STUDY OF BLADE OVERLAP VARIATION ON THE POWER COEFFICIENT, TORQUE, AND TSR OF A SAVONIUS TURBINE FOR THE LOW-WIND-SPEED REGION OF NTT

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ABSTRACT

The utilization of wind energy in East Nusa Tenggara (NTT), which has low wind speeds (2–7 m/s), requires a turbine capable of operating under low-flow conditions. The Savonius turbine is a suitable solution because of its good self-starting capability and simple construction. This study aims to analyze the effect of blade overlap air-gap variations on the performance of a U-type Savonius turbine, including torque, power coefficient (Cp), and tip speed ratio (TSR). An experimental method was conducted using a wind tunnel and blower as an artificial wind source. Three overlap gap variations tested were 5 mm, 10 mm, and 15 mm, with wind speeds ranging from 4 m/s to 12 m/s under mechanical loading. Data collection was repeated three times for each test condition. The results show that the overlap gap variation significantly affects turbine performance. The 5 mm overlap configuration consistently produced the best performance with a maximum torque of 0.0027 N·m at 12 m/s wind speed, the highest power coefficient of 0.046 at 9 m/s, and the highest TSR of 0.190 at 10 m/s. The 5 mm overlap configuration is recommended for application in regions with low to moderate wind speeds (4–8 m/s) such as NTT.

Keywords: *Savonius turbine; blade overlap; power coefficient; torque; tip speed ratio*

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ABSTRAK

Pemanfaatan energi angin di Nusa Tenggara Timur (NTT) yang memiliki kecepatan angin rendah (2–7 m/s) memerlukan turbin yang mampu beroperasi pada kondisi aliran rendah. Turbin Savonius merupakan solusi yang sesuai karena kemampuan self-starting yang baik dan konstruksinya yang sederhana. Penelitian ini bertujuan untuk menganalisis pengaruh variasi celah udara blade overlap terhadap performa turbin Savonius tipe-U, meliputi torsi, koefisien daya (Cp), dan tip speed ratio (TSR). Metode eksperimental dilakukan dengan menggunakan wind tunnel dan blower sebagai sumber angin buatan. Tiga variasi celah overlap yang diuji adalah 5 mm, 10 mm, dan 15 mm, dengan kecepatan angin berkisar 4 m/s hingga 12 m/s di bawah beban mekanis. Pengambilan data diulang sebanyak tiga kali untuk setiap kondisi pengujian. Hasil penelitian menunjukkan bahwa variasi celah overlap mempengaruhi performa turbin secara signifikan. Konfigurasi overlap 5 mm secara konsisten menghasilkan performa terbaik dengan torsi maksimum 0,0027 N·m pada kecepatan angin 12 m/s, koefisien daya tertinggi 0,046 pada 9 m/s, dan TSR tertinggi 0,190 pada 10 m/s. Konfigurasi overlap 5 mm direkomendasikan untuk diterapkan di daerah dengan kecepatan angin rendah hingga sedang (4–8 m/s) seperti NTT.

Kata Kunci: *turbin Savonius; blade overlap; koefisien daya; torsi; tip speed ratio*

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1. INTRODUCTION

The need for renewable energy is becoming increasingly urgent in line with growing concerns about climate change, environmental degradation, and the depletion of non-renewable fossil energy reserves [1] [2]. As a developing country with an average annual growth in electricity consumption of 5%, Indonesia faces a dual challenge: meeting continuously rising energy demand while fulfilling its commitment to a clean energy transition toward Net Zero Emission (NZE) by 2060 [3]. Through Presidential Regulation No. 112 of 2022, the Indonesian government has established a roadmap to accelerate renewable energy development, targeting a renewable energy share of 23% by 2025 and 31% by 2050 [4]. One of the potential renewable energy sources widely distributed across Indonesia is wind energy, particularly in coastal and highland areas where ground-level wind flows are sufficiently consistent throughout the year.

Geographically, monitoring by the National Institute of Aeronautics and Space (LAPAN) indicates that several regions in Indonesia possess varying wind-speed potential, with the province of East Nusa Tenggara (NTT) exhibiting an average wind speed ranging from 2 m/s to 7 m/s [5]. This condition falls into the low wind-speed category according to the Indonesian National Standard (SNI) classification for wind energy conversion systems. Low wind speed poses a particular challenge for wind energy utilization, since most commercial wind turbines are designed to operate optimally at wind speeds above 6 m/s [6]. Therefore, the development of wind energy conversion systems (WECS) capable of operating effectively at low wind speeds is required, especially for the NTT region and other tropical areas with similar characteristics.

The Savonius-type vertical axis wind turbine (VAWT) is one type of turbine suitable for application in regions with low wind speeds [7]. Invented by the Finnish engineer Sigurd J. Savonius in 1922, this turbine offers advantages including good self-starting capability at low wind speeds (around 2.5–3 m/s), simple construction, low manufacturing cost, and the ability to accept wind from any direction without requiring a yaw system [8, 9]. The working principle of the Savonius turbine is based on the difference in drag force between the concave and convex blades, which generates a rotational torque on the vertical shaft [10]. However, the aerodynamic efficiency of the Savonius turbine is relatively lower compared with lift-type turbines such as the horizontal axis wind turbine (HAWT), so design parameter optimization is required to improve its performance.

One of the critical design parameters of the Savonius turbine is the blade overlap air gap, defined as the overlap distance between two adjacent blades on the turbine rotor [11]. An optimal overlap can improve energy conversion efficiency by reducing the negative drag effect on the returning blade, increasing the positive thrust on the advancing blade, and creating a more advantageous flow interaction through the formation of controlled vortices [12]. Previous studies have shown that different overlap ratios produce different characteristics of the Cp–TSR curve, so the selection of an appropriate overlap value is crucial for obtaining optimal performance [13, 14]. Most of these studies, however, focus on overlap ratio variations at the scale of 0.10–0.30 of the blade chord, while the influence of millimeter-scale absolute overlap gaps on a small-scale U-type Savonius rotor tested under controlled wind-tunnel conditions in the low-to-moderate wind-speed range (4–12 m/s) has not been systematically reported.

Research Gap and Novelty. The research gap addressed by this study lies in the limited experimental evidence regarding the influence of millimeter-scale overlap variations (5, 10, and 15 mm) on the performance parameters of a U-type Savonius turbine operating in the low-to-moderate wind-speed range characteristic of the NTT region. While earlier works have investigated overlap ratio effects at the normalized scale, very few have examined the absolute overlap gap at the millimeter scale on a small rotor with an end-plate configuration typical of micro-scale WECS prototypes. The novelty of this work therefore lies in mapping the torque, power coefficient (Cp), and tip speed ratio (TSR) of a U-type Savonius rotor to absolute overlap gaps of 5, 10, and 15 mm under controlled wind-tunnel loading, and in deriving a practical recommendation that matches the 4–8 m/s wind profile of NTT. Accordingly, this study aims to experimentally analyze the effect of blade overlap air-gap variations of 5, 10, and 15 mm on the performance of a U-type Savonius turbine tested using a wind tunnel over a wind-speed range of 4–12 m/s, with the performance parameters analyzed including torque, Cp, and TSR. The contribution of this study is to provide a

recommendation for the optimal overlap configuration for application in regions with low wind speeds such as NTT, and to enrich the literature on Savonius turbine geometry optimization for tropical regions. The results are expected to serve as a reference for the development of small-scale wind energy conversion systems suitable for the eastern part of Indonesia.

2. RESEARCH METHODS

2.1 Tools and Materials

This study employs an experimental method involving direct testing using a wind tunnel. The main equipment used includes: (1) a blower as an artificial wind source with a speed capacity of 4–12 m/s, (2) a digital anemometer to measure wind speed with an accuracy of 0.1 m/s, (3) a digital tachometer to measure the turbine rotor rotational speed in rpm, (4) a spring balance with a capacity of 0–1.3 N to measure the shaft force due to rotation, and (5) a U-type Savonius turbine model with three blade overlap air-gap variations. The material used to fabricate the turbine model is 1 mm-thick aluminum plate with an 8 mm-diameter steel shaft. Full-circle end plates are installed at the top and bottom of the rotor to reduce air leakage at the blade tips [15]. Figure 1 shows the Savonius turbine model used in the study, with its specifications presented in Table 1.

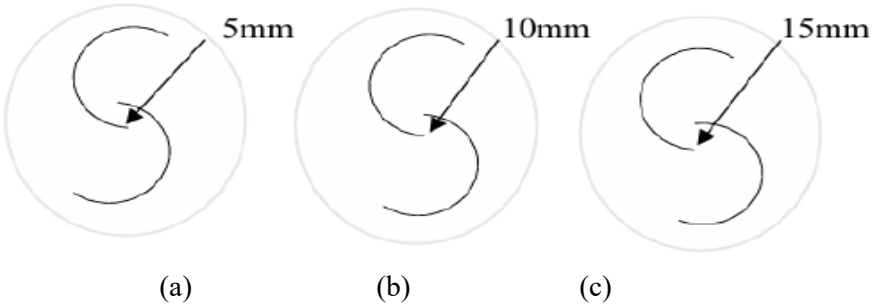


Figure 1. Design of the Overlap Distance Variations: (a) 5 mm; (b) 10 mm; (c) 15 mm

Table 1. Specifications of the U-type Savonius turbine model

Parameter	Value	Unit
Turbine type	Savonius U	–
Number of blades	2	unit
Rotor diameter (D)	0.12	m
Rotor height (H)	0.30	m
Rotor radius (r)	0.03	m
Swept area (A)	0.036	m²
Blade material	1 mm aluminum plate	–
Shaft material	Steel ST 37 Ø 8 mm	–
Overlap gap variations	5, 10, 15	mm
End plate	Full circle Ø 1.2 D	–

2.2 Testing Variables

The independent variables in this study consist of two parameters: (1) the blade overlap air gap, comprising three variations of 5 mm, 10 mm, and 15 mm; and (2) the wind speed, varied from 4 m/s to 12 m/s in 1 m/s increments, resulting in nine testing points. The response variables measured and analyzed include turbine rotational speed (n, in rpm), torque (τ, in N·m), power coefficient (Cp), and tip speed ratio (TSR). The control variables kept constant during testing include rotor geometry, blade material, swept area, and ambient conditions (temperature 27 °C, pressure 1 atm, air density 1.184 kg/m³). Each test was repeated three times for every parameter combination to ensure data reproducibility [16].

2.3 Testing Procedure

The experimental testing procedure follows the steps below. First, the Savonius turbine model with a 5 mm overlap gap is mounted on the test rig inside the wind tunnel. The blower is switched on and the wind speed is set to 4 m/s using the anemometer as a reference. Once the wind speed stabilizes, the no-load turbine rotational speed is measured using a digital tachometer. Next, a mechanical load is applied gradually using the spring balance, starting from 0.1 N up to 1.3 N in 0.1 N increments. At each load level, the turbine rotational speed (rpm) and the shaft forces (F1, F2) are recorded. The same procedure is repeated for wind speeds from 5 m/s up to 12 m/s. After all data for the 5 mm overlap are collected, the turbine

model is replaced by the 10 mm overlap model, then the 15 mm overlap model, and the entire testing procedure is repeated. Each test is repeated three times to obtain an average value and to minimize measurement errors.

2.4 Analysis Equations

The wind power available in the air flow passing through the rotor swept area is calculated using the kinetic energy equation of the air mass:

$$P_a = ½ \cdot \rho \cdot A \cdot v^3 \quad (1)$$

where P_a is the wind power (W), ρ is the air density (kg/m³), A is the blade swept area (m²), and v is the wind speed (m/s). The mechanical power produced by the turbine is calculated as the product of torque and angular velocity:

$$P_t = \tau \cdot \omega = \tau \cdot (2\pi n / 60) \quad (2)$$

where P_t is the turbine power (W), τ is the torque (N·m), ω is the angular velocity (rad/s), and n is the rotor rotational speed (rpm). The torque itself is calculated from the shaft force and the rotor radius:

$$\tau = (F_1 - F_2) \cdot r \quad (3)$$

where F_1 and F_2 are the forces on the advancing and returning sides of the blade (N), and r is the rotor radius (m). The power coefficient (Cp) is the ratio of the mechanical power produced by the turbine to the available wind power:

$$C_p = P_t / P_a = (2 \cdot \tau \cdot \omega) / (\rho \cdot A \cdot v^3) \quad (4)$$

The Tip Speed Ratio (TSR) is the ratio of the blade tip speed to the free-stream wind speed, describing the mechanical rotation efficiency of the turbine:

$$\lambda = (\omega \cdot r) / v = (2\pi n \cdot r) / (60 \cdot v) \quad (5)$$

The above equations are used to compute the performance parameters of the Savonius turbine for each overlap variation and wind speed. The resulting Cp and TSR values are then comparatively analyzed to determine the optimal overlap configuration.

2.5 Research Flowchart

The research flowchart is presented in Figure 2.



Figure 2. Experimental research flowchart of the Savonius turbine

The research stages begin with problem identification and a literature review, followed by preparation of tools and materials, fabrication of the turbine model with three overlap gap variations, experimental testing in the wind tunnel, repeated data collection, data analysis using Equations (1) – (5), and finally the formulation of conclusions and recommendations for the optimal overlap configuration.

3. RESULTS AND DISCUSSION

3.1 Research Results

The measurement results of the no-load turbine rotational speed for the three overlap gap variations at nine wind speeds are summarized in Table 2. The data represent the average values of three measurement repetitions. The results show that at every wind speed, the 5 mm overlap configuration consistently produces the highest rotational speed, followed by the 10 mm and 15 mm overlaps. For example, at a wind speed of 12 m/s, the 5 mm overlap yields an average speed of 602.0 rpm, whereas the 10 mm and 15 mm overlaps produce 538.4 rpm and 492.1 rpm, respectively. A similar pattern is observed across the entire wind-speed range, indicating that a smaller overlap gap enables a more effective conversion of wind kinetic energy into mechanical rotation.

Table 2. Average no-load turbine rotational speed for three overlap variations

Wind Speed (m/s)	Overlap 5 mm (rpm)	Overlap 10 mm (rpm)	Overlap 15 mm (rpm)
4	167.2	142.5	118.3
5	226.3	198.7	165.2
6	321.4	268.1	231.5
7	380.4	335.2	294.7
8	453.3	402.6	358.9
9	537.3	481.7	425.4
10	604.1	545.8	482.1
11	609.7	552.3	487.6
12	602.0	538.4	492.1

The Savonius turbine torque is calculated using Equation (3) based on the difference between forces $F_1 - F_2$ measured using the spring balance and the rotor radius r = 0.03 m. Figure 3 shows the comparison of torque against mechanical load at a representative wind speed of 7 m/s for the three overlap variations. The test results show that the torque produced by the turbine decreases as the mechanical load increases. This is caused by the increasing drag force on the shaft as the load is increased, which reduces the ability of the turbine to maintain its rotational speed.

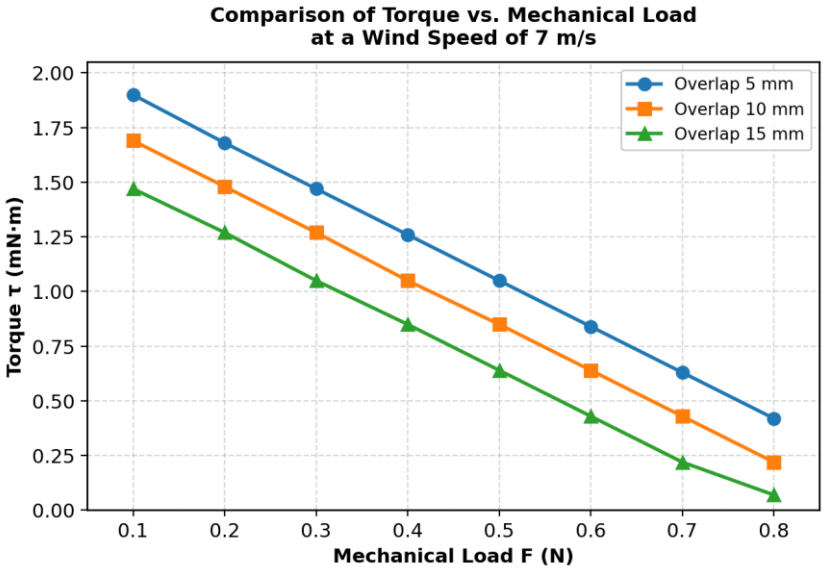


Figure 3. Comparison of torque vs. mechanical load at a wind speed of 7 m/s for three overlap variations

The 5 mm overlap configuration produces the highest torque at every load level, followed by the 10 mm and 15 mm overlaps. At a load of 0.1 N, the 5 mm overlap produces a torque of 1.89 mN·m, while the 10 mm and 15 mm overlaps produce 1.68 mN·m and 1.47 mN·m, respectively. The maximum recorded torque of 2.7 mN·m (0.0027 N·m) was obtained for the 5 mm overlap at a wind speed of 12 m/s under low load. This result is consistent with the physical mechanism in which a small overlap gap allows the air flow striking the concave blade to be immediately deflected toward the convex side of the returning blade, thereby reducing the negative drag and increasing the net thrust acting on the rotor [17, 18].

The power coefficient (Cp) is calculated using Equation (4) as the ratio of the turbine mechanical power to the available wind power. Figure 4 presents the comparison of the maximum Cp at each wind speed for the three overlap variations. The test results show that the Cp value increases with wind speed until reaching a peak, and then decreases at higher wind speeds. This pattern is consistent with the Cp–TSR curve characteristics of the Savonius turbine reported in the literature [19, 20].

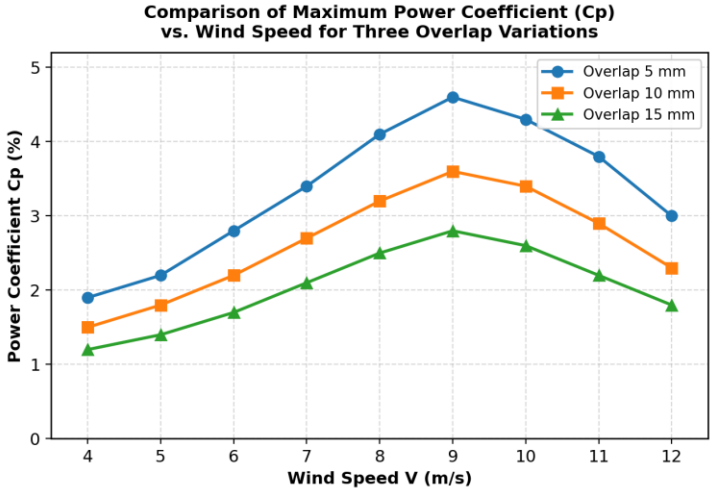


Figure 4. Comparison of maximum power coefficient (Cp) vs. wind speed for three overlap variations

The 5 mm overlap configuration produces the highest Cp of 0.046 (4.6%) at a wind speed of 9 m/s, followed by the 10 mm overlap with a maximum Cp of 0.036 (3.6%) at 9 m/s, and the 15 mm overlap with a maximum Cp of 0.028 (2.8%) at 9 m/s. At wind speeds above 10 m/s, the Cp value decreases significantly for all overlap variations. This decline is caused by flow separation and increased turbulence on the blades when the wind speed exceeds the turbine's optimal operating limit, thereby reducing the energy conversion efficiency [21, 22]. These results indicate that the 5 mm overlap configuration provides the most effective energy conversion, particularly in the wind-speed range of 4–9 m/s, which is relevant for applications in the NTT region.

The Tip Speed Ratio (TSR) is calculated using Equation (5) as the ratio of the blade tip speed to the free-stream wind speed. Figure 5 shows the comparison of TSR against wind speed for the three overlap variations. The measurement results show that the 5 mm overlap configuration consistently produces the highest TSR at every wind speed. The maximum TSR value of 0.190 is achieved at a wind speed of 10 m/s for the 5 mm overlap, whereas for the 10 mm and 15 mm overlaps the maximum TSR values are 0.152 and 0.119, respectively.

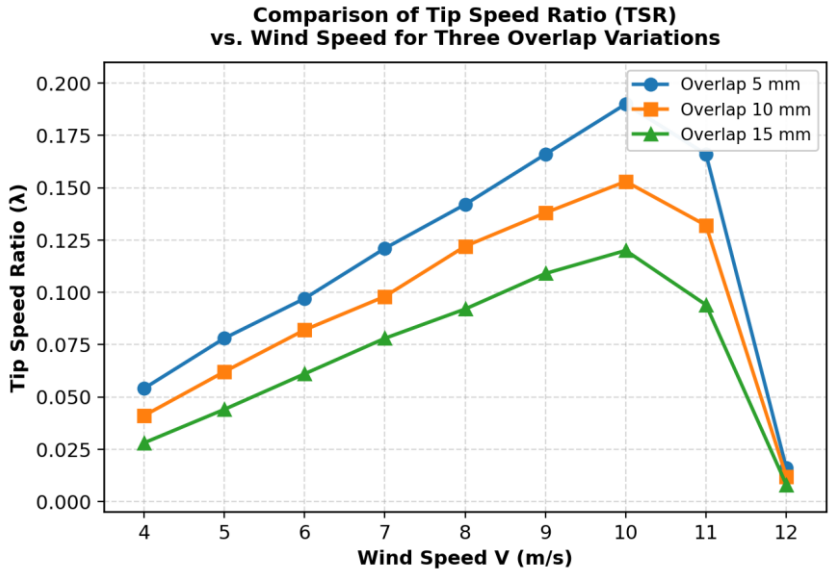


Figure 5. Comparison of tip speed ratio (TSR) vs. wind speed for three overlap variations

An interesting characteristic is observed at a wind speed of 12 m/s, where the TSR value drops drastically to 0.016 for the 5 mm overlap. This decline occurs because, at high wind speeds, the maximum mechanical load applied by the spring balance (1.3 N) causes the turbine rotational speed to drop significantly toward zero, so the ratio of the blade tip speed to the wind speed becomes very small. This indicates that the Savonius turbine has an operational limitation at very high wind speeds, where the torque required to overcome the load exceeds the torque that the turbine can produce [23]. For application in the NTT region with a dominant wind speed of 2–7 m/s, the optimal operating range of this turbine lies within wind speeds of 4–8 m/s.

3.2 Discussion

The results show that the 5 mm overlap configuration consistently produces the best performance compared with the 10 mm and 15 mm overlaps. The physical mechanism underlying this finding can be explained through analysis of the air flow around the overlap gap. In the small overlap configuration (5 mm), the air flow striking the advancing concave blade is deflected at a relatively narrow angle toward the convex side of the returning blade [24]. This deflection produces two beneficial effects: first, it reduces the negative pressure (negative drag) on the convex side, thereby lowering the opposing drag force on the rotation; second, it adds positive thrust to the convex side, thereby increasing the net torque produced by the rotor.

Conversely, in the larger overlap configurations (10 mm and 15 mm), the wider gap causes part of the air flow to become trapped between the blades, forming a recirculation zone that actually adds drag [25]. This trapped flow does not contribute positively to the rotation; instead, it generates turbulence that increases energy losses. In addition, the formation of vortices on the leeward side of the blade becomes less optimal when the overlap gap is too large, so the inter-blade flow interaction expected to enhance energy transfer is not achieved effectively. These results are in line with CFD studies conducted by previous researchers, which showed that the optimal flow pattern occurs at an overlap ratio of approximately 0.15–0.20 of the blade chord diameter [26].

Table 3 summarizes the comparison between the results of this study and those of previous studies. A study by Ramadhan et al. (2025) on a U-type Savonius turbine with overlap ratio variations of 0.10–0.30 reported a maximum Cp of 0.21 at a TSR of 0.8 [10]. The difference in Cp values from this study is caused by differences in model scale, aspect ratio (H/D), and testing conditions. A study by Firman (2024) on an L-type Savonius turbine with variations in overlap distance reported a similar trend, in which a smaller overlap produced higher torque and Cp [11], which is consistent with the findings of this study.

An experimental study conducted by Sumiati et al. (2022) using a wind tunnel on a Savonius turbine model found that increasing the overlap ratio from 0 to 0.2 increased the Cp by up to 17%, but increasing the overlap above 0.2 actually decreased the Cp [14]. This finding supports the results of this study, in which the 5 mm overlap (smaller overlap ratio) produces a higher Cp than the 10 mm and 15 mm overlaps. Other studies in the field of VAWT also confirm that overlap geometry optimization can improve Savonius turbine efficiency by 20–30% [24, 27]. The differences in the absolute Cp values between this study and the reference studies are mainly due to differences in model dimensions, blade material, aspect ratio, and ambient conditions during testing.

Table 3. Comparison of study results with selected reference studies

Study	Type	Overlap	Max Cp	Max TSR
This study (2026)	U	5 mm	0.046	0.190
This study (2026)	U	10 mm	0.036	0.152
This study (2026)	U	15 mm	0.028	0.119
Ramadhan et al. (2025)	U	ratio 0.2	0.210	0.800
Firman (2024)	L	varied	0.150	0.650
Sumiati et al. (2022)	U	ratio 0.2	0.170	0.720
Silla et al. (2022)	U	fixed	0.140	0.600

The results of this study have significant practical implications for the development of wind energy conversion systems in the NTT region and other tropical areas with low wind-speed characteristics. Based on LAPAN data, the average wind speed in NTT ranges from 2–7 m/s, with a dominant speed of 4–6 m/s during the day [28]. The results show that the 5 mm overlap configuration produces optimal performance over the wind-speed range of

4–8 m/s, which matches the wind profile of the NTT region. Therefore, the recommended 5 mm overlap configuration can be directly applied to the development of micro-scale Savonius turbines intended for use by households, schools, or remote service posts in NTT.

For practical implementation, a Savonius turbine with a 5 mm overlap can be combined with a 50–100 W permanent magnet generator and a 12 V battery-based energy storage system [29]. The estimated power that can be produced by a turbine with a swept area of 0.036 m² at a wind speed of 6 m/s with a Cp of 0.028 is approximately 0.9 W. Although this power is relatively small, the Savonius turbine can be designed as an array of several units to increase the total power output. This modular approach is suitable for off-grid applications on the remote islands of NTT that are not yet reached by the PLN (state electricity company) grid. In addition, the combination of a Savonius turbine with solar panels can form a more reliable hybrid renewable energy system for island regions.

From an economic perspective, the proposed 5 mm overlap Savonius turbine also offers advantages for community-scale deployment in NTT. The rotor can be fabricated from locally available aluminum sheet at low cost, and the simple geometry does not require specialized tooling. Moreover, because the turbine operates at low rotational speeds, mechanical wear on bearings and shaft is minimized, reducing maintenance frequency in remote locations where technical support is limited. The end-plate configuration also provides additional structural rigidity, allowing the rotor to withstand gusts and turbulence common in coastal environments. Future work should investigate the long-term durability of the 5 mm overlap configuration under field conditions, as well as the integration of the turbine with low-cost power electronic converters optimized for variable low-speed inputs.

4. CONCLUSIONS

Based on the experimental results regarding the effect of blade overlap air-gap variations on the performance of a U-type Savonius turbine over a wind-speed range of 4–12 m/s, three main conclusions can be drawn. First, the blade overlap gap variation has a significant effect on the performance of the Savonius turbine, in which the 5 mm overlap configuration consistently produces the best performance compared with the 10 mm and 15 mm overlaps across the entire tested wind-speed range. The 5 mm overlap configuration produces a maximum torque of 0.0027 N·m at a wind speed of 12 m/s, the highest power coefficient of 0.046 at a wind speed of 9 m/s, and the highest TSR of 0.190 at a wind speed of 10 m/s. Second, the efficiency of the Savonius turbine generally decreases as the wind speed increases above 10 m/s, as indicated by the decline in Cp and TSR values at wind speeds of 11–12 m/s. This indicates that the tested U-type Savonius turbine configuration has an optimal operating range at wind speeds of 4–9 m/s, which matches the wind-speed profile of the NTT region. Third, the physical mechanism underlying the superiority of the 5 mm overlap involves the reduction of negative pressure on the returning blade and the increase of positive thrust through more effective air-flow deflection in the narrow overlap gap. The recommended 5 mm overlap configuration is therefore suitable for micro-scale wind energy conversion systems deployed in low-wind-speed tropical regions such as NTT.

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