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Analysis Of The Utilization Of A House Scale Exhaust Fan On The Performance Of A Wind Turbine Type Savonius Vertical Axis

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Abstract: The fossil fuel crisis in Indonesia, which contributes 85% of the national energy mix, has driven the need to utilize renewable energy sources, one of which is exhaust wind as industrial waste energy that has high speed (5-7 m/s) and good flow continuity. This study developed a vertical Savonius turbine with variations in exhaust-turbine distance (20, 30, 40 cm) and measured wind speed (5.3, 6, 6.4 m/s) to optimize the utilization of this energy. The results showed that the 20 cm configuration produced the best performance with a maximum power of 5.98 watts at a speed of 6.4 m/s and a Coefficient Performance (CP) of 0.16, which is 31% more efficient than a distance of 40 cm, proving the potential of exhaust wind as a renewable energy solution that is applicable in industry with a payback period of less than 3 years and the potential for reducing the load on the electricity network by up to 15%.
Keywords: Savonius turbine; exhaust fan; waste energy; Coefficient Performance; renewable energy

1. Introduction

Rapid population growth in Indonesia has been accompanied by a significant increase in electrical energy demand. In addition to demographic growth, other factors such as industrialization and changing energy consumption patterns are also driving the increase in national electricity demand [1]. In addition, burning fossil fuels produces greenhouse gas emissions, such as carbon monoxide (CO) and carbon dioxide (CO_2), which contribute to global warming and climate change. Therefore, the development and utilization of clean and environmentally friendly renewable energy sources is urgently needed to support a sustainable energy transition. The application of wind power generation systems is still limited and not technically or economically efficient [2]. In addition to natural wind sources, artificial wind sources, such as exhaust air from cooling and ventilation systems (e.g., exhaust fans), have great potential as alternative energy sources [3]. Such exhaust air generally has a high, consistent, and predictable flow velocity, making it a viable source of kinetic energy that can be converted into electrical energy.

In the context of energy conversion, a turbine is a mechanical device that converts kinetic energy from fluid flow into mechanical energy. The turbine consists of a rotor that rotates owing to the push of a fluid, such as water, steam, or gas, directed through a nozzle at a certain speed, thus producing mechanical energy to drive loads, such as generators or pumps [4]. One type of wind turbine that is suitable for use in low wind speed conditions, especially in urban environments, is the Savonius-type vertical axis turbine.

The working principle of the turbine is shown in **Figure1**. Savonius turbines have the advantage of high torque even at low rotational speeds and do not require a wind direction tracking system [5]. These characteristics make them ideal for utilizing irregular wind flows, such as those from exhaust fan systems [6]. The Savonius turbine shown in **Figure 2** has a simple design and can operate at low wind speeds, making it a potential solution for artificial wind energy utilization, especially in dense urban areas.

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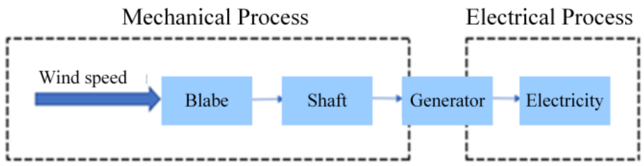

Figure 1. How wind turbines work
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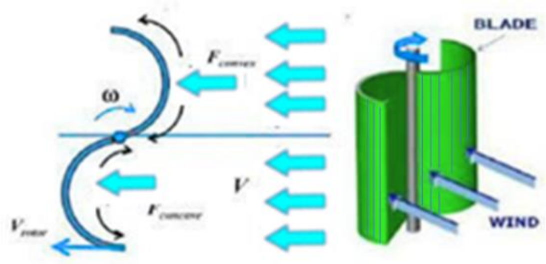


Figure 2. Savonius turbine and wind flow direction

As research in this field has developed, various studies have been conducted to improve the efficiency and performance of Savonius turbines through design modifications. Manganhar [4] found that adjustments to blade geometry, such as the addition of overlaps and endplates, can increase the output voltage at varying wind speeds. They also concluded that tighter blade spacing can result in greater thrust owing to the formation of constructive turbulence. Hady Aboujaoude [7] conducted a power analysis of Savonius-type vertical wind turbines through CFD simulations and experiments and found that the theoretical power (CFD) was always higher than the experimental results, which was due to friction losses and transmission system imperfections. The mechanical efficiency of the energy conversion system is key to approaching the theoretical power. They also noted that the arrangement of blades and the distance between blades had a significant effect on the power output. Furthermore, another study reported that the addition of a layer on the blade surface can increase the power coefficient by up to 22.4% at wind speeds between 6.5 and 7.3 m/s. This shows that blade surface modification is an effective approach for improving turbine aerodynamic performance [8].

In addition to physical modifications, computational approaches have also begun to be integrated into the design optimization process. Singh et al. [9] used a combination of Kriging surrogate model and Grey Wolf optimization algorithm to obtain the optimal design configuration. The results showed an increase in the power coefficient of 34.24%, indicating the great potential of applying artificial intelligence-based methods in Savonius turbine design. In addition, another study highlighted the importance of adding a guide vane with a specific tilt angle as an auxiliary element to direct the wind flow more efficiently toward the turbine blades. The use of this guide vane was proven to improve turbine performance by 65.89%, which further reinforces the importance of wind flow direction regulation in Savonius turbine-based energy conversion systems [10].

In contrast to previous research, this study aimed to design and test the performance of a modified Savonius turbine to capture energy from exhaust fan exhaust air, with variations in wind speed parameters (5.3, 6.0, and 6.4 m/s) and installation distance to the wind source (20, 30, and 40 cm). The novelty of this research lies in the utilization of an artificial wind source that has not been widely studied, as well as an experimental approach that combines distance and speed variables for the optimization of Savonius turbine performance in urban environments.

2. Methodology

This research was conducted through several main stages, which include the design and manufacture of Savonius-type wind turbines, theoretical calculations of turbine performance parameters, and experimental testing to obtain actual performance data from the prototype that has been made. Each stage was carried out systematically to ensure the accuracy of the results and relevance to the research objectives.

2.1 Design and Manufacture of Savonius Turbine

The initial stage of this research involved designing a Savonius wind turbine by considering aspects such as aerodynamics, energy conversion efficiency, and ease of manufacturing. The turbine was designed using a half-cylindrical two-blade model with a vertical orientation. The fabrication process was carried out using lightweight and corrosion-resistant materials to ensure resistance to environmental influences. The turbine dimensions were determined based on the experimental parameters and relevant literature, such as the rotor diameter, turbine height, and blade shape.

2.2 Theoretical Calculations

Theoretical calculations were performed to determine the potential energy that can be converted by the turbine and the key parameters that affect its performance. This analysis includes several important components, namely the tip Speed Ratio, output power, theoretical data, and experimental results. Tip Speed Ratio (TSR) is the ratio between the linear speed of the blade tip and the wind speed. In Savonius turbines, the TSR value is generally less than 1 because these turbines operate on the principle of drag. The TSR value can be calculated using the following equation:

$$\omega = \frac{2\pi RPM}{60} \tag{1}$$

$$\lambda = \frac{\omega \times Rrotor}{v\ wind} \tag{2}$$

The output power was measured by recording the voltage and current using a digital multimeter. The electrical power was calculated using the following equation:

$$P = I \times V \tag{3}$$

The theoretical power generated by a Savonius turbine is calculated by considering the air density, rotor sweep area, and wind speed as follows:

$$P = \frac{1}{2}\rho A v^3 wind \tag{4}$$

Torque is the moment of force that causes the turbine rotor to rotate in the wind turbine. The torque value can be calculated using the following equation:

$$\tau = \frac{V^2 R^2}{\lambda^2} \tag{5}$$

The coefficient of performance is used to assess the efficiency of the energy conversion by the turbine. Its value is determined from the ratio of the actual power of the turbine to the maximum power available from the wind:

$$CP = \frac{Pturbine}{Pin\ max} \tag{6}$$

2.3 Experimental Testing

Experimental testing was conducted to obtain empirical data related to the performance of Savonius turbines. This process included two main measurements: the rotational speed and the electrical power output produced by the turbine.

a. Turbine rotational speed measurement (**Figure 3**): The rotational speed of the turbine was measured using a digital tachometer that operated by reflecting a laser beam onto a reflector attached to the top of the blade. The rotation value was automatically displayed on the screen of the measuring instrument. Each parameter was tested thrice to improve data reliability. Tests were conducted by varying the wind speed (5.3, 6.0, and 6.4 m/s) and the exhaust fan-to-blade distance (gap) (20, 30, and 40 cm). The data obtained were analyzed and compared with the results of theoretical calculations to evaluate the conformity between the initial design and the actual performance of the turbine.
b. Turbine power output measurement (**Figure 4**): Power output data were collected using a digital AVO meter to ensure the accuracy of the current and voltage measurements. These values were then used to calculate the electrical power generated by the turbine using Equation (3), and the figure below shows the process of capturing the turbine power output data during the test.

Figure 3. Turbine rotation speed measurement

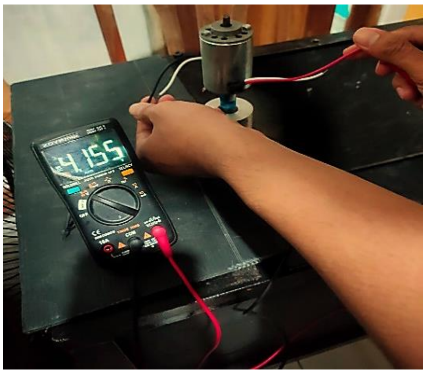


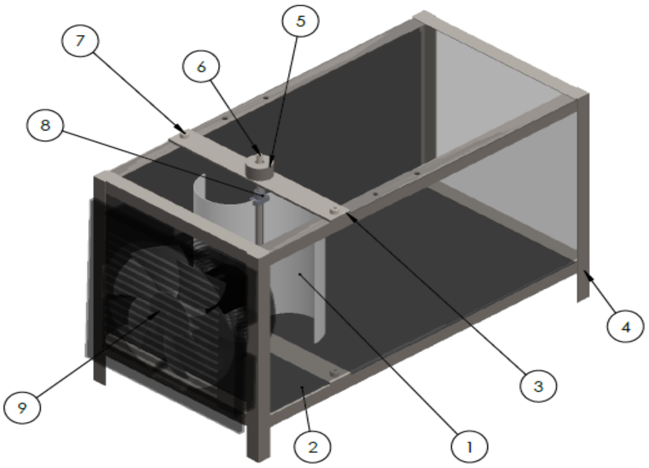
Figure 4. Turbine power measurement

3. Results and discussion

3.1 Result of Design

The device was designed as a basis for the manufacture of a laboratory-scale Savonius wind turbine prototype. The tool set was designed to withstand mechanical loads, facilitate the measurement process, and allow variations in parameters such as wind speed and exhaust fan-to-blade distance. **Figure 5** shows a three-dimensional model of the tool-design concept used in this study. The design includes several major components that are systematically arranged to support the performance testing of wind turbines. The main frame was made of a sturdy metal material to support the entire structure, and a wind tunnel was used to direct the airflow in a focused manner towards the turbine blades. An exhaust fan was positioned at the rear to generate the required wind speed during the test.

This design also allows the installation of a reflector for the tachometer to measure the rotational speed, as well as electrical connections for the direct recording of voltage and current. Overall, the design was developed with airflow efficiency, ease of assembly, and accuracy of the data capture process in mind.



Remarks:

1. Turbine blade
2. Wind tunnels
3. Adjuster shaft
4. Turbine frame
5. Bearing housing
6. Turbine shaft
7. M10 bolt
8. Join the blades
9. Exhaust fan

Figure 5. Vertical axis turbine design concept

3.2 Turbine Rotational Speed Testing

Measurement of turbine rotation using a digital tachometer. The tachometer was directed towards the wind turbine. RPM measurements were taken three times at each speed to ensure the accuracy of the obtained data. The turbine rotation test data are presented in **Table 1** and **Figure 6**.

Table 1. Turbine rotational speed test results

Wind speed	Distance 20 cm			Average	Distance 30 cm			Average	Distance 40 cm			Average
(m/s)	1	2	3		1	2	3		1	2	3	
5,3	397	394	396	396	328	342	339	336	266	285	282	278
6	449	445	456	450	363	394	391	383	308	350	353	337
6,4	513	508	511	511	412	437	452	434	411	410	430	417

Table 1 presents the measurement data of voltage, current, and electrical power generated by the Savonius wind turbine at various wind speeds (5.3, 6.0, and 6.4 m/s) and exhaust fan-to-blade distances (20, 30, and 40 cm). The data show that an increase in wind speed is directly proportional to an increase in the output power generated. For example, at an exhaust fan to blade distance of 20 cm, the output power increased from 1.35 W at a wind speed of 5.3 m/s to 3.00 W at 6.4 m/s. In addition, the distance from the exhaust fan to the blade affects the turbine performance. The 20 cm distance produced the highest output power compared to the 30 cm and 40 cm distances at the same wind speed. This shows that setting the optimal exhaust fan-to-blade distance can increase the efficiency of the turbine. Figure 6 shows the relationship between the wind speed and turbine output power for various exhaust fan-to-blade distances. The graph shows an increasing trend in the output power as the wind speed increases. The curve for the exhaust fan to blade distance of 20 cm is above the other curves, confirming that this configuration provided the best performance under the test conditions.

The results of this study are in line with those of [9,11], which showed that Savonius turbine design optimization, including the use of cylindrical deflectors, can increase the coefficient of power (Cp) by up to 26.94% at a Tip Speed Ratio (TSR) of 0.9. Although this study did not use a deflector, the effect of the exhaust fan on the blade distance on the increase in output power shows that modifying the physical design of the turbine can significantly contribute to the efficiency of the energy produced [11]. Although the approach used is different, the results of this study support the conclusion that design parameters, such as the exhaust fan-to-blade distance, have a significant impact on turbine performance [9].

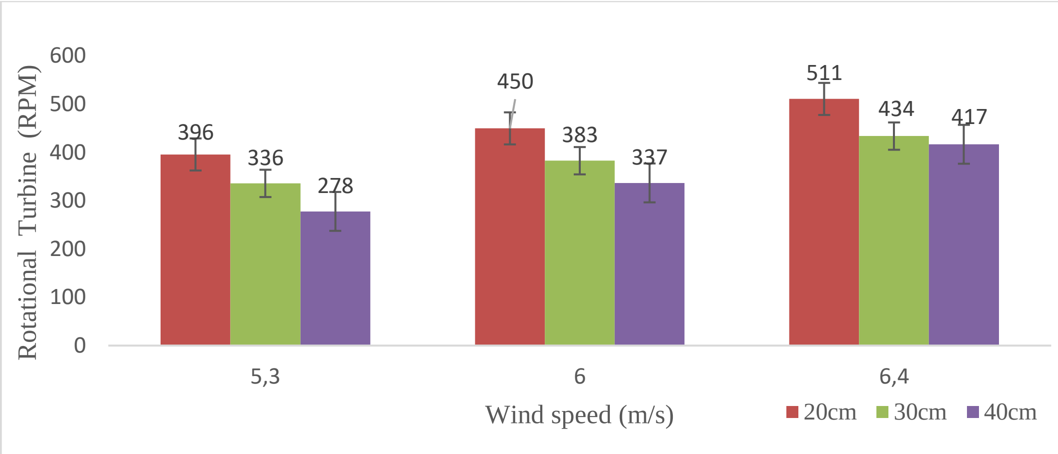


Figure 6. Graph of the relationship between rotational speed and wind speed

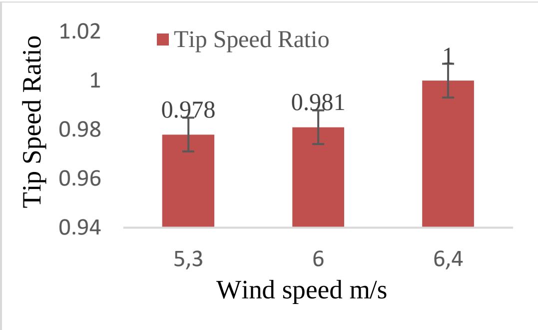


Figure 7. Graph of the relationship between wind speed and tip speed ratio at a blade distance of 20 cm

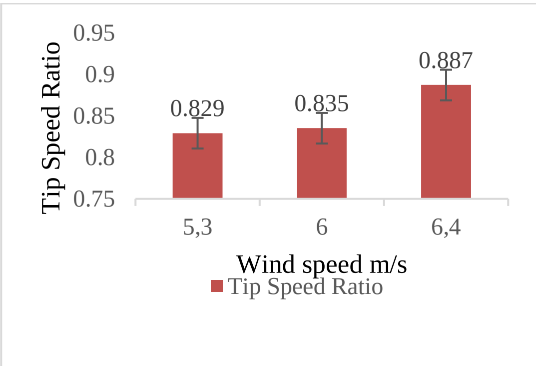


Figure 8. Graph of the relationship between wind speed and tip speed ratio at a blade distance of 30 cm

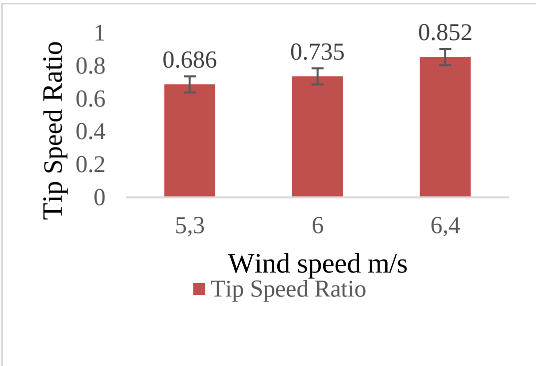


Figure 9. Graph of the relationship between wind speed and tip speed ratio at a blade distance of 40 cm

Figure 7 shows the relationship between wind speed and tip speed ratio (TSR) for a blade spacing of 20 cm. At a wind speed of 5.3 m/s, the TSR reaches a value of 0.829-0.88, then fluctuates as the wind speed increases. The highest TSR value (0.98-1) was achieved in the speed range of 6-6.4 m/s, indicating that the turbine was operating close to optimal conditions. Fluctuations in the TSR at low speeds (5.3-5.5 m/s) may be due to the initial rotational inertia of the blades. The stability of the TSR at high speeds indicates that the 20 cm blade spacing can maintain the efficiency of converting wind kinetic energy into rotational energy. **Figure 8** shows the relationship between wind speed and TSR for a blade spacing of 30 cm. The TSR of the 30 cm blade spacing tended to be lower than that of the 20 cm blade spacing, with values ranging from 0.686-0.852 at 5.3-6.4 m/s. There was no achievement of TSR > 0.9, even at the maximum speed (6.4 m/s). The decrease in the TSR indicates that the 30 cm blade requires more wind energy to achieve optimal rotation. This could be due to a higher moment of inertia or aerodynamic drag, which reduces the responsiveness of the blades. **Figure 9** shows the relationship between wind speed and TSR for the 40 cm blade. The 40 cm spacing recorded the lowest TSR (0.2-0.735) with significant variation. At 5.3 m/s, the TSR was only 0.2, and then increased unsteadily to 0.735 at 6.4 m/s. The low TSR confirmed that large blades were less efficient in energy conversion at low wind speeds. The instability of the TSR may be due to airflow turbulence or structural imbalance of the blades.

Effect of blade spacing: small spacing (20 cm) has a higher and more stable TSR, which is suitable for locations with moderate wind speed (5-7 m/s). Large spacing (30-40 cm): Requires higher wind speeds to achieve optimal TSR, thus more suitable for areas with strong winds (>7 m/s). A 20 cm spacing can be considered for small-scale applications (e.g., residential), while 30-40 cm spacing requires design modifications (e.g., lighter material) to reduce inertia. The TSR values of all blades were still below the Betz limit (ideal TSR ≈ 5-8), indicating opportunities for improvement through aerodynamic engineering. These results reinforce previous findings that the wind turbine blade size significantly affects the TSR and system efficiency. The blade design selection should be tailored to the wind speed profile of the installation site.

The results of this study are in line with the findings of Nawir et al. [12], who showed that modifying Savonius turbine blades with a tilt angle of 45° in a two-blade configuration produced the highest power of 1.88 W and efficiency of up to 36.92% at a wind speed of 6 m/s. Although the modification approach used in this study is different, both studies emphasize the importance of blade design as a major factor in improving turbine performance. Furthermore, this finding is reinforced by the results of Kurniawan et al. [8], who proved that changes in blade design, such as the addition of layers or shape variations, can significantly improve turbine efficiency. Thus, blade design remains a key component in optimizing Savonius turbine performance at low wind speeds, whether through angle setting or surface geometry modification. Furthermore, although the approach used differs from direct blade modification, a study by Salim et al. [10] showed that airflow regulation through additional elements, such as a guide vane, can also substantially improve turbine efficiency. In their study, the use of a guide vane with a specific tilt angle increased the efficiency by 65.89%, indicating that managing the direction and concentration of wind flow on the blades plays a major role in the effectiveness of energy conversion.

3.3 Voltage and Current Measurement Results

Analyzing the results of the voltage and current measurements in **Table 2**, the average voltage increased from 4.35 V (5.3 m/s) to 5.98 V (6.4 m/s) as the distance to the 20 cm blade increased. The average current increased from 0.31 A to 0.50 A. This indicates that the best electrical performance was achieved when the distance to the blade was 20 cm, where the wind flowed more efficiently and hit the blade to produce optimal rotation. As shown in **Table 3**, at a distance to blade of 30 cm, the voltage increased from 3.13 to 4.43 V, while the current increased from 0.24 to 0.38 A. Despite the increase, the values were lower than those of the 20 cm configuration, indicating a decrease in efficiency due to the larger distance to the blade. Furthermore, in **Table 4**, a with distance to blades of 40 cm, the voltage increased from 2.87 V to 4.33 V, while the current increased from 0.19 A to 0.30 A. This was the lowest performance of the three configurations, indicating that blades with a distance that is too wide caused air turbulence and loss of wind momentum.

The higher the wind speed, the greater is the voltage and current generated. A smaller exhaust fan-to-blade distance (20 cm) produced the highest output, indicating a more effective design for harvesting wind kinetic energy. Tummala et al. [13] explained that the efficiency of Savonius turbines is strongly influenced by blade geometry and spacing. These findings are consistent with the results of this study, where 20 cm blade spacing produced the highest voltage and current at various wind speeds.

In addition, a study by Menet and Bourabaa [14] showed that a configuration of two Savonius blades arranged at narrow spacing provided the highest conversion efficiency of up to 30% at low-to-medium wind speeds. A shorter exhaust fan-to-blade distance (20 cm) provided the highest electrical output. Higher wind speeds significantly contributed to the increase in voltage and current. The results of this study emphasize the importance of blade design optimization (including spacing) for maximizing Savonius turbine efficiency.

Table 2. Voltage and current measurement results at 20 cm turbine distance

Wind speed (m/s)	Voltage (V)			Average Voltage (V)	Current (A)			Average Current (A)
	1	2	3		1	2	3	
5,3	4	3,9	4,2	4,35	0,31	0,31	0,31	0,31
6	5	5	4,9	5,23	0,42	0,43	0,45	0,43
6,4	5,8	5,9	5,8	5,98	0,50	0,50	0,48	0,5

Table 3. Voltage and current measurement results at 30 cm turbine distance

Wind speed (m/s)	Voltage (V)			Average Voltage (V)	Current (A)			Average Current (A)
	1	2	3		1	2	3	
5,3	3,1	3,2	3,1	3,13	0,23	0,24	0,24	0,24
6	3,8	3,7	3,5	3,67	0,34	0,36	0,36	0,35
6,4	4,4	4,6	4,3	4,43	0,38	0,38	0,38	0,38

Table 4. Voltage and current measurement results at 40 cm turbine distance

Wind speed (m/s)	Voltage (V)			Average Voltage (V)	Current (A)			Average Current (A)
	1	2	3		1	2	3	
5,3	3	2,8	2,8	2,87	0,18	0,19	0,20	0,19
6	3,7	3,4	3,6	3,57	0,23	0,21	0,24	0,23
6,4	4,3	4,4	4,3	4,33	0,28	0,28	0,30	0,3

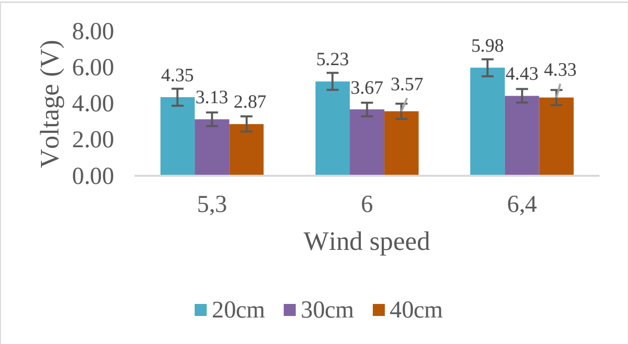


Figure 10. Voltage output graph

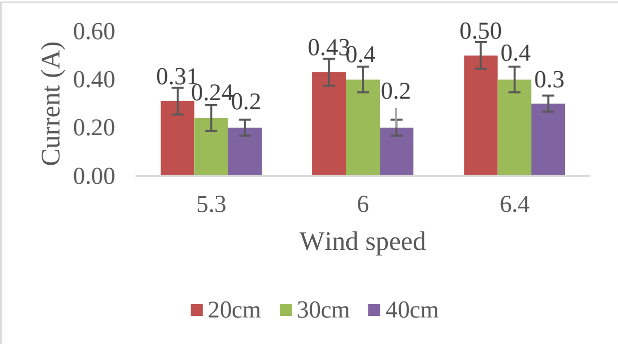


Figure 11. Current output graph

Figure 10 shows that the voltage produced increased as the wind speed increased. The highest voltage was recorded at a distance of 20 cm with a wind speed of 6.4 m/s, resulting in a voltage of 5.98 V. In contrast, at a distance of 40 cm, the output voltage was lower despite the same wind speed. This suggests that a closer distance to the blades allows for more effective air interaction with the turbine blades, thereby improving energy conversion. **Figure 11** shows the current output, which indicates that the electric current also increases with an increase in wind speed, following a similar pattern to that of the voltage. The highest current of 0.50 A also occurred at a distance of 20 cm and speed of 6.4 m/s. Larger exhaust fan-to-blade distances (30 and 40 cm) showed a significant decrease in output current, indicating reduced system efficiency.

This study supports the result that a shorter exhaust fan-to-blade distance (20 cm) results in the best efficiency. The maximum voltage and current in this study also occurred at the minimum exhaust fan-to-blade distance. This demonstrates that aerodynamic factors, such as overlap, distance to the blade, and airflow control, significantly affect the electrical output efficiency of Savonius-type wind turbines. An increase in wind speed directly increases the voltage and currents. The exhaust fan-to-blade distance of 20 cm was found to be the most optimal for producing maximum voltage and current. These results are in line with Manganhar et al. 's research [4], which emphasizes that an efficient exhaust fan to blade geometry and distance design can improve the performance of Savonius turbines in low-to-moderate wind conditions. This study provides important insights into the optimization of Savonius turbine design for energy generation in areas with low-medium wind speeds.

3.4 Effect of Wind Speed and Distance to Blades on Wind Turbine Power

Wind energy is a potential renewable energy source. Wind turbines play an important role in converting wind kinetic energy into electrical energy (EA). One of the factors that affects wind turbine performance is wind speed and blade diameter. To understand these relationships, wind turbine power measurements were performed with variations in wind speed and blade diameter, as presented in Table 5.

Table 5. Wind turbine power

Wind speed	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)
(m/s)	20 cm			30 cm			40 cm		
5.3	4.35	0.31	1.35	3.13	0.24	1	2.87	0.2	0.57
6	5.23	0.43	2.25	3.67	0.4	1.5	3.57	0.28	1
6.4	5.98	0.5	3	4.43	0.4	2	4.33	0.3	1.3

Table 5 shows the measurement data of voltage (V), current (A), and power (W) produced by the wind turbine with three variations of exhaust fan to blade distance, namely 20, 30, and 40 cm, at various wind speeds. Here are some interesting findings from the data.

a. Effect of wind speed: The higher the wind speed, the more power is generated. For example, at a distance of 20 cm, when the wind speed increased from 5.3 m/s to 6.4 m/s, the power generated increased from 1.35 W to 3 W. This occurred because the greater kinetic energy of the wind rotated the turbine blades faster, thus increasing the electrical output.
b. Effect of distance to blade: The distance to the blade also significantly affects the turbine power. At a wind speed of 6 m/s, a distance of 20 cm produced 2.25 W of power, whereas distances of 30 and 40 cm produced lower power, 1.5 W and 1 W, respectively. This phenomenon could be attributed to the design factors or different system efficiencies for each blade size.
c. Turbine Performance Optimization: These data provide important insights into wind turbine optimization. If the goal is to generate maximum power at low wind speeds, blades with smaller diameters may prove more effective. However, for high wind speeds, the optimal combination of blade size and design must be further investigated. These measurements show that the wind speed and wind turbine blade diameter have a direct influence on the power generated. Choosing the appropriate blade size according to local wind conditions can improve turbine efficiency. Further research can be conducted by exploring variations in blade design and materials to obtain optimal performances. Thus, wind turbines can be a more effective renewable energy solution in the future.

Figure 12 shows that the generator output power increases as the wind speed increases, and that a distance to the blades of 20 cm provides the highest power. At a wind speed of 5.3 m/s, the maximum power of 1.35 W was obtained at a distance of 20 cm, whereas at a distance of 40 cm, it was only 0.57 W. At a wind speed of 6.4 m/s, the maximum power reached 3.0 W at a distance of 20 cm. These results indicate that a smaller exhaust fan-to-blade distance allows for better wind energy capture efficiency. **Figure 13** shows the effect of wind speed on the output power at a distance of 20 cm. There was a linear increasing trend, from 1.35 W (5.3 m/s), to 2.25 W (6 m/s), to 3.0 W (6.4 m/s). This confirms that wind speed is the dominant factor in the increase in wind turbine output power. Figure 14 compares the theoretical power (blue) with the directly measured power at three wind speeds. The theoretical power is much higher; for example, at 6.4 m/s, 18.81 W was recorded, whereas the highest measured result was only 3.0 W. This indicates significant power loss due to mechanical factors such as friction, energy conversion, and transmission efficiency from the rotor to the generator.

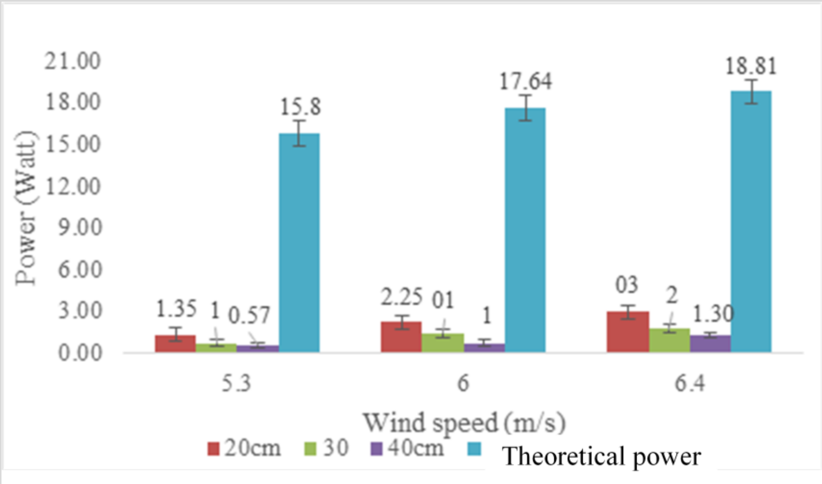


Figure 12. Power graph of calculated results compared to measurement results

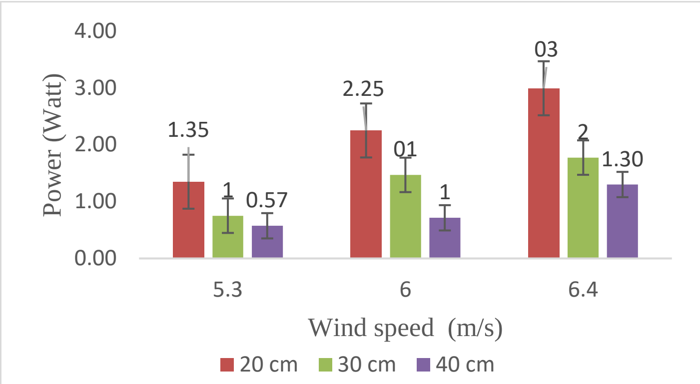


Figure 13. Graph of the relationship between power and wind speed and distance

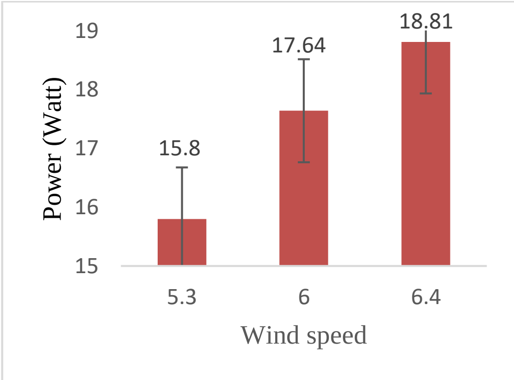


Figure 14. Graph of the relationship between power and wind speed

The decrease in real power to theoretical power (**Figure 14**) is consistent with the results of studies that also experienced low efficiency owing to mechanical losses [7]. The effect of the distance to the blade on performance (**Figure 13**) is also consistent with their findings, which suggests that the optimization of the blade configuration and reduction of the distance can improve efficiency. Wind speed is a major factor in the increase in turbine power, with a significant power increase at 6.4 m/s. The exhaust fan-to-blade distance of 20 cm was the most efficient in generating power compared to longer distances. There is a large difference between the theoretical power and direct measurement owing to mechanical energy loss and low conversion efficiency. These results are consistent with findings that demonstrate the importance of mechanical optimization and geometry design in Savonius turbine systems [7].

Table 6. Turbine torque values for 20 cm distance variation

Radius (cm)	Wind speed (m/s)	RPM	Tip speed ratio	Torque (Nm)
12,5	5,3	396	0,98	0,457
12,5	6	450	0,98	0,584
12.,5	6,4	511	1	0,64

Table 7. Turbine torque value of 30 cm distance variation

Radius (cm)	Wind speed (m/s)	RPM	Tip speed ratio	Torque (Nm)
12,5	5,3	336	0,829	0,6386
12,5	6	383	0,835	0,8067
12,5	6,4	434	0,887	0,8134

Table 8. Turbine torque value of 40 cm distance variation

Radius (cm)	Wind speed (m/s)	RPM	Tip speed ratio	Torque (Nm)
12,5	5,3	278	0,686	0,934
12,5	6	337	0,735	1,0412
12,5	6,4	417	0,852	0,8816

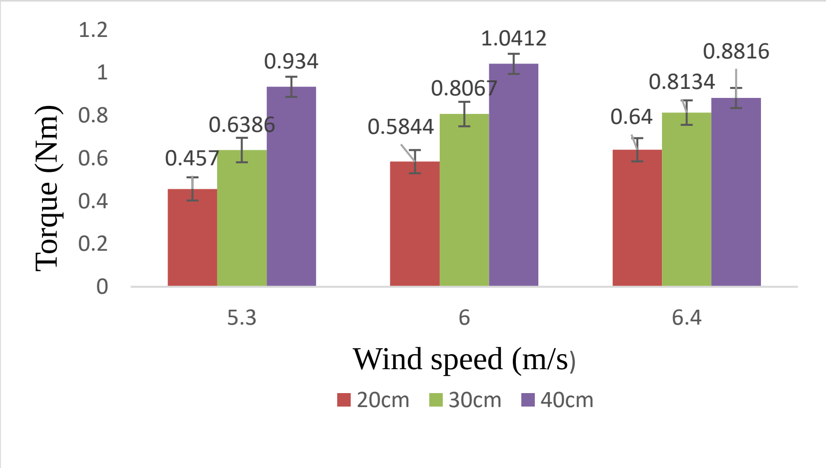


Figure 15. Graph of torque relationship with wind speed

Tables 6–8 present the results of turbine torque measurements at exhaust fan-to-blade distances of 20, 30, and 40 cm against three different wind speed values of 5.3, 6, and 6.4 m/s, respectively. The data are then visualized in **Figure 15** to show the trend of the relationship between wind speed and torque value at each distance configuration. Based on **Figure 15**, the torque value increases significantly with an increase in wind speed for all spacing configurations. At a distance of 20 cm, the torque increased from 0.457 Nm (5.3 m/s) to 0.64 Nm (6.4 m/s). A similar trend was observed at 30 cm, where the torque increased from 0.6386 Nm to 0.8134 Nm. Meanwhile, the 40 cm spacing configuration produced the highest torque of 1.0412 Nm at 6 m/s wind speed, but experienced a slight decrease to 0.8816 Nm when the speed was increased to 6.4 m/s.

This phenomenon of increasing torque is physically influenced by the increase in the wind compressive force against the turbine blade, which produces a greater torsional moment against the turbine shaft. In addition, increasing the distance between the exhaust fan and the blade expands the turbine sweep range against the wind flow, thereby increasing the potential for kinetic energy capture. However, the decrease in torque at the highest speed (6.4 m/s) at a distance of 40 cm can be attributed to the appearance of turbulence and aerodynamic efficiency loss phenomenon known as dynamic stall, which destabilizes the flow and decreases the blade lift.

This finding is reinforced by the results of a study that analyzed the performance of a vertical-axis wind turbine (VAWT) with variations in the distance to the blade. The study concluded that increasing the distance between the exhaust fan and the blade generally contributes to an increase in torque, particularly at low-to-medium wind speeds. However, at high speeds, the torque efficiency can decrease because of flow instability and increased aerodynamic resistance (drag losses). Thus, it can be concluded that the blade-to-blade configuration and wind speed significantly influence the turbine torque performance. To maximize the power generated, it is necessary to set the optimal distance to the blades according to the average wind speed characteristics at the turbine operating site [15].

Table 9. Relationship between wind speed and CP

Wind speed	Distance 20 cm			Distance 30 cm			Distance 40 cm		
m/s	P turbine	P in Max	CP	P turbine	P in Max	CP	P turbine	P in Max	CP
5,3	1,35	15,8	0,09	1	15,8	0,06	0,57	15,8	0,04
6	2,25	17,64	0,13	1,5	17,64	0,09	1	17,64	0,06
6,4	3	18,81	0,16	2	18,81	0,11	1,3	18,81	0,07

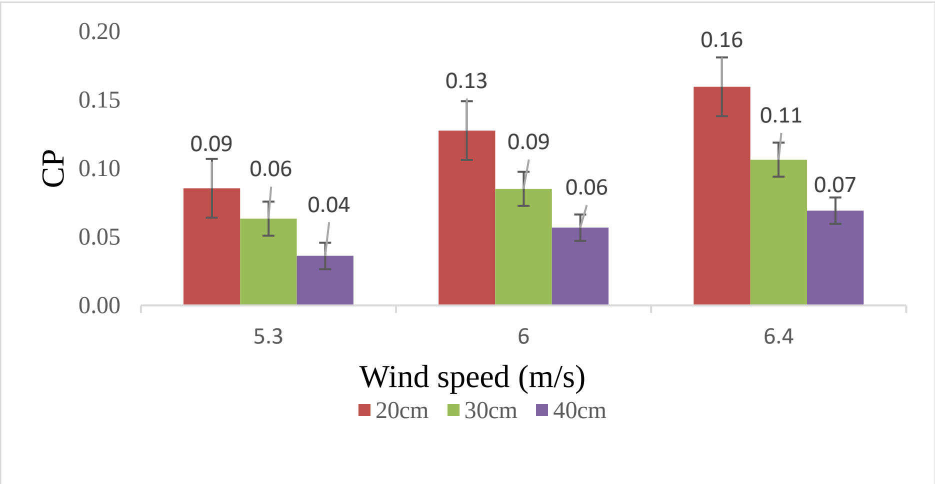


Figure 16. Graph of coefficient of performance at a distance of 20 cm, 30 cm, 40 cm

Table 9 shows the CP for a 20 cm blade, at a wind speed of 5.3 m/s, the turbine produced 1.35 W of power (P_turbine) with a CP of 0.09. The CP value increases linearly to 0.16 when the wind speed reaches 6.4 m/s, indicating a better energy conversion efficiency at high speeds. The theoretical maximum power (P_max) that the system can achieve ranges from to 15.8-18.81 W. In the CP for a 30 cm fan-to-blade distance, the turbine with a 30 cm fan-to-blade distance has a lower CP than the 20 cm, that is, at 6.4 m/s, the CP is only 0.11 (vs. 0.16 for a 20 cm fan-to-blade distance). This indicates that reducing the blade distance from 30 to 20 cm can increase the efficiency by 31% at the same speed. In the CP for the 40 cm blade-to-fan, the lowest performance was shown by the 40 cm blade-to-fan with a CP of 0.04-0.07. This low CP value may be due to the larger drag factor or the rotational inertia of the long blades.

Figure 16 shows the CP trends of the three distances to the blade against wind speed: 20 cm distance (blue line) has the steepest slope, confirming the most sensitive response to increasing wind speed. Distance to blade 30 cm (red line) and 40 cm (green line) showed a more gradual increase in CP, with Distance to blade of 40 cm consistently at the bottom. Line intersection points: At a speed of ≈5.8 m/s, the CP of the Distance to the 20 cm blade started to deviate significantly from those of the other two blades, marking the design optimization threshold. This finding is in line with wind energy theory, which states that CP ∝ wind speed, and an increase in wind speed magnifies the kinetic energy that can be converted. Distance-to-blade size trade-off: distance-to-blade (20 cm) is more efficient in capturing energy at low-medium speeds, whereas large blades may require higher wind speeds to achieve maximum CP. The results indicate that for on-site applications with an average wind speed of 5-7 m/s, a distance of 20 cm from the blade is optimal.

4. Conclusion

This study analyzed the effect of exhaust fan to blade distance (20, 30, and 40 cm) and wind speed (5.3–6.4 m/s) on wind turbine performance using the coefficient of performance (CP) parameter. The data showed a positive relationship between wind speed and CP, as well as a significant variation in performance between blade distances, from which experiments were obtained.

The highest rotational speed was observed at the 20 cm spacing variation, which was 511 rpm at a wind speed of 6, 4 m/s. The lowest puataran was found in the 40 cm spacing variation, which was 278 rpm at a wind speed of 5.3 m/s.

The maximum power generated by the turbine, which was at a distance variation of 20 cm, was 5.98 watts at a wind speed of 6.4 m/s. The lowest power generated by the turbine, which was at a distance variation of 40 cm, was 2.87 watts at a wind speed of 5.3 m/s.

The lowest torque was found at a distance variation of 20 cm, which was 0.45 Nm at a wind speed of 5.3 m/s. The highest torque value is found at a distance variation of 40 cm, which is 1.041 Nm at a wind speed of 6 m/s. The torque value increased as the distance between the exhaust fan and turbine increased. This indicates that the greater the distance between the exhaust fan and turbine, the greater the torque produced.

Distance and wind speed variations significantly affect the performance of Savonius wind turbines. The variations in distance and wind speed are directly proportional to the rotational speed, tip speed ratio, and turbine power. The closer the exhaust fan distance and the greater the wind speed, the greater the rotational speed, tip-speed ratio, and turbine power.

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