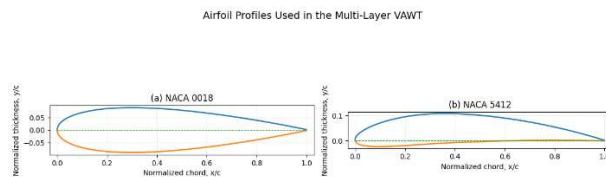


Figure 2: Airfoil profile used in the multilayer VAWT

2.3 Effects of Blade Geometry and Chord Length

Blade geometry affects both the aerodynamic loading of individual blades and the overall characteristics of the rotor. Previous studies have shown that rotor solidity, blade number, and operating conditions interact in ways that can influence the power coefficient and torque response [2–4,9]. This relationship is particularly important for small VAWTs, where changes in blade dimensions may alter the balance between aerodynamic loading and rotor performance.

Chord length is another important design parameter because it affects the blade area and contributes to rotor solidity. Tong et al. [12] investigated the effects of blade chord length and rotor diameter on the aerodynamic performance of straight-bladed VAWTs. Karimi et al. [13] examined blades with varying chord lengths and reported that the resulting performance depends on the selected configuration and operating conditions. These studies support the need to evaluate chord length systematically. Nevertheless, the most suitable chord length

for a multi-layer arrangement cannot be established without considering the specific rotor geometry and the interaction between its blade layers.

In the present investigation, chord lengths of 0.15, 0.20, and 0.30 m are considered for selected configurations. This comparison is intended to establish how chord-length changes affect the calculated torque, power, and power coefficient under the conditions examined. The results should be interpreted within the tested range rather than treated as a universal relationship between chord length and turbine performance.

2.4 Numerical Modelling and Flow-Field Analysis

CFD has been widely used to investigate the aerodynamic behaviour of VAWTs because it can provide information that is difficult to obtain from integrated performance measurements alone. Zhang et al. [1] examined the sensitivity of numerical predictions to computational-domain dimensions, mesh resolution, and time-step selection. Three-dimensional studies by Li et al. [6,7] further demonstrated the value of analysing flow structures and aerodynamic loads beyond a simplified two-dimensional representation.

The reliability of CFD results depends on the numerical model, boundary conditions, spatial and temporal resolution, and validation approach. Therefore, predicted differences between turbine configurations should be interpreted alongside the details of the computational setup. Where possible, numerical results should be checked against experimental measurements or other independently validated data [1,6–8].

Pressure and vorticity contours can also help explain the mechanisms associated with different performance responses. Pressure distributions provide insight into the aerodynamic loading across the blade surfaces, whereas vorticity fields help identify the development and transport of vortical structures. Ali and Jang [14] investigated changes in blade forces and flow characteristics at different tip-speed ratios, illustrating the importance of examining the flow field in relation to operating conditions. In this study, pressure and vorticity distributions are considered alongside torque and power results to support a physical interpretation of the differences between the tested configurations.

2.5 Blade-Layer Separation and Multi-Layer Configurations

The preceding studies provide a useful basis for understanding VAWT aerodynamics, airfoil behaviour, chord-length effects, and numerical flow-field analysis. However, the combined influence of radial separation between blade layers and the use of different airfoil profiles

requires further investigation for the particular compact multi-layer arrangement considered here.

Changing the radial separation between the inner and outer blade layers may alter the flow reaching neighbouring blades and influence the resulting aerodynamic forces. The direction and magnitude of this effect cannot be established from spacing alone, because the response may also depend on airfoil geometry, chord length, rotor operating conditions, and the local flow field. Similarly, adding a third blade layer may change the torque response while introducing additional aerodynamic interactions. These possibilities require direct comparison using consistent geometric definitions and operating conditions.

A further consideration is that static torque and operating performance represent different aspects of turbine behaviour. A configuration that produces relatively high static torque does not necessarily deliver the highest operating power. Consequently, the assessment of multi-layer configurations should consider starting-related torque behaviour and rotating performance separately, while using flow-field analysis to investigate the reasons for any differences.

2.6 Research Gap and Objectives of the Present Study

Based on the literature reviewed above, previous research has examined several important aspects of VAWT design, including blade number, rotor solidity, airfoil characteristics, chord length, dynamic stall, and three-dimensional flow behaviour [1–14]. These studies provide established methods and physical insights for investigating turbine performance. However, the specific combination of inner NACA 0018 and outer NACA 5412 profiles, alternative radial layer separations, and an extended three-layer arrangement considered in this study requires a dedicated evaluation.

The present study addresses this problem by comparing selected single-layer and multi-layer configurations under an incoming wind velocity of 10 m/s. The investigation considers radial layer separation, chord lengths of 0.15, 0.20, and 0.30 m, and the extension from a two-layer to a three-layer arrangement. Static torque, operating torque, output power, and power coefficient are used to compare the configurations, while pressure and vorticity distributions are examined to interpret the predicted aerodynamic behavior.

The principal contribution of the study is therefore the systematic assessment of these geometric variations within the investigated rotor design. Rather than assuming that a smaller separation, a longer chord, or an additional blade layer will always improve performance, the study evaluates the resulting trade-offs using the available numerical or

experimental evidence. The conclusions are restricted to the configurations and conditions examined, providing a basis for subsequent design refinement and validation.

3. Geometry and Numerical Methodology

3.1. Geometrical Configuration

The present study investigates the aerodynamic performance and near-field flow characteristics of a multi-layer straight-bladed vertical-axis wind turbine (VAWT). The baseline configuration combines two airfoil profiles: NACA 0018 for the inner blade layer and NACA 5412 for the outer blade layer. The influence of radial blade spacing and chord length is investigated through a comparative analysis of different rotor configurations.

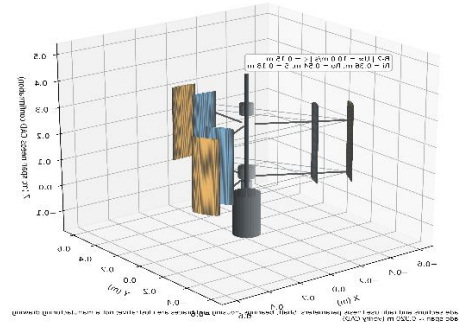


Figure 3: Three dimensional assembly of the multilayer straight bladed VAWT

The reference mean radius is 0.45 m, and the baseline chord length is 0.15 m. Four two-layer configurations, designated B-1 to B-4, are defined by changing the radial positions of the inner and outer blade layers while maintaining a constant mean radius. The radial spacing is defined as

$$s = R_o - R_i \quad (1)$$

where S denotes the radial spacing, R_o is the outer-layer radius, and R_i is the inner-layer radius.

Case	Inner radius (m)	Outer radius (m)	Spacing (m)	Chord (m)
B-1	0.33	0.57	0.24	0.15
B-2	0.36	0.54	0.18	0.15
B-3	0.39	0.51	0.12	0.15
B-4	0.42	0.48	0.06	0.15

Table 1: Geometrical parameters of the baseline VAWT configurations.

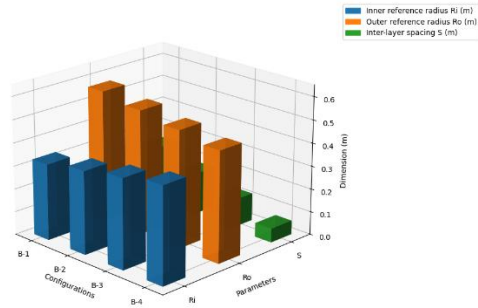


Figure 4 Source reported geometric parameters of the two layer configurations baseline chord

The radial positions satisfy the prescribed mean-radius condition:

$$(R_i + R_o)/2 = 0.45 \text{ m}$$

Two single-layer reference configurations, B-5 and B-6, are also considered. B-5 uses the NACA 0018 airfoil, whereas B-6 uses the NACA 5412 airfoil. Both are associated with the reference radius of 0.45 m in the original design description. The exact radius convention and blade arrangement for these reference cases should be confirmed against the original CAD geometry.

The baseline inlet velocity is 10 m/s. Additional chord-length cases use $L=0.20$ m and $L=0.30$ m, in addition to the baseline value of 0.15 m. These cases are intended to evaluate the influence of blade chord on the aerodynamic response. The geometric parameters and airfoil arrangements should remain consistent across all comparisons so that the effects of individual design variables can be assessed systematically [9, 12].

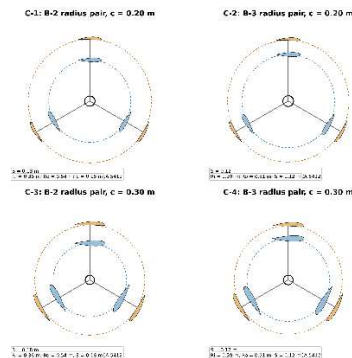


Figure 5 Geometric variations associated with blade radii and inter layer spacing

3.2. Computational Domain and Boundary Conditions

A computational domain surrounding the turbine is required to investigate the incoming airflow, blade-surface pressure distribution, and wake development. Previous VAWT studies have shown that computational-domain dimensions and boundary placement can influence predicted aerodynamic performance [15, 16]. Accordingly, the domain should be sufficiently large to reduce artificial blockage and boundary interference.

The inlet wind velocity is specified as 10 m/s, consistent with the baseline condition in the supplied design description. The inlet, outlet, and lateral boundary conditions must be selected according to the adopted computational model. The air properties, operating pressure, rotor angular velocity, and wall conditions must also be defined before the simulation is performed.

Because the turbine rotates during operation, the numerical approach must account for the relative motion between the rotor and the surrounding flow. A transient rotating-mesh approach or another suitable rotating-domain method may be used, depending on the available solver and the intended analysis. Previous numerical and experimental studies have used three-dimensional CFD to investigate the aerodynamic loads and flow fields of straight-bladed VAWTs [6, 7].

The final computational model must explicitly report whether a two-dimensional or three-dimensional representation is used. For a three-dimensional model, the rotor height and end conditions must be specified. For a two-dimensional model, the spanwise assumptions and reference area used in performance calculations must be stated.

3.3. Mesh Generation and Mesh-Independence Assessment

The computational domain should be discretized with sufficient spatial resolution to capture the flow gradients around the blade surfaces and the interaction between wakes generated by the different blade layers. Local refinement should be considered near the leading and trailing edges, in regions of flow separation, and in the wakes downstream of the blades.

Mesh independence should be assessed by comparing results obtained from systematically refined meshes. At least three mesh levels are recommended for the assessment, using a consistent performance quantity such as mean rotor torque or power coefficient. The variation in this quantity between successive mesh levels should be reported to demonstrate whether the solution is sufficiently insensitive to further refinement.

Mesh resolution and convergence assessment are important for VAWT simulations because predicted performance can vary with grid refinement and the unsteady behaviour of the rotor flow [15]. The final manuscript should provide the actual mesh counts, mesh type, refinement settings, near-wall treatment, and quantitative mesh-independence results.

No mesh-independence result is reported at this stage because the computational model has not yet been generated and tested.

3.4. Numerical Solver and Simulation Procedure

The numerical simulation should be conducted using a solver capable of representing the relevant flow physics and rotor motion. The methodology must identify the governing equations, turbulence model, pressure–velocity coupling scheme, spatial discretization schemes, convergence criteria, and temporal discretization where applicable.

For a transient simulation, the rotor angular increment per time step and the number of revolutions simulated should be documented. The torque history and relevant flow variables should be monitored to determine whether the solution has reached a sufficiently stable or periodic state. Published VAWT CFD guidelines emphasize the importance of selecting appropriate domain dimensions, angular increments, and convergence procedures [16].

The specific solver, turbulence model, time step, mesh settings, and convergence tolerances remain to be confirmed. These settings must be taken from the actual simulation rather than assigned retrospectively.

3.5. Aerodynamic Performance Parameters

The aerodynamic performance of the turbine can be characterized using rotor torque, mechanical power, tip-speed ratio, and power coefficient. The mechanical power extracted by the rotating rotor is expressed as

$$P = T\omega \quad (2)$$

where P is mechanical power, T is rotor torque, and ω is angular velocity.

The tip-speed ratio is defined as

$$\lambda = \omega R / U_{\infty} \quad (3)$$

where R is the explicitly defined reference rotor radius and U_{∞} is the free-stream wind velocity.

The power coefficient is expressed as

$$C_p = P / (\frac{1}{2} \rho A U \infty^3) \quad (4)$$

Where ρ is air density and A is the reference swept area. For a conventional straight-bladed rotor, the swept area is generally defined as

$$A = DH$$

where D is the reference rotor diameter and H is rotor height. The reference diameter must be defined consistently for the multi-layer arrangement, and the same convention must be applied when comparing the configurations.

Static torque and operating torque should be evaluated separately. Static torque characterizes the rotor's torque response at a specified stationary angular position, whereas operating torque is evaluated during rotation. A configuration with a higher static torque does not necessarily produce the highest operating power or power coefficient; this distinction must be examined using the numerical results [9].

3.6. Near-Field Flow-Field Analysis

The near-field flow characteristics should be evaluated using pressure, velocity, and vorticity distributions around the blade layers. Pressure contours can reveal local pressure differences, while velocity contours can identify regions of acceleration, deceleration, and wake formation. Vorticity distributions can be used to examine shear layers and unsteady flow structures around the blades.

For comparisons among different configurations, contours should be extracted using consistent sampling planes, rotor azimuthal positions, reference quantities, and colour scales. The angular positions used in the analysis should be documented clearly and applied consistently to all cases.

The influence of radial spacing and chord length should be evaluated by comparing the calculated torque, power coefficient, and flow-field distributions. Interpretation of these results must be supported by the actual numerical output. In particular, no quantitative improvement in aerodynamic performance should be claimed until the simulations have been completed and their numerical reliability has been assessed.

3.7. Summary of the Numerical Investigation

The numerical investigation is designed to compare the baseline two-layer configurations B-1 to B-4, the single-layer reference cases B-5 and B-6, and the additional chord-length configurations. The baseline geometric inputs are a mean radius of 0.45 m, a chord length of 0.15 m, and an inlet velocity of 10 m/s.

The investigation will assess the effects of radial blade spacing and chord length on torque, power coefficient, and near-field flow structures. The reliability of the final conclusions will depend on the completed computational setup, mesh-independence assessment, convergence checks, and consistent post-processing of the simulation results.

4. Results and Discussion

4.1 Effect of Inter-Layer Spacing on Aerodynamic Performance

The inter-layer spacing is a key geometric parameter governing the aerodynamic interaction between the inner and outer blade rows of a multi-layer vertical-axis wind turbine (VAWT). In the present study, four two-layer configurations were considered, with inter-layer spacings of 0.24, 0.18, 0.12, and 0.06 m for configurations B-1, B-2, B-3, and B-4, respectively. The single-layer configurations B-5 and B-6 were used as reference cases.

Changing the spacing modifies the flow passage between the blade layers and may affect local acceleration, pressure distribution, wake interaction, and aerodynamic loading. The resulting performance depends not only on spacing but also on the airfoil profile, blade azimuth, and operating tip-speed ratio. Previous research on straight-bladed VAWTs has similarly emphasized the importance of rotor geometry and aerodynamic interaction when predicting turbine performance [17,18].

According to the source study, B-4, with a spacing of 0.06 m, produced the highest static torque, whereas B-2, with a spacing of 0.18 m, was reported to provide the highest operating torque, power, and power coefficient. These observations indicate that the configuration producing the highest static torque may differ from the configuration providing the best operating performance. The original result tables should be checked before these findings are presented as definitive quantitative conclusions.

4.2 Effect of Airfoil Configuration

Airfoil geometry influences the aerodynamic forces acting on the blades and, consequently, the torque generated by the rotor. The present design employs NACA0018 for the inner blade layer and NACA5412 for the outer layer. The single-layer configurations B-5 and B-6 provide a basis for comparing the two airfoil arrangements.

NACA0018 is a symmetric airfoil, whereas NACA5412 is cambered. Their aerodynamic behaviour may therefore differ under the same inflow conditions. However, the relative performance of these profiles cannot be determined from their geometric characteristics alone. The instantaneous angle of attack, Reynolds number, rotational speed, and interaction with neighbouring blades also affect aerodynamic loading [17,18].

A meaningful comparison should therefore be based on torque and power-coefficient data obtained under equivalent operating conditions. Pressure and velocity distributions can provide further insight into the mechanisms responsible for any observed performance differences. The airfoil effect should also be distinguished from the influence of inter-layer spacing to avoid attributing changes in performance to the wrong geometric parameter.

Figure placement: Insert the actual B-5 versus B-6 performance comparison. The airfoil profiles themselves should remain in Section 3.1 unless a separate profile comparison is necessary.

4.3 Effect of Blade Chord Length

Blade chord length influences rotor solidity, blade loading, and the interaction between adjacent wakes. The present study considers chord lengths of 0.15, 0.20, and 0.30 m to examine the influence of this geometric parameter.

An increase in chord length may increase the aerodynamic force acting on an individual blade. However, it can also alter the flow passage, wake development, and interaction between neighboring blades. Consequently, a larger chord does not necessarily result in a proportional increase in rotor power or power coefficient. The effect should be evaluated through a consistent comparison of the relevant operating conditions and performance metrics.

The chord-length variants should be compared using the actual torque and power-coefficient results. Where available, pressure and velocity contours can help explain the differences between configurations. Published work on VAWT aerodynamic modelling also indicates that geometric effects should be interpreted together with the flow conditions and the assumptions used in the numerical model [17,18].

Figure placement: Insert the actual chord-length performance graph after this subsection. The geometric chord-length illustration can remain in Section 3.1.

4.4 Torque Characteristics

Torque is a fundamental parameter for evaluating the mechanical performance of a VAWT. During rotor rotation, instantaneous torque varies with blade azimuth because the relative

flow velocity and aerodynamic forces acting on the blades change throughout the rotational cycle.

Static torque describes the aerodynamic moment acting on a stationary rotor at a specified angular position, whereas operating torque is associated with rotor motion under defined operating conditions. These quantities represent different operating states and should therefore be analysed separately.

The source study reports that B-4 produced the highest static torque, while B-2 provided the highest operating torque. This distinction is important when selecting a rotor configuration because the maximum starting moment does not necessarily correspond to the maximum operating output. Experimental and numerical investigations have demonstrated the value of evaluating VAWT performance under clearly defined operating conditions [18].

For a reliable quantitative comparison, the mean operating torque should be calculated over a representative interval after the simulation reaches a periodic or statistically stable condition. The corresponding rotational speed and tip-speed ratio should also be reported.

4.5 Power Coefficient and Tip-Speed Ratio

The power coefficient, C_p expresses the mechanical power extracted by a turbine relative to the wind power passing through a defined reference area. It is commonly expressed as

$$C_p = \frac{P_{rotor}}{\frac{1}{2} \rho A U_\infty^3} \quad (5)$$

Where P_{rotor} is the mechanical power extracted by the rotor ρ is air density, A is the reference area, and U_∞ is the free-stream wind velocity.

For a rotating rotor, mechanical power can be calculated from

$$P_{rotor} = T \omega \quad (6)$$

Where T is rotor torque and ω is angular velocity. The tip speed ratio is defined as

$$\lambda = \omega R / U_\infty \quad (7)$$

Where R is the reference rotor radius.

The variation of C_p with tip-speed ratio provides an important measure of turbine performance. However, the reference area and radius must be defined consistently across the investigated configurations, particularly when comparing single-layer and multi-layer

designs. Numerical studies have shown that predicted power coefficients can be sensitive to turbulence-model selection and the associated numerical assumptions [19].

The source study identifies B-2 as the configuration with the highest operating power coefficient. The corresponding peak value, its tip-speed ratio, and the difference from the baseline configuration should be reported only after checking the original simulation results.

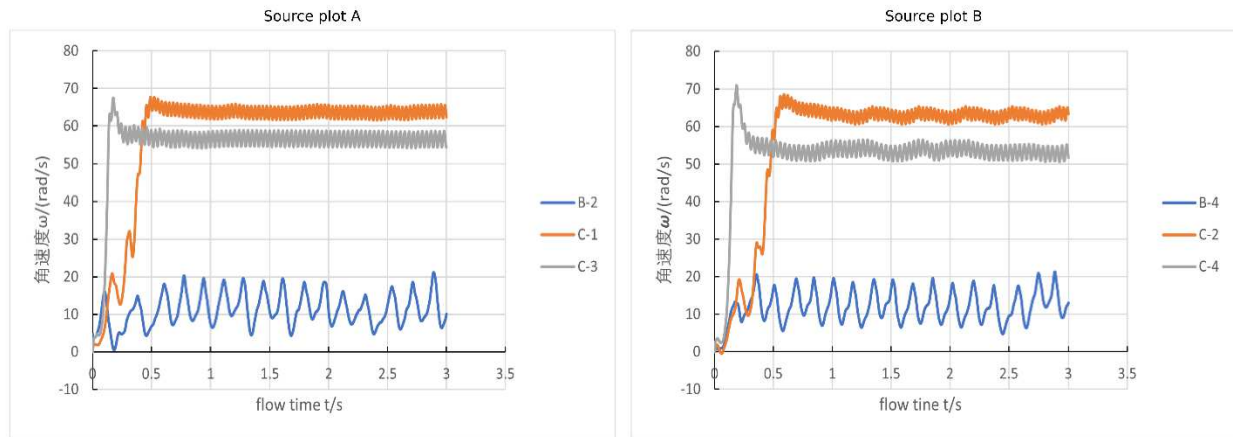


Figure 6. Variation of power coefficient with tip-speed ratio for the investigated VAWT configurations.

4.6 Pressure Distribution and Near-Field Flow Characteristics

The pressure distribution around the blades provides insight into the aerodynamic loading and interaction between the inner and outer blade layers. Pressure differences across an airfoil contribute to the resultant aerodynamic force and influence the torque generated at different blade positions.

In a rotating VAWT, the pressure field varies with blade azimuth because the relative flow conditions change throughout the rotational cycle. Contours at selected angular positions can therefore be used to examine the evolution of the pressure field and identify regions of high and low pressure.

For the present multi-layer configuration, particular attention should be given to the pressure distribution in the passage between the inner and outer blades. Nevertheless, the magnitude and location of pressure differences must be established from the computed solution rather than inferred from geometry alone.

Experimental and numerical investigations of VAWTs have demonstrated the importance of comparing local aerodynamic behaviour with the corresponding performance predictions [18,20]. Such comparisons can help establish whether the simulated flow structures provide a physically consistent explanation of the observed torque and power characteristics.

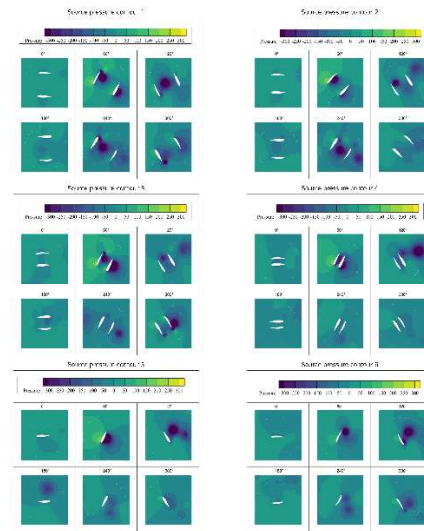


Figure 7. Pressure distribution around the investigated VAWT at selected blade azimuthal positions.

4.7 Velocity Distribution and Wake Development

The velocity field illustrates the acceleration and deceleration of air around the blades and the development of the downstream wake. The distribution depends on blade geometry, rotational motion, local pressure gradients, and interactions between neighboring blades.

In the multi-layer configurations, the spacing between the inner and outer blades may influence the velocity distribution through the inter-layer passage. Comparing velocity contours at equivalent azimuthal positions can help identify regions of flow acceleration, reduced velocity, and wake interaction.

Local flow-field validation is particularly relevant when interpreting numerical predictions. Arpino et al. [20] presented particle-image-velocimetry measurements for a Darrieus-type VAWT and established a benchmark for evaluating predicted local velocity distributions. Their work supports the use of velocity-field comparisons as a complement to global performance metrics.

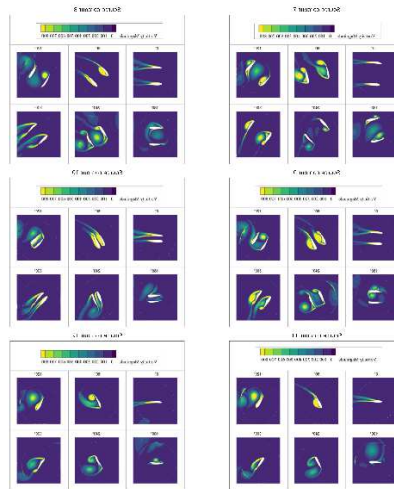


Figure 8. Velocity distribution and wake development around the investigated VAWT configurations.

4.8 Vorticity Distribution and Unsteady Flow Behavior

Vorticity contours can be used to identify rotational flow structures associated with separation, blade motion, and wake interaction. In a straight-bladed VAWT, the changing angle of attack during rotation may produce unsteady aerodynamic behaviour and vortical structures near the blade surfaces.

The distribution of vorticity may vary with blade spacing, airfoil profile, chord length, and azimuthal position. In a multi-layer rotor, structures generated by the inner and outer blades may interact. Whether such interaction improves or reduces performance must be established by examining the computed flow field together with the corresponding torque and power results.

For a meaningful comparison, the same vorticity definition and consistent contour limits should be used across configurations. The analysis should rely on actual computed fields and should not interpret schematic flow illustrations as numerical results.

4.9 Three-Layer Configuration and Performance Trade-Offs

The source study also considers a three-layer extension of the rotor geometry. The reported observations indicate that this arrangement can produce higher torque, power, and power coefficient, while exhibiting less favourable self-starting behaviour and a longer time to reach steady operation.

These observations suggest that the performance of a multi-layer VAWT should not be evaluated using peak operating output alone. Starting torque, transient response, and the ability to reach stable operation are also relevant design considerations.

A recent experimental study of a triple-layer Darrieus VAWT investigated how the relative orientation and radial position of an auxiliary blade affected starting and operating performance [21]. Because the blade arrangement differs from the configuration considered in the present study, its quantitative results should not be transferred directly. Instead, the study demonstrates that the arrangement of the blade layers can be an important design variable.

A quantitative comparison of the present two-layer and three-layer configurations should include verified torque, power coefficient, and startup-response data obtained under equivalent conditions.

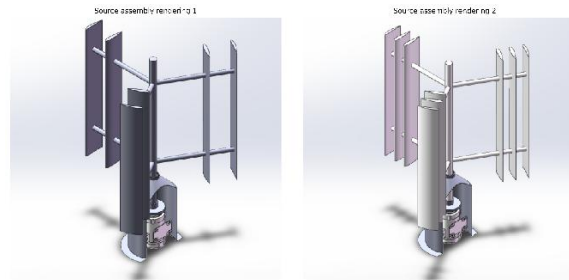


Figure 9. Comparison of the aerodynamic performance and transient response of the two-layer and three-layer VAWT configurations.

4.10 Overall Discussion

The investigated configurations provide a basis for examining the combined effects of inter-layer spacing, airfoil profile, and chord length on the aerodynamic behaviour of a multi-layer straight-bladed VAWT. These parameters may influence the flow passage, pressure distribution, wake interaction, and aerodynamic loading throughout the rotor cycle.

The source study distinguishes between static and operating performance. B-4 is reported to produce the highest static torque, whereas B-2 is reported to provide the highest operating torque, power, and power coefficient. These observations should be confirmed against the original result tables and simulation conditions before a final design recommendation is made.

A robust comparison should combine torque and power-coefficient results with pressure, velocity, and vorticity distributions. Mesh independence, numerical convergence, and validation should also be documented. Published investigations show that VAWT performance predictions can be sensitive to the turbulence model and that experimental comparisons are important for assessing numerical reliability [18–20].

The preferred configuration should therefore be selected using verified numerical results and clearly defined performance criteria rather than geometric reasoning alone.

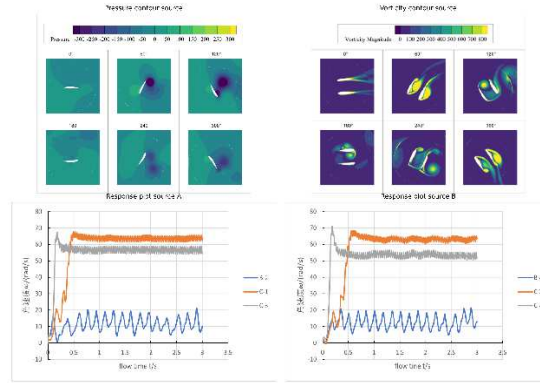


Figure 10. Comparative aerodynamic performance of the multi-layer vertical-axis wind turbine configurations.

5. Conclusions

This study investigates the geometric and aerodynamic characteristics of a multi-layer straight-bladed vertical-axis wind turbine, focusing on inter-layer spacing, airfoil configuration, blade chord length, and near-field flow behaviour.

The following conclusions are supported by the design parameters and observations reported in the source study:

1. Inter-layer spacing is an important design parameter. Four two-layer configurations were considered with spacings of 0.24, 0.18, 0.12, and 0.06 m. These configurations provide a basis for evaluating the influence of blade separation on aerodynamic performance.
2. Static and operating torque should be evaluated separately. The source study reports the highest static torque for B-4, with a spacing of 0.06 m, and the highest operating torque for B-2, with a spacing of 0.18 m. These observations require confirmation against the original numerical results.
3. Airfoil selection requires quantitative assessment. The use of NACA0018 for the inner layer and NACA5412 for the outer layer provides a basis for analyzing the effects of airfoil geometry on aerodynamic loading. The relative performance of these profiles must be established using the computed results.
4. Chord length should be assessed alongside other geometric parameters. The investigated chord lengths of 0.15, 0.20, and 0.30 m may affect blade loading and wake interaction. Their quantitative effects on power coefficient should be established using the corresponding results.

5. Near-field flow analysis can help interpret performance differences. Pressure, velocity, and vorticity distributions at selected azimuthal positions can help explain the aerodynamic behaviour of the different configurations. These fields should be connected to the actual torque and power calculations.

6. Multi-layer designs involve performance trade-offs. The source study reports improved operating performance for its three-layer extension alongside less favourable self-starting behaviour and a longer time to reach steady operation. Both operating output and transient response should therefore be considered during design selection.

Overall, B-2 is reported as a potentially promising two-layer configuration for operating performance, while B-4 is reported to provide the highest static torque. A definitive design recommendation requires verification of the original numerical data, consistent performance definitions, and documentation of numerical convergence and validation.

6. Limitations and Future Work

The present study examines selected geometric variations of a multi-layer VAWT. Several aspects require further investigation to establish the reliability and practical applicability of the findings.

First, the numerical methodology should be documented in sufficient detail, including the computational domain, mesh characteristics, turbulence model, solver settings, time-step selection, convergence criteria, and boundary conditions. Mesh-independence assessment and validation against appropriate experimental or published data should be included where available. Previous research has demonstrated that turbulence-model selection can influence predicted VAWT power coefficients, wake characteristics, and blade aerodynamics [19].

Second, the performance comparison should be supported by verified torque and power-coefficient data. The reference area, rotor radius, and operating conditions used in the calculations should be defined consistently across all configurations.

Third, future work could investigate a wider range of inlet velocities and tip-speed ratios. Experimental measurements, including local velocity-field measurements where feasible, could be used to validate the numerical predictions [18,20].

Finally, the influence of support structures, mechanical losses, three-dimensional flow effects, and transient starting behaviour could be examined in subsequent studies. These investigations would provide a more comprehensive assessment of the suitability of multi-layer VAWTs for practical applications.

References

- [1] Li, Y., Zheng, Y., Zhao, S., Feng, F., Li, J., Wang, N., & Bai, R. (2017). A review on aerodynamic characteristics of straight-bladed vertical axis wind turbine. *Acta Aerodynamica Sinica*, 35(3), 368–382. <https://doi.org/10.7638/kqdlxxb-2016.0189>
- [2] Rogowski, K., Hansen, M. O. L., & Maroński, R. (2018). Steady and unsteady analysis of NACA 0018 airfoil in vertical-axis wind turbine. *Journal of Theoretical and Applied Mechanics*, 56(1), 203–212. <https://doi.org/10.15632/jtam-pl.56.1.203>
- [3] Rogowski, K., Królak, G., & Bangga, G. (2021). Numerical study on the aerodynamic characteristics of the NACA 0018 airfoil at low Reynolds number for Darrieus wind turbines using the Transition SST model. *Processes*, 9(3), 477. <https://doi.org/10.3390/pr9030477>
- [4] Arpino, F., Cortellessa, G., Scungio, M., Fresilli, G., Facci, A., & Frattolillo, A. (2021). PIV measurements over a double bladed Darrieus-type vertical axis wind turbine: A validation benchmark. *Flow Measurement and Instrumentation*, 82, 102064. <https://doi.org/10.1016/j.flowmeasinst.2021.102064>
- [5] Scungio, M., Arpino, F., Focanti, V., Profili, M., & Rotondi, M. (2016). Wind tunnel testing of scaled models of a newly developed Darrieus-style vertical axis wind turbine with auxiliary straight blades. *Energy Conversion and Management*. <https://doi.org/10.1016/j.enconman.2016.10.033>
- [6] Computational fluid dynamics (CFD) mesh independency techniques for a straight blade vertical axis wind turbine. (2013). *Energy*, 58, 483–493. <https://doi.org/10.1016/j.energy.2013.06.012>
- [7] Effect of solidity on aerodynamic forces around straight-bladed vertical axis wind turbine by wind tunnel experiments (depending on number of blades). (2016). *Renewable Energy*, 96, 928–939. <https://doi.org/10.1016/j.renene.2016.05.054>
- [8] Towards optimal aerodynamic design of vertical axis wind turbines: Impact of solidity and number of blades. (2018). *Energy*, 165, 1129–1148. <https://doi.org/10.1016/j.energy.2018.09.192>
- [9] Dimensionless numbers for the assessment of mesh and timestep requirements in CFD simulations of Darrieus wind turbines. (2016). *Energy*, 97, 246–261. <https://doi.org/10.1016/j.energy.2015.12.111>

- [10] Paraschivoiu, I. (2002). Wind Turbine Design: With Emphasis on Darrieus Concept. Presses Internationales Polytechnique.
- [11] The Darrieus wind turbine: Proposal for a new performance prediction model based on CFD. (2011). *Energy*, 36(8), 4919–4934. <https://doi.org/10.1016/j.energy.2011.05.036>
- [12] Comparative analysis of turbulence models for the aerodynamic simulation of H-Darrieus rotors. (2015). *Energy*. <https://www.sciencedirect.com/science/article/pii/S0360544215009974>
- [13] Understanding the aerodynamic behavior and energy conversion capability of small Darrieus vertical axis wind turbines in turbulent flows. (2020). *Energies*, 13(11), 2936. <https://www.mdpi.com/1996-1073/13/11/2936>
- [14] Li, Y., Zheng, Y., Zhao, S., Feng, F., Li, J., Wang, N., & Bai, R. (2017). A review on aerodynamic characteristics of straight-bladed vertical axis wind turbine. *Acta Aerodynamica Sinica*, 35(3), 368–382. <https://doi.org/10.7638/kqdlxxb-2016.0189>
- [15] Experimental study on the performance of a triple-layer Darrieus vertical axis wind turbine. (2026). *Energy Conversion and Management: X*, 31, 102126. <https://doi.org/10.1016/j.ecmx.2026.102126>
- [16] Enhancing Darrieus wind turbine performance through varied plain flap configurations for the solar and wind tree. (2024). <https://pmc.ncbi.nlm.nih.gov/articles/PMC11612441/>
- [17] Rogowski, K., Królak, G., & Bangga, G. (2021). Numerical study on the aerodynamic characteristics of the NACA 0018 airfoil at low Reynolds number for Darrieus wind turbines using the Transition SST model. *Processes*, 9(3), 477. <https://doi.org/10.3390/pr9030477>
- [18] Scungio, M., Arpino, F., Focanti, V., Profili, M., & Rotondi, M. (2016). Wind tunnel testing of scaled models of a newly developed Darrieus-style vertical axis wind turbine with auxiliary straight blades. *Energy Conversion and Management*. <https://doi.org/10.1016/j.enconman.2016.10.033>
- [19] Computational fluid dynamics (CFD) mesh independency techniques for a straight blade vertical axis wind turbine. (2013). *Energy*, 58, 483–493. <https://doi.org/10.1016/j.energy.2013.06.012>
- [20] Effect of solidity on aerodynamic forces around straight-bladed vertical axis wind turbine by wind tunnel experiments (depending on number of blades). (2016). *Renewable Energy*, 96, 928–939. <https://doi.org/10.1016/j.renene.2016.05.054>

[21] Arpino, F., et al. (2021). PIV measurements over a double bladed Darrieus-type vertical axis wind turbine: A validation benchmark. *Flow Measurement and Instrumentation*, 82, 102064. <https://doi.org/10.1016/j.flowmeasinst.2021.102064>