Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN : 2549-1999 No. : 2 Month : April
p-ISSN : 1693-5462 Volume : 24 Year : 2026

Processing dates: received on 2026-3-09, reviewed on 2026-03-19, accepted on 2026-03-24 and online availability on 2026-04-25

Comparative of field study of three- and four-bladed archimedes spiral wind turbines under natural low wind conditions

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Abstract

Archimedes Spiral Wind Turbines (ASWTs) are suitable for small-scale energy harvesting in low wind environments.However, field-based evaluation on the effect of blade number under natural wind conditions remains limited. This study experimentally examines the influence of blade number on rotational behavior and electrical performance under natural wind conditions, providing empirical insights beyond controlled laboratory and numerical studies. Three-bladed and four-bladed turbine configurations were fabricated and tested in field conditions with wind speeds ranging from 0.8 to 4.0 m/s. Wind speed, rotational speed, voltage, current, and electrical power were measured and analyzed. The results show that the four-bladed turbine achieved earlier cut-in behavior and consistently higher electrical output across the tested range, reaching a peak power of approximately 0.29 W at wind speeds of 4.0 m/s, compared with about 0.09 W for the three-bladed configuration. The improved performance was attributed to enhanced torque continuity and rotational stability rather than increased rotational speed alone. Transient current peaks and zero-current events observed near 1.5 to 2.0 m/s were attributed near-cut in electromechanical behavior under short-term wind fluctuations. These results confirm that blade number significantly affects ASWT performance in low wind environments and provide practical guidance for optimizing small-scale wind turbine design.

Keywords:
Archimedes; blade number; field study; low wind speed; wind turbine

1 Introduction

The increasing global demand for electricity, concerns over energy security, and the need to reduce greenhouse gas emissions have accelerated the transition toward renewable energy [1]. These challenges are reflected in the United Nations Sustainable Development Goals (SDGs), particularly those addressing affordable and clean energy (SDG 7), climate action (SDG 13), and sustainable urban development (SDG 11). Among renewable energy sources, wind energy plays a central role in this transition due to its abundance, technological maturity, and economic competitiveness [2]. However, wind power benefits are unevenly distributed, as many tropical, urban, and densely populated regions experience persistently low wind speeds that limit conventional turbine performance [3].

Most commercial wind power systems are based on horizontal-axis wind turbines (HAWTs), which are optimized for moderate to high wind speeds, typically above 5 m/s [4]. Under low wind conditions, these turbines suffer from high cut-in speeds, reduced aerodynamic efficiency, and increased mechanical complexity related to yaw and pitch control systems [5]. Consequently, their deployment in low wind regions often results in poor energy yield and unfavorable economic performance [6]. This technological mismatch has constrained the contribution of wind energy to local energy access and sustainability goals in such areas.

In response to these limitations, alternative turbine concepts have gained increasing attention, particularly those designed to operate effectively at low wind speeds [7]–[10]. The Archimedes wind turbine (ASWT) represents one such approach. Drawing inspiration from the Archimedean screw, the ASWT employs a three-dimensional helical blade geometry that allows continuous interaction with airflow from multiple directions [11]. This configuration is associated with low cut-in speed, high starting torque, reduced sensitivity to wind direction, and relatively low noise emissions [12]. These characteristics make ASWTs well-suited for small-scale, decentralized energy systems, including applications in urban environments and off-grid or weak-grid communities [13], [14].

Previous studies on ASWT have consistently demonstrated that turbine performance is highly sensitive to geometric design parameters. CFD-based aerodynamic optimization studies show that optimal blade geometry and operating conditions can achieve power coefficients of approximately 0.25-0.28, while excessive blade numbers increase drag and reduce performance [15]. Experimental and numerical investigations indicate that surface modifications and blade design refinements improve flow attachment and efficiency, though gains remain modest under low wind speeds [16].

With respect to blade number, the available literature remains notably limited. Recent CFD studies indicate that three-bladed ASWTs achieve higher torque and power coefficients across a range of tip-speed ratios, whereas turbines with four or more blades experience performance degradation due to increased drag and reduced inter-blade flow effectiveness [17]. Experimental evidence remains scarce; however, wind-tunnel studies confirm that blade number strongly influences ASWT performance, with three-bladed configurations producing up to 158% higher electrical power than four-bladed designs under controlled flow conditions [18].

Despite these advances, most existing studies rely on numerical simulations or laboratory wind tunnel experiments conducted under steady and idealized flow conditions. Such approaches do not fully capture the temporal variability, turbulence intensity, and intermittent behavior characteristic of natural low-wind environments. In particular, experimental evidence examining how blade number influences the electromechanical performance of ASWTS under real operating conditions remains limited. This gap is significant, as turbine performance in low wind regimes is strongly affected by transient aerodynamic loading and generator coupling effect that cannot be fully represented in a controlled environment. To address this gap, the present study experimentally compares three-bladed and four-bladed ASWTs operating under natural low wind speed conditions through direct field measurements. The investigation focuses on wind speed, rotational speed, voltage, current, and electrical power output to evaluate the electromechanical performance of each configuration. By isolating blade number while maintaining consistent geometric and operational parameters, this study aims to (1) quantify the effect of blade number on turbine performance under real wind conditions, and (2) elucidate the underlying mechanisms governing torque generation, rotational stability, and electrical output. The findings are expected to provide field-based insight into ASWT performance and support more informed design strategies for small-scale wind energy systems in low-wind environments.

2 Research methodology

2.1 Experimental approach

This study employed a field-based experimental approach to evaluate the performance of ASWTs with different blade numbers under low wind speed conditions. Two turbine configurations, three-bladed and four-bladed ASWTs, were designed, fabricated, and tested under identical environmental and electrical loading conditions. The experimental design aimed to isolate the effect of blade number on turbine rotational behavior and electrical power output. All measurements were conducted under natural low wind speed conditions (0.8-4 m/s), without artificial flow generation, to ensure that the results reflect realistic operating environments typical of low-wind urban areas.

2.2 Turbine configuration and design parameters

Both turbine configurations were based on the Archimedes spiral concept, featuring helical blades arranged around a vertical rotor axis. The turbines were designed with identical overall dimensions to ensure fair comparison. Each rotor had an outer diameter of 1.0 m, a constant swept area, and identical shaft, bearing, and generator arrangements. The blades were evenly distributed around the rotor circumference to maintain geometric symmetry and minimize imbalance during operation. A blade pitch angle of 60° was selected for the experimental tests, based on our preliminary computer-based simulation performance considerations for low wind speed operation [19].

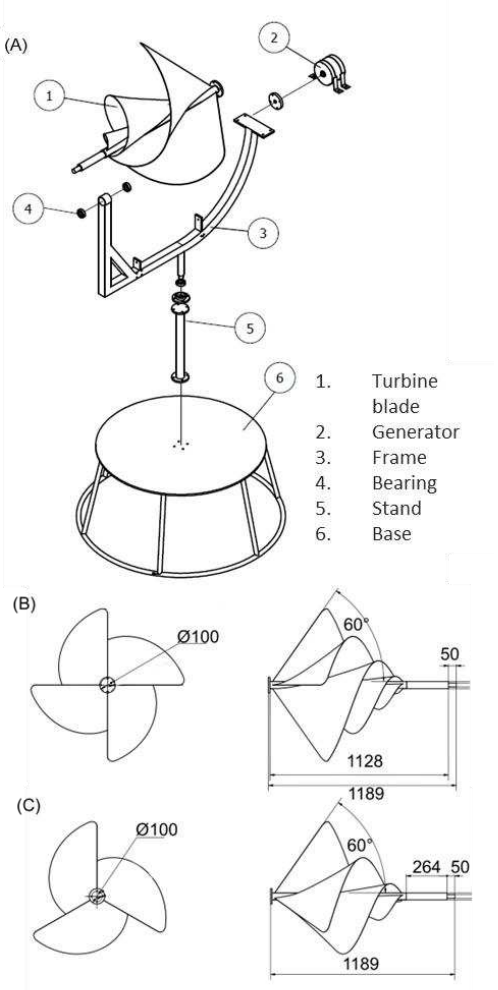

Fig 1. Illustration of the ASWT system. (A) Three-dimensional assembly of the turbine, (B) Geometric dimensions of the four-blade, and (C) Three-blade ASWT

2.3 Turbine fabrication and assembly

The turbine blades were fabricated from plastic fiber sheets with a thickness of 1 mm, as illustrated in Fig. 1. Each blade was cut according to a spiral template and shaped using controlled heating and forming jigs to achieve the desired helical geometry. The turbine hub was manufactured from steel or aluminum plates with pre-drilled mounting holes to ensure consistent blade positioning. A central steel shaft with a diameter of 20 mm was used for both turbine configurations and supported by rolling bearings to reduce mechanical friction. Each turbine was coupled to a permanent magnet DC (PMDC) generator with a nominal voltage of 12 V. The generator was mounted on a rigid steel frame to maintain shaft alignment and minimize mechanical losses during operation. The turbine assembly was installed on a steel tower with a height of 1.5 m, allowing adequate exposure to ambient wind flow while maintaining structural stability. The fabricated ASWTs system is depicted in Fig. 2.

Fig 2. Photograph of the fabricated three-blade (A) and four-blade (B) ASWT

2.4 Experimental site and environmental conditions

Field-testing was conducted in an open area located in Bank Raya St, Palembang, South Sumatra, Indonesia (2°58'36.5"S and 104°43'45.4" E), characterized by relatively low and variable wind speeds. The site exhibits average wind velocities in the range of 2-3 m/s, representative of typical low-wind urban environments in tropical regions. The experiment was carried out over seven days, from 01 to 07 January 2026, with measurements taken between 10:00 and 18:00 local time to capture daytime wind variability.

2.5 Instrumentation and measurement setup

Wind speed was measured using a handheld cup or propeller anemometer (Benetecch GM816 digital; test range of 0-30 m/s, accuracy of ±0.05 m/s). Rotor rotational speed was measured using a handheld tachometer (TaffSTUDIO DT-2234C; test range of 2.5-99,999 RPM; accuracy of ±0.05, sampling time of 0.8 s). Electrical output parameters, including voltage and current, were measured using a true RMS digital multimeter (ANENG, NCV LCD 6000 count-SZ312, test range of 0-750 V and 0-20 A, accuracy of ±0.015), with a clamp meter used when necessary to measure current without interrupting the circuit. The experimental setup used for the field test is summarized in Fig. 3.

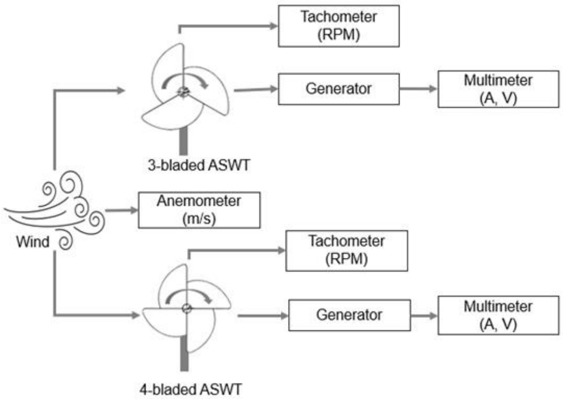

Fig 3. Schematic diagram of the field-test measurement setup

2.6 Data collection procedure

Each turbine configuration was tested separately to prevent aerodynamic interference. At each measurement interval, wind speed, rotor rotational speed, output voltage, and output current were recorded simultaneously. Measurements were recorded at 1-hour intervals, resulting in a total of approximately 70 data points per turbine configuration over the testing period. Although the measurement period was limited to seven days, the recorded data captured a representative range of low wind speed conditions (0.8–4.0 m/s) with varying levels of temporal fluctuation. The observed variability in daily mean wind speed and standard deviation indicates that the dataset sufficiently reflects the unsteady nature of low-wind environments. Therefore, the collected data are considered adequate for evaluating the comparative performance of the two turbine configurations under realistic operating conditions.

2.7 Performance evaluation

The primary performance indicator used in this study was the electrical power output, calculated using equation (1):

$$P = VxI \qquad (1)$$

where P is the electrical power (W), V is the measured voltage (V), and I is the measured current (A) [20]. The collected data were analyzed to compare the electrical power generation and rotational behavior of the three-bladed and four-bladed ASWT under low wind speed conditions.

3 Result and discussion

3.1 Field wind speed characteristics

The wind speed conditions recorded during the seven-day field-testing period are presented in Fig. 4. The measured wind speeds exhibited clear temporal variability, reflecting the unsteady nature of low wind environments. Across all measurement days, wind speeds generally ranged from 0.8 to 4.0 m/s, with the majority of observations concentrated between 2.0 and 3.0 m/s. This confirms that the experiments were conducted under representative low-wind conditions [21].

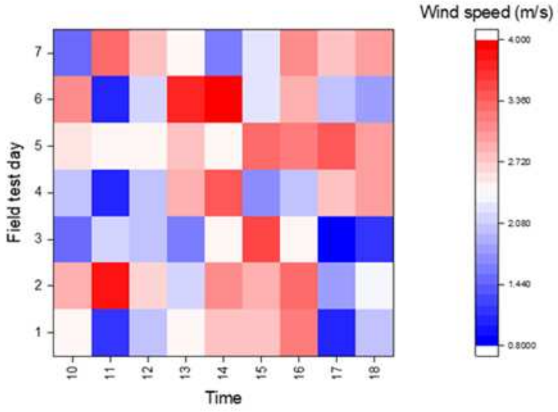

Fig 4. Wind speed measured during the field-testing period

As summarized in Table 1, the daily mean wind speeds varied between 1.97 m/s and 2.84 m/s, with the lowest average on day 3 and the highest on day 5. Maximum wind speeds reached 4.0 m/s (day 6), while the minimum recorded wind speed was 0.8 m/s (day 3). These values confirm the absence of sustained high wind events during testing, highlighting the suitability of the test conditions for evaluating turbine performance in low wind regimes.

Wind variability was reflected in standard deviation (SD) values ranging from 0.39 to 0.94 m/s. Higher variability was observed on day 6 (SD of 0.94 m/s), whereas day 5 exhibited relatively more stable wind conditions (SD of 0.39 m/s). Despite these fluctuations, overall wind characteristics remained comparable across testing days, ensuring consistent environmental conditions for both turbine configurations. Therefore, differences observed in subsequent sections can be attributed primarily to blade number effects rather than variations in wind availability.

Table 1. Wind speed data during the field-testing period

Parameter	Wind speed (m/s)						
	day 1	day 2	day 3	day 4	day 5	day 6	day 7
mean	2.22	2.77	1.97	2.32	2.84	2.54	2.53
max	3.20	3.80	3.50	3.40	3.40	3.70	3.30
min	1.10	1.80	0.80	1.10	2.40	1.10	1.50
SD	0.72	0.62	0.81	0.74	0.39	0.94	0.64

3.2 Electrical output characteristics

Fig. 5 presents the relationship between wind speed and electrical output, with averaged values summarized in Table 2. The results show a consistent increase in output voltage and current with increasing wind speed for both turbine configurations, confirming the dependence of electrical performance on available wind energy under low wind conditions [22].

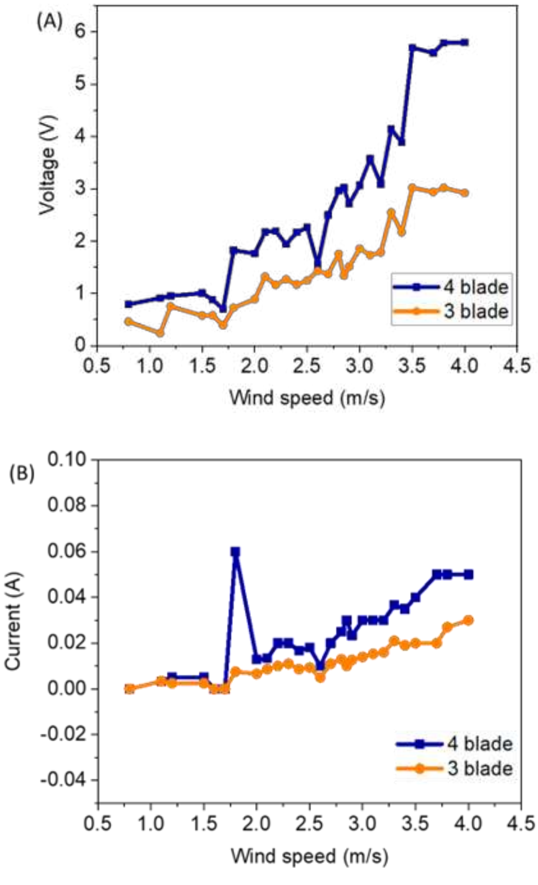

Fig 5. Voltage (A) and current output (B) obtained during the field test as a function of wind speed

Across all wind speed intervals, the four-bladed turbine generated higher voltage output than the three-bladed turbine (Fig. 5A). At the lowest wind speed range (0.8-1.5 m/s), the four-bladed configuration produced an average voltage of 0.913±0.091 V, compared with 0.506 ± 0.214 V for the three-bladed turbine. This difference became more pronounced at higher wind speeds. In the 2.6-3.0 m/s interval, the average voltage increased to 2.635±0.573 V for the four-bladed turbine, while the three-bladed turbine reached 1.544±0.213 V. At the highest analyzed range (3.6-4 m/s), the four-bladed turbine achieved an average voltage of 5.73±0.113 V, nearly 94% greater of that the three-bladed turbine (2.960±0.053 V).

Table 2. Average voltage and current produced from both 4-blade and 3-blade ASWTs

Wind speed (m/s)	Voltage (V)		Current (mA)	
	4-blade	3-blade	4-blade	3-blade
0.8-1.5	0.91±0.09	0.51±0.21	3.33±2.36	2.08±1.44
1.6-2.0	1.29±0.59	0.65±0.21	18.21±28.50	3.52±4.08
2.1-2.5	2.15±0.12	1.40±0.07	20.58±2.77	10.31±0.99
2.6-3.0	2.64±0.57	1.54±0.21	23.06±7.49	10.94±3.25
3.1-3.5	4.08±0.99	2.25±0.54	34.33±4.35	18.27±2.49
3.6-4.0	5.73±0.11	2.96±0.05	50.00±0.00	25.67±5.13

Current output exhibited trends consistent with the voltage measurements (Fig. 5B), reflecting the shared dependence of both quantities on rotor speed and generator response. However, intermittent behavior was observed near the cut-in operating region (1.5-2.0 m/s), including occasional zero-current readings and localized current peaks (at 1.8 m/s). These effects are associated with transient torque fluctuations under natural field conditions, where short-term wind gusts can momentarily stabilize rotor rotation while brief lulls reduce torque below the level required for sustained electrical generation [23]. Previous studies on DC motor dynamics have shown that, near cut-in, the current response of a PMDC generator is highly sensitive to torque availability [24], [25], leading to disproportionate variations in current despite relatively small changes in wind speed. As these anomalies were not consistently observed across adjacent wind-speed intervals, they are interpreted as transient responses rather than systematic behavior.

Despite this instability, the averaged data showed a clear trend (Table 2). The four-bladed turbine produced approximately 20.576±2.772 mA at wind speeds of 2.1-2.5 m/s, 100% higher compared with 10.309 ± 0.985 mA for the three-bladed turbine, and this performance gap widened further at higher wind speeds. These results indicate that, despite short-term fluctuations inherent to field-testing, the four-bladed configuration delivers more stable and higher current output across the low wind speed range investigated. At the highest analyzed wind speed interval (3.1-3.5 m/s), the current increased to 34.333±4.346 mA for the four-bladed turbine, compared with 18.267±2.487 mA for the three-bladed configuration. The higher current output indicates more effective mechanical-to-electrical energy conversion, driven by increased shaft torque and reduced rotational speed fluctuations [26].

3.3 Power output comparison

The ability of an ASWT to generate usable electrical power under low wind conditions depends on the combined interaction of rotor torque, rotational stability, and generator response [27]. In this operating regime, power output does not increase linearly with wind speed but instead reflects threshold behavior associated with the cut-in operation and load engagement. As shown in Fig. 6, power generation remained negligible below approximately 1.5 m/s, consistent with cut-in behavior discussed earlier. A sharp increase was observed near 1.8 m/s. At this point, the four-bladed turbine reached approximately 0.095 W, whereas the three-bladed turbine produced only about 0.006 W. This disparity highlights the greater sensitivity of the four-bladed configuration to marginal increases in wind speed near cut-in operation.

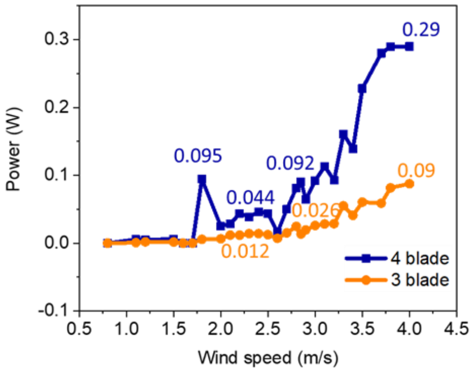

Fig 6. Power output obtained during the field test as a function of wind speed

As wind speed increased further, the performance gap widened progressively. At approximately 2.5 m/s, the four-bladed turbine generated around 0.044 W, more than three times the output of the three-bladed turbine, which remained near 0.012 W. A similar trend was observed at 3.0 m/s, where the four-bladed turbine produced close to 0.092 W compared with approximately 0.026 W for the three-bladed configuration. These results reflect the nonlinear nature of power generation in small-scale wind systems [28]. The significant increase in electrical power can be attributed to modest increases in wind speed when stable rotational conditions are established [29].

At higher wind speeds above 3.0 m/s, power output increased rapidly, reaching 0.28-0.29 W at 3.8-4.0 m/s for the four-bladed turbine, which is about 222% higher than the three-bladed turbine (0.09 W). The magnitude of the measured power output aligns with previous studies on three-bladed ASWTs, where optimized designs achieved power coefficients of approximately 0.24-0.25 under controlled conditions [30]. Similarly, a larger-scale ASWT operating at higher wind speeds has been reported to reach a maximum power coefficient of 0.293 [31], which is comparable in magnitude despite differences in turbine scale and operating conditions. This suggests that, although absolute power is limited by the available wind energy at low wind speeds, the underlying energy conversion capability remains within the expected performance range of ASWT systems. The smoother and steeper rise in power observed for the four-bladed turbine further indicates more continuous torque delivery and improved rotor-generator coupling, reducing sensitivity to short-term wind fluctuations. Although increased blade solidity enhances aerodynamic drag [32], the results indicate that this effect is outweighed by increased pressure-driven forces along the blade surfaces, which result in improved torque availability and rotational stability [33]. This, in turn, leads to significantly higher electrical power generation in environments characterized by weak and variable wind resources.

3.4 Effect of blade number on aerodynamic torque and rotational behavior

Fig. 7 shows the variation of rotational speed with wind velocity. Both turbines exhibited increasing rotational speed with wind speed, consistent with PMDC generator characteristics [34]. However, across the entire wind speed range, the four-bladed turbine exhibited consistently higher rotational speeds than the three-bladed configuration.

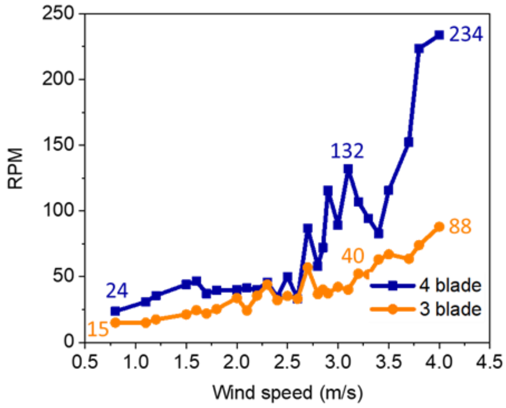

Fig 7. ASWTs' rotation per minute during the field test as a function of wind speed

At low wind speeds, the four-bladed turbine reached approximately 24 rpm compared to 15 rpm for the three-bladed configuration. This difference became more pronounced at higher wind speeds. At 2.5-3.0 m/s, the four-bladed turbine exhibited a rapid increase to exceeding 130 rpm, whereas the three-bladed turbine remained below 40 rpm. This divergence suggests that the four-bladed rotor benefits from more continuous aerodynamic loading along the helical blades, resulting in steadier torque delivery and reduced susceptibility to partial stalling [35]. In contrast, the three-bladed turbine appears more sensitive to local flow variations [36], leading to slower rotational acceleration under the same wind conditions.

At higher wind speeds above 3.5 m/s, the rotational speed of the four-bladed turbine increased sharply above 230 rpm, compared to less than 90 rpm for the three-bladed configuration. Higher rotational speed alone does not guarantee improved power generation. However, the pronounced difference indicates that the four-bladed turbine maintains stronger aerodynamic coupling with the flow, enabling sustained acceleration rather than intermittent rotation [37]. The smoother increase in rpm also implies reduced rotational instability, which is particularly important for small-scale wind turbines operating under naturally fluctuating wind conditions.

These results confirm that the superiority of the four-bladed ASWTs arises from enhanced torque delivery and rotational stability rather than increased rotational speed alone, enabling more effective energy transfer from the rotor to the generator [38]. From an aerodynamic perspective, these results highlight the role of blade number in shaping the torque–speed relationship of ASWTs.

3.5 Performance trade-offs between three- and four-bladed ASWTs in low wind conditions

The field experiment results reveal a clear trade-off between blade number, aerodynamic loading, and operational efficiency in ASWT operating under low wind speed conditions. While both three-bladed and four-bladed configurations are capable of extracting energy from weak and variable winds, their performance characteristics differ substantially due to differences in blade solidity and resulting torque behavior.

The three-bladed turbine benefits from lower aerodynamic drag and inertia, which can favor higher rotational speeds under ideal conditions [39]. Previous studies have reported higher electrical power output of up to 15-160% for three-bladed ASWTs compared to higher blade numbers under controlled environments [17], [18]. However, in the low wind regime investigated in this study, these advantages were not fully realized. Instead, the reduced blade solidity limits torque availability, leading to delayed cut-in, lower rotational stability, and reduced electrical output [16]. The RPM and electrical data indicate that the three-bladed turbine was more susceptible to intermittent rotation and current interruption, particularly near the cut-in threshold, resulting in modest power generation even as wind speed increased.

In contrast, the four-bladed turbine exhibited higher aerodynamic loading and increased drag in this operating regime. The increased blade solidity enhanced torque continuity [33], resulting in earlier cut-in, steadier rotation, and consistently higher electrical output. Similar trends have been reported in studies showing improved torque stability, reduced rotational intermittency, and higher energy capture with increased blade number under low wind conditions [30], [40].

The power output data further emphasizes this trade-off. Although the four-bladed turbine experienced higher drag, it achieved more than three times the peak electrical power of the three-bladed turbine under comparable wind conditions. This outcome highlights that, in low wind environments, maximizing torque continuity and reducing rotational instability are more critical than minimizing drag or achieving higher peak rotational speed. The additional blade, therefore, acts to stabilize energy conversion rather than to simply increase aerodynamic loading.

These findings suggest that blade number optimization for ASWTs should be guided by the intended operating wind regime. In environments characterized by weak and highly variable winds, such as urban or semi-urban locations, higher blade numbers may offer superior overall performance despite increased drag penalties. Conversely, in regions with stronger and more consistent winds, lower blade solidity configurations may become more competitive. The present results demonstrate that design strategies commonly adopted for conventional horizontal-axis wind turbines do not directly translate to ASWTs, underscoring the need for application-specific optimization.

A key strength of this study lies in its field-based experimental approach under natural low wind conditions, allowing realistic evaluation of ASWT performance that is often not captured in controlled or numerical studies. However, several limitations should be noted. The experimental campaign was conducted over a relatively short duration of seven days and within a limited wind speed range (0.8-4.0 m/s), which may not fully represent long-term wind variability. In addition, measurements under natural conditions introduce inherent fluctuations that may contribute to data dispersion.

4 Implications for small-scale and urban wind energy applications

The findings of this study have direct implications for the deployment of ASWTs in small-scale and urban wind energy applications, where wind resources are typically weak, highly variable, and influenced by surrounding structures. Rather than emphasizing aerodynamic efficiency alone, the results highlight the importance of ensuring consistent and reliable energy generation under marginal wind conditions.

This perspective is particularly relevant in the context of wind energy development where wind resources remain largely underutilized, such as in Indonesia, which has an estimated technical potential exceeding 150 GW, with current installed capacity representing less than 0.1% of this potential [41]. One of the key barriers is the difficulty of achieving stable and predictable energy output under low and fluctuating wind conditions. In this regard, turbine configurations that prioritize operational stability over peak efficiency may offer a more practical pathway for expanding wind energy utilization.

The superior performance of the four-bladed ASWT observed in this study suggests that increased blade solidity can play a beneficial role in enhancing energy capture under marginal wind conditions. The earlier cut-in behavior, higher rotational stability, and stronger electrical output demonstrated by the four-bladed configuration indicate that this design is better suited for environments where wind speeds frequently remain below 3 m/s. These characteristics are particularly relevant for rooftop, roadside, and residential installations, where intermittent wind conditions and frequent speed fluctuations are common. This is consistent with recent studies demonstrating the application of ASWTs in urban and decentralized energy systems, where turbine designs are tailored for low and variable wind environments [42].

From a design standpoint, the results suggest that blade number selection should be treated as a context-dependent parameter rather than a fixed optimization variable. For low wind environments, turbine configurations that enable continuous operation and reduced sensitivity to wind intermittency are more advantageous than those optimized solely for high-efficiency performance under ideal conditions. This shift in design priority aligns with broader challenges in wind energy deployment, where variability and uncertainty in wind behavior often limit system reliability.

In the context of decentralized energy systems, the ability to generate even modest electrical power at low wind speeds can contribute meaningfully to local energy resilience. While the absolute power levels measured in this study are small, they are representative of early-stage prototypes and can be scaled through array configurations or combined with energy storage systems. When integrated into hybrid renewable systems alongside solar photovoltaics, ASWTs optimized for low wind conditions may help smooth power supply variability, particularly during periods of low solar output.

More broadly, the results support the role of appropriately designed small-scale wind turbines in advancing sustainable energy goals in urban and semi-urban settings. By enabling energy harvesting from wind resources that are typically considered marginal, optimized ASWT designs can contribute to localized clean energy generation, supporting efforts toward sustainable cities and affordable, clean energy access [43], [44].

5 Conclusion

This study experimentally investigated the influence of blade number on the rotational behavior and electrical performance of ASWTs operating under natural low wind conditions. The main conclusions of this study are as follows: (1) Blade number significantly influences the rotational behavior and electrical performance of ASWTs under low wind conditions (0.8-4.0 m/s). The four-bladed turbine exhibited earlier cut-in, higher rotational stability, and consistently better electrical output than the three-bladed configuration; (2) Electrical power of 0.29 W at wind speeds of 3.8-4.0 m/s was achieved by the four-bladed ASWT which was more than three times higher than that of the three-bladed turbine (0.09 W). It also produced higher voltage and current at moderate wind speeds (2.5–3.0 m/s); (3) The enhanced performance of the four-bladed turbine is attributed to increased aerodynamic torque and improved torque continuity resulting from higher blade solidity, rather than increased rotational speed alone. This leads to stronger electromechanical coupling and reduced current interruption near the cut-in region; (4) The results confirm that increasing the blade number from three to four provides a more favorable balance between aerodynamic loading and electrical performance under low and fluctuating wind conditions.

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