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Performance Analysis of a Laboratory-Scale Wind Turbine: Blade Angle and Its Effect on Efficiency

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ABSTRACT

A wind turbine power plant (WTPP) is a renewable energy system that harnesses wind energy to generate electricity. Indonesia has been identified as a region with considerable wind energy potential, making it a promising location for developing this technology. In alignment with this potential, the Indonesian government has set a target of approximately 7 GW of installed wind turbine capacity by 2030. This study examines the influence of blade angle on the efficiency of electrical energy generation. Three blade angle variations—20°, 30°, and 40°—were analyzed using an experimental setup featuring a horizontal-axis wind turbine with five blades and a constant wind speed of 6.2 m/s. The rotation of the blades converts wind energy into kinetic energy, which is subsequently transferred to a generator to produce electricity. Experimental investigations were conducted using a laboratory-scale prototype, revealing that a blade angle of 40° achieved the highest efficiency. Specifically, the turbine exhibited an efficiency of approximately 29% after 3 minutes of rotation, which increased to 42% after 8 minutes. These findings highlight the pivotal role of blade angle optimization in enhancing WTPP performance. Moreover, this study provides a valuable reference for advancing wind energy applications in Indonesia, supporting the transition towards more sustainable and efficient renewable energy solutions.

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1. Introduction

Energy consumption in Indonesia has been increasing annually, a trend that correlates with population growth and economic development, particularly in the electricity sector [1]. Currently, the Republic of Indonesia continues to rely on coal as a primary source of energy to meet its electricity demand [2]. However, coal is a finite resource, as it is a primary energy source. According to the Ministry of Energy and Mineral Resources (ESDM), coal reserves are projected to be depleted within 83 years at their current rate of consumption [3]. To address this impending challenge, it is essential to investigate alternative, sustainable energy sources. Renewable energy sources, particularly wind energy, have emerged as viable alternatives to replace coal [4]. The effectiveness of wind farms in converting wind energy into environmentally sustainable electricity has also been demonstrated. Consequently, these technologies contribute to meeting national energy requirements.

The variability in wind speed across Indonesia, a renewable energy source, is presented in **Table 1** [5]. This variation can be attributed to the diverse wind patterns that are influenced by the country's unique geographical and meteorological characteristics [6]. Studies have shown that wind turbine height plays a crucial role in performance optimization. The IESR meters report (beyond 443 GW: Indonesia's infinite renewable energy potential) indicates that the technical potential for wind power reaches 106 GW at a hub height of 50 m and 88 GW at 100 m. These findings correspond to minimum speed thresholds of 6 m/s and 6.6 m/s at 50 and 100 m, respectively [7]. Effective harnessing of wind energy requires adherence to specific speed parameters. The established classification system delineates wind speeds suitable for energy conversion as ranging from 1.6 m/s to 17.1 m/s. When designing wind turbine installations, it is crucial to select locations with appropriate wind speed profiles. This consideration is paramount, as speeds outside the optimal range, whether excessive or insufficient, compromise system efficiency and effectiveness. Moreover, such conditions may result in degradation of turbine components [8]. The turbine blade, which is a critical element in the system, significantly influences the utilization of wind speed for energy generation.

Table 1. Average ($\bar{v}$) wind speed in Indonesia.

Place	$\bar{v}$ (m/s)	Place	$\bar{v}$ (m/s)
Nusa Panida, Bali	2.73	Baron, DIY	6.13
Bantul, DIY	4.00	Sukabumi, Jawa Barat	6.27
Selayar, Sulawesi Selatan	4.60	Sidrap, Sulawesi Selatan	6.43
Purworejo, Jawa Tengah	5.16	Garut, Jawa Barat	6.57
Lebak, Banten	5.58	Joneponto, Sulawesi Selatan	7.96
Olebubuk, NTT	6.10		

The blades of wind turbines are designated as "rotor blades." These blades are typically affixed to wind turbine rotors. A substantial body of research has been dedicated to the development of wind turbines, with a particular focus on wind turbine power plants (WTPP) to enhance their performance. Research conducted by Adam utilizing 5-blade rotors operating at a maximum wind speed of 4 m/s has demonstrated an efficiency value of 3.07%, along with an average voltage of 2.56 volts and a wind power of 27.6 watt, while the generator power produced 136.3 watt [9]. In contrast, research conducted by Buana, who examined the number of blades, blade angle of the wind turbine, and wind speed, yielded optimal values. Specifically, a study found that a wind turbine with three blades operating at 30° and a wind speed of 5 m/s, with a rotation of 570 rpm, produced the highest level of optimization [10]. Research conducted by Aris concluded that an average wind speed of 5 m/s produces a kinetic energy of 3.12 J. This kinetic energy is sufficient to illuminate 12-volt lamps for up to 11.25 hours [11]. In addition, the wind turbine can be optimized by incorporating several other components, such as pulleys. A pulley was used to increase the initial rotational force of the motor, thereby enhancing the resulting power output. Furthermore, the optimization of wind turbines warrants attention. Kaputra's (2022) research has yielded notable findings regarding the optimization using the impact of blade angle on turbine efficiency. Their experimental observations indicated that a propeller angle of 40° resulted in an efficiency of approximately 2.44% [12]. Subsequently, Sitanggang (2024) conducted a study involving the modification of wind turbines through the incorporation of grooves on blade surfaces. This research yielded an estimated power output of approximately 22.75% [13]. In conclusion, the optimization of wind energy as a renewable energy source necessitates a comprehensive approach that encompasses various aspects of design and technology.

Wind energy has become a promising alternative for sustainable electricity generation, particularly in regions with moderate wind speeds, such as Indonesia. However, optimizing wind turbine performance remains a complex challenge that requires a comprehensive analysis of the design parameters that influence energy conversion efficiency. This study investigated the impact of varying blade angles (20°, 30°, and 40°) on the overall efficiency of a wind energy system. Each blade configuration interacts differently with the wind flow, affecting the turbine's ability to harness and convert kinetic energy into mechanical power. The 20° blade angle, while offering a broader surface area to capture wind, exhibited limitations in energy conversion owing to its suboptimal aerodynamic profile. In contrast, the 40° blade angle demonstrated a more effective interaction with the wind, facilitating a smoother and more stable rotation, which contributed to improved energy conversion. To assess these effects, a laboratory-scale wind turbine power plant (WTPP) was designed and developed by integrating supporting components, such as pulleys, to enhance mechanical efficiency. Turbine blades were fabricated using 3D printing technology with polylactic acid (PLA), chosen for its environmental sustainability, ease of processing, and structural reliability for prototype applications. The controlled experimental setup, operating at a wind speed of 6.2 m/s, provided insights into the relationship between blade geometry, system performance, and power generation efficiency. The observations revealed that turbines equipped with a 40° blade angle maintained a steady rotational movement, leading to more consistent energy generation over time. Additionally, incorporating pulleys contributed to smoother torque transmission, allowing the system to sustain the power output more effectively. These findings underscore the significance of refining turbine blade design and operational strategies to optimize wind energy utilization in Indonesia. By offering a deeper understanding of how blade geometry influences energy conversion, this study lays the groundwork for further innovations in wind energy systems, supporting the transition toward more sustainable and environmentally friendly electricity generation solutions.

2. Methods

2.1. Blade design and manufacturing

The blade design was developed using SolidWorks software, as illustrated in **Figure 1**. This process was conducted to identify the optimal performance parameters of the WTPP. The blade was designed to optimize the geometric and aerodynamic efficiencies. Consequently, the methodology involves the preliminary determination of critical parameters, including the number of blades, blade angle, and airfoil profile. These parameters were subsequently customized to satisfy the performance specifications [14]. The revolve feature is employed to shape the blades to the requisite dimensions, whereas the helix feature is utilized to attain the optimal blade angle and generate a curvature that promotes the airflow. This objective was achieved through symmetrical replication of the blades around the central axis, thereby ensuring a uniform force distribution and balanced design. The design process is systematically executed in stages to ensure that the blade possesses an effective structure and is prepared to fulfill its designated function.

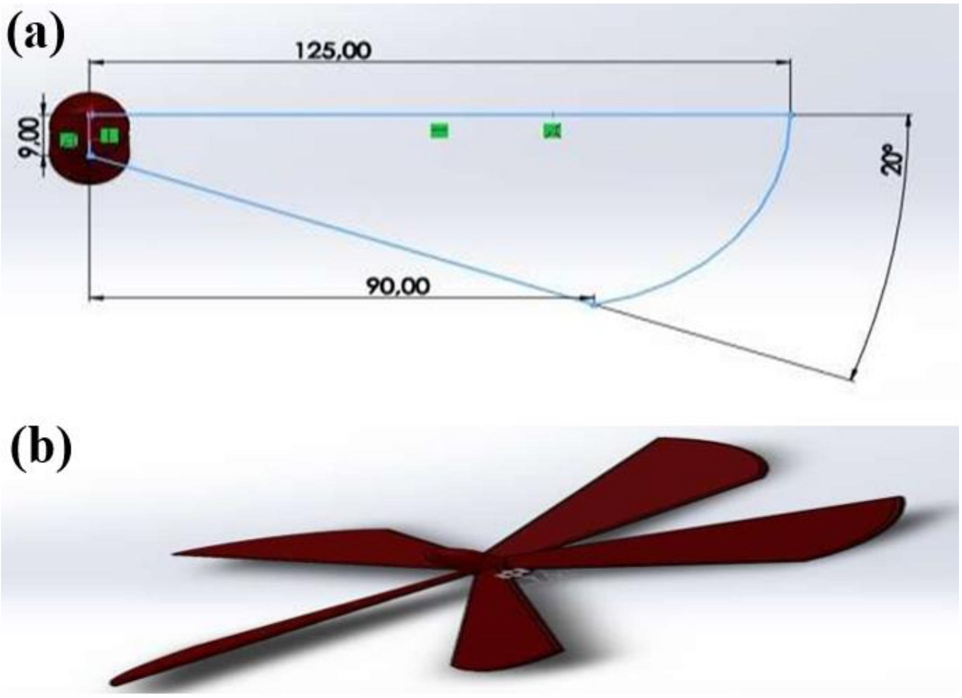

Figure 1. (a) Illustration of geometric design with dimensions and angles (b) Blade model design with five-blade aerodynamic configuration.

This study investigates the effects of blade angles of 20°, 30°, and 40 °on the system efficiency. The rationale for this investigation is that each blade angle has a different effect on the turbine performance in terms of wind energy adsorption and power generation. A 20° blade angle provided a larger cross-sectional area in the direction of the wind flow. However, the efficiency may be lower owing to the nonideal angle of attack. Conversely, a 40° blade angle provided the optimal angle of attack, enabling the turbine to absorb more energy. The primary objective of this study was to ascertain the most efficient angle for optimizing turbine performance under diverse wind conditions. The investigation also sought to elucidate the correlation between the vane angle and system efficiency.

In addition, the turbine blade manufacturing process utilizes a 3D printer that employs polylactic acid (PLA). The selection of PLA material is predicated on its ease of printing, environmental friendliness, and adequate structural strength for prototype applications [15]. Prior to the printing process, the 3D printer was meticulously prepared to ensure the appropriate installation of the PLA spool and the cleanliness and planarity of the print platform. The printing procedure involved layer-by-layer thermal deposition and accumulation. The 3D printer melted the PLA from the spool and extruded it through a fine nozzle onto the print platform. Subsequently, the material extruded from the nozzle melted and was precisely deposited, forming a blade according to a predetermined design. Each successive layer adhered to the previous layer and a blade was gradually constructed until completion. This process offers the advantage of producing blades with complex and precise designs in a relatively expedient manner and at a lower cost than conventional manufacturing methods.

2.2. Measuring performance

The performance of the WTPP depends on wind characteristics, including kinetic energy, which can be quantified using Equation (1) [16]. The rotation of wind turbine blades facilitates the conversion of kinetic energy from moving air to power [17]. As the wind traverses the swept area of the turbine blades, the air mass (m) moving at a velocity ($\mathcal{v}$) generates kinetic energy. A portion of this kinetic energy is harnessed by turbine blades, which are aerodynamically designed to optimize energy conversion. The transformation of kinetic energy into mechanical energy manifests as blade rotation. This energy-conversion process enables the wind turbine to generate mechanical energy, which is subsequently converted into electrical energy by the generator.

$$EK = \frac{1}{2} m \mathcal{v}^2 \tag{1}$$

where EK is the kinetic energy in Joules (J), m is air mass (kg), and $\mathcal{v}$ is the air speed (m/s). Subsequently, this energy can be characterized as wind power with subject processing, utilizing the derivative equation of energy per unit time, as illustrated in Equations (2–7) [18]. In the design of the WTPP for generating electrical energy, this equation was employed to determine the potential wind energy that could be harnessed.

$$P_{wind} = \frac{\text{Energy}}{\text{time}} \tag{2}$$

$$P_{wind} = \frac{\frac{1}{2} m \mathcal{v}^2}{t} \tag{3}$$

because $m = \rho \mathcal{V}$, therefore, the equation is as follows:

$$P_{wind} = \frac{\frac{1}{2} (\rho \mathcal{V}) \mathcal{v}^2}{t} \tag{4}$$

The volume of air that flows per unit time is expressed as $\frac{\mathcal{V}}{\mathrm{t}} = A\mathcal{v}$, which can be expressed simply as $\mathcal{V} = A\mathcal{v}\mathrm{t}$. Therefore, the equation is as follows:

$$P_{wind} = \frac{\frac{1}{2} \rho (A\mathcal{v}t) \mathcal{v}^2}{t} \tag{5}$$

$$P_{wind} = \frac{1}{2}(\rho A v)v^2 \quad (6)$$

$$P_{wind} = \frac{1}{2}\rho A v^3 \quad (7)$$

where P_{wind} denotes wind power in watts (W), ρ is the air density in kg/m^3 (in this work, it is subjected to 1.225 kg/m^3) [19], A is blade sweep area in m^2, and v is the speed of air (m/s).

Subsequently, the power output of the generator produced by the airflow was calculated using Equation (8) [20]. This equation is crucial for evaluating the efficacy of a WTPP system for generating electricity in accordance with demand.

$$P_{generator} = V \text{ x } I \quad (8)$$

where $P_{generator}$ denotes the generator power in watts (W), V is the voltage generated in the WTPP system (V), and I is the electrical current generated in the WTPP system (A).

Efficiency is a critical component in the evaluation of wind turbine systems because it assesses the energy conversion performance. The turbine blades capture the kinetic energy of the wind and transform it into mechanical energy, which is subsequently converted into electrical energy by a generator. The efficiency of this conversion process can be quantified using Equation (9) [20], which is essential for analyzing and optimizing wind turbine systems because it quantifies the proportion of wind energy converted into electrical energy.

$$\eta_{generator} = \frac{P_{generator}}{P_{wind}} \text{ x } 100\% \quad (9)$$

where η is the efficiency, expressed as a percentage, $P_{generator}$ is the power generated by the airflow, measured in watts (W), and P_{wind} is the power of the wind, measured in watts (W).

3. Results and Discussion

The prototype-scale WTPP was designed to harness renewable energy for electricity generation, emphasizing its efficiency and sustainability, as shown in Figure 2. The selection of PLA as the primary manufacturing material plays a crucial role in the development process owing to its ease of fabrication, environmental friendliness, and compatibility with 3D printing technology. The low melting point of PLA facilitates the precise and rapid production of turbine components, ensuring structural integrity while maintaining low manufacturing costs.

A turbine system integrates several key components that contribute to its operational effectiveness. The blade and shaft holder, with a surface area of 36,694.82 mm², was designed to provide optimal aerodynamic performance while maintaining stability under varying wind conditions. The shaft, made of 304 stainless steel with an 8 mm diameter, acts as a vital connecting element, linking the turbine blades to the transmission system. This choice of material ensures durability, corrosion resistance, and mechanical strength, which are essential for long-term operation.

The system incorporates a 69 mm diameter pulley connected to the generator to facilitate efficient energy transfer through a timing belt mechanism. This configuration enhances rotational energy transmission, effectively allowing the turbine to convert wind energy into mechanical motion. The timing belt plays a crucial role in synchronizing the motion, reducing energy losses, and stabilizing the power output.

The integration of these components demonstrates a well-structured approach to small-scale wind energy generation. This design optimizes the energy conversion efficiency by utilizing 3D printing for precision manufacturing while maintaining a cost-effective and environmentally conscious production process. This study highlights the significance of material selection, blade geometry, and transmission mechanisms in improving the performance of prototype wind turbines, providing valuable insights for further advancements in renewable energy applications.

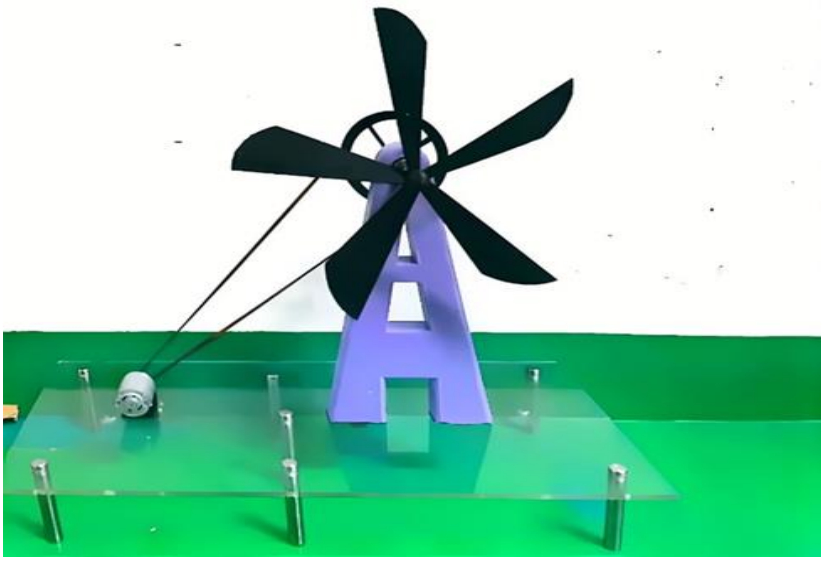

Figure 2. Design of a WTPP on a prototype scale

The prototype-scale WTPP was tested under various conditions to evaluate its performance. As shown in Figure 3, the data indicate that the blade angle, in combination with inclination variations of 20°, 30°, and 40°, plays a crucial role in determining the voltage output. The results reveal that a blade angle of 20° produced a maximum voltage of 30.8 V, with a recovery time of 8 min. This finding supports the hypothesis that waiting and recovery times are directly proportional to the consistency of the voltage output in wind turbines. Additionally, the distance between the wind turbine and wind source has been shown to significantly impact power generation, which is consistent with findings from previous studies. Specifically, the results indicated that turbines with larger radii consistently generated higher power outputs than those with smaller radii. This observation aligns with the established theory that increasing the surface area exposed to wind enhances the conversion of wind energy into electricity [21]. Furthermore, research by Toding [22], has demonstrated that voltage instability can be partially attributed to perturbations caused by load variations. Current measurements were also conducted, revealing that blade angle variations between 20° and 40° produced distinct current patterns. Notably, a blade angle of 40° generated the highest current, measuring 0.08 A after 8 min, as summarized in Figure 4.

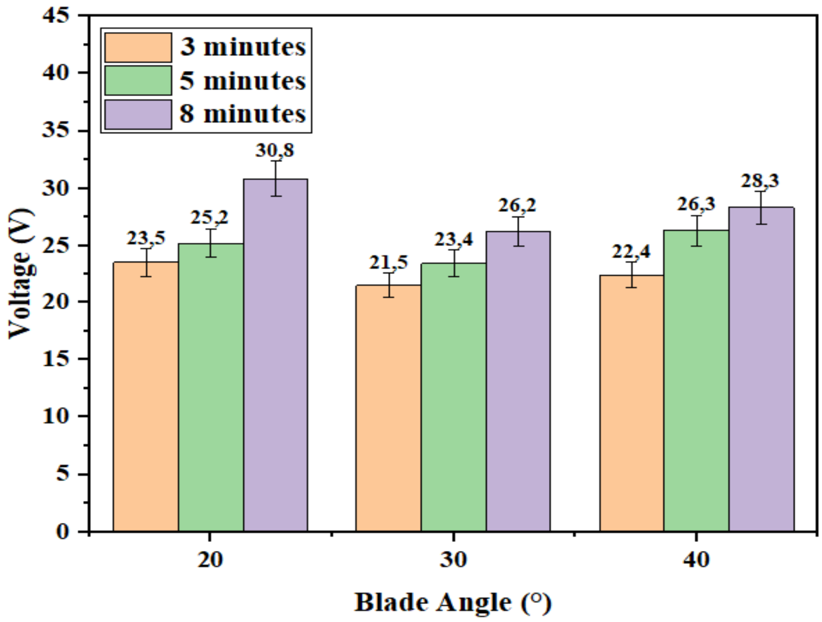

Figure 3. Relationship between blade angle and voltage.

Subsequently, the voltage and current data were analyzed to derive the power value using Equation (8). The data displayed from the angle of the blade with tilt angle variations of 20°, 30°, and 40° shows that the angle that produces the most significant generator power is on the blade with a tilt angle of 40°, which produces a power of 2.26 watt within 8 min, as summarized in Table 2. Furthermore, the findings of this study demonstrate that an increase in the blade angle exerts a substantial influence on the power production efficiency of the generator. The 40° blade angle yielded the highest power output and demonstrated consistent performance over 8 min. This observation suggests that this configuration may be optimal under specific operating conditions. Selecting an appropriate blade angle is paramount in designing wind turbines because it maximizes the energy output and system efficiency. The 40° blade angle yielded the highest power output and demonstrated consistent performance over 8 min. This observation suggests that this configuration may be optimal under specific operating conditions. Selecting an appropriate blade angle is paramount in designing wind turbines because it maximizes the energy output and system efficiency.

Table 2. The generator power is produced at each blade angle.

	Generator Power (W)		
Angle	**3 minutes**	**5 minutes**	**8 minutes**
20º	0,94	1,26	1,54
30º	0,86	1,40	1,31
40º	1,12	1,57	2,26

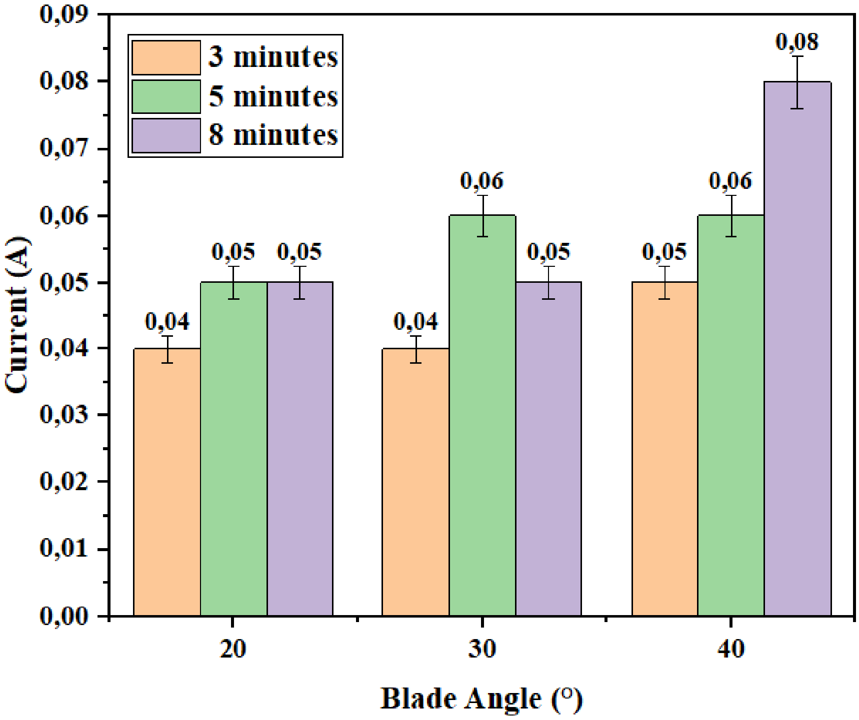

Figure 4. Relationship between blade angle and current.

Furthermore, the generator efficiency was determined using Equation (9) as a key metric for evaluating the overall performance of the system. As illustrated in Figure 5, efficiency data were collected for blade angles of 20°, 30°, and 40°, revealing that a 40° blade angle yielded the highest generator efficiency, reaching 42% within eight minutes of operation.

The blade angle plays a crucial role in optimizing turbine efficiency by directly influencing the fluid flow patterns and the conversion of kinetic energy into mechanical energy. At an angle of 40°, the improved efficiency suggests that this configuration enhances the interaction between the wind and turbine blades, allowing for better energy capture. From a fluid dynamics perspective, an optimized blade angle reduces energy losses due to turbulence while also increasing pressure and velocity, facilitating a smoother and more effective conversion of wind energy into rotational motion.

Additionally, the duration of operation significantly affects the efficiency. The study found that the efficiency increases over time, particularly at the optimal blade angle, as the system stabilizes and transient effects—initially causing inefficiencies—diminish. This observation highlights the importance of allowing turbines to reach steady-state conditions to achieve maximum performance. Compared with previous research, this study demonstrated notable improvements in efficiency, as summarized in Table 3, which was reported in [12] [13]. The efficiency observed in this study exceeded that of prior research, highlighting the effectiveness of the optimized blade angle and system configuration. These findings have significant implications for the design and optimization of turbine systems across various applications. By carefully selecting the blade angle and considering the impact of the operational duration, engineers can achieve notable improvements in turbine-based energy conversion systems.

Future research could explore the influence of other design parameters, such as blade shape, material properties, and airflow dynamics, to further optimize turbine efficiency. Investigating these factors would expand the applicability of these findings to different turbine types and varied fluid flow conditions, paving the way for more efficient and adaptable renewable energy solutions.

Table 3. Comparison with previous studies.

Authors (Year)	Efficiency (%)	Reference
Kaputra et al (2022)	2.44	[12]
Sitanggang et al (2024)	22.75	[13]
Present study	42.00	-

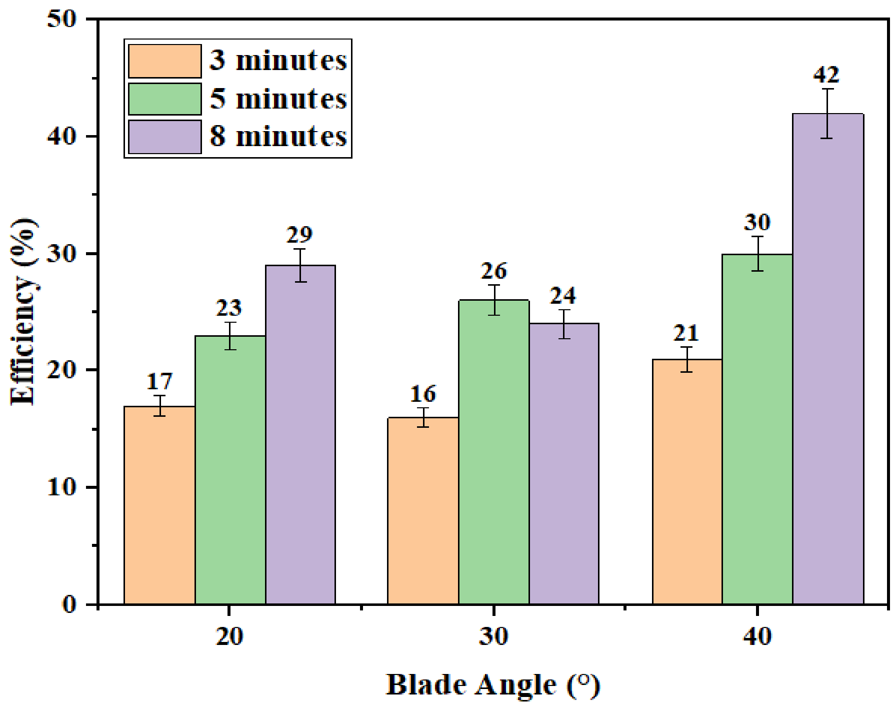

Figure 5. Efficiency of the WTTP produced in this study.

4. Conclusions

This study successfully developed a laboratory-scale wind turbine power plant (WTPP) to evaluate the potential of local wind resources in Indonesia, focusing on the effect of blade angle on efficiency. Blades with angles of 20°, 30°, and 40° were designed and fabricated using 3D printing technology and polylactic acid (PLA) material. The experimental analysis assessed the WTPP performance based on kinetic energy, wind, generator, and efficiency. The results demonstrated that a blade angle of 40° achieved the highest performance, generating a voltage of 30.8 V, current of 0.08 A, generator power of 2.26 W, and efficiency of 42% after 8 min of operation. Furthermore, these findings highlight the critical role of blade geometry and operational parameters in optimizing the energy conversion efficiency in renewable energy systems. The observed increase in efficiency from 29% at 3 min to 42% at 8 min suggests that stable aerodynamic performance contributes to sustained energy generation. This study provides a valuable foundation for further advancements in wind energy technology and serves as a reference for developing wind power solutions suited to Indonesia's local conditions. Ultimately, this study supports the nation's transition toward a more sustainable and environmentally friendly energy sector.

Author's declaration

Authors' contributions and responsibilities

Muhammad Muhtar Syafari was responsible for data collection, conducting the investigation, and drafting the original manuscript. **Sukarman** supervised the study and validated the results. **Muhamad Taufik Ulhakim** contributed to writing, reviewing, and editing the manuscript, as well as providing supervision, developing the methodology, and conceptualizing the project.

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Availability of data and materials

All data generated, analyzed, and used to support the findings of this study are available from the corresponding authors upon reasonable request. This includes raw, processed, and supplementary materials relevant to this research. Access to data may be granted for academic and research purposes, subject to institutional and ethical guidelines..

Competing interests

The authors declare no competing interests or conflicts of interest related to this study.

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