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# Performance Analysis of a Three-Blade Savonius Vertical-Axis Wind Turbine Prototype for Charging a 12 V 7 Ah Maintenance-Free Battery

Ihat Solihat[1], Firmansyah[2]
Program Studi Teknik Mesin, Fakultas Teknik, Universitas Pamulang, Jl. Witana Harja No. 18B, Pamulang Barat, Kecamatan Pamulang, Kota Tangerang Selatan 15417, Banten, Indonesia
Email: dosen00990@unpam.ac.id

The increasing demand for renewable energy has encouraged the development of small-scale wind energy conversion systems for standalone electricity generation. This study evaluates the performance of a three-blade Savonius vertical-axis wind turbine prototype in charging 12 V, 7 Ah Maintenance-Free and Flooded Lead-Acid batteries. Experimental testing was conducted indoors using a blower as the wind source with three wind source distances (100 cm, 150 cm, and 200 cm), corresponding to different wind speeds. The system performance was evaluated based on wind speed, generator rotational speed, electrical current, output power, power conversion efficiency, battery charging time, and battery endurance under lamp loads of 15 W, 25 W, and 30 W. The results showed that decreasing the distance between the wind source and the turbine increased wind speed, generator rotational speed, charging current, and electrical output power while reducing the battery charging time. The highest output power was obtained at the 100 cm distance with a charging current of 3.4 A and an output power of 10.8 W. The theoretical charging time ranged from 2.0 to 2.8 h; however, the actual charging time was longer because of electrical losses, charging controller characteristics, and battery operating conditions. Battery endurance decreased as the electrical load increased, indicating that higher discharge currents accelerated battery depletion. Overall, the prototype demonstrated the feasibility of using a Savonius vertical-axis wind turbine for small-scale battery charging applications, although improvements in turbine efficiency, energy conversion, and charging system performance are required to enhance practical performance.
**Keywords:** Savonius wind turbine, vertical-axis wind turbine, battery charging, Maintenance-Free battery, Flooded Lead-Acid battery, renewable energy.



**Corresponding Author:**
Ihat Solihat
Program Studi Teknik Mesin, Fakultas Teknik, Universitas Pamulang Kampus Witana, Jl. Witana Harja No. 18B, Pamulang Barat, Kecamatan Pamulang, Kota Tangerang Selatan 15417, Banten
dosen00990@unpam.ac.id

## 1. Introduction

The increasing demand for electricity, coupled with the depletion of non-renewable energy resources, has become a major challenge in achieving sustainable energy development. Population growth and industrial expansion have significantly increased electricity consumption, while the availability of fossil-based energy resources continues to decline. To address this issue, the Indonesian government has promoted energy conservation and encouraged the development of renewable energy technologies as part of the national energy policy (Meliala et al., 2020).

Among various renewable energy sources, wind energy has attracted considerable attention because it is abundant, environmentally friendly, and capable of reducing carbon dioxide emissions. Wind turbines convert the kinetic energy of moving air into mechanical energy, which is subsequently transformed into electrical energy through a generator. This electricity can be stored in batteries and later utilized to supply electrical loads, providing an alternative and sustainable energy solution for residential and small-scale applications (Latif et al., 2022).

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Vertical Axis Wind Turbines (VAWTs), particularly the Savonius type, offer several advantages over conventional horizontal-axis turbines. Savonius turbines are capable of operating at relatively low wind speeds, have a simple structural design, require minimal maintenance, and can capture wind from any direction without requiring a yaw mechanism. These characteristics make Savonius turbines suitable for urban environments and regions with fluctuating wind directions (Hidayat & Surbakti, 2021). Furthermore, computational fluid dynamics (CFD) simulations conducted by Arif (2019) demonstrated that appropriate blade configurations and flow-directing components can significantly improve the static torque and aerodynamic performance of Savonius turbines.

The electrical performance of a wind turbine is not determined solely by rotor design but also by the effectiveness of the energy storage system. Valve-Regulated Lead Acid (VRLA) maintenance-free batteries are widely used because they require minimal maintenance, exhibit low electrolyte evaporation, and provide reliable electrical storage for renewable energy systems. In comparison, Flooded Lead Acid (FLA) batteries require periodic maintenance but remain commonly applied because of their relatively low cost and high current capability (Sulthan Qintara et al., 2020). Therefore, evaluating battery charging performance under different operating conditions is essential to determine the overall effectiveness of a wind energy system.

Several previous studies have investigated the performance of Savonius wind turbines by examining blade geometry, airflow characteristics, and electrical output. However, limited research has comprehensively analyzed the combined effects of wind-source distance, generator rotational speed, charging characteristics, and battery endurance using a three-blade Savonius vertical-axis wind turbine prototype. Moreover, comparative evaluation between maintenance-free and flooded lead-acid batteries under identical operating conditions has received relatively little attention.

Therefore, this study aims to analyze the performance of a three-blade Savonius vertical-axis wind turbine prototype for charging a 12 V 7 Ah maintenance-free battery by evaluating the influence of wind-source distance on wind speed, generator speed, electrical output, charging time, power efficiency, and battery endurance. The findings are expected to contribute to the development of efficient small-scale wind energy systems and provide practical recommendations for optimizing renewable energy utilization in household electricity applications.

## 2. Literature Review and Problem Statement

### Wind Energy and Savonius Vertical-Axis Wind Turbine

Wind energy is one of the most promising renewable energy sources because it is environmentally friendly, sustainable, and capable of reducing dependence on fossil fuels. Wind turbines convert the kinetic energy of moving air into mechanical energy, which is subsequently transformed into electrical energy through a generator. Compared with conventional energy sources, wind energy offers a cleaner alternative with minimal greenhouse gas emissions and long-term sustainability (Meliala et al., 2020).

Wind turbines are generally classified into Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT). Among VAWTs, the Savonius turbine is widely recognized for its simple construction, ability to operate at relatively low wind speeds, and capability to capture wind from multiple directions without requiring a yaw control mechanism. These characteristics make Savonius turbines suitable for small-scale electricity generation and urban applications where wind direction changes frequently (Hidayat & Surbakti, 2021; Hernowo, 2020). Computational Fluid Dynamics (CFD) simulations conducted by Arif (2019) further demonstrated that optimizing blade configuration and flow direction can significantly improve the aerodynamic performance and static torque of Savonius turbines.

**Generator Performance and Battery Charging System**

The performance of a wind energy conversion system depends not only on turbine characteristics but also on the effectiveness of its electrical conversion and storage components. Mechanical energy generated by the turbine is converted into electrical energy through a DC generator, where the generated output power is determined by voltage and current. Consequently, generator rotational speed directly influences electrical output and battery charging performance.

Electrical energy produced by the generator is stored in rechargeable batteries for later use. In renewable energy systems, Valve Regulated Lead Acid (VRLA) or maintenance-free batteries are widely adopted because they require minimal maintenance and provide stable energy storage. Conversely, Flooded Lead Acid (FLA) batteries remain attractive because of their lower cost and high-current capability despite requiring periodic maintenance. Evaluating the charging characteristics and endurance of both battery types is therefore important for determining the overall effectiveness of small-scale wind energy systems.
2.3 Wind Turbine Performance

The effectiveness of a wind turbine is commonly evaluated through several performance indicators, including wind speed, generator rotational speed, electrical output power, charging time, and conversion efficiency. Wind speed is the primary factor affecting the amount of kinetic energy available for conversion. As wind speed increases, the rotational speed of the turbine and generator also increases, resulting in higher electrical output. Likewise, power efficiency represents the proportion of available wind energy successfully converted into usable electrical energy.

In this study, turbine performance is assessed under different blower distances to produce varying wind speeds. The electrical output is further analyzed based on battery charging time and battery endurance under different LED lamp loads. These performance indicators provide a comprehensive evaluation of the capability of a three-blade Savonius wind turbine prototype for small-scale electricity generation.

**Problem Statement**

Previous studies have demonstrated that Savonius wind turbines can effectively generate electrical energy under low wind-speed conditions and that improvements in blade configuration can enhance turbine performance (Arif, 2019; Hidayat & Surbakti, 2021). Existing research has also examined the influence of wind speed on electrical output and the general characteristics of renewable energy storage systems. However, relatively few studies have comprehensively investigated the combined effects of wind-source distance, generator rotational speed, electrical output, charging time, power efficiency, and battery endurance using a three-blade Savonius vertical-axis wind turbine prototype under controlled laboratory conditions.

Moreover, comparative evaluations between maintenance-free (VRLA) and Flooded Lead Acid (FLA) batteries under identical experimental conditions remain limited. Such comparisons are important for identifying the most suitable battery technology for small-scale wind energy applications. Therefore, this study addresses these research gaps by analyzing the performance of a three-blade Savonius vertical-axis wind turbine prototype in charging a 12 V 7 Ah maintenance-free battery, while evaluating the influence of wind-source distance on electrical performance, charging characteristics, and overall system efficiency.

## 3. Method

This study employed an experimental research design to evaluate the performance of a three-blade Savonius vertical-axis wind turbine prototype for charging a 12 V 7 Ah maintenance-free battery. The experiment was conducted by varying the distance between the wind source and the turbine to investigate

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its effect on wind speed, generator rotational speed, electrical output, charging performance, power efficiency, and battery endurance. The study was carried out in a closed indoor environment in Cilenggang, Serpong, South Tangerang, Indonesia, between December 2025 and January 2026 to minimize environmental disturbances and maintain consistent testing conditions.

The experimental setup consisted of a three-blade Savonius vertical-axis wind turbine with blade dimensions of 40 cm × 40 cm, coupled to a 300 W DC generator through a pulley and V-belt transmission system. A blower was used as the wind source, while a solar charge controller regulated battery charging. The generated electrical energy was stored in a 12 V 7 Ah Valve Regulated Lead Acid (VRLA) maintenance-free battery and compared with a 12 V 7 Ah Flooded Lead Acid (FLA) battery. The system was equipped with an anemometer to measure wind speed, a tachometer to determine generator rotational speed (RPM), and a digital multimeter to record voltage and current. Battery endurance was evaluated using 15 W, 25 W, and 30 W LED lamps as electrical loads.

Three experimental conditions were established by positioning the blower at distances of 100 cm, 150 cm, and 200 cm from the turbine. Each condition was tested repeatedly, and measurements were recorded over a 10-minute observation period. The measured variables included wind speed (m/s), generator rotational speed (RPM), output voltage (V), output current (A), electrical power (W), charging time, and battery operating duration under different loading conditions.

The collected data were analyzed using descriptive quantitative methods. Wind power input was calculated based on air density, rotor swept area, and wind velocity, while electrical output power was determined from the product of voltage and current. Turbine efficiency was calculated as the ratio of output power to wind power input. Battery charging time was estimated using battery capacity and charging current, whereas battery endurance was calculated from battery capacity and load current. The results were subsequently presented in tables and graphs to compare the performance of the prototype under different wind-source distances and battery types.

## 4. Results and Discussion

### Effect of Wind Speed on Input Power

The performance of the three-blade Savonius vertical-axis wind turbine was evaluated by varying the distance between the blower and the turbine at 100 cm, 150 cm, and 200 cm. The turbine used in this study had a blade height of 40 cm, a blade width of 40 cm, and three blades. The air density was assumed to be 1.2 kg/m$^3$, while each measurement was conducted for 10 minutes under controlled indoor conditions. Wind speed was measured using an anemometer, generator rotational speed was recorded using a tachometer, and the electrical output was measured using a digital multimeter.

Table 1 presents the wind speed measurements obtained under the three experimental conditions. At a blower distance of 100 cm, the measured wind speeds were 4.1 m/s, 4.2 m/s, and 3.8 m/s, with an average wind speed of 4.0 m/s. At a distance of 150 cm, the measured wind speeds were 4.0 m/s, 3.8 m/s, and 3.4 m/s, resulting in an average of 3.8 m/s. Meanwhile, at a distance of 200 cm, the wind speeds decreased to 3.7 m/s, 3.2 m/s, and 3.0 m/s, with an average of 3.3 m/s. These results indicate that increasing the distance between the blower and the turbine reduced the wind speed received by the rotor.

 

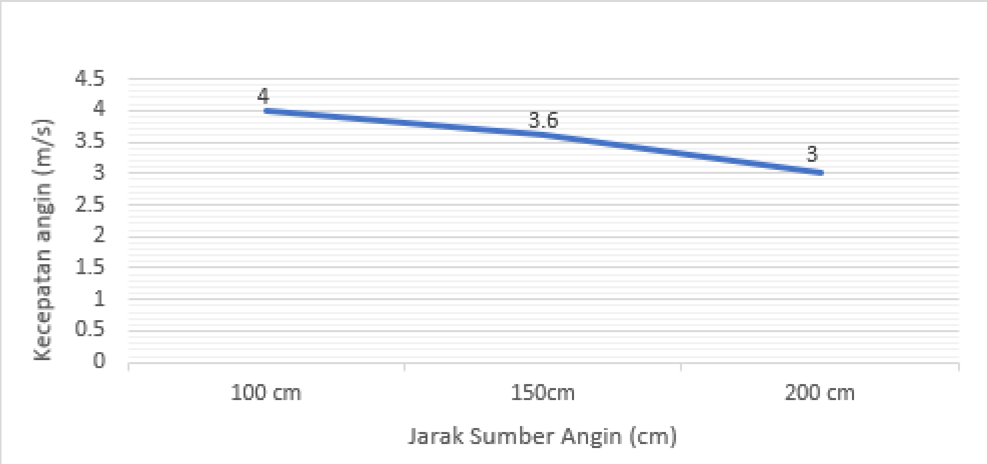


**Figure 1.** Effect of Wind Source Distance on Wind Speed

The experimental results also demonstrate slight variations among repeated measurements at each testing distance. These differences indicate that the airflow produced by the blower was not perfectly constant throughout the experiment, although the variations remained relatively small and within an acceptable experimental range. Despite these fluctuations, the overall trend consistently shows that a shorter blower distance produces higher wind speeds, while greater distances reduce the available wind energy reaching the turbine.

Based on the measured wind speed values, the input power of the wind turbine was subsequently calculated using the fundamental equations of fluid mechanics to determine the kinetic power available from the airflow. The calculated wind power served as the basis for evaluating the turbine's energy conversion performance and efficiency in the subsequent analysis.

**Wind Power Input**

**Table 1.** Wind Kinetic Power at Different Wind Source Distances

| Wind Source Distance (cm) | Wind Speed (m/s) | Generator Speed (rpm) | Current (A) | Voltage (V) | Mechanical Power (W) |
|---|---|---|---|---|---|
| 100 | 4.1 | 101.8 | 3.4 | 3.2 | 18.8 |
| 150 | 3.6 | 94.5 | 3.1 | 2.8 | 13.7 |
| 200 | 2.8 | 81 | 2.5 | 2.2 | 7.9 |

The wind power input was calculated using the classical kinetic power equation:

$$P_{in} = \frac{1}{2}\rho A v^3$$

where:

$P_{in}$= wind kinetic power (W)
$v$= wind speed (m/s)
$\rho$= air density (1.2 kg/m³)
$A$= rotor swept area multiplied by the number of blades (m²)

The wind kinetic power calculations were performed as follows:

a. Wind kinetic power at a wind speed of 4.0 m/s

$$P_{in} = \frac{1}{2}(1.2)(0.16 \times 3)(4.0)^3$$
$$P_{in} = 18.8 \text{ W}$$

b. Wind kinetic power at a wind speed of 3.6 m/s

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$$P_{in} = \frac{1}{2}(1.2)(0.16 \times 3)(3.6)^3$$
$$P_{in} = 13.7 \text{ W}$$

c. Wind kinetic power at a wind speed of 3.0 m/s

$$P_{in} = \frac{1}{2}(1.225)(0.16 \times 3)(3.0)^3$$
$$P_{in} = 7.9 \text{ W}$$

Based on the fluid mechanics equation used to determine the wind power input, the blower testing produced different input-power values at each wind source distance.

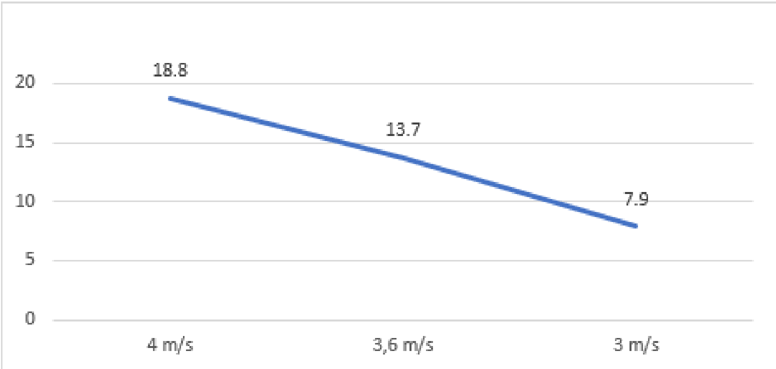


**Figure 2.** Effect of Wind Speed on Wind Power Input

The highest wind power input was 18.8 W at the highest wind speed of approximately 4.0 m/s. As the wind source distance increased, the wind speed gradually decreased, resulting in a lower wind power input. At the lowest wind speed of approximately 3.0 m/s, the calculated wind power input decreased to 7.9 W. These findings indicate that wind power input is strongly influenced by wind speed because the available wind power is proportional to the cube of wind velocity.

**Output Power**

**Table 2.** Output Power of the Wind Turbine at Different Wind Source Distances

| Wind Source Distance (cm) | Wind Speed (m/s) | Generator Speed (rpm) | Current (A) | Voltage (V) | Output Power (W) |
|---|---|---|---|---|---|
| 100 | 4 | 101.8 | 3.4 | 3.2 | 10.8 |
| 150 | 3.6 | 94.5 | 3.1 | 2.8 | 8.6 |
| 200 | 3 | 81 | 2.5 | 2.2 | 5.5 |

The electrical output power generated by the Savonius wind turbine prototype was evaluated at three different wind source distances. As shown in Table 4.3, the highest output power was obtained when the blower was positioned 100 cm from the turbine, producing a wind speed of 4.0 m/s and a generator rotational speed of 101.8 rpm. Under these conditions, the generator produced a current of 3.4 A and a voltage of 3.2 V, resulting in an electrical output power of 10.8 W.

At a wind source distance of 150 cm, the average wind speed decreased to 3.6 m/s, reducing the generator speed to 94.5 rpm. Consequently, the electrical output also decreased to 3.1 A and 2.8 V, producing an output power of 8.6 W. When the distance was further increased to 200 cm, the wind speed dropped to 3.0 m/s, the generator rotated at 81.0 rpm, and the electrical output declined to 2.5 A and 2.2 V, resulting in an output power of 5.5 W.

Since the prototype employed a direct current (DC) generator, the electrical output power was calculated using the following equation:

$$P_{\text{out}} = V \times I$$

where:

$P_{out}$= electrical output power (W)
$V$= output voltage (V)
$I$= output current (A)

The calculated output power for each experimental condition is presented below.

a. Wind source distance of 100 cm

$$P_{out} = 3.2 \times 3.4 = 10.8 \text{ W}$$

b. Wind source distance of 150 cm

$$P_{out} = 2.8 \times 3.1 = 8.6 \text{ W}$$

c. Wind source distance of 200 cm

$$P_{out} = 2.2 \times 2.5 = 5.5 \text{ W}$$

The experimental results indicate a clear relationship between wind speed and the electrical output power generated by the wind turbine. As the wind speed increased, the generator rotated at a higher speed, producing greater voltage and current, which ultimately increased the electrical power output. Conversely, increasing the distance between the blower and the turbine reduced the available wind speed, leading to lower generator speed and reduced electrical output.

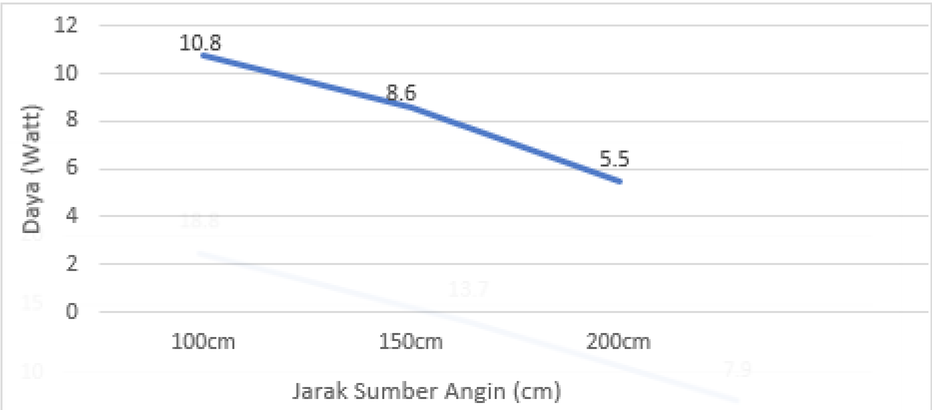


**Figure 3.** Effect of Wind Source Distance on Output Power

These findings demonstrate that the electrical performance of the three-blade Savonius wind turbine is highly dependent on the kinetic energy available in the airflow. The highest output power of 10.8 W was achieved at a wind speed of 4.0 m/s, whereas the lowest output power of 5.5 W occurred at 3.0 m/s. This trend confirms that higher wind velocities improve the energy conversion capability of the turbine and enhance the overall electrical performance of the wind energy conversion system.

**Power Efficiency**

**Table 3.** Power Conversion Efficiency of the Savonius Wind Turbine

| Wind Source Distance (cm) | Wind Speed (m/s) | Wind Mechanical Power (W) | Output Power (W) | Efficiency (%) |
|---|---|---|---|---|
| 100 | 4 | 18.8 | 10.8 | 57.44 |
| 150 | 3.6 | 13.7 | 8.6 | 62.77 |
| 200 | 3 | 7.9 | 5.5 | 69.82 |

The power conversion efficiency of the Savonius wind turbine was determined by comparing the electrical output power generated by the DC generator with the available wind mechanical power. The efficiency was calculated using the following equation:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\%$$

where:

$\eta$= power conversion efficiency (%)

$P_{\text{out}}$= electrical output power (W)

$P_{\text{in}}$= wind mechanical power (W)

The calculated efficiencies for each experimental condition are presented below.

a. Wind source distance of 100 cm

At a wind speed of 4.0 m/s, the wind mechanical power was 18.8 W, while the electrical output power was 10.8 W.

$$\eta = \frac{10.8}{18.8} \times 100\% = 57.44\%$$

b. Wind source distance of 150 cm

At a wind speed of 3.6 m/s, the wind mechanical power was 13.7 W, and the electrical output power reached 8.6 W.

$$\eta = \frac{8.6}{13.7} \times 100\% = 62.77\%$$

c. Wind source distance of 200 cm

At a wind speed of 3.0 m/s, the wind mechanical power was 7.9 W, while the electrical output power was 5.5 W.

$$\eta = \frac{5.5}{7.9} \times 100\% = 69.82\%$$

The experimental results indicate that the calculated power conversion efficiency increased from 57.44% at a wind speed of 4.0 m/s to 69.82% at 3.0 m/s. This trend shows that, under the laboratory conditions employed in this study, the ratio of electrical output power to available wind power became higher as the wind speed decreased.

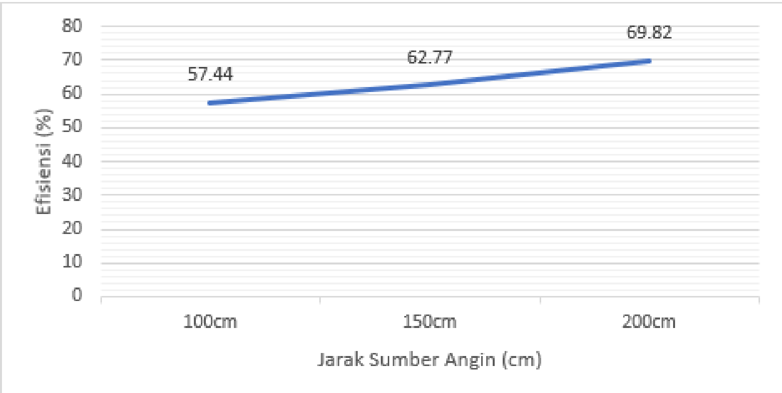


**Figure 4.** Effect of Wind Source Distance on Power Conversion Efficiency

It should be noted that the efficiency values reported in this study were obtained from experiments conducted indoors using a blower as the wind source, rather than under natural atmospheric conditions. Consequently, the calculated efficiencies may differ from the theoretical Betz limit, which states that the maximum energy extraction efficiency of an ideal wind turbine operating in free-stream wind is 59.3%. Because the airflow generated by a blower does not fully represent open-field wind conditions, the calculated efficiency values in this experimental setup may exceed the theoretical Betz limit and therefore should be interpreted as experimental system efficiencies rather than the aerodynamic efficiency of the turbine rotor alone.

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**Battery Charging Time**

**Table 4.** Battery Charging Time at Different Wind Source Distances

| Wind Source Distance (cm) | Wind Speed (m/s) | Charging Current (A) | Output Power (W) | Theoretical Charging Time (h) |
|---|---|---|---|---|
| 100 | 4 | 3.4 | 10.8 | 2 |
| 150 | 3.6 | 3.1 | 8.6 | 2.3 |
| 200 | 3 | 2.5 | 5.5 | 2.8 |

The charging time of the 12 V, 7 Ah maintenance-free battery was estimated based on the charging current produced by the wind turbine at different wind source distances. As shown in Table 4.5, the theoretical charging time increased as the wind speed and charging current decreased. At a wind speed of 4.0 m/s, the charging current reached 3.4 A, resulting in the shortest theoretical charging time of approximately 2.0 h. When the wind speed decreased to 3.6 m/s and 3.0 m/s, the charging current dropped to 3.1 A and 2.5 A, increasing the theoretical charging time to 2.3 h and 2.8 h, respectively.
The theoretical battery charging time was calculated using the following equation:

$$T = \frac{C}{I}$$

where:
- $T$= charging time (h)
- $C$= battery capacity (Ah)
- $I$= charging current (A)

The charging time for each test condition was calculated as follows.
a. Wind source distance of 100 cm

$$T = \frac{7}{3.4} = 2.0 \text{ h}$$

b. Wind source distance of 150 cm

$$T = \frac{7}{3.1} = 2.3 \text{ h}$$

c. Wind source distance of 200 cm

$$T = \frac{7}{2.5} = 2.8 \text{ h}$$

Although the theoretical calculations predicted charging times between 2.0 and 2.8 h, the actual charging tests required significantly longer durations. Under experimental conditions, the battery required approximately 3–4 h at a wind source distance of 100 cm, 3.5–4.8 h at 150 cm, and 4.5–5.5 h at 200 cm to reach a full charge.

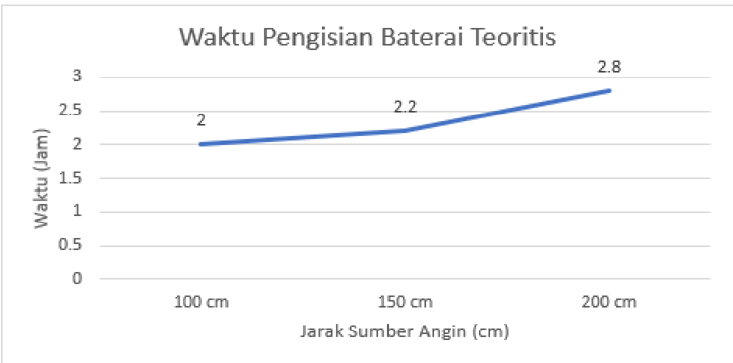


**Figure 5.** Effect of Wind Source Distance on Battery Charging Time

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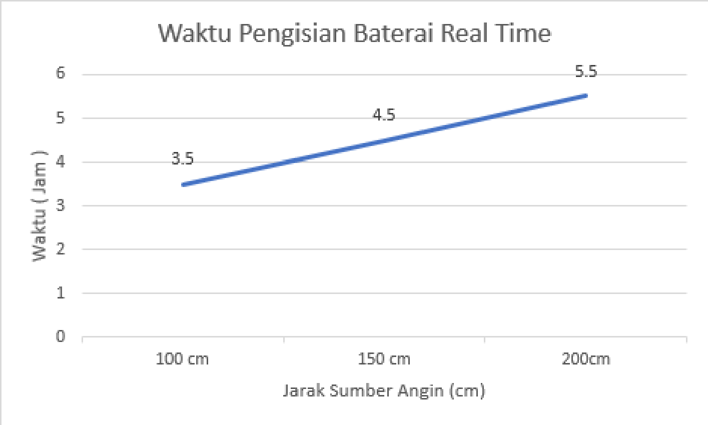


**Figure 6.** Effect of Wind Source Distance on Real-Time Battery Charging Time

The discrepancy between the theoretical and experimental charging times can be attributed to several practical factors, including energy losses in electrical components and cables, fluctuations in the charging current, battery temperature, and the efficiency of the charging system. Moreover, the theoretical calculation assumes a constant charging current throughout the charging process. In practice, the battery charging controller changes the charging mode from Constant Current (CC) to Constant Voltage (CV) as the battery approaches approximately 80% of its capacity. During the CV stage, the charging current gradually decreases to protect the battery and prevent overcharging, thereby extending the total charging time.

These results demonstrate that the theoretical charging time provides only an ideal estimate, whereas the actual charging duration is strongly influenced by the performance of the charging controller and the operating characteristics of the battery.

**Battery Endurance**

**Table 5.** Battery Endurance under Different Lamp Loads

| Lamp Load (W) | Battery Capacity (Ah) | Battery Voltage (V) | Lamp Current (A) | Theoretical Battery Endurance (h) |
|---|---|---|---|---|
| 15 | 7 | 12 | 1.25 | 5.6 |
| 25 | 7 | 12 | 2.8 | 2.8 |
| 30 | 7 | 12 | 2.5 | 2.5 |

The endurance of the 12 V, 7 Ah battery was evaluated using lamp loads of 15 W, 25 W, and 30 W. The electrical current required by each lamp was determined using the following equation:

$$I = \frac{P}{V}$$

where:

$I$ = lamp current (A)
$P$ = lamp power (W)
$V$ = battery voltage (V)

The current calculations for each lamp load are presented as follows.

a. A 15 W lamp

$$I = \frac{15}{12} = 1.25 \text{ A}$$

b. A 25 W lamp

According to the experimental data, the current used in calculating battery endurance was 2.8 A.

c. A 30 W lamp

$$I = \frac{30}{12} = 2.5 \text{ A}$$

After determining the current required by each lamp, the theoretical battery endurance was calculated using the following equation:

$$T = \frac{C}{I}$$

where:

$T$= theoretical battery endurance (h)
$C$= battery capacity (Ah)
$I$= load current (A)

Battery endurance with a 15 W lamp

$$T = \frac{7}{1.25} = 5.6 \text{ h}$$

The theoretical calculation indicates that the battery should operate for approximately 5.6 h, equivalent to 5 h and 36 min, when supplying a 15 W lamp. However, during the actual test, the battery operated for only approximately 3.5–4 h.

Battery endurance with a 25 W lamp

$$T = \frac{7}{2.8} = 2.5 \text{ h}$$

Theoretically, the battery should operate for approximately 2.5 h, equivalent to 2 h and 30 min, under a 25 W lamp load. In the actual test, however, the battery endurance ranged from approximately 1.5 to 2 h.

Battery endurance with a 30 W lamp

$$T = \frac{7}{2.5} = 2.8 \text{ h}$$

The theoretical battery endurance under a 30 W lamp load was approximately 2.8 h, equivalent to 2 h and 48 min. Nevertheless, the actual test showed that the battery operated for only approximately 1.5–2 h.

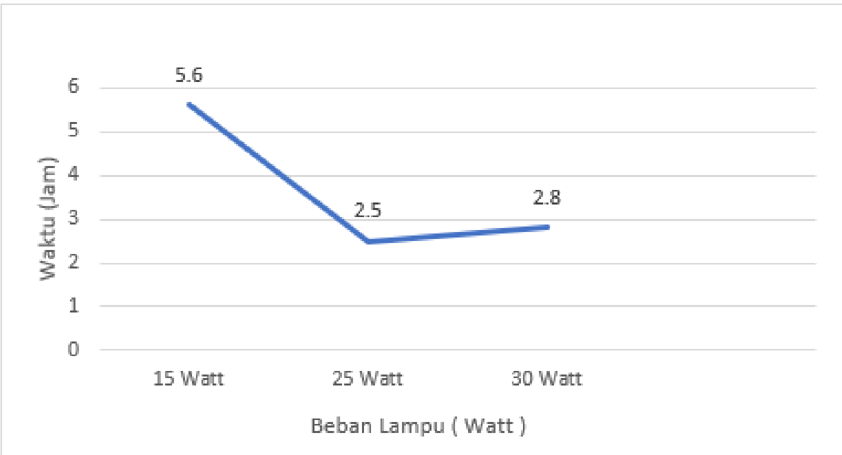


**Figure 7.** Effect of Lamp Load Variation on Battery Endurance

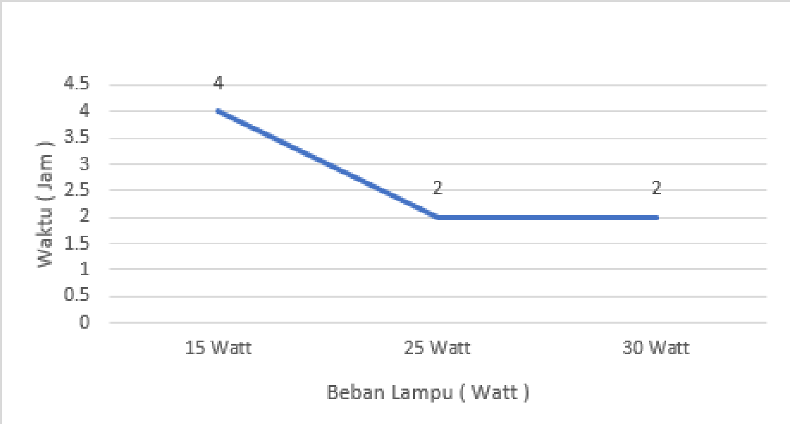


**Figure 8.** Effect of Lamp Load Variation on Real-Time Battery Endurance

Overall, the actual battery endurance was shorter than the theoretical value. This difference can be attributed to several technical factors, including energy losses in cables and electrical components, variations in load current, battery internal resistance, system inefficiency, ambient temperature, and the stability of the electrical load during testing. These factors are not fully represented in an ideal linear calculation.

The results are also consistent with Peukert's law, which explains that the effective capacity of a lead-acid battery decreases as the discharge current increases. A higher lamp load draws a greater current from the battery, increases internal losses and heat generation, and consequently reduces the actual battery operating time. Therefore, the battery endurance does not decrease in a perfectly linear manner as the electrical load increases.

## 5. Conclusion

The performance of the three-blade Savonius vertical-axis wind turbine was strongly influenced by wind speed and generator rotational speed. A higher wind speed increased the turbine and DC generator rotational speeds, resulting in greater electrical current and output power. Consequently, the charging time of both Maintenance-Free and Flooded Lead-Acid batteries became shorter as the generated current increased. However, the actual charging time was longer than the theoretical value because of system inefficiencies, electrical losses in cables and components, fluctuations in wind speed and charging current, and changes in the charging process from constant-current to constant-voltage operation.

Battery endurance was primarily determined by the magnitude of the lamp load and the condition of the battery. A lower lamp load provided a longer operating time, whereas a higher load discharged the battery more rapidly. The 15 W lamp produced the longest theoretical battery endurance, while the 30 W lamp resulted in a shorter operating duration. In actual testing, battery endurance was lower than the theoretical calculation because of internal battery resistance, energy losses, temperature effects, and battery age. Therefore, the overall performance of the wind turbine–battery system depends on stable wind conditions, efficient energy conversion, appropriate electrical loads, and the physical condition of the battery.

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