# Experimental Study of Low-Speed Wind Turbine Performance with SG6043 Airfoil for Frontier Regions in Indonesia

Benny Susanto[1], Muhammad Agung Bramantya[2,3,*], Indarto[2,3] and Deendarlianto[2,3]

[1] PT PLN (Persero) PUSLITBANG, Indonesia
[2] Department of Mechanical and Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, Indonesia
[3] Energy Studies Research Center (PSE), Universitas Gadjah Mada, Indonesia
* bramantya@ugm.ac.id

**Abstract.** This study evaluates the aerodynamic performance of low-speed horizontal-axis wind turbines for application in Indonesia's 3T frontier regions (Terdepan, Terluar, Tertinggal), where wind resources are limited and access to reliable electricity is scarce. The investigation focuses on turbine blades employing the SG6043 airfoil, selected for its high lift-to-drag ratio at low Reynolds numbers, making it well suited to low-wind environments. Blades were manufactured from carbon composite materials to enhance strength-to-weight performance and durability. Experimental testing was conducted at the PLTH facility in Pantai Baru, Yogyakarta, using two generator capacities (600 W and 1000 W) and three blade configurations, including a baseline blade for the 1000 W generator. The highest electrical output, 121 W, was achieved by the 600 W generator with Blade B at 581 rpm and 9.4 m/s wind speed. The lowest output, 1.2 W, was recorded for the 1000 W generator with Blade A at 346 rpm and 5.8 m/s wind speed. The results confirm the SG6043's suitability for small-scale wind turbines in low-wind, resource-constrained settings, and highlight its potential for improving rural energy access.

**Keywords:** low-speed wind turbines, horizontal-axis wind turbines, SG6043 airfoil, frontier region.

## 1 Introduction

The global demand for renewable energy continues to increase in response to the urgent need to reduce the dependence on fossil fuels and mitigate their detrimental environmental impacts. Among the various renewable energy technologies, wind turbines have emerged as a viable and widely implemented solution, particularly in the 3T regions of Indonesia, Terdepan (frontier), Terluar (outermost), and Tertinggal (underdeveloped), where conventional energy infrastructure is often inaccessible [1]. However, a major challenge in deploying wind turbines in such regions is the predominance of low wind speeds, which necessitates optimized turbine designs for efficient performance under suboptimal wind conditions [2].


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Low-speed wind turbines are specifically engineered to harness wind energy in regions with limited wind resources, while maintaining satisfactory operational efficiency. A critical aspect of their design is the selection of an airfoil profile that aligns with local wind flow characteristics [3]. Previous Computational Fluid Dynamics (CFD) studies have demonstrated that the SG6043 airfoil exhibits a high lift-to-drag ratio (Cl/Cd) under low Reynolds number conditions, making it well-suited for low-wind-speed applications [4]. This characteristic enables the generation of a higher aerodynamic lift with minimal drag, which enhances power output at lower wind speeds. Additionally, the SG6043 airfoil achieves a maximum power coefficient (Cp) at a tip-speed ratio (TSR) of approximately 6 [5], which lies within the optimal TSR range of 6–8 for maximizing the energy extraction from the wind [6]. Comparative studies by Pourrajabian et al. further revealed that SG6043 outperforms the NACA 4412 airfoil in terms of lift-to-drag ratio, underscoring its superior aerodynamic efficiency in low-speed wind turbine applications [7]. Nevertheless, these findings, based on simulations, require experimental validation under real-world conditions to ensure their reliability.

In parallel, advances in composite materials for turbine blade construction have gained attention, particularly the utilization of industrial by-products, such as fly ash from diesel power plant (PLTD) combustion. The lightweight nature of carbon composites, combined with reinforcement from fly ash, offers potential improvements in the mechanical performance. Rahmat et al. reported that incorporating fly ash into aluminum-based metal matrix composites reduced the porosity (up to 5 wt. %) and increased bending strength, while hardness improved at concentrations up to 7.5 wt.% [8]. [9] found that combining fly ash with MgO increased the density at sintering temperatures of up to 1150 °C, although excessive MgO (>5%) reduced the mechanical strength owing to the diminished glassy binding phase [9]. Similarly, Srivastava et al. observed that 6.5% fly ash enhanced the strength of glass fiber-reinforced polymer (GFRP) composites, but reduced the fracture toughness of carbon fiber-reinforced polymer (CFRP). Moreover, fly ash improves the GFRP fracture energy by limiting crack propagation and reducing void formation [10]. These findings suggest that fly ash is a promising and sustainable reinforcement material for turbine blade applications.

This study investigates the performance of horizontal-axis wind turbines equipped with SG6043 airfoil blades fabricated from carbon composite materials. The research encompasses blade manufacturing and field testing with multiple generators and blade configurations to determine the optimal combination for electrical power generation. Experiments were conducted at the Pantai Baru Hybrid Power Plant (PLTH) in Yogyakarta, a location with wind speeds ranging from 3 m/s to 9 m/s. These conditions are representative of 3T regions, highlighting the potential of low-speed wind turbine technology to expand sustainable energy access in remote and underserved areas.

## 2 Methodology

This study employed a field-based experimental approach conducted at a Hybrid Power Plant (PLTH) located in Pantai Baru, Yogyakarta. This location was selected because it is classified as a low-wind-speed area, making it representative of the conditions in many 3T (Terdepan, Terluar, Tertinggal) regions. The wind profile of the site, with speeds ranging from 3 to 9 m/s, provided a suitable environment for evaluating the performance of the low-speed wind turbines.

Three variable categories were considered: independent, dependent, and controlled. The independent variables included the generator capacity and turbine blade type. Two generator capacities, 600 and 1000 W, were tested. Additionally, three blade types (A, B, and C) were evaluated. Blade C was the standard blade supplied with the 1000 W generator system and served as a benchmark for comparison with custom-manufactured blades. The specifications for each blade type are listed in Table 1. The dependent variables consisted of the wind speed, electrical power generated by the turbine, and rotational speed (rpm) of the rotor. Controlled variables included the number of blades (three in all configurations) and fixed testing location, ensuring consistent wind conditions and eliminating the influence of topographic or aerodynamic variability across trials.

**Table 1.** Specification of Blade

| Specification | Blade A | Blade B | Blade C |
|---|---|---|---|
| Airfoil Type | SG6043 | SG6043 | unknown |
| Rotor diameter | 1000 mm | 1000 mm | 650 mm |
| Blade number | 3 | 3 | 3 |
| Blade material | Carbon Composite | Carbon Composite | Plastic |

Before manufacturing, the wind turbine blades were designed using Autodesk Inventor software (Fig. 1). The SG6043 airfoil profile was selected because previous computational studies have confirmed its superior aerodynamic efficiency under low wind speed conditions. The design considerations included chord length distribution and twist angle, which were optimized to achieve the ideal Tip Speed Ratio (TSR) for maximum energy extraction.

Following the design stage, blade fabrication was carried out in three primary steps: mold fabrication, composite lamination, and finishing. All the processes were executed with precise adherence to the CAD model to ensure aerodynamic conformity and structural robustness.

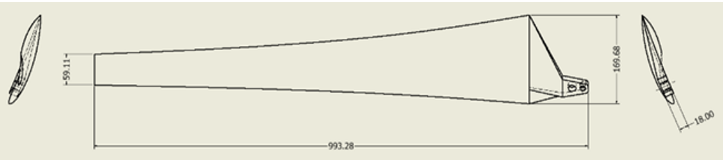
The process began with the creation of a master pattern shaped from wood or foam to match the CAD blade profile. This master pattern was used to produce a mold from fiberglass or silicone, yielding a smooth and durable surface suitable for lamination (Fig. 2). The dimensional accuracy and profile conformity were verified using precision measuring instruments to ensure alignment with the intended aerodynamic geometry.

Blades were fabricated using carbon fiber as the reinforcing material and epoxy resin as the matrix. The carbon fiber sheets were cut according to the layer patterns defined in the design and sequentially placed within the mold (Fig. 3). Epoxy resin was uniformly applied to ensure full adhesion between the layers and optimal structural integrity. The vacuum-bagging technique was employed to eliminate air entrapment and ensure even resin distribution. Curing was performed in a temperature-controlled oven to achieve maximum composite strength and dimensional stability.

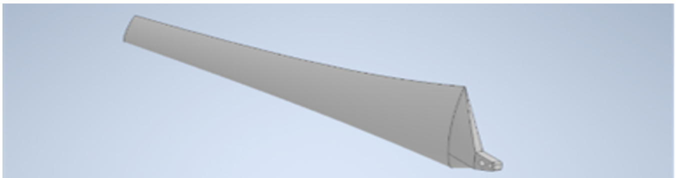
Upon the completion of curing, the blades were demolded, followed by sanding and polishing to remove surface imperfections. The tips and root sections were trimmed to the final specifications to ensure precise fitting with the rotor hub (Fig. 4). This stage was critical for guaranteeing aerodynamic accuracy and preparing blades for optimal performance during the field trials.

Field testing was conducted at the Pantai Baru Hybrid Power Plant (PLTH) over three consecutive days for each configuration. Two generator capacities (600 and 1000 W) and three blade types (A, B, and C) were evaluated under consistent low-wind conditions.

Wind speed, electrical output, and rotor speed (rpm)were recorded manually at 10-minute intervals for 4–6 h per day. The measurement system (Fig. 5) included an anemometer, digital tachometer, and wattmeter, with a 12 V battery for energy storage and eight series-connected lamps as a dump load when fully charged.




(a)



(b)

**Fig. 1.** SG6043 airfoil design: (a) 2D and (b) 3D.

**Fig. 2.** Turbine Mold Fabrication.

**Fig. 3.** Blade Manufacturing with Carbon Fiber Composites.

**Fig. 4.** Blade manufacturing results.

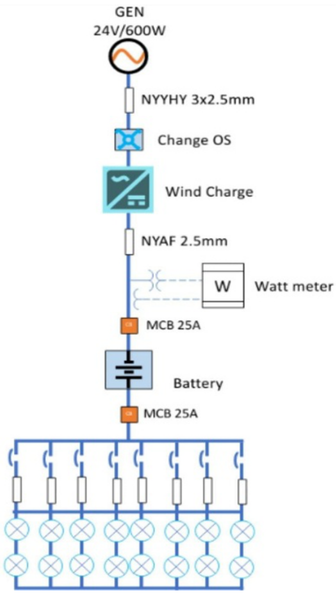



**Fig. 5.** Control system circuit for data capture.

## 3 Results and Discussion

The experimental results are presented in terms of the generator output power, power coefficient (Cp), and Tip Speed Ratio (TSR).

The generator output power was calculated as the product of the rotor torque and shaft angular velocity. Fig. 6 illustrates the relationship between the wind speed and output power for different blade–generator configurations. Across all configurations, the power increased with wind speed. The combination of Blade B with the 600 W generator yielded the highest performance, producing up to 121 W at a wind speed of 9 m/s. In contrast, Blades A, B, and C paired with the 1000 W generator produced comparatively lower power over the same wind speed range.

The superior performance of Blade B with the 600 W generator can be attributed to its aerodynamic profile, which appears to generate higher torque at moderate wind speeds. This finding highlights the importance of matching the blade geometry with the generator capacity to optimize small-scale wind turbine performance.

Fig. 7 shows the relationship between the angular velocity and power output. A similar trend is observed: the power increases with the rotational speed, with Blade B–600 W achieving nearly 150 W at approximately 600 rpm. Other configurations produced lower outputs at equivalent angular velocities, further suggesting that Blade B is capable of delivering a higher torque and more effective shaft drive performance.

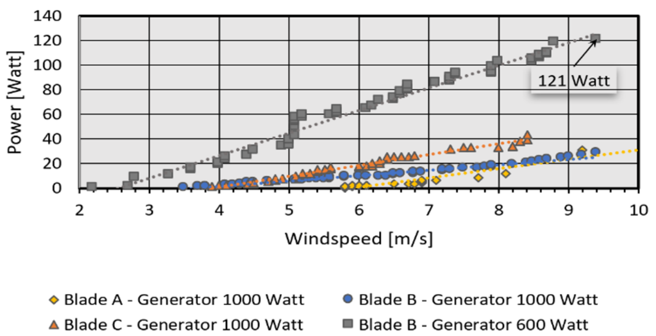



**Fig. 6.** Relationship between the wind speed and power produced by the generator.

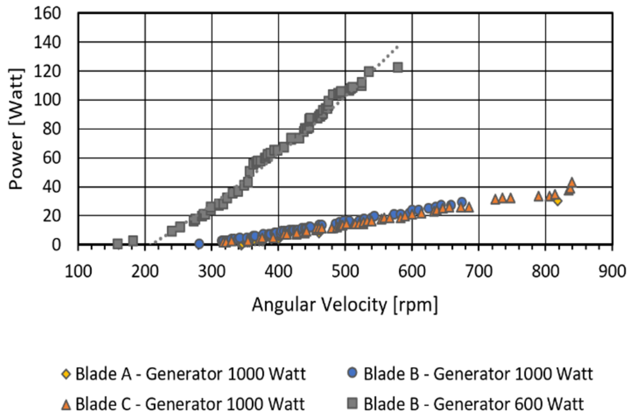



**Fig. 7.** Relationship between angular velocity and power produced by the generator.

The power coefficient, defined as the ratio of the turbine output power to the available wind power in the rotor-swept area, is shown in Fig. 8. In all cases, Cp increased with wind speed until it reached a peak, after which it declined. This is consistent with the characteristic behavior of wind turbines, where aerodynamic losses and generator constraints reduce the efficiency beyond the optimal operating range.

The highest Cp 0.22 was achieved by Blade B with the 600 W generator at a wind speed of 5 m/s. In comparison, Blade C with the 1000 W generator exhibited a maximum Cp of 0.10, with other configurations performing below these levels. As the wind speeds exceeded 6 m/s, all configurations showed a reduction in Cp, confirming the influence of aerodynamic inefficiencies and generator loading at higher speeds.

These results reaffirm the significance of appropriate blade–generator pairing to maximize energy capture in small-scale systems, particularly under medium wind speed conditions.

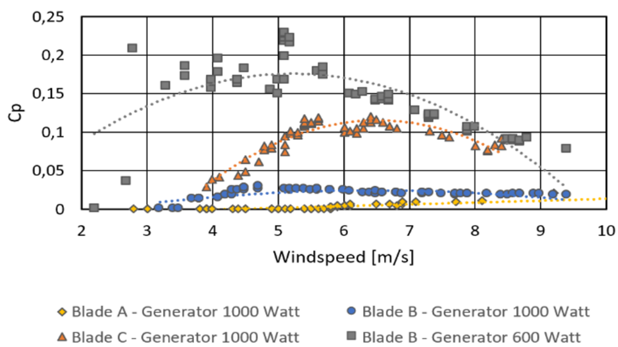



**Fig. 8.** Relationship between wind speed and power coefficient (Cp) for different blade and generator combinations.

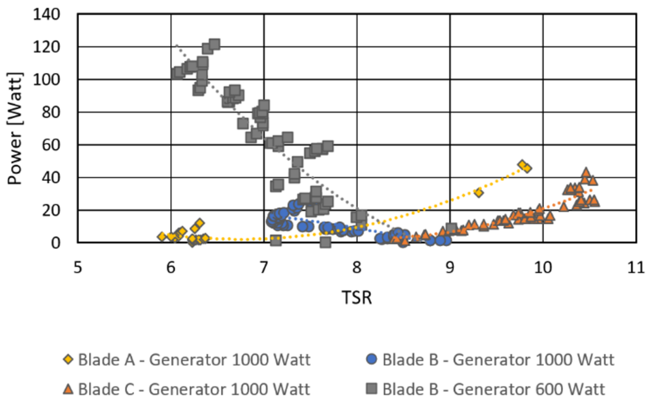



**Fig. 9.** Relationship between tip speed ratio (TSR) and power coefficient (Cp) for different blade and generator combinations.

Fig. 9 shows the relationship between the TSR and the power output for the tested configurations. The TSR, defined as the ratio of the blade tip speed to the free-stream wind speed, strongly influences the turbine performance. The power generally increased with TSR until an optimal point, beyond which it declined.

Blade B with the 600 W generator achieved its maximum power output of 121 W within a TSR range of 6.5–7.0, indicating this as the optimal operating window. In contrast, Blade C with the 1000 W generator showed a stable, moderate output at a higher TSR range of 9.5–10.0. Blade A and Blade B paired with the 1000 W generator consistently produced lower outputs, suggesting less effective aerodynamic–generator matching.

The observed power decline beyond the optimal TSR is consistent with the increased aerodynamic drag and reduced energy-conversion efficiency. This reinforces the necessity of designing turbine–generator systems that operate within the ideal TSR range to maximize performance under variable wind conditions.

## 4 Conclusion

The experimental results demonstrate that the power output performance of a wind turbine is strongly influenced by the interaction between the blade type, generator capacity, and key operational parameters, including wind speed, angular velocity, and tip speed ratio (TSR). Among the tested configurations, the Blade B–600 W generator combination exhibited the highest performance, producing a maximum output power of 121 W at a wind speed of 9 m/s, and achieved the highest power coefficient Cp of 0.22 at 5 m/s.

The power generation efficiency was also found to be dependent on the optimal TSR range for each configuration. The Blade B–600 W combination operated most effectively within a TSR range of 6.5–7.0, whereas Blade C paired with a 1000 W generator achieved moderate but stable performance within a higher TSR range of 9.5–10.0. In contrast, Blade A and Blade B with the 1000 W generator produced lower power outputs and Cp values across the tested wind speed range.

These findings underscore the critical importance of appropriate blade–generator matching in enhancing the efficiency of small-scale wind turbine systems. Additionally, variations in the axial distance ratios and component configurations influence not only the peak power generation but also the performance stability under fluctuating wind conditions. Future research should focus on refining aerodynamic blade designs and developing adaptive control strategies to optimize wind turbine performance across a broader range of environmental conditions.

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