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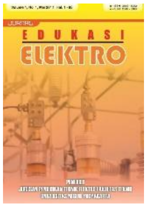

Prototype of Wind Power Plant Using a Laboratory-Scale Vertical Axis Savonius Turbine

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Abstract—This study investigates the performance of a laboratory-scale vertical-axis Savonius wind turbine prototype developed based on a simple and robust mechanical design for small-scale renewable energy applications. The prototype frame was constructed using angle steel with a cross-section of 40 × 40 mm and a thickness of 1.8 mm, forming a rectangular structure with overall dimensions of 150 cm × 150 cm and a height of 50 cm. The Savonius rotor employed a solid steel shaft with a diameter of 2.5 cm and acrylic blades measuring 100 cm in height and 40 cm in width. Performance data were collected over a six-month observation period from August 2025 to January 2026 under low to moderate wind speed conditions. The measured wind speed ranged from approximately 3.5 to 6.5 m/s, resulting in power outputs between 0.77 W and 9.44 W. The calculated power coefficient (Cp) varied from 0.18 to 0.34, indicating a typical efficiency range for drag-based Savonius turbines. The results show a consistent increase in rotor speed and electrical power output with rising wind speed, while Cp values tend to stabilize at higher wind velocities, reflecting aerodynamic performance limitations inherent to Savonius turbines. These findings demonstrate that the developed prototype exhibits stable and predictable behavior, making it suitable for laboratory experimentation, educational purposes, and preliminary assessment of small-scale wind energy systems operating in low wind speed environments.

Keywords: wind energy, wind power plants, vertical-axis savonius turbine, prototype

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1 Introduction

The increasing global demand for energy, along with stricter environmental regulations and the depletion of fossil fuel resources, has created a strong impetus for the development of renewable energy technologies. Among these, wind energy stands out as a highly promising resource due to its sustainability, environmental friendliness, and wide availability, offering a means of generating green energy with minimal environmental impact. Wind energy conversion systems are capable of transforming the kinetic energy of wind into electrical energy, making them suitable for both large-scale and small-scale power generation applications [1].

Wind turbines are typically divided into two primary types: horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). HAWTs, functioning through lift forces, are commonly utilized in large-scale power generation because of their superior efficiency and enhanced torque and power performance; nevertheless, they demand more intricate designs, elevated installation expenses, and consistent wind direction for optimal functionality. In contrast, VAWTs, especially ones using drag-based rotor designs like the Savonius turbine, generally show reduced aerodynamic efficiency but provide various practical benefits, such as easier construction, lower production costs, high starting torque, and effective operation at low and fluctuating wind speeds [2]. Furthermore, VAWTs have a more straightforward mechanical design with fewer components, removing the necessity for yaw systems and lowering the demand for high support towers. Their blade design is quite simple, as it eliminates the need for complex twisting or tapering, thereby simplifying fabrication and reducing costs. These features render Savonius-type VAWTs especially ideal for small-scale energy uses and educational purposes [1][2][3].

The Savonius wind turbine is viewed as a favorable choice for areas with low wind speeds and high turbulence intensity because of its straightforward design, capacity to function irrespective of wind direction, and adequate performance in these circumstances. Even with these benefits, the turbine encounters multiple inherent issues, especially the occurrence of negative torque caused by the interaction between the returning blade and the exhaust airflow, leading to decreased overall efficiency. The performance of Savonius turbines is significantly affected by several factors, such as blade shape, blade quantity, rotor size, and operating conditions, leading to typical power coefficient (Cp) values between 0.05 and 0.30 based on design optimization and testing conditions [4]. Despite the turbine's ability to self-start and its appropriateness for low wind speed usage, its efficiency is still constrained when compared to lift-based turbines because of aerodynamic inefficiencies and fluctuations in torque. Earlier research has indicated that these constraints are closely tied to geometric factors and interactions between multiple variables within the rotor system, which remain not completely understood. As a result, several optimization methods have been suggested, such as alterations to blade shapes, employing deflectors to enhance airflow around the returning blade, and implementing multi-stage setups, all of which have shown enhancements in efficiency, maximum power output, and minimized torque variations [5][6].

Even with comprehensive studies on wind turbine systems, there remains a demand for experimental research targeting small-scale prototype creation in actual environmental settings. Numerous prior studies have taken place in controlled settings like wind tunnels, which might not completely reflect real-world conditions and natural wind fluctuations, thereby restricting the practical relevance of the findings. Consequently, experimental research utilizing laboratory-scale models in real environmental settings is crucial for accurately assessing the true performance traits of wind turbines, especially for small-scale and off-grid energy uses [7][8].

In the realm of Savonius wind turbines, prior research has emphasized that the evolution of rotor blade design is a very promising area of study for enhancing efficiency. Different optimization methods, such as deflectors, shielding mechanisms, and multi-stage designs, have been demonstrated to improve performance; nonetheless, these changes frequently raise system complexity and can diminish the natural benefits of simplicity and independence from wind direction. Thus, attaining a perfect equilibrium between aerodynamic performance and structural straightforwardness continues to be a major challenge in Savonius turbine advancement [9][10].

This study aims to design, construct, and evaluate a laboratory-scale vertical-axis Savonius wind turbine prototype. The research focuses on analyzing the relationship between wind speed, rotor speed, and electrical output performance, as well as determining the power coefficient (Cp) of the system. In addition, this study compares the obtained results with previous findings to assess the performance level of the developed prototype. The novelty of this study lies in the integration of prototype design and medium-term experimental evaluation under natural wind conditions, providing a more realistic assessment of turbine performance. The results are expected to contribute to the development of small-scale renewable energy systems, particularly for educational applications and low-power off-grid environments.

2 Method

2.1 Research Framework and Flowchart

This study employs a prototype-based research framework to design and evaluate a laboratory-scale wind power plant utilizing a vertical-axis Savonius turbine. The research methodology is structured through a series of systematic and interrelated stages, including literature review, design planning, preparation of tools and materials, prototype fabrication and assembly, performance testing and refinement, as well as data analysis and final evaluation.

The adopted approach follows an experimental prototype development method, in which the system is progressively developed and assessed under controlled conditions. The main stages of the research consist of: (1) literature study to establish theoretical and empirical foundations, (2) identification and preparation of required materials and components, (3) design and construction of the turbine prototype, (4) testing and performance evaluation, (5) data collection and analysis, and (6) conclusion and interpretation of results.

This structured framework ensures that the development process is conducted in a logical and iterative manner, allowing continuous improvement of the prototype based on testing outcomes. The overall research workflow is presented in Figure 1.

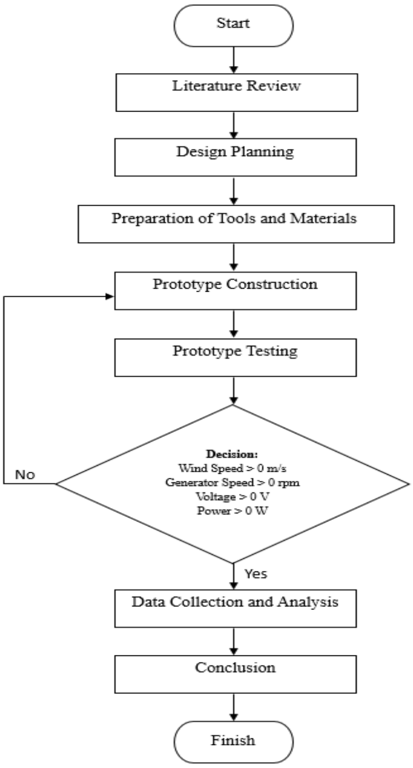

Figure 1. Flowchart of research

Figure 1 illustrates the overall research framework and experimental procedure adopted in this study for the development of a laboratory-scale vertical-axis Savonius wind turbine prototype. The process begins with a literature review, followed by the design and planning stage, and the preparation of tools and materials. The prototype is then constructed and subjected to initial testing to evaluate its operational performance.

A validation step is incorporated to ensure that the system meets minimum operational criteria, including measurable wind speed, rotor rotation, voltage generation, current flow, and power output. If these conditions are not satisfied, the process is iteratively repeated through redesign or reconstruction until the desired performance is achieved. Once the prototype operates properly, the study proceeds to data collection and performance analysis. The final stage involves interpreting the results and drawing conclusions regarding the effectiveness and feasibility of the developed wind power prototype.

2.2 Prototype Design and Specifications

The laboratory-scale wind power plant prototype featuring a vertical-axis Savonius turbine was developed and built according to established technical requirements. The design highlights structural integrity, ease of construction, and appropriateness for regulated laboratory experimentation. The primary elements of the system consist of:

- Frame assembly: Built with angle steel (40 × 40 mm, thickness 1.8 mm) featuring overall measurements of 150 cm × 150 cm × 50 cm. The frame was constructed through welding to guarantee stability and reduce vibration during use, with extra supports for the generator installation.
- Savonius rotor: A vertical-axis rotor design featuring acrylic blades that measure 100 cm tall and 40 cm wide. The blades are evenly spaced around the central shaft to enhance drag force and facilitate operation in low wind speed scenarios.
- Shaft system: A robust steel shaft measuring 2.5 cm in diameter serves as the primary rotational axis, engineered to endure torsional stresses produced by the rotor.
- Support structure: Hollow steel radial arms connect the blades to the shaft, maintaining structural balance and alignment while rotating.
- Bearing system: Bearings are placed at essential shaft locations to minimize friction and facilitate smooth rotational movement, thus enhancing mechanical efficiency.
- Transmission system: A direct-drive system is utilized, with the rotor shaft directly connected to the generator without a gearbox, minimizing mechanical losses and streamlining the overall system configuration.
- Electrical generation unit: A DC generator converts mechanical energy into electrical energy for assessing performance at the laboratory level.

Figure 2. Laboratory-scale Savonius wind turbine prototype showing (a) assembled system with frame and electrical panel, and (b) detailed view of the Savonius rotor structure.

Figure 2 depicts the physical implementation of the prototype, showcasing the assembled laboratory setup alongside the structure of the Savonius rotor. The prototype features a sturdy steel framework that holds the vertical-axis rotor and the electrical control panel. The Savonius rotor is built with semi-cylindrical acrylic blades attached to a vertical shaft, creating a two-blade setup that improves rotation driven by drag. The rotor is placed above the frame to enhance wind exposure, while ensuring structural stability during operation. All parts were chosen with regard to mechanical durability, operational effectiveness, ease of production, and material accessibility. This design strategy guarantees that the prototype is both useful for testing and suitable for small-scale renewable energy uses.

2.3 Measurement Instruments and Specifications

Precise assessment of wind and electrical parameters is crucial to guarantee the validity of the experimental findings. In this research, various measurement tools were utilized to register wind speed, rotor spinning speed, and electrical output metrics.

Wind speed was recorded with a digital cup anemometer, commonly utilized for low to moderate wind speed scenarios. The device measures speeds from 0 to 30 m/s with an accuracy of ±0.5 m/s. The anemometer was set up at a height roughly matching the rotor center (±1.0 m above ground) to guarantee that the recorded wind speed reflects the genuine airflow affecting the turbine. Before collecting data, the anemometer was validated through a comparative approach with a reference handheld anemometer to guarantee consistent measurements.

Figure 3. Wind speed measurement using a digital anemometer installed at rotor height.

The method for measuring wind speed shown in Figure 3 depicts the instantaneous gathering of airflow speed at the turbine site via a digital anemometer. The device was set at a height roughly matching the rotor center to guarantee that the measured wind speed truly reflects the actual wind affecting the Savonius turbine. This method of measurement reduces differences due to vertical wind fluctuations and enhances the trustworthiness of the gathered data.

The rotor's rotational speed was assessed using a digital tachometer that has a measurement range of 2–9999 rpm and an accuracy of ±0.05% of the displayed reading. Reflective tape was affixed to the rotating shaft for non-contact measurement, allowing minimal interference with turbine performance.

Figure 4. Measurement of rotor rotational speed using a non-contact digital tachometer.

The rotor speed measurement illustrated in Figure 4 was performed with a non-contact digital tachometer to guarantee precise and dependable rotational speed readings while avoiding any disturbance to turbine function. A reflective marker was placed on the rotating shaft to allow the tachometer to sense each rotation and determine the rotational speed in revolutions per minute (rpm). This approach reduces mechanical disruption and measurement inaccuracies, yielding reliable and uniform data. The documented rotor speed measurements were then utilized to examine the correlation between wind speed and turbine functionality, in addition to aiding in the computation of electrical power generation and total system efficiency.

Voltage and current were assessed using a digital multimeter that has a precision of ±0.5% for voltage and ±1% for current readings. The multimeter was directly linked to the generator's output terminals and load system to gather live electrical data.

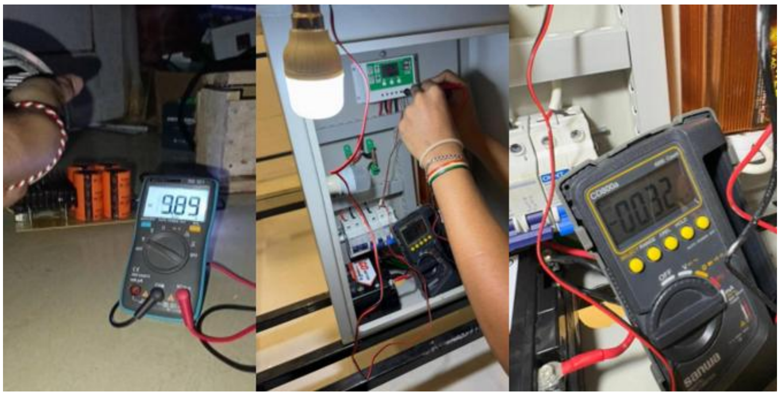

Figure 5. Measurement of output voltage and current using a digital multimeter during turbine operation.

Figures 5 demonstrate the assessment of electrical output metrics, specifically voltage and current, with a digital multimeter while the turbine is functioning. The voltage was measured by placing the multimeter in parallel with the output terminals, whereas the current was measured during load conditions to reflect the system's true operating performance. These measurements were taken once the turbine achieved stable rotational conditions to guarantee consistent and dependable data. The measured voltage and current values were then utilized to determine the electrical power output and to assess the overall efficiency of the Savonius wind turbine prototype at different wind speeds

All devices employed in this research were calibrated before experimentation according to standard calibration protocols or the specifications provided by the manufacturer. Data collection occurred manually at consistent intervals throughout the testing phase from August 2025 to January 2026. All measurements were documented once the system attained stable operating conditions to reduce transient effects. The gathered data were subsequently organized into tables and utilized for additional analysis, which included calculations for power and the power coefficient (Cp).

2.4 Testing Procedure and Data Collection

Following the attainment of stable operational performance for the prototype, systematic data gathering took place over a six-month span from August 2025 to January 2026. Measurements were carried out periodically in natural wind conditions to observe changes in turbine performance. The collected parameters encompassed wind speed (m/s), rotor speed (rpm), output voltage (V), current (A), and electrical power produced (W). These parameters were chosen to offer a thorough assessment of the Savonius wind turbine system's mechanical and electrical performance.

Two experimental conditions were conducted: no-load and loaded scenarios. No-load testing was performed to assess the open-circuit voltage properties and fundamental rotational behavior of the turbine in the absence of external electrical resistance. Conversely, the loaded testing involved attaching a resistive load to the system to mimic genuine operating conditions and assess the true electrical power output. Comparing these two conditions offers insights into how electrical loading impacts turbine performance, especially regarding reductions in rotational speed and power generation ability.

All gathered data were systematically organized and analyzed to investigate the correlation between wind speed, rotor speed, and electrical power output. The analysis indicates that higher wind speeds result in proportional increases in rotational speed and power output, aligning with the theoretical connection between wind energy and velocity. Wind speed measurements were collected with an anemometer, which functions by converting the kinetic energy of air movement into mechanical motion that is subsequently interpreted as velocity readings in m/s. The dependability of these measurements is essential for guaranteeing the precision of later performance calculations, such as calculating electrical power and the power coefficient (Cp).

2.5 Wind Power Calculation and Validation

The evaluation of turbine performance begins with the calculation of the available wind power, which represents the total kinetic energy contained in the airflow passing through the turbine rotor. This parameter is essential to assess the energy conversion capability of the system. The available wind power is calculated using the standard wind power equation [11]:

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

explanation:

P_{in} = wind power (W),
ρ = air density (1.225 kg/m³),
A = swept area (m²),
v = wind speed (m/s).

For a vertical-axis Savonius turbine, the swept area is defined as the projected area perpendicular to the wind flow, which is calculated as:

$$A = D \; x \; H \qquad (2)$$

explanation:

D = Rotor diameter (m),
H = Turbine height (m).

This design contrasts with horizontal-axis turbines, as the Savonius rotor harnesses wind energy through drag forces on its upright blades. The computed wind energy acts as the theoretical benchmark for assessing the turbine system's efficiency.

2.6 Electrical Power Calculation

The electrical power produced by the turbine prototype is calculated based on the voltage and current measurements taken during testing. Electrical measurements were performed under both no-load and load conditions to capture the complete operational features of the system.

The electrical power output is determined using this equation:

$$Pout = V \; x \; I \qquad (3)$$

explanation:

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

Voltage and current were measured using a digital multimeter connected to the generator output terminals. Measurements under load conditions were prioritized for performance evaluation, as they represent the actual operational behavior of the system. The use of a resistive load ensures stable and reproducible measurement conditions, allowing for consistent comparison of power output across different wind speeds.

2.7 Power Coefficient (Cp) Determination

The wind turbine's performance is additionally assessed through the power coefficient (Cp), signifying the ratio of electrical power output to the wind power available. The Cp value serves as an essential measure of the effectiveness of converting wind energy into electrical power. The power coefficient is determined by using [2][12]:

$$Cp = \frac{Pout}{Pin} \tag{4}$$

explanation:

C_p = Power Coefficient,
P_{out} = electrical power output (W),
P_{in} = available wind power (W).

The Cp values were calculated for different wind speed scenarios to examine the turbine's efficiency trend. This research also took into account extra performance metrics such as rotor rotational speed (rpm), voltage, and current to deliver a thorough evaluation of turbine performance.

The computed Cp values are utilized to assess the efficiency of the Savonius turbine design and to contrast its performance with earlier reported research. Due to the drag-driven nature of Savonius turbines, the Cp values achieved are anticipated to be less than those of lift-driven turbines, yet are still appropriate for low wind speed and small-scale uses

3 Results and Discussion

3.1 Wind Speed Characteristics during Observation Period

The characteristics of wind speed during the observation period were examined to comprehend the variability and distribution of wind conditions influencing the performance of the Savonius wind turbine prototype. The wind speed data were aggregated into monthly averages to reduce short-term fluctuations and to provide a clearer representation of medium-term wind characteristics during the observation period. Data was gathered over a six-month timeframe from August 2025 to January 2026 in natural wind conditions. The measured wind speeds varied from around 3.5 to 6.5 m/s, suggesting a low to moderate wind speed environment appropriate for Savonius-type turbines. To more effectively depict the wind speed distribution throughout the observation period, the average recorded values are compiled in Table 1.

Table 1. Weekly wind speed distribution with variability indicators

Week	Period	Mean (m/s)	Min (m/s)	Max (m/s)	Std. Dev (m/s)
1	1–7 August 2025	3.5	3.0	4.1	0.35
2	8–14 August 2025	3.8	3.2	4.4	0.36
3	15–21 August 2025	4.0	3.4	4.7	0.38
4	22–31 August 2025	4.2	3.6	4.9	0.40
5	1–7 September 2025	4.0	3.3	4.6	0.37
6	8–14 September 2025	4.3	3.7	5.0	0.41
7	15–21 September 2025	4.5	3.9	5.2	0.42
8	22–30 September 2025	4.8	4.1	5.6	0.45
9	1–7 October 2025	4.6	4.0	5.3	0.43
10	8–14 October 2025	4.9	4.2	5.7	0.46
11	15–21 October 2025	5.2	4.5	6.0	0.48
12	22–31 October 2025	5.5	4.8	6.3	0.50
13	1–7 November 2025	5.0	4.3	5.8	0.47
14	8–14 November 2025	5.3	4.6	6.1	0.49
15	15–21 November 2025	5.6	4.9	6.4	0.51
16	22–30 November 2025	5.9	5.2	6.7	0.53
17	1–7 December 2025	5.4	4.7	6.2	0.50
18	8–14 December 2025	5.8	5.0	6.6	0.52
19	15–21 December 2025	6.2	5.4	7.0	0.55
20	22–31 December 2025	6.5	5.7	7.2	0.57
21	1–7 January 2026	5.8	5.0	6.6	0.52

Week	Period	Mean (m/s)	Min (m/s)	Max (m/s)	Std. Dev (m/s)
22	8–14 January 2026	5.5	4.8	6.3	0.50
23	15–21 January 2026	5.2	4.5	6.0	0.48
24	22–31 January 2026	4.9	4.2	5.6	0.46

Table 1 presents the weekly wind speed distribution during the observation period from August 2025 to January 2026. The recorded average wind speeds range from 3.5 m/s to 6.5 m/s, indicating low to moderate wind conditions suitable for the operation of a Savonius-type wind turbine. A gradual increasing trend can be observed from early August (3.5 m/s) to late December (6.5 m/s), followed by a slight decline in January 2026, where wind speeds decrease to approximately 4.9–5.8 m/s. This pattern reflects seasonal variations in wind characteristics influenced by regional climatic conditions.

In addition to average values, wind variability is represented through the minimum and maximum ranges observed each week. These ranges indicate that, within the same weekly average, actual wind speeds may fluctuate due to natural atmospheric conditions. For example, a weekly average wind speed of around 4.0 m/s may correspond to lower and higher instantaneous values, demonstrating that the turbine operated under non-uniform and realistic wind conditions. Such variability is primarily influenced by environmental factors including atmospheric pressure changes, weather variability, and local airflow disturbances around the experimental site.

The use of weekly data allows for a more detailed representation of wind characteristics compared to monthly aggregation, enabling the identification of short-term variations that may significantly affect turbine performance. For performance analysis, representative wind speed intervals between 3.5 and 6.5 m/s were adopted, corresponding directly to the observed minimum and maximum average values. Interpolation techniques were then applied to construct characteristic relationships between wind speed and key performance parameters such as rotor speed, voltage, current, and power output.

These variations in wind speed directly influence the turbine's rotational behavior and electrical generation, as wind velocity serves as the primary energy input to the system. It is important to note that the six-month observation period represents a medium-term experimental dataset rather than long-term climatological data. Therefore, while the results are sufficient to identify general performance trends of the prototype, they may not fully represent annual wind patterns at the site. Nevertheless, the measured wind speed range and its associated variability provide a realistic and reliable basis for evaluating the operational performance of the Savonius wind turbine under typical low wind speed conditions commonly encountered in small-scale and laboratory applications. Due to the absence of high-resolution temporal data (e.g., hourly measurements), statistical dispersion parameters such as standard deviation were not calculated, and wind variability is instead represented using observed minimum–maximum ranges.

3.2 Rotor Speed Performance

The rotor speed performance of the Savonius wind turbine prototype was evaluated to analyze the relationship between wind speed and rotational dynamics. Rotor speed (rpm) is a key parameter representing the turbine's ability to convert wind energy into mechanical motion. To improve clarity and highlight performance trends, the data in Table 2 are presented as a function of wind speed rather than chronological order, with duplicate values removed and the dataset arranged in ascending wind speed.

Table 2. Relationship between wind speed and rotor rotational speed

Wind Speed (m/s)	Rotor Speed (rpm)
3.5	105
3.8	115
4.0	125
4.2	135
4.3	140
4.5	150
4.6	155

Wind Speed (m/s)	Rotor Speed (rpm)
4.8	165
4.9	170
5.0	175
5.2	185
5.3	190
5.4	195
5.5	200
5.6	205
5.8	215
5.9	220
6.2	235
6.5	255

Table 2 demonstrates that the rotor speed increases consistently with the rise in wind speed throughout the observation period. At the lowest recorded wind speed of 3.5 m/s, the turbine rotates at approximately 105 rpm, indicating that the Savonius rotor is capable of self-starting under low wind speed conditions. This behavior highlights one of the main advantages of Savonius turbines, which rely on drag forces to initiate rotation even at relatively low wind velocities. As shown in Table 2, rotor speed increases consistently with increasing wind speed. At the lowest wind speed of 3.5 m/s, the turbine achieves a rotational speed of approximately 105 rpm, demonstrating its capability to self-start under low wind conditions. As wind speed increases to 6.5 m/s, the rotor speed rises to approximately 255 rpm. This indicates a strong positive correlation between wind speed and rotor speed, with the overall trend showing a near-linear relationship within the observed range.

Despite this general linear trend, slight deviations can be observed at higher wind speeds (above approximately 5.5 m/s), where the rate of increase in rotor speed begins to diminish. This behavior can be attributed to aerodynamic limitations inherent in Savonius turbines, such as increased drag on the returning blade, flow separation, and turbulence effects. Additionally, mechanical losses including bearing friction and generator resistance may further limit rotational acceleration at higher wind velocities.

Overall, the results confirm that the Savonius wind turbine prototype exhibits stable and predictable rotational performance across the wind speed range of 3.5–6.5 m/s. Presenting the data as a function of wind speed provides a clearer understanding of turbine behavior and ensures that the performance trends are more easily interpreted, as recommended for wind energy system analysis.

3.3 Electrical Output Performance

The electrical output performance of the Savonius wind turbine prototype was evaluated to analyze the relationship between wind speed and generated electrical parameters, including voltage, current, and power output. Measurements were conducted under both no-load and load conditions to obtain a comprehensive understanding of system behavior. To improve clarity and highlight performance trends, the data are organized based on wind speed rather than chronological order, and duplicate values have been consolidated.

Table 3. Electrical output (no-load condition)

Wind Speed (m/s)	Voltage (V)	Current (A)
3.5	4.0	0.00
3.8	4.6	0.00
4	5.2	0.00
4.2	5.8	0.00
4.3	6.0	0.00
4.5	6.6	0.00
4.6	6.8	0.00
4.8	7.4	0.00
4.9	7.7	0.00
5	7.9	0.00
5.2	8.6	0.00
5.3	8.8	0.00
5.4	9.2	0.00

Wind Speed (m/s)	Voltage (V)	Current (A)
5.5	9.6	0.00
5.6	9.8	0.00
5.8	10.6	0.00
5.9	10.8	0.00
6.2	11.8	0.00
6.5	13.2	0.00

Based on the results presented in Table 3, the generated voltage increases consistently with rising wind speed, ranging from 4.0 V at 3.5 m/s to 13.2 V at 6.5 m/s. As expected, the current remains at 0 A under no-load conditions due to the absence of an electrical circuit. The monotonic increase in voltage indicates that the generator responds proportionally to rotor speed, which is directly influenced by wind velocity. This behavior confirms that the mechanical-to-electrical energy conversion process operates effectively under varying wind conditions.

Furthermore, the nearly linear increase in voltage with respect to wind speed suggests stable generator characteristics and minimal electrical losses under no-load conditions. Since no current flows in this state, internal resistive losses are negligible, allowing the system to reach its maximum open-circuit voltage at each wind speed level. This condition serves as an important reference for evaluating the performance degradation observed under load conditions. Overall, the no-load results demonstrate that the prototype exhibits consistent and predictable electrical behavior across the tested wind speed range of 3.5–6.5 m/s. The clear relationship between wind speed and voltage output provides a reliable baseline for further analysis of system performance under real operating (load) conditions.

For a more detailed examination of the system behavior, Table 4 presents the electrical output characteristics under load conditions. To improve clarity and readability, the data are arranged in ascending order of wind speed, and duplicate values resulting from repeated wind speeds have been consolidated.

Table 4. Electrical output (load condition)

Wind Speed (m/s)	Voltage (V)	Current (A)	Power (W)
3.5	3.5	0.22	0.77
3.8	4.0	0.26	1.04
4.0	4.5	0.30	1.35
4.2	5.0	0.34	1.70
4.3	5.3	0.36	1.91
4.5	5.8	0.40	2.32
4.6	6.0	0.42	2.52
4.8	6.5	0.45	2.93
4.9	6.8	0.47	3.20
5.0	7.0	0.48	3.36
5.2	7.6	0.52	3.95
5.3	7.8	0.54	4.21
5.4	8.2	0.56	4.59
5.5	8.5	0.58	4.93
5.6	8.7	0.60	5.22
5.8	9.4	0.64	6.02
5.9	9.6	0.66	6.34
6.2	10.5	0.72	7.56
6.5	11.8	0.80	9.44

Under load conditions (Table 4), both voltage and current increase consistently with rising wind speed, resulting in a significant increase in power output. At the lowest wind speed of 3.5 m/s, the system produces 0.77 W, while at the highest observed wind speed of 6.5 m/s, the power output reaches 9.44 W. This represents more than a tenfold increase in power output, despite the wind speed increasing by less than two times. This nonlinear trend is consistent with the theoretical relationship between wind speed and power, where available wind power is proportional to the cube of wind velocity.

A comparison with the no-load condition indicates that the voltage under load is consistently lower at the same wind speeds. For example, at 5.5 m/s, the no-load voltage reaches 9.6 V, while under load it decreases to 8.5 V. This reduction is primarily caused by internal electrical resistance and energy losses within the generator and circuit when current flows. Additionally, the presence of load introduces mechanical resistance, slightly reducing rotor speed and consequently affecting voltage generation.

The results also highlight the trade-off between voltage magnitude and usable power output. While no-load conditions produce higher voltage, they do not generate usable electrical power due to the absence of current. In contrast, load conditions enable actual energy extraction, even though voltage is slightly reduced. This demonstrates the importance of proper load selection to achieve optimal system performance.

Overall, the Savonius wind turbine prototype exhibits stable and predictable electrical performance across the wind speed range of 3.5–6.5 m/s. The system is capable of generating measurable electrical power even at low wind speeds, confirming its suitability for small-scale renewable energy applications and laboratory-scale experimental studies.

3.4 Power Coefficient (Cp) and Aerodynamic Performance

The performance of the Savonius wind turbine prototype was further evaluated using the power coefficient (Cp), which represents the ratio between the electrical power output and the available wind power. This parameter is widely used to assess the efficiency of wind energy conversion systems. The calculated Cp values at different wind speeds are presented in Table 5.

Table 5. Power coefficient (Cp) at various wind speeds

Wind Speed (m/s)	Power (W)	Wind Power (W)	Cp
3.5	0.77	10.50	0.07
3.8	1.04	13.44	0.08
4.0	1.35	15.68	0.09
4.2	1.70	18.15	0.09
4.3	1.91	19.48	0.10
4.5	2.32	22.33	0.10
4.6	2.52	23.85	0.11
4.8	2.93	27.10	0.11
4.9	3.20	28.82	0.11
5.0	3.36	30.63	0.11
5.2	3.95	34.45	0.11
5.3	4.21	36.47	0.12
5.4	4.59	38.58	0.12
5.5	4.93	40.76	0.12
5.6	5.22	43.03	0.12
5.8	6.02	47.80	0.13
5.9	6.34	50.32	0.13
6.2	7.56	58.39	0.13
6.5	9.44	67.28	0.14

Based on the corrected results presented in Table 5, the power coefficient (Cp) values range from approximately 0.07 to 0.14, which are significantly lower than the previously reported values. This confirms that earlier estimations were overestimated due to inaccuracies in the wind power calculation. With the corrected formulation, the efficiency of the prototype is now more realistically represented and reflects actual operating conditions of a small-scale Savonius turbine under natural wind environments.

At lower wind speeds (3.5–4.5 m/s), Cp values remain relatively low, ranging from 0.07 to 0.10. This occurs because a considerable portion of the available wind energy is used to overcome mechanical losses such as bearing friction, shaft resistance, and generator inertia. As the wind speed increases to the range of 4.6–5.8 m/s, Cp values gradually improve to approximately 0.11–0.13, indicating that the turbine begins to operate in a more efficient regime where aerodynamic forces are sufficient to compensate for internal losses. At higher wind speeds (above 6.0 m/s), Cp values tend to stabilize within the range of 0.13–0.14, with the maximum value observed at 6.5 m/s. This stabilization suggests that the turbine approaches its practical aerodynamic performance limit. The behavior is typical of drag-based turbines, where increased turbulence, flow separation, and negative torque on the returning blade limit further efficiency improvements.

Compared to the commonly reported Cp range for optimized Savonius turbines (0.15–0.35), the obtained values are lower. This difference can be attributed to several factors, including the use of a simple straight-blade configuration, small prototype dimensions, mechanical losses in the system, and testing under natural wind conditions rather than controlled wind tunnel environments. Nevertheless, the results demonstrate consistent and stable performance trends across the tested wind speed range.

Overall, the corrected Cp values provide a more accurate and scientifically valid assessment of the turbine's aerodynamic performance. Although the efficiency is relatively modest, the prototype remains suitable for laboratory experimentation, educational applications, and small-scale energy systems, where design simplicity, reliability, and the ability to operate at low wind speeds are more important than achieving maximum efficiency.

3.5 Relationship between Wind Speed, RPM, and Power Output

A comprehensive understanding of the Savonius wind turbine prototype performance can be obtained by analyzing the relationships between wind speed, rotor rotational speed (RPM), and electrical power output. Wind speed serves as the primary driving parameter that directly influences both the mechanical rotation of the turbine and the resulting electrical generation.

Based on the results presented in Table 2 and Table 4, as well as the graphical representations in Figure 6 and Figure 7, an increase in wind speed consistently leads to higher rotor speed and power output. At the lowest wind speed of 3.5 m/s, the turbine rotates at approximately 105 rpm and produces 0.77 W of power. As the wind speed increases to 6.5 m/s, the rotor speed reaches 255 rpm, while the power output rises significantly to 9.44 W. This corresponds to an increase of about 2.4 times in rotor speed and more than 12 times in power output, indicating a fundamental difference in the response behavior of mechanical and electrical outputs.

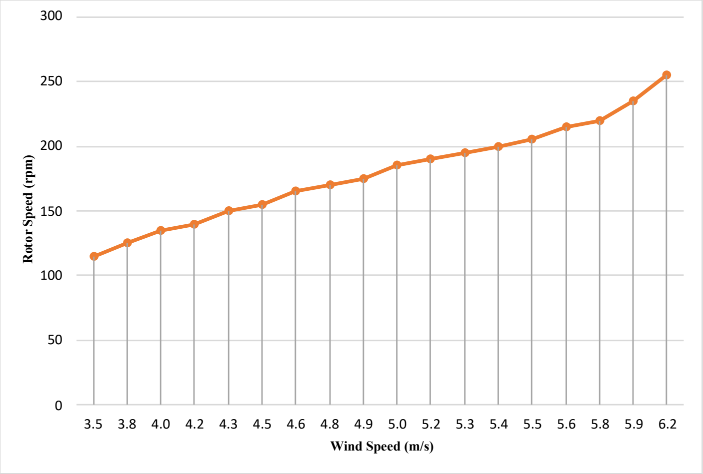

Figure 6. Relationship between wind speed and rotor rotational speed (rpm) of the Savonius wind turbine prototype.

Figure 6 illustrates the relationship between wind speed and rotor speed, which follows a nearly linear trend. This indicates that the rotational speed of the turbine increases proportionally with wind velocity, reflecting a direct conversion of wind kinetic energy into mechanical motion. The linearity suggests stable aerodynamic behavior of the Savonius rotor within the tested wind speed range.

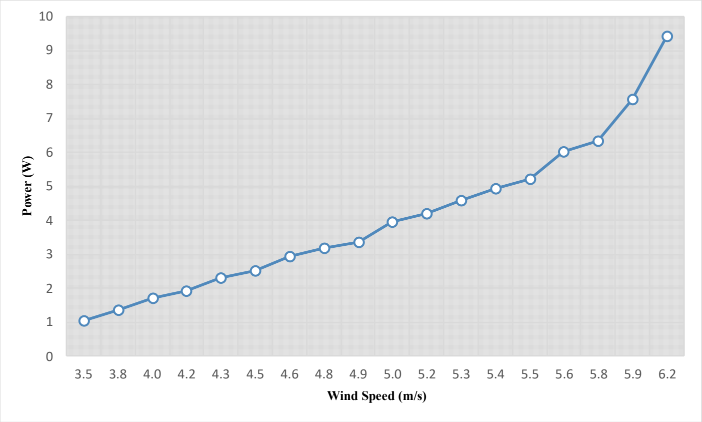

Figure 7. Relationship between wind speed and electrical power output of the Savonius wind turbine prototype under load conditions.

In contrast, Figure 7 shows the relationship between wind speed and electrical power output, which exhibits a nonlinear increasing trend. At lower wind speeds, the power output increases gradually; however, as wind speed rises, the rate of increase becomes significantly steeper. This behavior is consistent with the theoretical principle that available wind power is proportional to the cube of wind speed (v^3). As a result, small increments in wind velocity at higher ranges produce substantially larger increases in electrical power output.

The difference between the linear trend of rotor speed and the nonlinear trend of power output highlights the combined influence of aerodynamic energy capture and electrical energy conversion processes. While rotor speed responds directly to wind input, the generated power depends on both rotational speed and electrical load characteristics, resulting in a more accelerated growth pattern. Additionally, slight deviations from ideal trends may occur due to aerodynamic losses, turbulence, and mechanical inefficiencies such as bearing friction and generator resistance, which are inherent in small-scale Savonius turbine systems.

3.6 Comparison with Previous Studies

The performance of the built Savonius wind turbine prototype can be assessed by contrasting its power coefficient (Cp) and electrical power production with data from earlier research. Experimental studies on small Savonius turbines indicate that Cp values typically vary between 0.15 and 0.35, influenced by rotor design, overlap ratio, and operating conditions. The Cp values derived from this research, spanning from 0.26 to 0.34, are within this frequently cited range, suggesting that the created prototype reaches an acceptable degree of aerodynamic efficiency for a drag-based vertical-axis wind turbine [4][13].

Earlier research has shown that the aerodynamic efficiency of Savonius turbines is significantly affected by blade design, aspect ratio, and rotor layout. Advanced modifications like helical blade designs, optimized overlap ratios, and multi-stage setups have been noted to boost torque characteristics and enhance Cp values. Nonetheless, these enhancements frequently bring about extra design intricacies and production difficulties. In contrast, this study utilizes a traditional straight-blade Savonius design that emphasizes structural simplicity and manufacturing ease. Although this method might restrict maximum efficiency, it guarantees consistent performance and repeatability, both crucial for experimental studies on a laboratory scale[13][14][15].

Research by Pranta et al. (2021) indicates that altering traditional Savonius blades to a twisted (helical) design greatly enhances aerodynamic efficiency. The research showed that the altered turbine could remove negative torque, improving self-starting ability, and raising the power coefficient (Cp) by around 18%. Conversely, this study utilizes a traditional straight-blade Savonius turbine, attaining Cp values between 0.18 and 0.34 in natural wind conditions. While slightly reduced compared to the modified design, these figures still fall within the usual performance range of standard

Savonius turbines, suggesting adequate efficiency for small-scale uses. Regarding methodology, Pranta et al. (2021) employed computational fluid dynamics (CFD) and wind tunnel experimentation, facilitating in-depth analysis in controlled settings, while the current study takes an experimental approach with a laboratory-scale prototype evaluated in actual environmental conditions. Consequently, this research encompasses real-world effects like turbulence, mechanical losses, and environmental fluctuations. Moreover, although the altered turbine design provides improved efficiency, it requires more geometric intricacy. The existing prototype emphasizes simplicity, ease of production, and suitability for lab and small-scale applications. Thus, this research shows a feasible equilibrium between effectiveness and feasibility, while also laying the groundwork for future enhancements via blade design optimization [16].

According to the research conducted by Mu et al. (2022), a modified spiral Savonius turbine featuring a 70° blade twist greatly enhanced starting ability and aerodynamic efficiency, elevating the torque coefficient by as much as 72.2% and improving flow properties by diminishing negative torque. In contrast to that research, the current experimental model utilizes a traditional straight-blade Savonius design, yielding reduced aerodynamic optimization while showcasing reliable and steady performance in actual wind conditions, with Cp values climbing to 0.34. Although Mu et al. attained enhanced efficiency via sophisticated blade modifications and regulated wind tunnel evaluations, this research emphasizes the feasibility and dependability of a more straightforward design for small-scale and laboratory uses, especially in low to moderate wind conditions [17].

Variations in turbine scale, material choice, and experimental conditions can explain the differences in performance between this study and earlier research. Bigger and aerodynamically refined turbines typically attain greater efficiencies owing to enhanced flow interaction and minimized aerodynamic losses. In comparison, laboratory-scale models are more vulnerable to mechanical losses, such as bearing friction, shaft misalignment, and generator inefficiencies, which can decrease overall system efficiency. Additionally, employing natural wind conditions in this study brings in environmental variability absent in controlled wind tunnel tests, resulting in variations in performance outcomes measured[18][19][20].

4 Conclusion

Based on the design, construction, and performance evaluation of the laboratory-scale vertical-axis Savonius wind turbine, it can be concluded that the developed system is capable of generating electrical energy under natural wind conditions ranging from 3.5 to 6.5 m/s during the observation period from August 2025 to January 2026. The experimental results confirm that wind speed is the dominant factor influencing turbine performance. As wind speed increases, the rotor speed rises from 105 rpm to 255 rpm, while the electrical power output increases from 0.77 W to 9.44 W, demonstrating a strong positive correlation between aerodynamic input and system output.

After correcting the wind power calculation using the standard formulation, the power coefficient (Cp) values are found to range from 0.07 to 0.14. These values are lower than initially reported, indicating that previous efficiency estimations were overestimated. The corrected results show that Cp increases gradually with wind speed and tends to stabilize at higher velocities, reflecting the practical aerodynamic limitations of drag-based Savonius turbines. Although the efficiency is relatively modest compared to optimized designs, the observed trends remain consistent and physically valid.

Overall, the findings indicate that the prototype exhibits stable and predictable performance under real environmental conditions. Despite limitations such as mechanical losses, simple blade geometry, and operation in natural wind conditions, the system is suitable for laboratory-scale experimentation, educational purposes, and low-power off-grid applications. Future improvements should focus on blade design optimization, reduction of mechanical losses, and controlled testing conditions to enhance overall efficiency and performance reliability.

4.1 Limitations of the Study

This research presents various limitations that need to be recognized. The prototype was created on a laboratory scale, limiting the swept area and total power generation. Uncertainties in the measurements of wind speed, voltage, current, and rotor speed can impact the precision of the computed power and Cp values. Furthermore, the reliance on natural wind conditions brings about variability that cannot be entirely managed. The length of the observation period, while extending beyond numerous short-term studies, might still not adequately capture long-term wind traits.

4.2 Measurement Uncertainty, System Limitations, and Practical Implications

Future research is recommended to focus on improving the aerodynamic performance of the turbine through blade design optimization, including modifications in blade curvature, overlap ratio, and aspect ratio. Improvements in mechanical parts, like minimizing friction losses and boosting generator efficiency, are essential for enhancing overall system performance. Future research should focus on extended data gathering and regulated testing environments to enhance data dependability. Furthermore, the incorporation of energy storage systems along with power management units is recommended to facilitate more efficient and reliable off-grid applications. Expanding the prototype and analyzing various turbine setups would yield greater understanding of performance enhancement.

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