

NACA 0020 Horizontal Axis Wind Turbine Design Optimization to Increase Coefficient of Power (C_p)

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ABSTRACT

Renewable energy is the primary solution to future energy challenges. Horizontal-axis wind turbines (HAWTs) have great potential as a source of clean energy, especially in remote areas. This study aims to optimize the number of HAWT blades to increase the Coefficient of Power (C_p) through simulation and experimental methods. Optimization is done by modifying the angle of attack and the number of blades. Aerodynamic simulations using the QBLADE software were validated through laboratory experiments with small-scale prototypes. The study calculated the harvestable wind energy using the Betz limit (59%) and the C_p range from the previous study (35-45%). The turbine's efficiency is strongly influenced by the number of blades operating based on lift, with the glide ratio being an important parameter. The turbine blade was manufactured using NACA 0020 at the Mechanical Engineering workshop at Khairun University. Testing is carried out in the laboratory to measure the relationship between the number of blades, rotor rotation, and the generator's output power. This process accounts for mechanical, generator, and heat losses. The experimental data is validated by simulation and calculation to formulate the number of blade relationships as design recommendations. Based on analyses of the relationships among C_p , C_m , and TSR, and comparisons with previous studies, the number of wind turbine blades was shown to have a significant effect on aerodynamic efficiency, initial torque, and energy conversion performance. The 2-blade turbine is well-suited to strong winds due to its high efficiency at high TSRs, but it is less stable and has low starting torque. The 6-blade turbine excels at low TSR with ample initial torque, ideal for slow winds and mechanical applications, although its efficiency decreases at high TSR. 3-blade turbines offer the best compromise, making them a top choice in commercial systems.

Keywords: Horizontal axis wind turbine, NACA 0020, Coefficient of power, Wind energy

ABSTRAK

Energi terbarukan adalah solusi utama menghadapi tantangan energi masa depan. Turbin angin sumbu horizontal (HAWT) memiliki potensi besar sebagai sumber energi bersih, terutama di daerah terpencil. Penelitian ini bertujuan mengoptimalkan jumlah blade HAWT untuk meningkatkan Coefficient of Power (C_p) melalui metode simulasi dan eksperimen. Optimasi dilakukan dengan memodifikasi sudut serang dan jumlah blade. Simulasi aerodinamika menggunakan perangkat lunak QBLADE divalidasi melalui eksperimen di laboratorium menggunakan prototipe skala kecil. Penelitian menghitung energi angin yang dapat dipanen, mengacu pada Betz limit (59%) dan nilai C_p dari studi sebelumnya (35-45%). Efisiensi turbin sangat dipengaruhi jumlah blade yang bekerja berdasarkan lift, dengan glide ratio (perbandingan lift terhadap drag) sebagai parameter penting. Blade turbin dibuat dengan type NACA 0020 di workshop Teknik Mesin, Universitas Khairun. Pengujian dilakukan di laboratorium untuk mengukur hubungan jumlah blade terhadap putaran rotor dan daya keluaran generator. Proses ini mempertimbangkan rugi-rugi mekanik, generator, dan panas. Data eksperimen divalidasi

dengan simulasi dan perhitungan untuk merumuskan hubungan jumlah blade sebagai rekomendasi desain. Berdasarkan analisis hubungan C_p dan C_m terhadap TSR serta pembandingan dari studi sebelumnya, jumlah bilah turbin angin terbukti berpengaruh signifikan terhadap efisiensi aerodinamis, torsi awal, dan performa konversi energi. Turbin 2 bilah cocok untuk angin kencang karena efisiensi tinggi pada TSR besar, namun kurang stabil dan memiliki torsi awal rendah. Turbin 6 bilah unggul pada TSR rendah dengan torsi awal besar, ideal untuk angin lambat dan aplikasi mekanis, meski efisiensinya menurun pada TSR tinggi. Turbin 3 bilah menawarkan kompromi terbaik, menjadikannya pilihan utama dalam sistem komersial.

Kata kunci: Turbin angin sumbu horizontal, NACA 0020, Coefficient of power, Energi angin

INTRODUCTION

Wind energy is one of the renewable energy sources with great potential to meet energy needs sustainably. Horizontal Axis Wind Turbine (HAWT) is a commonly used technology because of its efficiency in converting wind kinetic energy into electrical energy (Wicaksono & Saefudin, 2023). However, the efficiency of the HAWT is greatly influenced by the blade design, especially the aerodynamic profile and blade count.

NACA (National Advisory Committee for Aeronautics) blade profiles, such as NACA 0020, exhibit symmetrical characteristics that provide stable aerodynamic performance across a wide range of wind conditions. Variations in the number of turbine blades also affect performance. Blades with more numbers can increase torque but potentially increase drag, while fewer blades result in higher rotational speeds but with lower torque (Eltayeb *et al.*, 2024). Therefore, it is necessary to optimize the NACA 0020 blade design by varying the number of blades to improve the coefficient of power (C_p) and overall turbine efficiency (El-Askary *et al.*, 2023).

This study aims to determine the optimal blade design by considering the angle of attack, the number of blades, and their effects on turbine performance. The approach is carried out through aerodynamic simulations and experimental testing to validate the most efficient design. The problem formulation in this study covers three main aspects related to the design of horizontal-axis wind turbines with the NACA 0020 profile. First, how does the variation in the number of blades affect the aerodynamic performance of the wind turbine, including efficiency and ability to produce energy? Second, what is the optimal number of blades that can make the best coefficient of power (C_p) to improve the overall performance of the wind turbine? Third, how to validate the results of aerodynamic simulations conducted alongside experimental tests to ensure the suitability and accuracy of the NACA 0020 blade design for determining wind turbine efficiency in real-world conditions.

The problem-solving approach in this study involves theoretical calculations of wind turbines, simulation using relevant software, and validation through laboratory experimental tests. Previous research was used to determine the research gap and confirm the research results. Optimizing the number of blades in a horizontal-axis wind turbine (HAWT) is essential to improving turbine efficiency. The number of blades directly affects aerodynamic performance, power generation, and overall turbine efficiency. Various studies have explored the impact of blade count on HAWT performance, revealing a complex interaction between aerodynamic factors and mechanical constraints. The following section investigates the findings of recent research on this topic.

A study using CFD simulations and experimental setups found that the three-blade configuration achieved the highest power coefficient among the five- and six-blade configurations, with increases of about 2% and 4%, respectively (Eltayesh *et al.*, 2021). The

number of blades affects the swept area and, consequently, the power extracted from the wind. However, increasing the number of blades can cause a slipstream effect, reducing. From a mechanical perspective, more blades increase turbine weight and production costs, which can offset the benefits of increased power generation. Therefore, finding the optimal number of blades is essential to balance performance and cost (Adeyeye *et al.*, 2021).

Numerical studies using QBlade software have shown that although adding blades can improve efficiency, the design and selection of airfoils are essential to maximize power output (Nasab *et al.*, 2019). Experimental investigations have shown that turbines with more blades produce higher torque due to increased pressure on the blade surface. However, the differences between experimental and numerical results suggest that unidentified losses can affect real-world performance (Sudarma *et al.*, 2020). Advanced design methodologies, such as those using OpenFOAM, have been developed to optimize blade designs, achieving significant efficiency improvements over traditional designs (Hamlaoui *et al.*, 2023).

Increasing the efficiency of horizontal-axis wind turbines is achieved through blade design optimization. Previous research included simulations using Computational Fluid Dynamics (CFD) to analyze the performance of a propeller-type wind turbine with three blades on a dual-rotor system under geometric variations (Koehuan *et al.*, 2023). Simulations of the conversion of kinetic energy into electrical energy for a horizontal three-axis blade wind turbine have also been carried out to ensure the design operates optimally before prototyping. (Horizontal axis wind turbine blade selection display of taperless and untwisted foil water model, n.d.).

Based on previous research, the coefficient of power (C_p) as a function of the tip speed ratio (TSR) varies across different types of wind turbines. The Savonius turbine has the lowest C_p value, which is around 0.15. Meanwhile, the Darrieus turbine, a lift-based vertical-axis wind turbine, has a higher C_p value than the Savonius turbine, ranging from 0.2 to 0.35. Horizontal axis wind turbines have a higher C_p value, which is about 0.4 to 0.5 (Figure 3. C_p to TSR in Different Types of Wind Turbines (Alabdali *et al.*, 2020). This turbine performance comparison has been discussed in several publications, which show that horizontal-axis wind turbines generally have the highest C_p values (Eftekhar *et al.*, 2022; El Khchine & Sriti, 2017). Simulation of the conversion of kinetic energy into electrical energy on a 3-spoon horizontal-axis windmill is also carried out to ensure the design runs smoothly before the actual prototype is built. (Conversion *et al.*, 2023).

This study offers novelty in the study of horizontal-axis wind turbines using the NACA 0020 airfoil profile. Most previous studies addressed only a single blade count or used another profile, whereas this study specifically examined variations in blade count within NACA 0020 profiles to assess their effect on power coefficients (C_p).

In addition, the study uses numerical simulations with QBlade, enabling more thorough and varied analysis without directly building a physical prototype. Through QBlade, various operating conditions and configurations can be tested virtually beforehand, allowing the results to serve as a reference for designing targeted, time-saving, cost-efficient real-world experiments. This combined approach, combining QBlade simulation with experimental test results, provides a more comprehensive understanding of wind turbine aerodynamic performance and enables a more efficient, economical design for field application.

METHODOLOGY

The flow chart in this study, shown in Figure 1, illustrates the systematic steps for designing and testing the performance of a Horizontal Axis Wind Turbine (HAWT) based on the NACA

0020 profile. The process begins with the first step: determining data related to wind turbines, including turbine type, the independent variables to be analyzed, the solution method, and other assumptions relevant to horizontal-axis wind turbines. The next step is to conduct simulations using Qblade software to model the wind turbine and obtain conditions that closely match the real state. In the third stage, the modeling results were evaluated; if they were as expected, the process could continue. However, if the modeling fails or the results are inadequate, then the simulation parameters will be corrected and the simulation repeated until the corresponding results are obtained.

The results of these simulations are used to determine key HAWT parameters, such as efficiency and aerodynamic characteristics. The parameters obtained then serve as the basis for manufacturing wind turbine blades in the workshop, which will be produced according to the simulated design. The process continues with testing the laboratory-manufactured blades to measure their performance under real conditions. In the next step, an evaluation is conducted to determine whether the experiment's results meet the predetermined criteria. If the results are insufficient, the design will be corrected and the test repeated. However, if the experimental results meet expectations, validation is performed to ensure the model's consistency with reality. The final stage is to conclude all simulation and experimental results, marking the completion of the research process.

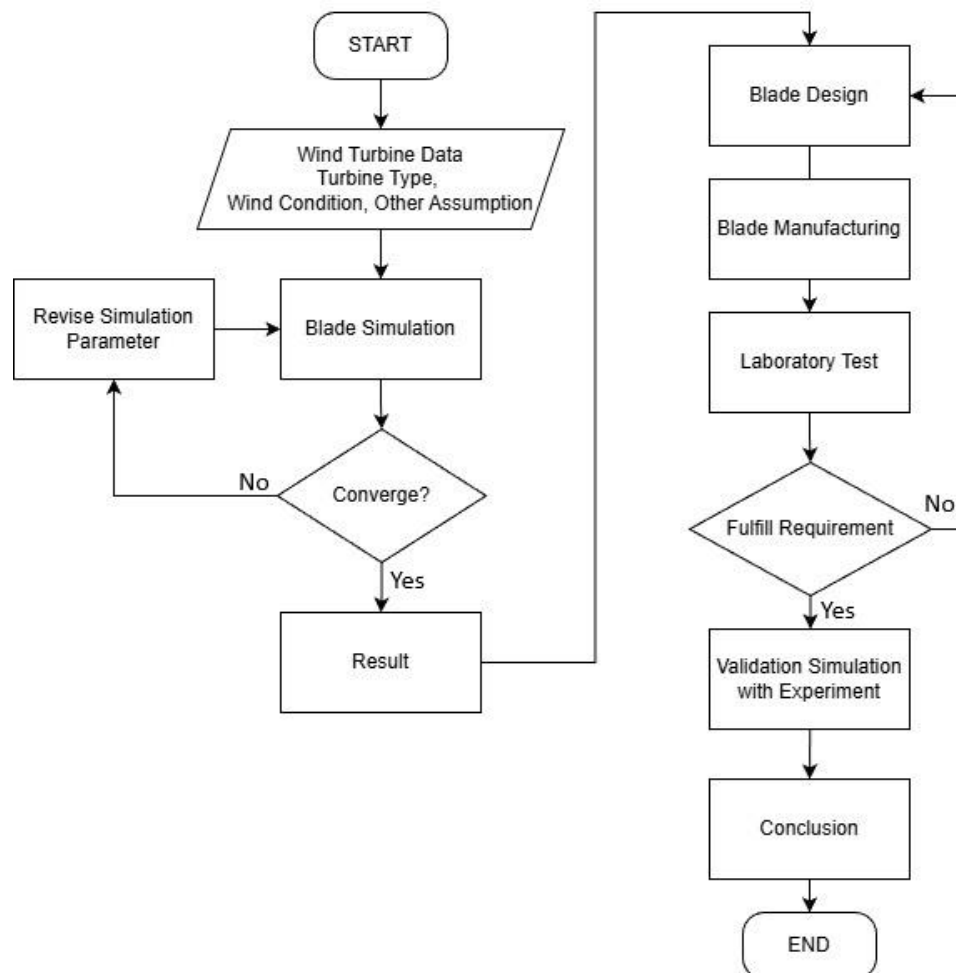


Figure 1 Research flow diagram

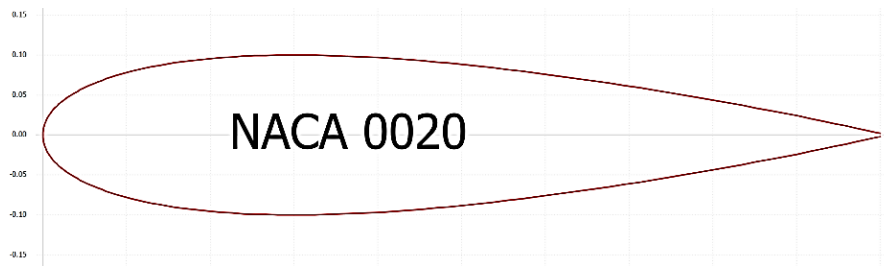


Figure 2. Profile of NACA 0020

Figure 2 shows NACA 0020, a type of wing profile designed by the National Advisory Committee for Aeronautics (NACA), now known as NASA. This profile belongs to the category of symmetrical airfoils, meaning the upper and lower surfaces are identical, resulting in balanced aerodynamic characteristics. The number "0020" refers to the two main parameters of the profile design, where the first number (0) indicates the maximum thickness of the airfoil in percent of the chord length (i.e., 0% at the middle position of the chord) and the second number (20) indicates its relative thickness, which reaches 20% of the chord length.

NACA 0020 profiles are often used in a variety of applications, including aircraft wing designs, wind turbines, and other aerodynamic structures. One of its advantages is good stability in a wide range of airflow conditions, especially at low to medium speeds. Due to its symmetrical shape, NACA 0020 can be used on wing designs that require symmetry at the top and bottom to reduce the pitching moment (wing rotation).

Although these profiles have good efficiency in terms of stability and lift, the NACA 0020 may not perform as well at very high flow rates as asymmetric airfoils designed specifically for high-speed applications. However, in the design of horizontal-axis wind turbines, this profile is still chosen for its simplicity and its ability to generate power across a wide range of wind speeds, especially at small and medium scales.

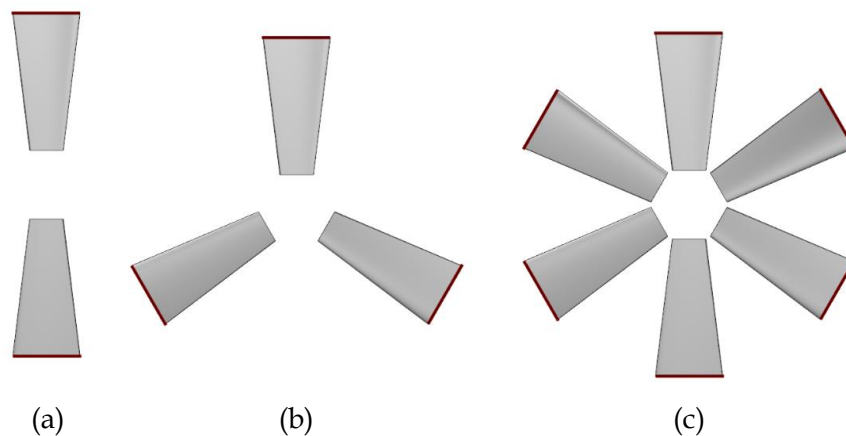


Figure 3. Blade design: (a) 2 blade, (b) 3 blade, (c) 6 blade

Figure 3 shows the design of the wind turbine blade generated with QBlade software, with 2, 3, and 6 blades. These three-blade designs were compared in this study to analyze the effect of blade numbers on the aerodynamic performance of wind turbines. Figure 4 shows a 3D view of the blade design, providing a clearer visual picture of the shape and configuration of each blade on the wind turbine being tested. This design is essential for visualizing the structural differences between different blade counts and for evaluating the potential energy efficiency of each configuration.

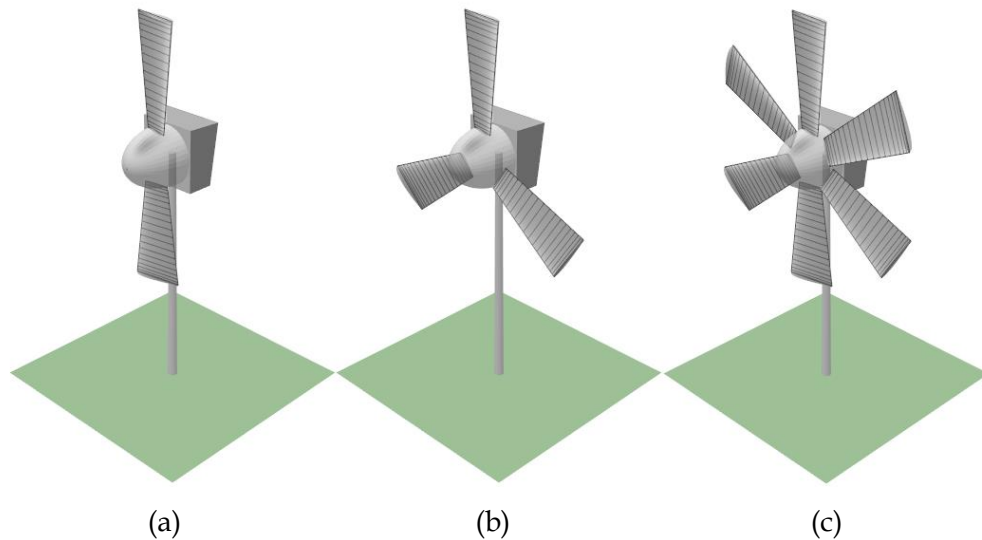


Figure 4. Blade design in 3D view: (a) 2 blade, (b) 3 blade, (c) 6 blade

RESULTS AND DISCUSSION

Figure 5 presents a graphical analysis of the power coefficient (C_p) as a function of the Tip Speed Ratio (TSR) for various numbers of turbine blades, along with comparisons with several similar studies. The image shows the relationship between the Tip Speed Ratio (TSR) and the power coefficient (C_p) for three configurations of the number of wind turbine blades: 2, 3, and 6. The horizontal axis represents the TSR, the ratio of the blade tip speed to the wind speed. In contrast, the vertical axis shows the C_p value, which means the efficiency of converting wind energy into mechanical energy. This graph shows that blade configuration has a significant impact on wind turbine performance across different wind speeds.

The red curve describes a turbine with two blades. The simulation results showed that the maximum C_p value was achieved at a high TSR of 5–6. This reflects the advantage of fewer blades, which allows the turbine to rotate at high speeds due to minimal aerodynamic drag. Although efficient at generating power in strong winds, this configuration has disadvantages in terms of operating stability, is susceptible to wind fluctuations, and produces higher noise levels. Meanwhile, the green curve indicates a 3-blade configuration, which is generally the industry standard on commercial turbines. The maximum C_p value is achieved at a TSR of around 4–5, which reflects the balance between efficiency and stability. This configuration produces sufficient power, remains stable against changes in wind speed, and offers even aerodynamic load distribution and lower vibration.

The blue curve shows a turbine with six blades, with maximum C_p at a low TSR of about 2–3. This configuration indicates that the blades produce more starting torque, but experience a drastic decrease in efficiency at high TSRs due to increased drag. This makes it ideal for applications in low-wind-speed areas or for simple mechanical systems such as water pumps, but less efficient for large-scale power generation.

The results of this simulation are in line with several previous studies. For example, numerical research using the NACA 0015 airfoil profile showed that a 2-blade turbine reached a maximum C_p of 0.48 at TSR 6, while a 3-blade turbine reached 0.46 at TSR 4.5, and a 5-blade turbine reached 0.41 at TSR 3.5. The decrease in efficiency with increasing blade count at high TSR is

consistent with the simulation results above, although the resulting torque tends to be higher with more blades.

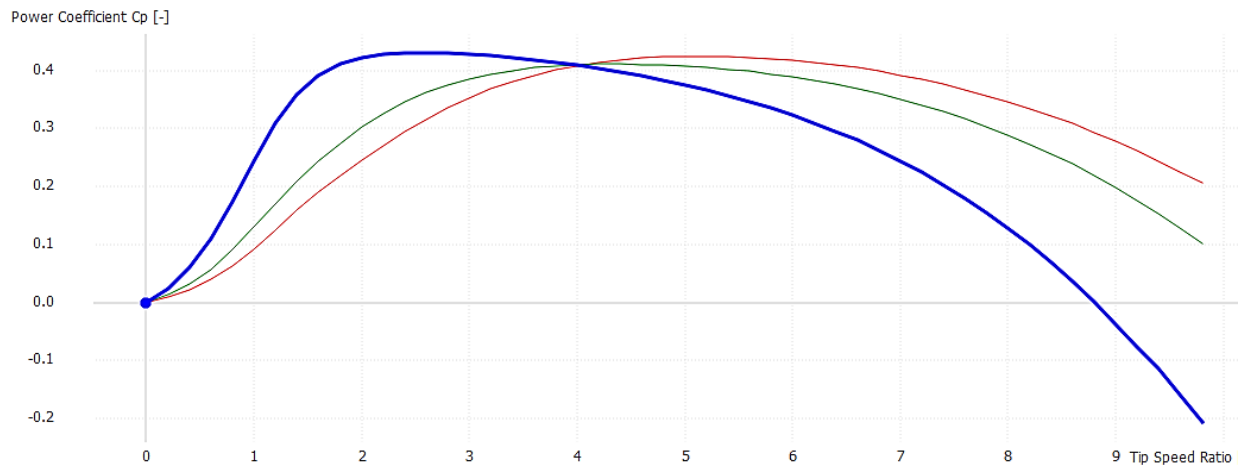


Figure 5 Simulation results for power coefficient

Figure 6 shows the relationship between Torque Coefficient (C_m) and Tip Speed Ratio (TSR) for wind turbines with three blade count configurations: 2 (red line), 3 (green line), and six blades (blue line). This graph shows that the 6-blade configuration produces the highest C_m value at low TSR (about 1.2), demonstrating the ability to generate ample initial torque, well-suited for applications with low wind speeds. In contrast, the 2-blade configuration has the lowest C_m at low TSR but maintains a more stable C_m at high TSR, indicating its efficiency at high rotational speeds. The 3-blade configuration features balanced switching characteristics between the two, making it the most common choice in wind turbine designs due to the combination of adequate starting torque and consistent performance across a wide range of TSRs.

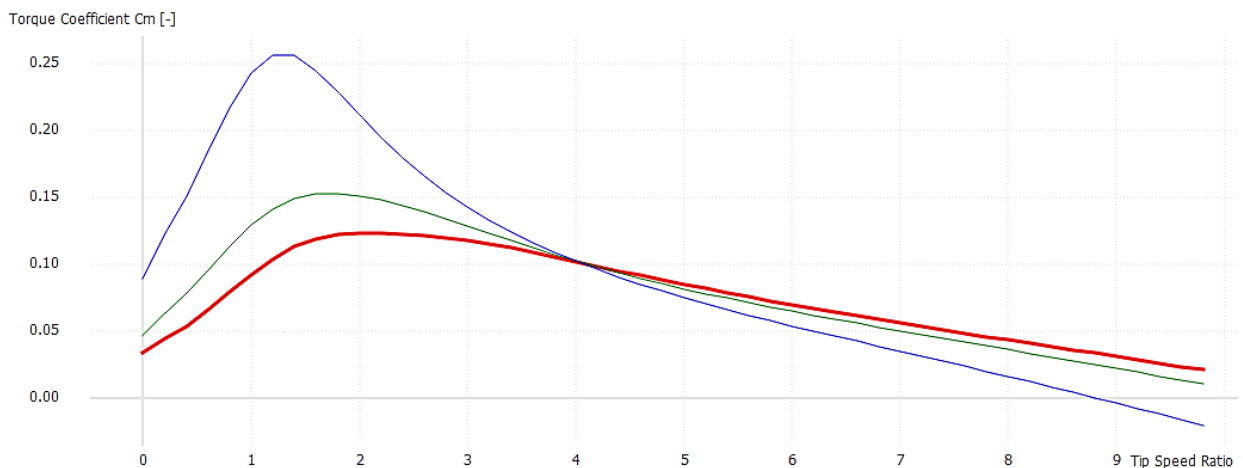


Figure 6 Simulation results for torque coefficient

Other studies on crossflow-type vertical-axis wind turbines also showed increases in optimal C_p and TSR with increasing blade number. Turbines with 8, 12, and 16 blades show an increase in efficiency from C_p 0.00155 to 0.00273 with the TSR rising from 0.433 to 0.578. Although the C_p value is relatively small across different turbine types, this trend supports the simulation

results that the number of blades affects turbine performance, especially in adjusting to low wind speeds.

Other experimental research shows that the energy produced by a turbine is also strongly influenced by the number of blades. Under the same wind conditions, turbines with three blades produce more energy than those with 2 or 4 blades. This again reinforces the argument that the 3-blade configuration offers an optimal balance in efficiency, stability, and output energy. The image shows the power coefficient (C_p) curve as a function of the Tip Speed Ratio (TSR) for three wind turbine blade configurations: 2-, 3-, and 6-blade. This relationship is essential for determining the turbine's energy efficiency, as it determines the ratio of blade speed to wind speed. In this simulation, it was seen that a 2-blade turbine (red line) showed the highest efficiency at high TSR (~5-6), while a 6-blade turbine (blue line) was efficient at low TSR (~2-3), in line with the wind turbine momentum theory (Manwell *et al.*, 2009).

Research by Rahmawati (2022) showed similar results: a 2-bladed wind turbine achieved a maximum C_p of 0.48 at TSR 6, while a 3-bladed turbine reached 0.46 at TSR 4.5. This indicates that efficiency increases at fewer blades for high TSRs, but stability and vibration are better in 3-blade turbines (Rahmawati, 2022). Furthermore, a study by Rizky *et al.* (2020) on a crossflow-type vertical turbine showed that increasing the number of blades from 8 to 12 to 16 increased C_p from 0.00155 to 0.00273 and TSR from 0.433 to 0.578. Although the results are not as high as horizontal turbines, this trend supports the hypothesis that the number of blades is directly proportional to efficiency at low TSRs. Another experimental study by Yustika & Saragih (2021) showed that energy output increased significantly with three blades compared to 2 or 4 blades, with the highest output recorded at three blades at a wind speed of 5.4 m/s, amounting to 12,731 joules. This result reinforces the 3-blade configuration as the best compromise between turbine rotation efficiency and stability.

Overall, the results of simulations and similar studies show that the choice of blade number should be adjusted to the characteristics of the wind speed at the turbine installation site and the purpose of its use. The 2-blade turbine is suitable for areas with strong winds and high efficiency requirements. The 3-blade turbine is ideal for its versatility, capable of operating efficiently across a wide range of conditions. Meanwhile, the 6-blade turbine is suitable for applications with low wind speeds that require high starting torque. In the context of off-grid or off-grid technology, blade configurations can be beneficial even if the efficiency is theoretically low.

CONCLUSION

Based on the graphical analysis of the power coefficient (C_p) and torque coefficient (C_m) on the Tip Speed Ratio (TSR) and its comparison with various similar research results, it can be concluded that the number of blades of wind turbines significantly affects the aerodynamic performance, energy conversion efficiency, and initial torque characteristics of the turbine. Turbines with fewer blades (2) exhibit high power efficiency (C_p) at high TSR, making them suitable for environments with high wind speeds and fast rotation requirements. However, this configuration has disadvantages in terms of stability, low starting torque, and higher noise potential. In contrast, the 6-blade turbine excels at producing high initial torque at low TSR, making it ideal for applications in low-wind areas or for mechanical systems such as water pumps. However, its power efficiency decreases sharply at high TSR due to increased aerodynamic drag. The 3-blade configuration occupies an optimal central position, offering the best balance between power efficiency, mechanical stability, and initial torque, making it a top choice in modern commercial wind turbine systems. Therefore, the selection of the number of

blades should be based on the intended use, the characteristics of the wind location, and the trade-off between efficiency and torque requirements, where no single configuration is superior; instead, it needs to be contextually adapted to the turbine's operating environment.

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