Journal of Renewable Energy, Electrical, and Computer Engineering
Volume 4, Number 2, September 2024. 150-158
eISSN 2776-0049
Research Original Article
DOI: https://doi.org/10.29103/jreece.v4i2.16561

Design and Development of a Vertical Axis Wind Turbine with PVC Blades Using Solidworks Simulation

Ramadan Bimo Anggoro[1], Ramadhani Setyobudi[1], Amajida Sadrina✉[1], Siti Chalimah[1], Muhammad Hendra Budi Satria[1]
[1] Mechanical Engineering Department, Faculty of Engineering and Science, Universitas Pembangunan Nasional "Veteran" East Java, 60294, Indonesia.
✉Corresponding Author: amajidasadrina22@gmail.com | Phone: +6281331953450

Received: June 10, 2024 **Revision: August 22, 2024** **Accepted: September 20, 2024**

Abstract

Savonius wind turbines have better performance in locations with varying wind directions compared to horizontal axis wind turbines. However, their drawback lies in their low performance coefficient. The main objective of this study is to investigate the optimal design of a vertical axis wind turbine of the Savonius type. The parameters investigated include blade thickness and blade arc angle. This study was conducted using computational fluid dynamics (CFD) simulations with SolidWorks software. The simulation results show that at various blade thicknesses, there are significant differences in the obtained power coefficient (C_p) values. At a blade thickness of 2 mm, the highest power coefficient (C_p) reached 0.38 with a blade arc angle of 130°. Meanwhile, a blade thickness of 3 mm showed a maximum power coefficient (C_p) of 0.41 at a blade arc angle of 120°. However, at a thickness of 4 mm, there was a significant increase with the highest power coefficient (C_p) reaching 0.45 at a blade arc angle of 110°. This indicates that the most efficient shape for a Savonius wind turbine is with a blade thickness of 4 mm, a blade arc angle of 110°, a blade spacing of 3 cm, and an overlap ratio of 0.42, providing a maximum power coefficient (C_p) of 0.45.

Keywords: Savonius Wind Turbine; Computational Fluid Dynamics; Power Coefficient; Blade Arc Angle; Blade Thickness

Introduction

A study conducted by (Bela\"\id & Zrelli, 2019) highlights the fact that approximately 80% of the primary energy sources used by society come from the combustion of fossil fuels. This fact not only indicates a high dependence on limited resources but also has serious environmental impacts (Setyono & Kiono, 2021). The increasing air pollution and greenhouse gas emissions resulting from the combustion of fossil fuels have become the primary sources of global environmental issues such as climate change and ozone layer depletion (Murphy, 2024).

Additionally, the continued use of non-renewable natural resources such as gas, oil, and coal is problematic because they cannot be used in the long term (Parinduri & Parinduri, 2020). Therefore, renewable energy provides an environmentally friendly and sustainable alternative to replace fossil fuels, promoting a shift towards a cleaner future by utilizing renewable natural resources such as sunlight, wind, water, and geothermal energy (Murphy, 2024).

In recent decades, wind energy has become one of the types of renewable energy with the advantages of large reserves and wide distribution (Mahata et al., 2024). Wind turbines, as the main devices used to harness wind energy by converting kinetic energy into electrical energy, have proven to be effective in generating electricity with a lower environmental impact compared to conventional wind sources (Xu et al., 2019). Wind turbines can be divided into horizontal axis wind turbines and vertical axis wind turbines.

Vertical axis wind turbines currently have greater development potential than horizontal axis wind turbines (Bedon et al., 2017). Their advantages encompass several aspects that provide a stronger appeal. One of these is their ability to be less sensitive to wind direction since their rotational axis is perpendicular to the wind direction (Afidah et al., 2023). This means vertical axis wind turbines can operate efficiently in environments with changing wind directions. Other factors, such as easier installation, lower maintenance costs, and lower aerodynamic noise, also make vertical axis wind turbines an attractive option for development (Rezaeiha et al., 2017).

Therefore, this study aims to optimize the design of a vertical axis wind turbine of the Savonius type with PVC blades to reduce production costs and increase the power coefficient of the Savonius wind turbine. In this study, the parameters investigated include blade thickness with 3 variations (2 mm, 3 mm, and 4 mm) and blade arc angle with 5 variations (110°, 120°, 130°, 140°, and 150°) with an overlap of 12 cm and a blade spacing of 3 cm. All research was conducted using SolidWorks simulation. This study is expected to find a more efficient design than previous researchers and reduce the production costs of Savonius wind turbines.

Literature Review

Wind Turbine

Wind turbines are an important part of the Wind Energy Conversion System (WECS), which aims to convert wind energy into a more useful form (Sudrajat et al., 2020). Their function is to convert the kinetic energy of the wind into mechanical energy through the rotation of the shaft, which can then be used to generate electricity or for other purposes (Nakhoda & Saleh, 2015). There are two main types of wind turbines: horizontal axis wind turbines and vertical axis wind turbines. This study focuses on vertical axis wind turbines because they have greater development potential than horizontal axis wind turbines, including the ability to operate more efficiently in environments with changing wind directions, such as in urban areas (Rezaeiha et al., 2017).

Vertikal Axis Wind Turbine (VAWT)

A Vertical Axis Wind Turbine (VAWT) is a type of wind turbine where the main rotor shaft is arranged transverse to the wind while the main components are at the base of the turbine. There are two main types of vertical axis wind turbines: Savonius wind turbines and Darrieus wind turbines (Qasemi & Azadani, 2020). Darrieus rotors come in various shapes, including helical, H-rotor, and Gorlov. These turbines typically have three slender rotor blades driven by lift forces, allowing them to achieve high speeds. Savonius wind turbines perform better in locations with changing wind directions compared to horizontal axis wind turbines. This makes Savonius wind turbines a good alternative for distributed power generation devices in urban environments (Samosir et al., 2021).

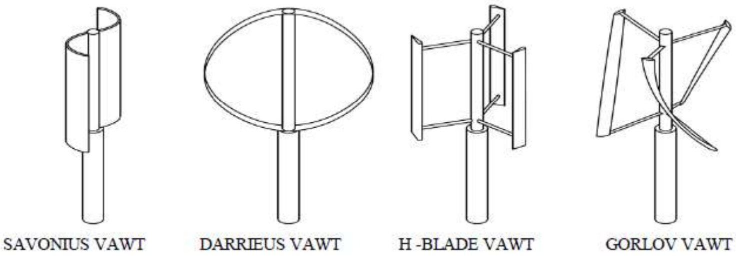


Figure 1. Types of wind turbines (Zilberman, 2017)

Power Characteristics

According to classical physics, the kinetic energy of an object with mass m and velocity v is E = 0.5 $m.v^2$, provided that the velocity does not approach the speed of light (Иванов et al., 2017). This formula also applies to wind, which is moving air. Thus, it can be written in equation (1).

$$E = \frac{1}{2}\, m.v^2 \qquad (1)$$

If the formula to determine the amount of mass passing through a certain point when a block of air has a cross-sectional area A (m^2), and moves with velocity v (m/s), can be written in equation (2).

$$m = A.v.\rho \qquad (2)$$

Thus, the energy from the wind that can be generated per unit of time can be written in equation (3).

$$P = \frac{1}{2}\, v^2.\rho.A.v \qquad (3)$$

Power Coefficient (C_p) indicates the efficiency of the turbine as shown in figure 2 (Ajayi, 2012). The power curve of the turbine is usually plotted against TSR. Different turbines have different efficiency levels. All simulations in this study were conducted at TSR 0.25, except for the validation section.

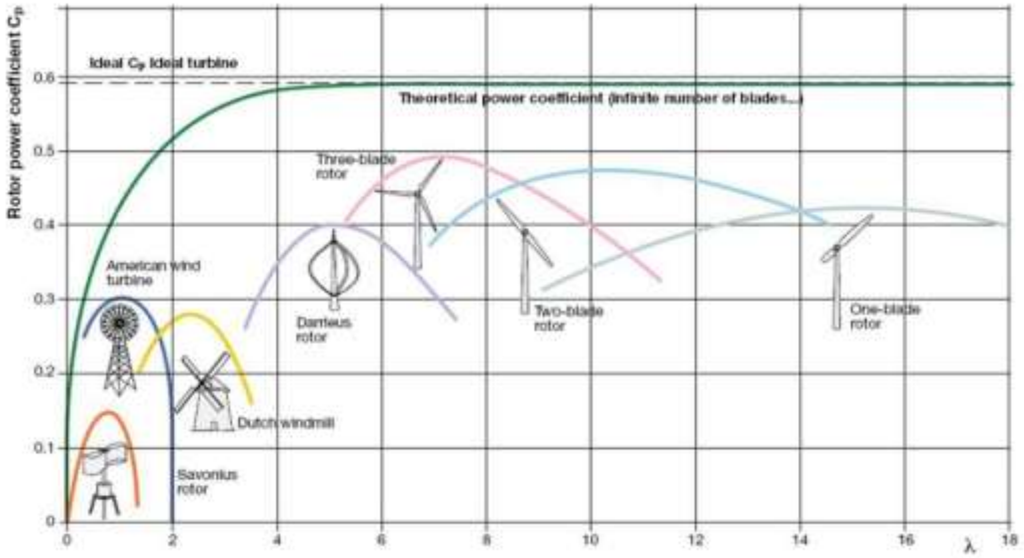


Figure 2. Curve of the average power coefficient (C_p) variation against tip speed ratio (TSR) for various types of wind turbines (Ajayi, 2012)

According to the German scientist Albert Betz, the C_p of a wind turbine is 0.59, meaning that a wind turbine can convert no more than 59% of the total wind power into useful power. This is called the Betz limit (Ebrahimpour et al., 2019). Mathematically, it can be written in equation (4).

$$C_p = \frac{Qn}{\frac{1}{2}\rho . v^3 A} \qquad (4)$$

To calculate the tip speed ratio (TSR), equation (5) can be used. TSR is useful for determining the turbine performance at different rotational speeds (Ebrahimpour et al., 2019).

$$\lambda = \frac{nR}{v} \qquad (5)$$

Various Blade Shapes

In figure 3, (Roy & Saha, 2015) conducted research on wind tunnels on newly developed blade shapes for Savonius wind turbines. They also examined other blade shapes as shown in figure 4. When compared to the four blade shapes, the blade shape in figure 3 resulted in an increase in maximum power coefficient by 3.3%. For static torque coefficient, it also showed an increase of 31.6%, 22.0%, 11.1%, and 4.2%. The study by (Roy & Saha, 2015) also indicated that the polynomial curvature 'Modify 4' has the highest static torque coefficient. This is due to the reduction of induced resistance on the returning blade caused by this polynomial curvature. Additionally, this curvature also has the highest torque coefficient and performance for a tip speed ratio of 0.9 (Nasr & others, 2023).

(Manavar, 2023) conducted a study optimizing the design of Savonius wind turbines for the ModBach shape in figure 5, using computational fluid dynamics (CFD) simulations. This research investigated two parameters: overlap ratio and blade spacing, aiming to find the optimal design parameter considering turbine efficiency. Findings showed that the most efficient blade shape reaching 30% had a blade arc angle of 110º, the optimal blade spacing was found to be 3.1 cm with an overlap ratio of 0.25.

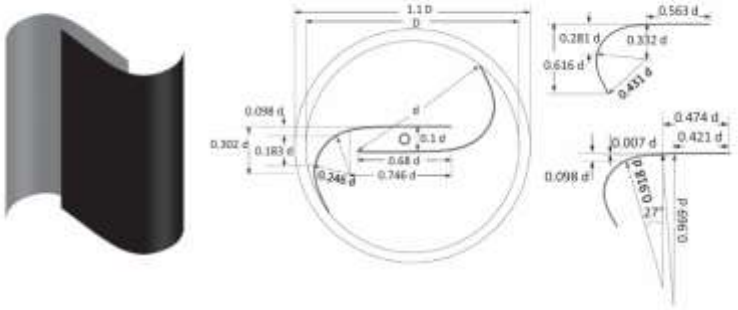
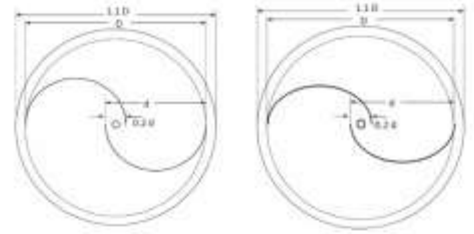
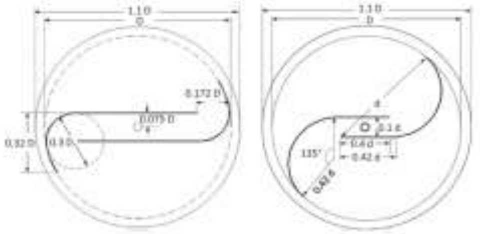


Figure 3. The newly developed blade shape (Roy & Saha, 2015)



(a) Conventional semi-circular (b) Semi-elliptic



(c) Benesh type (d) Modified Bach type

Figure 4. The dimensions of various blade profiles (Roy & Saha, 2015)

Materials & Methods

The aim of this study is to numerically investigate how various design parameter studies affect the performance of Savonius wind turbines. Additionally, the objective is to find geometries with the highest power coefficient. The design of Savonius wind turbines and numerical simulations were conducted using SolidWorks software. The process involves several stages, as depicted in the flowchart in figure 5.

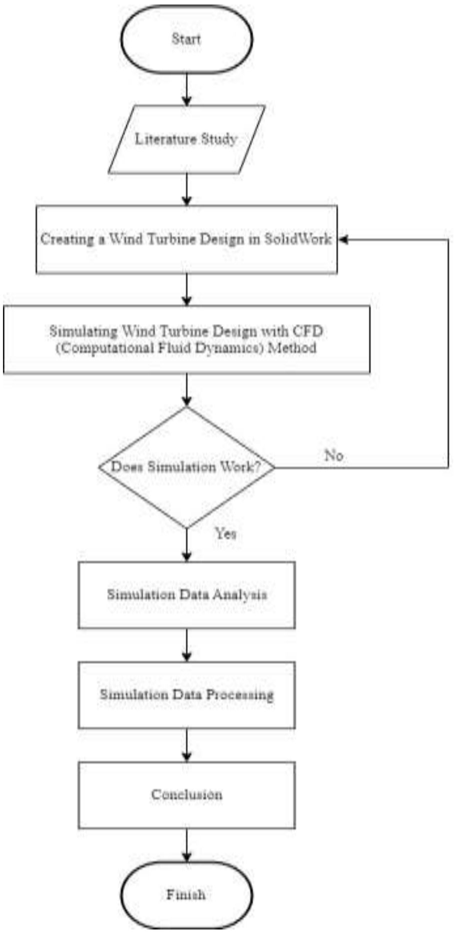


Figure 5. Research flowchart

Research stages:

1. This research begins with conducting a literature review of previous studies to optimize the design of more efficient Savonius wind turbines.
2. Creating a design of Savonius wind turbines using SolidWorks software with the following design variables:
   a. Blade Made of PVC Material
   One of the initial objectives of this research is to reduce the manufacturing cost of Savonius wind turbines, so the

turbine blades are made of PVC material.

b. Outer Diameter and Blade Height
In this design, the outer diameter of the blade is set at 50 cm and the blade height is set at 50 cm, as shown in figure 5.

c. Blade Thickness
The parameter study of blade thickness used in this research consists of three thicknesses: 2mm, 3mm, and 4mm. Changes in blade thickness can affect airflow around the blade. The appropriate blade thickness can help optimize pressure distribution on the blade surface, improving aerodynamic efficiency (Nasr & others, 2023).

d. Blade Arc Angle
The blade arc angle is the angle from the inside to the end of the blade. Changes in the blade arc angle can cause variations in drag force, and since Savonius rotors are drag-based, it is crucial to determine the most appropriate blade curvature angle for efficient performance. The parameter study of blade arc angle in this research selects angles of 110º, 120º, 130º, 140º, and 150º. Because in the research by (Manavar, 2023), further optimization is still needed in the variation of blade arc angles and only conducted in 2D simulations.

e. Blade Spacing
The distance between two blades is measured only from one blade to the other. In this study, a blade spacing of 3 cm is used. Based on the research conducted by (Manavar, 2023), it was found that a blade spacing of 3 cm is an efficient and optimal distance to achieve maximum performance.

f. Overlap Ratio
Overlap ratio (OR) is defined as the ratio of the length of overlap between two blades to the total length of one full turbine rotation. For example, in figure 6, Overlap = 12.00/29.54 = 0.40.

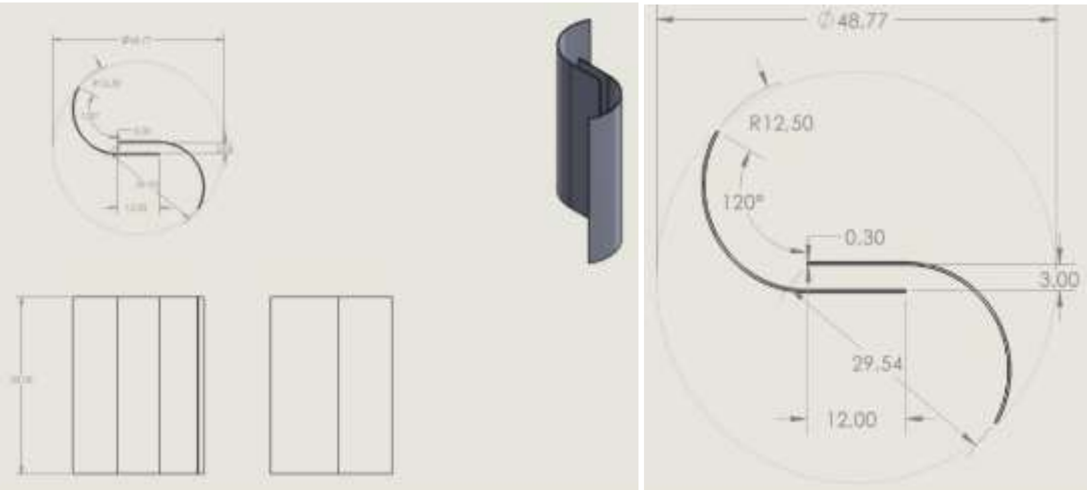


Figure 6. Design of Savonius Wind Turbine

3. The next step is to simulate the results of the wind turbine design using computational fluid dynamics (CFD).
4. After the simulation runs, the next step is the testing process to ensure whether the results meet the desired specifications. If not, then the wind turbine design will be revised in SolidWorks software. If the design is satisfactory, then it will proceed to the data analysis and processing of simulation data.

Finally, drawing conclusions from the results of the simulation data that have been conducted.

Results and Discussion

In this section, new simulation results are presented and compared with previous research. The influence of rotor performance is discussed by analyzing blade thickness and making modifications to the blade arc angle.

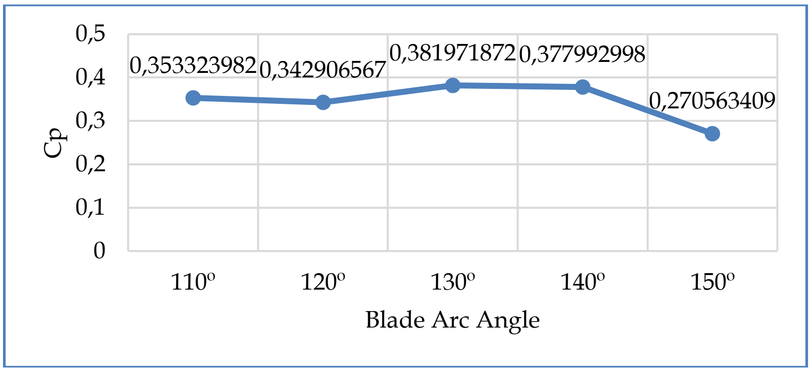


Figure 7. The graph depicting the relationship between blade arc angle and power coefficient (C_p) for a blade thickness of 2 mm.

Table 1. Results of power coefficient for various blade arc angle variations with a thickness of 2 mm.

Blade Arc Angle	Blade Thickness	TSR	Blade Spacing	Ratio Overlap	Coefficient Power (C_p)
110°	2 mm	0,25	3 cm	0,42	0,35
120°	2 mm	0,25	3 cm	0,42	0,34
130°	2 mm	0,25	3 cm	0,42	0,38
140°	2 mm	0,25	3 cm	0,42	0,37
150°	2 mm	0,25	3 cm	0,42	0,27

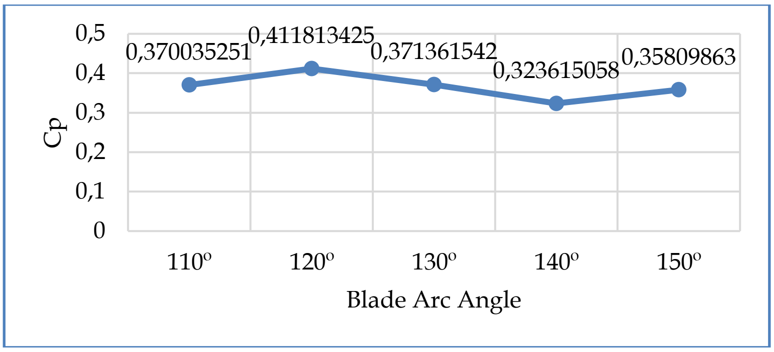


Figure 8. The graph illustrating the relationship between blade arc angle and power coefficient (C_p) for a blade thickness of 3 mm

Table 2. Results of power coefficient for various blade arc angle variations with a thickness of 3 mm.

Blade Arc Angle	Blade Thickness	TSR	Blade Spacing	Ratio Overlap	Coefficient Power (C_p)
110°	3 mm	0,25	3 cm	0,42	0,37
120°	3 mm	0,25	3 cm	0,42	0,41
130°	3 mm	0,25	3 cm	0,42	0,37
140°	3 mm	0,25	3 cm	0,42	0,32
150°	3 mm	0,25	3 cm	0,42	0,35

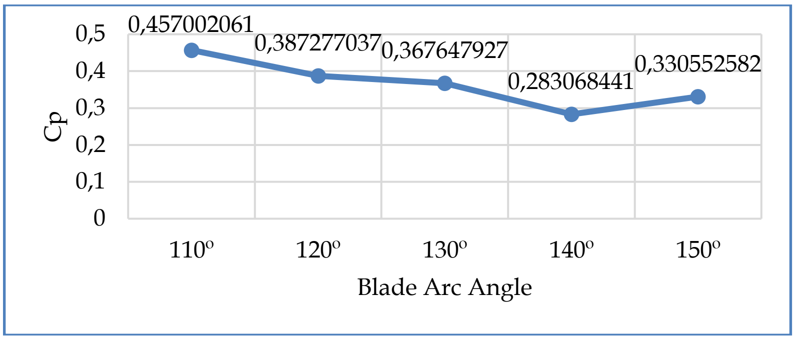


Figure 9. The graph depicting the relationship between blade arc angle and power coefficient (C_p) for a blade thickness of 4 mm

Table 3. Results of power coefficient for various blade arc angle variations with a thickness of 4 mm

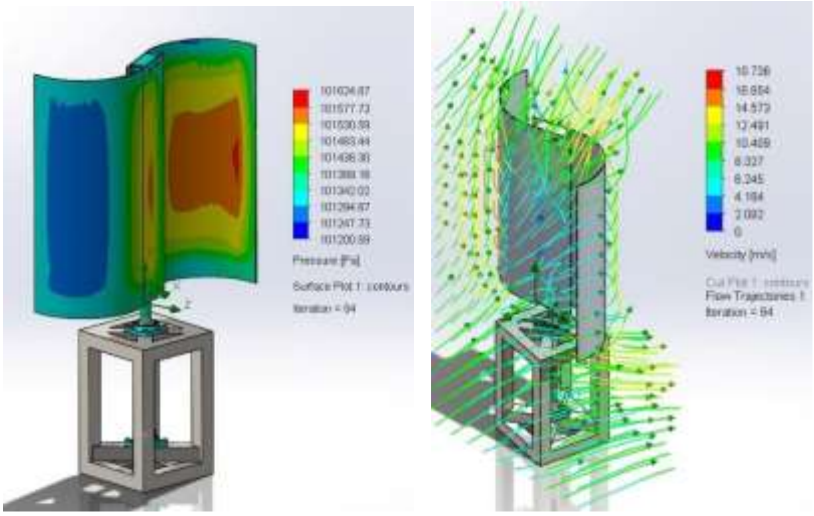
Blade Arc Angle	Blade Thickness	TSR	Blade Spacing	Ratio Overlap	Coefficient Power (C_p)
110°	4 mm	0,25	3 cm	0,42	0,45
120°	4 mm	0,25	3 cm	0,42	0,38
130°	4 mm	0,25	3 cm	0,42	0,36
140°	4 mm	0,25	3 cm	0,42	0,28
150°	4 mm	0,25	3 cm	0,42	0,33

The performance of the Savonius wind turbine with variations in blade arc angle at a thickness of 2 mm is shown in Figure 6, at a thickness of 3 mm in Figure 7, and at a thickness of 4 mm in Figure 8. The selection of geometries optimized from previous research ensures that most geometries show almost similar results. This is evident in the values for blade spacing of 3 cm and an overlap ratio of 0.42. All experiments were conducted at a tip speed ratio (TSR) of 0.25 with an incoming wind speed of 8 m/s.

In this study, a total of 15 geometries were investigated to evaluate the performance of the Savonius wind turbine. For a blade thickness of 2 mm, the highest power efficiency (C_p) reached 38% at a blade arc angle of 130°, with a blade spacing of 3 cm and an overlap ratio of 0.42. Meanwhile, for a blade thickness of 3 mm, the highest C_p value reached 41%

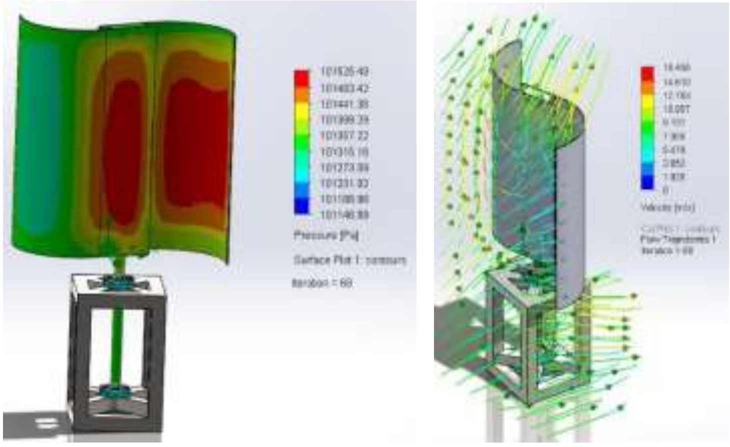
at a blade arc angle of 120°, with a blade spacing of 3 cm and an overlap ratio of 0.42. On the other hand, a blade thickness of 4 mm resulted in the highest power efficiency of 45% at a blade arc angle of 110°, with a blade spacing of 3 cm and an overlap ratio of 0.42. These results demonstrate how variations in blade thickness and blade arc angle affect the performance of the Savonius wind turbine.

Figure 9 shows the pressure contours and velocity contours plotted to demonstrate the pressure and velocity results when the Savonius wind turbine with a blade thickness of 2 mm and a blade arc angle of 130° is subjected to wind. Figure 10 shows the pressure contours and velocity contours generated when the turbine with a blade thickness of 3 mm and a blade arc angle of 120° is subjected to a wind speed of 8 m/s. Meanwhile, Figure 11 displays the pressure contours and velocity contours to demonstrate the pressure and velocity results when the turbine with a blade thickness of 4 mm and a blade arc angle of 110° is exposed to a wind speed of 8 m/s.



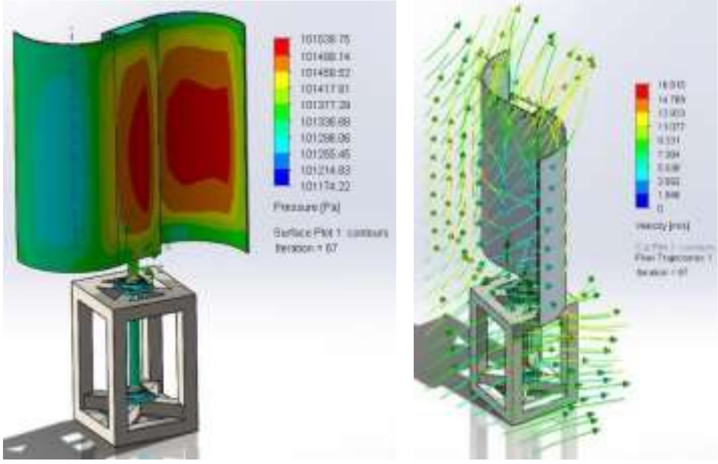
a b

Figure 10. Simulation results of Pressure (a). Simulation results of Velocity (b) with a blade thickness of 2 mm and a blade arc angle of 130°



a b

Figure 11. Simulation results of Pressure (a). Simulation results of Velocity (b) with a blade thickness of 3 mm and a blade arc angle of 120°



a b

Figure 12. Simulation results of Pressure (a). Simulation results of Velocity (b) with a blade thickness of 4 mm and a blade arc angle of 110º

Conclusions

This study aims to optimize the design of a Savonius wind turbine with PVC blades using CFD simulations in SolidWorks. Various parameters such as blade thickness and blade arc angle were considered to improve the turbine's power coefficient (C_p). To validate the results of this study, the simulation values were compared with similar previous research (Manavar, 2023).

The conclusion of this study is that the blade shape with an arc angle of 110º and a blade thickness of 4 mm provides the highest efficiency at 45%, as shown in Table 3. However, good performance results were also observed in other shapes in terms of strength. Due to time constraints, the number of simulations conducted was limited but still maximized. The results indicate that different blade thicknesses can affect power efficiency in combination with blade arc angles. This shows that design variables such as blade thickness significantly impact the performance of Savonius wind turbines.

Future research is expected to expand the scope of design variables that may affect turbine performance to achieve greater efficiency. This study is also based on 3D simulation results, and further experimental validation is needed to verify the accuracy of these results. By continuing this research, more in-depth insights into the factors influencing the performance of Savonius wind turbines can be obtained, ultimately supporting the development of more efficient and sustainable renewable energy technologies.

Acknowledgments

We would like to express our deepest gratitude to Mrs. Tria Puspa Sari, S.T., M.S., for her exceptional guidance and support in this research. Her dedication and direction have been invaluable to the progress and success of this study. The technical assistance and material support provided by Mrs. Tria Puspa Sari have made a significant contribution, enabling this research to be completed successfully. We greatly appreciate all the effort and time she has devoted to achieving the best possible results in this study.

References

Afidah, Z., Yushardi, Y., & Sudarti, S. (2023). Analisis Potensi Pembangkit Listrik Tenaga Bayu Dengan Turbin Angin Sumbu Vertikal Di Kecamatan Sangkapura Kabupaten Gresik. *Jurnal Engine: Energi, Manufaktur, Dan Material*, *7*(1), 8–14.

Ajayi, O. A. (2012). *Application Of Automotive Alternators In Small Wind Turbines*.

Bedon, G., Paulsen, U. S., Madsen, H. A., Belloni, F., Castelli, M. R., & Benini, E. (2017). Computational Assessment Of The Deepwind Aerodynamic Performance With Different Blade And Airfoil Configurations. *Applied Energy*, *185*, 1100–1108.

Bela\"\Id, F., & Zrelli, M. H. (2019). Renewable And Non-Renewable Electricity Consumption, Environmental Degradation And Economic Development: Evidence From Mediterranean Countries. *Energy Policy*, *133*, 110929.

Ebrahimpour, M., Shafaghat, R., Alamian, R., & Safdari Shadloo, M. (2019). Numerical Investigation Of The Savonius Vertical Axis Wind Turbine And Evaluation Of The Effect Of The Overlap Parameter In Both Horizontal And Vertical Directions On Its Performance. *Symmetry*, *11*(6), 821.

Mahata, S., Harsh, P., & Shekher, V. (2024). Comparative Study Of Time-Series Forecasting Models For Wind Power Generation In Gujarat, India. *E-Prime-Advances In Electrical Engineering, Electronics And Energy*, *8*, 100511.

Manavar, V. (2023). *Design Optimization Of Savonius Wind Turbine Using Cfd Simulations*.

Murphy, R. (2024). What Is Undermining Climate Change Mitigation? How Fossil-Fuelled Practices Challenge Low-Carbon Transitions. *Energy Research \& Social Science*, *108*, 103390.

Nakhoda, Y. I., & Saleh, C. (2015). Rancang Bangun Kincir Angin Pembangkit Tenaga Listrik Sumbu Vertikal Savonius Portabel Menggunakan Generator Magnet Permanen. *Industri Inovatif: Jurnal Teknik Industri*, *5*(2), 19–24.

Nasr, K., & Others. (2023). Computational Fluid Dynamics Investigations Over Conventional And Modified Savonius Wind Turbines. *Heliyon*, *9*(6).

Parinduri, L., & Parinduri, T. (2020). Konversi Biomassa Sebagai Sumber Energi Terbarukan. *Jet (Journal Of Electrical Technology)*, *5*(2), 88–92.

Qasemi, K., & Azadani, L. N. (2020). Optimization Of The Power Output Of A Vertical Axis Wind Turbine Augmented With A Flat Plate Deflector. *Energy*, *202*, 117745. Https://Doi.Org/10.1016/J.Energy.2020.117745

Rezaeiha, A., Kalkman, I., Montazeri, H., & Blocken, B. (2017). Effect Of The Shaft On The Aerodynamic Performance Of Urban Vertical Axis Wind Turbines. *Energy Conversion And Management*, *149*, 616–630.

Roy, S., & Saha, U. K. (2015). Wind Tunnel Experiments Of A Newly Developed Two-Bladed Savonius-Style Wind Turbine. *Applied Energy*, *137*, 117–125.

Samosir, R., Pane, M., & Lumbantoruan, J. H. (2021). Perancangan Turbin Angin Vertikal Modifikasi Gabungan Savonius Dan Darrieus Menggunakan Geometri Naca 0018. *Journal Of Mechanical Engineering Manufactures Materials And Energy*, *5*(1), 69–77.

Setyono, A. E., & Kiono, B. F. T. (2021). Dari Energi Fosil Menuju Energi Terbarukan: Potret Kondisi Minyak Dan Gas Bumi Indonesia Tahun 2020--2050. *Jurnal Energi Baru Dan Terbarukan*, *2*(3), 154–162.

Sudrajat, A., Hidayanti, F., Repi, V. V. R., & Widjayahakim, D. (2020). Perancangan Sistem Kontrol Otomatis Turbin Angin Yaw Direction. *Jurnal Ilmiah Giga*, *23*(2), 83–90.

Xu, Y.-L., Peng, Y.-X., & Zhan, S. (2019). Optimal Blade Pitch Function And Control Device For High-Solidity Straight-Bladed Vertical Axis Wind Turbines. *Applied Energy*, *242*, 1613–1625.

Zilberman, M. (2017). Optimization Of Small, Low Cost, Vertical Axis Wind Turbine For Private And Institutional Use. *Ace Res. Propos*, *9*, 43302.

Иванов, И. В., Ковалишена, О. В., & Швабский, О. Р. (2017). Опыт Аудита Обеспечения Качества И Безопасности Медицинской Деятельности В Медицинской Организации По Разделу" Эпидемиологическая Безопасность". *Вестник Росздравнадзора*, *4*, 9–14.