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# Analysis of Power and Efficiency of a Three-Stage Four-Blade Savonius Wind Turbine with Variations in Load and Wind Speed

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## Abstract

Indonesia's wind potential typically features low wind speeds, ranging from 3 m/s to 7 m/s, making vertical-axis wind turbines particularly suitable for these conditions. Therefore, the concept of developing a device emerged—designing a laboratory-scale Savonius wind turbine utilizing a wind tunnel so that a multi-stage windmill can operate using a 3D printing method. The testing was carried out using the observational method, which involved directly observing the object under study—in this case, a four-blade Savonius wind turbine—to determine the power output at specific wind speeds and loads using a wind tunnel. The experiment used two load variations of 0.01 kg and 0.02 kg, which were intended to simulate mechanical loads at wind speeds of 6 m/s and 7 m/s. At wind speeds of 6 m/s and 7 m/s, the turbine produced shaft rotations of 427 rpm, 259 rpm, 359 rpm, and 305 rpm with loads of 0.01 kg and 0.02 kg. For the four-blade configuration, the wind speeds of 6 m/s and 7 m/s generated turbine power outputs of 10.033 W and 6.318 W with loads of 0.01 kg and 0.02 kg, respectively. At wind speeds of 6 m/s and 7 m/s with loads of 0.01 kg and 0.02 kg, the turbine efficiencies were 0.707%, 0.682%, 1.193%, and 1.611%. For the four-blade configuration at 6 m/s and 7 m/s with loads of 0.01 kg and 0.02 kg, the generator power outputs were 7.08 W, 0 W, 3.29 W, and 0 W, respectively. Based on the test results and data analysis—including wind turbine rotational speed, turbine power, generator power, and turbine efficiency—the findings show a directly proportional relationship. Therefore, the higher the number of blades, the greater the turbine's rotational speed, turbine power, generator power, and efficiency.

**Keywords:** Savonius Turbine; Turbine Power; Turbine Efficiency

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## 1. Introduction

Currently, energy plays an important role in the development of renewable energy sources such as wind, water, and solar power. With the use of these renewable energies, we can reduce our dependence on fossil fuels, which are decreasing year by year [1]. This transition is critical given the finite and diminishing nature of fossil fuel reserves. Quantifiable data underscores this urgency: based on current production rates, global proven reserves for oil and natural gas are projected to last only approximately 47 years and 50 years, respectively [2]. In response to this depletion and climate concerns, the deployment of renewable technologies has surged, with global annual renewable capacity additions reaching nearly 510 GW in 2023—the fastest growth rate recorded in the last three decades [3]. This aggressive adoption, primarily led by solar PV and wind, is rapidly transforming the power mix. Consequently, the share of fossil fuels in global electricity generation dropped to its lowest point in 50 years (around 60%) in 2023, while renewables now contribute approximately 30% of the supply [4]. This trajectory confirms that the development of renewable energy is an indispensable strategy for achieving long-term energy independence and mitigating reliance on volatile and finite carbon resources.

One of the renewable energy sources examined in this study is wind energy. Wind is air that moves from an area of high pressure to an area of lower pressure. This movement of air can be utilized as an energy source by converting it into other forms of energy [2], [5]. The wind potential in Indonesia generally has low wind speeds ranging from 3 m/s to 7 m/s, making vertical-axis wind turbines highly suitable for use under low wind speed conditions [6]. This range is substantially below the economic threshold typically required for large-scale utility-grade Horizontal Axis Wind Turbines (HAWTs), which usually necessitate a cut-in speed of 3.5 m/s or higher and a much greater average wind speed to achieve their optimal rated power. Consequently, this specific meteorological profile makes Vertical Axis Wind Turbines (VAWTs) highly suitable, particularly for decentralized and distributed power generation. VAWT designs, such as the Savonius or Darrieus types, are engineered to initiate rotation at significantly lower wind velocities, with many models boasting cut-in speeds as low as 2.0 m/s [7].

Generally, the most commonly used wind turbines are horizontal-axis turbines, which generate large amounts of electrical energy. However, vertical-axis turbines have become an alternative for electricity generation. Vertical Axis Wind Turbines (VAWTs) are becoming an attractive alternative for electricity generation in low-wind-speed regions, as their development focuses on achieving cost-effective designs, enabling operation at lower wind speeds, and offering ease of installation at lower heights [3].

## 2. Methods

The testing device was built as a Savonius-type wind turbine prototype, which was used for data collection and performance testing. The design of the Savonius turbine used in this study can be seen in **Figure 1**.

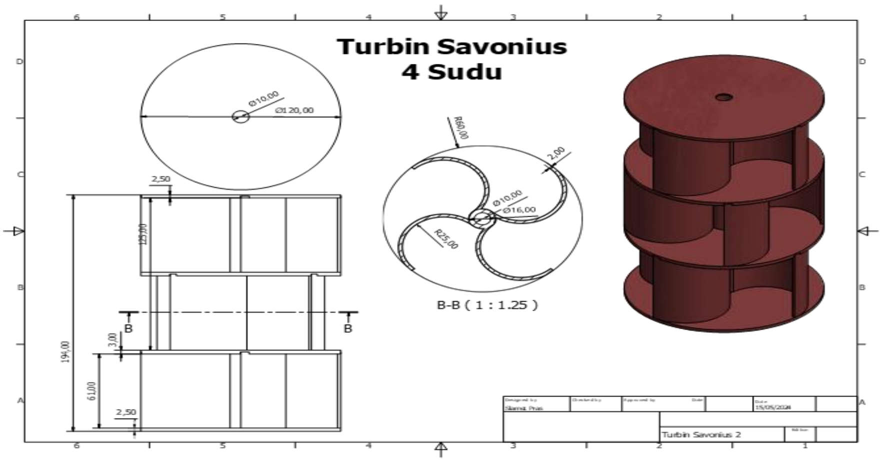


**Figure 1.** Design of a Four-Blade Savonius Turbine

The blower was selected based on its ability to generate the desired airflow range for the testing conditions. The FA-40Y model, with 130 Watts of power and 1400 rpm speed, was suitable for the desired wind speed range. In this study, a Drum Blower Model FA-40Y was chosen, with specifications of 130 Watts power, 220 Volts voltage, 50 Hz frequency, and 1400 rpm rotational speed. After that, the main turbine frame was built using 2 cm × 2 cm hollow steel bars. The frame has dimensions of 100 cm in length, 35.5 cm in width, and 18 cm in leg height. All parts of the frame were joined using welding techniques to ensure strength and stability.

Next, a 2 mm thick steel plate was shaped into a circular form with an inner diameter of 40 cm, an outer diameter of 45 cm, and a length of 85 cm. This part functions as a wind tunnel and is connected to the blower using bolts, resulting in a total system length of 100 cm. To facilitate maintenance and airflow adjustment, holes were made on both sides of the tunnel, fitted with sliding glass panels measuring 71.5 cm × 14 cm.

The next stage was the fabrication of the shaft support, which also serves as the generator mount. This support was made from a 2 cm diameter steel pipe with a length of 30 cm for the main section, and a 3 cm diameter horizontal pipe, 6 cm long, with a hole to accommodate the shaft. All components were welded together to ensure sturdiness in supporting the shaft and generator. The rotor head, or hub, was also fabricated to serve as the mounting point for the turbine blades. This component was designed to be detachable and adjustable to set the blade's angle of attack. The rotor head was made of steel, 4.5 cm in diameter and 3 cm long, and shaped like an aircraft nose using a lathe machine.

The next process involved manufacturing the shaft, with a diameter of 1 inch (25.4 mm) and a length of 27 cm, also using a lathe machine to ensure high precision. Once all components were fabricated, a painting process was carried out to protect the metal surfaces from corrosion. The final stage involved assembling all components into a complete Savonius wind turbine system.

Data collection in this study was conducted through a series of experimental tests on the assembled propeller-type wind turbine prototype. The main variables observed in this research included the number of blades, load (in kilograms), wind speed (in meters per second), turbine rotational speed (RPM), torque (Nm), turbine power (Watts), turbine efficiency (%), and generator output power (Watts). The data collection process was performed by varying wind speeds at 6 m/s and 7 m/s, and loads at 0.01 kg and 0.02 kg, to observe the effect of each parameter on turbine performance.

## 3.Results and Discussion

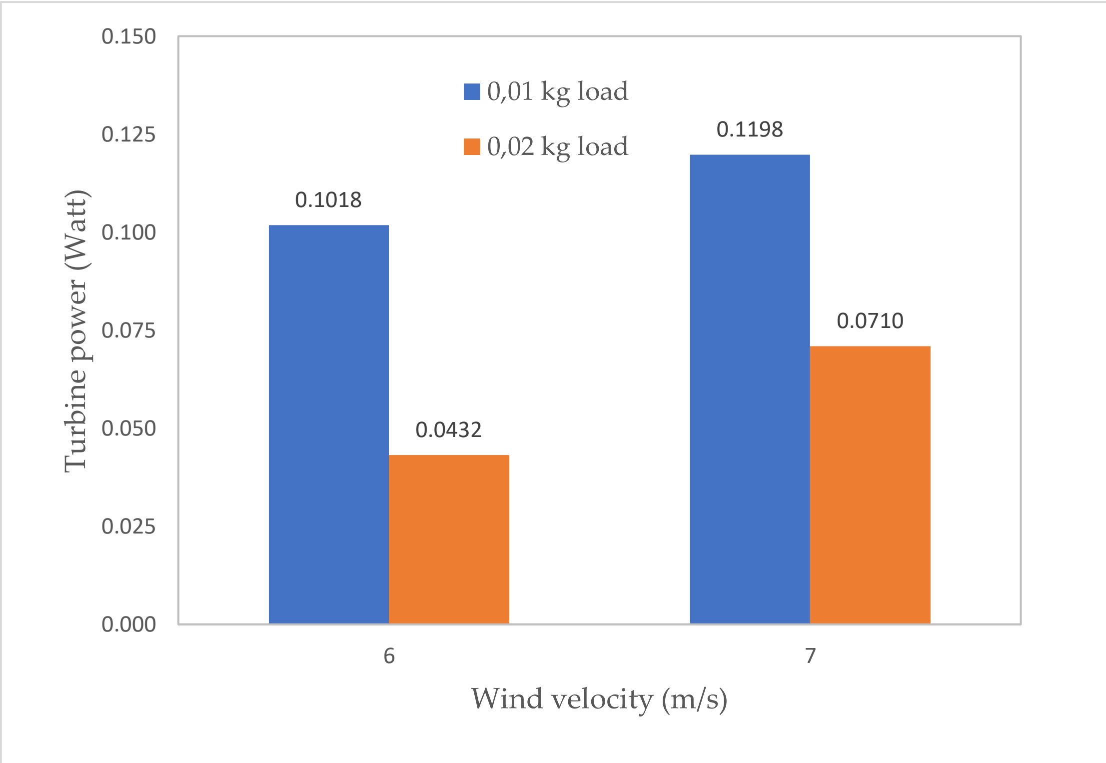


**Figure 2.** Relationship Between Wind Speed and Power Output of a Four-Blade Savonius Turbine

**Figure 2** shows the relationship between wind speed (m/s) and turbine power output (Watts) for a four-blade Savonius-type wind turbine with two load variations: 0.01 kg and 0.02 kg. In general, it can be seen that an increase in wind speed directly affects the increase in turbine power output for both load variations.

At a load of 0.01 kg, The turbine power increased from approximately 0.1 Watts at a wind speed of 6 m/s to around 0.12 Watts at 7 m/s. This increase in power indicates that lighter loads allow for faster turbine rotation, but the relationship between load and power should be examined carefully as lighter loads may reduce torque, which limits power generation [8]. Meanwhile, at a load of 0.02 kg, the power output was lower compared to the 0.01 kg load. The turbine power at a wind speed of 6 m/s was recorded at around 0.0432 Watts and increased to approximately 0.0710 Watts at 7 m/s. This shows that increasing the load requires greater torque for the turbine to rotate, which consequently reduces the rotational speed and the power generated [9].

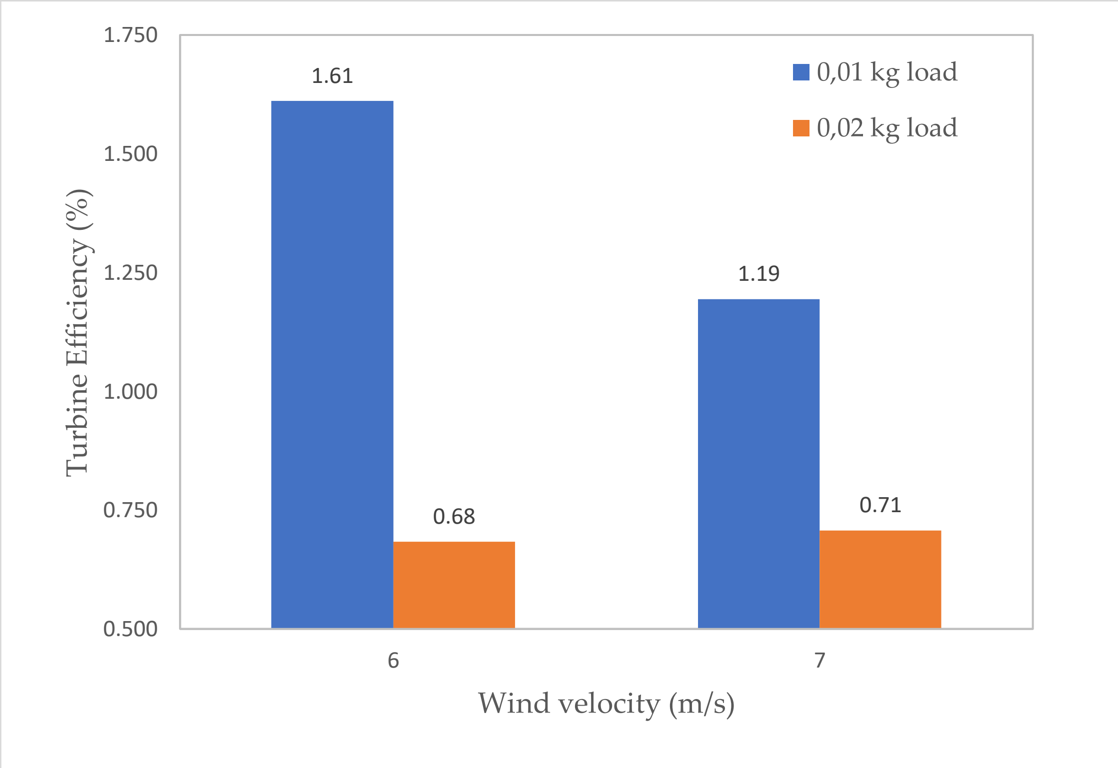


**Figure 3.** Relationship between wind speed and the power output of a four-blade Savonius turbine

**Figure 3** shows the relationship between wind speed (m/s) and the efficiency of the four-blade Savonius turbine (%) for two load variations: 0.01 kg and 0.02 kg. In general, it can be seen that changes in wind speed have different effects on turbine efficiency under each load condition. At a load of 0.01 kg, the efficiency decreases slightly with increasing wind speed. This may be due to aerodynamic losses as the turbine spins too quickly, reducing the effective conversion of wind energy [10]. At a wind speed of 6 m/s, the efficiency reaches 1.61%, but when the wind speed increases to 7 m/s, the efficiency drops to 1.19%. This decline indicates that under light load conditions, the increase in wind speed causes part of the wind's kinetic energy to not be fully converted into mechanical energy due to increased aerodynamic losses and turbulence around the turbine blades. In other words, at lighter loads, the turbine rotates too fast, causing some of the wind energy to be underutilized[11]. Conversely, at a load of 0.02 kg, the turbine efficiency shows a slight upward trend with increasing wind speed. The efficiency rises from 0.68% at 6 m/s to 0.71% at 7 m/s. This indicates that a slightly heavier load can help stabilize the turbine's rotation and improve the blades' ability to capture wind energy more effectively[12]. However, the efficiency values at 0.02 kg remain lower than those at 0.01 kg, indicating that excessive loading can reduce the overall performance of the turbine.

The results of this study show that the power output of the four-blade Savonius wind turbine consistently increases with the rise in wind speed for both load conditions (0.01 kg and 0.02 kg). This increase aligns with the fundamental principles of fluid mechanics in wind turbines, where wind power is proportional to the cube of the wind speed, meaning that the available kinetic energy for conversion becomes greater [5]. The power generated is inversely proportional to the load mass, as seen from the power at a 0.01 kg load, which is significantly higher (0.1018 W at 6 m/s) compared to the 0.02 kg load (0.0432 W at 6 m/s). This phenomenon is consistent with previous studies stating that an increase in mechanical load requires greater torque to overcome frictional forces, which ultimately reduces the turbine's rotational speed (RPM) and directly decreases the power output [6]. Savonius turbines are known to have high starting torque, but this advantage is significantly reduced when the load exceeds its aerodynamic torque capability at a given wind speed [13].

The efficiency analysis of the turbine reveals a complex interaction between wind speed and load, which is consistent with the characteristics of the Savonius turbine as a drag-type turbine. Under light load conditions (0.01 kg), the efficiency decreases significantly with increasing wind speed (from 1.61% to 1.19%) [7]. At lighter loads, the turbine operates at higher Tip Speed Ratios (TSR), which may lead to inefficient energy capture due to over-speeding and increased turbulence around the blades [14]. The excessively high rotational speed under light load conditions (over-speeding) prevents the airflow from being effectively captured and converted, instead generating unproductive drag [8]. Conversely, under heavier load conditions (0.02 kg), the efficiency shows a slight increase (from 0.68% to 0.71%) with the rise in wind speed. This indicates that the load helps stabilize the rotation and allows the turbine to operate closer to its optimal Tip Speed Ratio (TSR), thereby utilizing the available wind energy more effectively [9]. However, since the efficiency of the 0.02 kg load remains lower overall, it can be concluded that the optimal load for this turbine lies between 0.01 kg and 0.02 kg to obtain the highest efficiency performance, a finding that is in line with many studies that have focused on load optimization in small-scale Savonius turbines.

## 4. Conclusion

Based on the analysis of the relationship between wind speed and the power and efficiency of the four-blade Savonius turbine with two load variations (0.01 kg and 0.02 kg), an increase in wind speed generally leads to higher turbine power output; however, efficiency does not always improve due to aerodynamic losses and the turbine's operating conditions, particularly at higher wind speeds with lighter loads.

At a load of 0.01 kg, the turbine produces higher power compared to the 0.02 kg load because the lighter load allows the turbine to rotate faster. However, the efficiency at this load decreases as wind speed increases, indicating higher aerodynamic losses and turbulence caused by excessive rotational speed.

Conversely, at a 0.02 kg load, the turbine power output is lower, but its efficiency shows a slight increase with increasing wind speed. This suggests that a slightly heavier load helps stabilize the turbine's rotation and improves the blades' ability to capture wind energy more effectively.

Further optimization of load conditions and turbine blade design, along with more precise control of the TSR, could improve both power output and efficiency in future studies

## Authors' Declaration

**Authors' contributions and responsibilities** - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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