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# A Study on Wind Collection Effect of Vertical Axis Windmills

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**Abstract:** In recent years, global warming caused by greenhouse gasses such as carbon dioxide has become a concern. This has resulted in increased focus on environmentally friendly power systems. Consequently, renewable energy power generation methods, such as wind and solar power generation, have attracted attention. Wind power generation is expected to significantly increase in the future. However, in many inland areas in Japan, the average wind speed remains 6 m/s or less. In this study, we proposed the introduction of winglets and wind collectors (used in aircraft wings) into straight-wing vertical-axis wind turbines to improve their power generation efficiency. Field tests were conducted to confirm the effectiveness of the proposed method. Using winglets and wind collectors, the wind turbine rotation speed was increased at low wind speeds, which facilitated the generation of power. Moreover, it was confirmed that a wind turbine equipped with the proposed winglets and wind collectors could capture wind without its dispersal as it passed through the turbine.

**Keywords:** vertical axis windmills; winglet; wind collector; renewable energy power generation

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**Citation:** Hosoe, T.; Yukita, K. A Study on Wind Collection Effect of Vertical Axis Windmills. *Energies* **2024**, *17*, 6088. https://doi.org/10.3390/en17236088

Academic Editors: Yoshifumi Jodai and Yutaka Hara

Received: 27 October 2024
Revised: 24 November 2024
Accepted: 25 November 2024
Published: 3 December 2024

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## 1. Introduction

In recent years, Sustainable Development Goals (SDGs), a set of development goals aiming to achieve a sustainable world on a global scale, have attracted attention [1]. These include issues related to climate change and energy supply. One solution is promoting the use of renewable energy sources. Power generation methods using renewable energy such as solar and wind power are becoming widespread worldwide as a solution to the problem of reducing greenhouse gasses, including carbon dioxide. These power generation methods are distributed energy sources that provide the advantage of easy installation near high-demand areas. Their adoption and utilization are advancing as measures to combat global warming. Wind power generation is expected to increase significantly in the future. However, in Japan, the average wind speed is low and wind power generation is currently ineffective [2–4]. For this reason, blade shapes for small wind turbines have been studied and flow analysis around wind turbines has been conducted [5–7].

Focusing on simulation technology for wind turbines, it is increasingly recognized as essential for improving the efficiency and reliability of wind power, from design to operation and optimization. Simulations that model highly uncertain factors, such as wind speed and direction, are essential for improving energy prediction accuracy by utilizing temporal and spatial data [8]. Advanced simulation techniques using deep learning have been highlighted as a means to maximize operational efficiency [9,10]. Moreover, simulation methods leveraging neural networks have been proposed. These models incorporate factors such as turbine performance and failure probabilities, enabling more accurate short-term forecasting, minimizing power generation losses, and improving the stability of energy supply.

Furthermore, the ability to accurately capture wind speed fluctuations over time not only contributes to improved power generation efficiency but also offers significant potential for enhancing real-time operational management.

In this study, to improve power generation efficiency, winglets, which are also used in aircraft wings, and a wind collector to enhance the wind speed flowing into the wind turbine were introduced into a straight-wing vertical-axis wind turbine. Experiments using a blower and field tests under actual wind speed conditions were conducted.

This paper is organized into five chapters.

Chapter 2, Wind Energy Characteristics, explains the theoretical and practical principles of wind energy conversion, emphasizing the need for optimization. Winglets are discussed in relation to their ability to reduce air vortices and resistance while enhancing lift. Similarly, wind collectors are introduced as devices designed to channel wind into the turbine, thereby improving performance even under low wind conditions.

Chapter 3, Experimental Study of Wind Collection Effect, examines the impact of wind collector configurations on wind speed and power generation. Experiments were conducted to evaluate how different angles and positions of the wind collector plate influence performance. The results demonstrated significant improvements in wind speed and power output, particularly with specific configurations and blade numbers.

Chapter 4, Field Test of Wind Collection Effect, compares the performance of wind turbines equipped with winglets and wind collectors to traditional designs. The findings confirm that these modifications increase rotational speed and power generation, especially under both low and high-wind-speed conditions. Winglets improved efficiency in low wind conditions, while wind collectors delivered substantial overall gains.

Chapter 5, Conclusions, reaffirms the effectiveness of winglets and wind collectors in enhancing the efficiency of vertical-axis wind turbines. The study highlights the potential of these enhancements to optimize power generation and suggests further research into their performance under varying wind conditions.

## 2. Wind Energy Characteristics

Wind power is converted into mechanical energy by a wind turbine rotor, which reduces the velocity of the air mass. However, it is not possible to fully harness the energy contained in the wind. The full exploitation of wind power for rotating a wind turbine implies that the air flow is completely stopped within the rotor's area A. If the air flow does not reduce its velocity at all when it passes through area A, no energy is extracted from the wind [11]. Therefore, between these two extreme cases, there must be an optimal state for utilizing wind power by reducing wind speed. In 1920, Betz and Glauert demonstrated that a wind turbine placed in a free stream could extract the maximum power when the incoming wind speed was reduced by one-third in the turbine wake. The maximum power coefficient in this case was Cp = 16/27 = 0.59. Thus, even if we assume no loss when the wind turbine extracts power from the wind, only 59% of the wind power can be extracted. In general, the theoretical energy $P$ (W) held by wind in wind power generation is expressed as Equation (1), where $A$ ($m^2$) is the swept area of the wind turbine, $V$ (m/s) is the wind speed, and $\rho$ ($kg/m^3$) is the air density. This equation indicates that the theoretical energy held by the wind is proportional to the air density and swept area and to the cube of the wind speed. If the wind speed doubles, the amount of power generated will increase eightfold, as calculated using Equation (1). Therefore, the introduction of winglets and wind collectors is expected to improve wind turbine efficiency.

$$P = \frac{1}{2}\rho A V^3 \quad (1)$$

### *2.1. Winglets*

When wind flows into the blades of a wind turbine, air escapes from the front to the back at the tip, generating vortices. Therefore, by installing a winglet, the generation of air vortices at the tip of the wing and air resistance are reduced. In addition, lift is generated along the forward direction. In aircrafts, winglets are installed at the wing tips to improve fuel efficiency. In this study, a winglet, as shown in Figure 1, was installed on a small wind turbine and consequently examined to improve its efficiency.

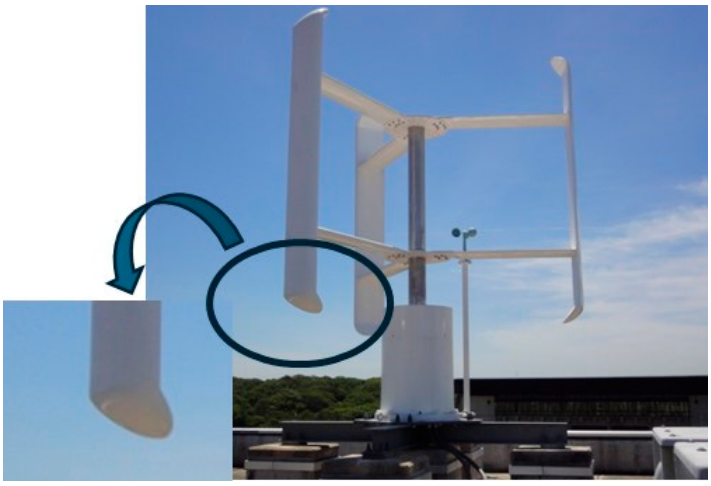
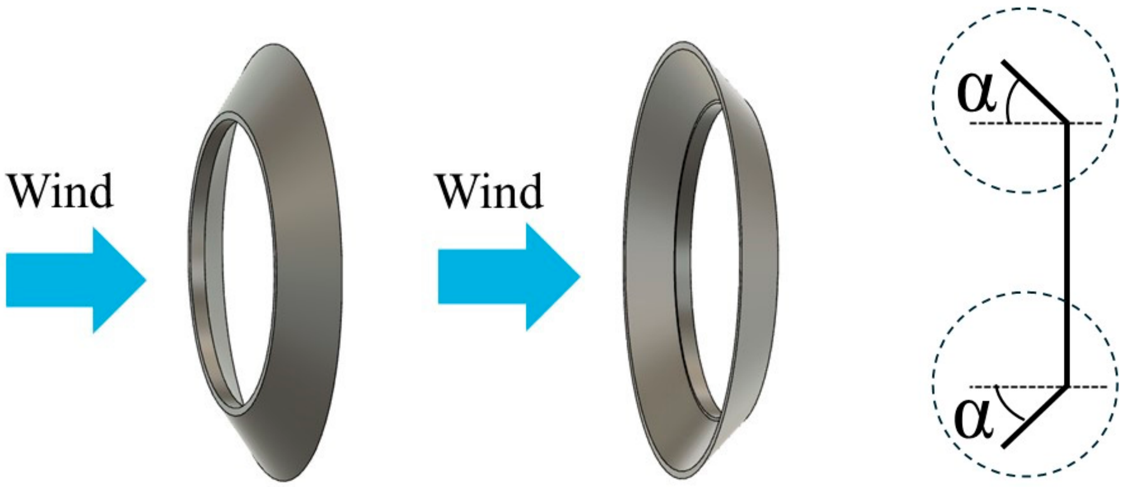


**Figure 1.** Winglet appearance.

### 2.2. Wind Collector

A wind collector increases the amount of wind flowing into a wind turbine by collecting the wind flowing above or below it inside the turbine. This facilitates the generation of electricity even under weak winds. A wind collector primarily comprises a wind collector section that allows the wind passing outside the wind turbine blades to flow into the wind turbine blades and a diffusion prevention section that prevents the wind from diffusing along the direction of the blade's rotation axis. In previous research, we proposed a wind collector for small wind turbines, conducted tests using actual wind turbines, and developed a wind collector specifically for small wind turbines [12,13]. The horizontal-axis-type wind collector is shown in Figure 2. Figure 2a,b shows an expanded and reduced type wind collector, respectively. The dotted circle shown in Figure 2c represents the wind collection angle $\alpha$ of the horizontal-axis wind collector. This wind collection angle $\alpha$ was changed to study the angle $\alpha$ that maximized the wind collection effect.




(**a**) Horizontal axis expanded type. (**b**) Horizontal axis reduced type. (**c**) Wind collection angle $\alpha$.

**Figure 2.** Horizontal axis wind collector exterior.

Figure 3 shows the results of field tests conducted using a horizontal-axis wind collector. The tests were performed with expanded-type collectors (wind collection angles $\alpha$ of 54° and 58°) and reduced-type collectors (wind collection angles $\alpha$ of 54° and 58°). A comparison of the expanded and reduced types revealed the former to be more effective. The field test results showed that the wind speed was maximized when the wind collection angle $\alpha$ of the expanded type was set to 54°. These results indicated that the enlarged type had a wind collection effect of approximately 1.7 times, with a wind collection angle of 54°. In this study, we proposed a wind collection device for small straight-blade vertical-axis wind turbines and investigated the optimal angle of the wind collection plate. Figure 4 shows the wind collector following the installation of the wind collection device.

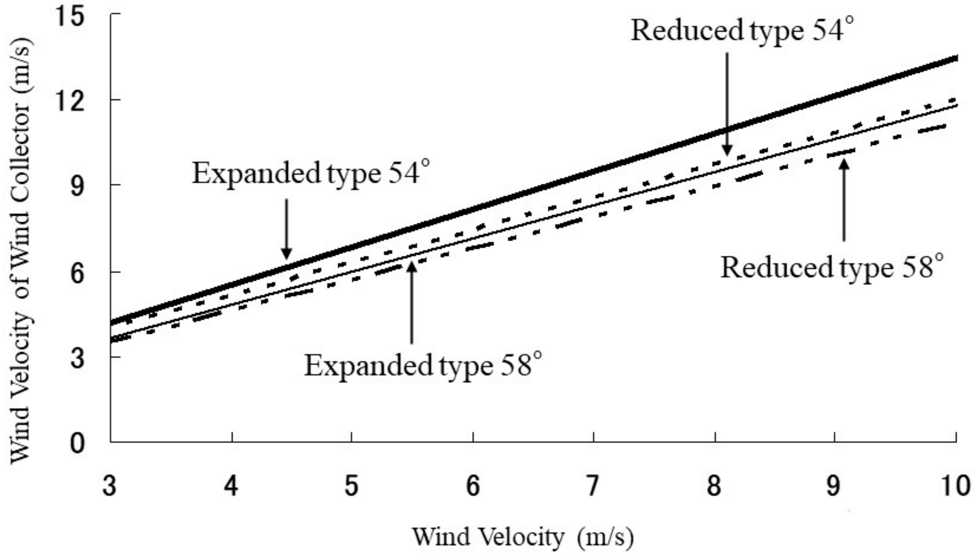



**Figure 3.** Horizontal-axis wind collection effect.


**Figure 4.** Vertical-axis wind collector.

## 3. Experimental Study of Wind Collection Effect

The system configuration of the wind collector for the small vertical-axis wind power generation used in this study is shown in Figure 5. Two experiments were conducted. In Experiment 1, the wind speed characteristics were examined according to the mounting angle of the wind collector plate of the wind collector shown in the figure and the position of the wind collector. In Experiment 2, a comparative study was conducted on the power generation characteristics when a small vertical-axis wind turbine was introduced into the wind collector.

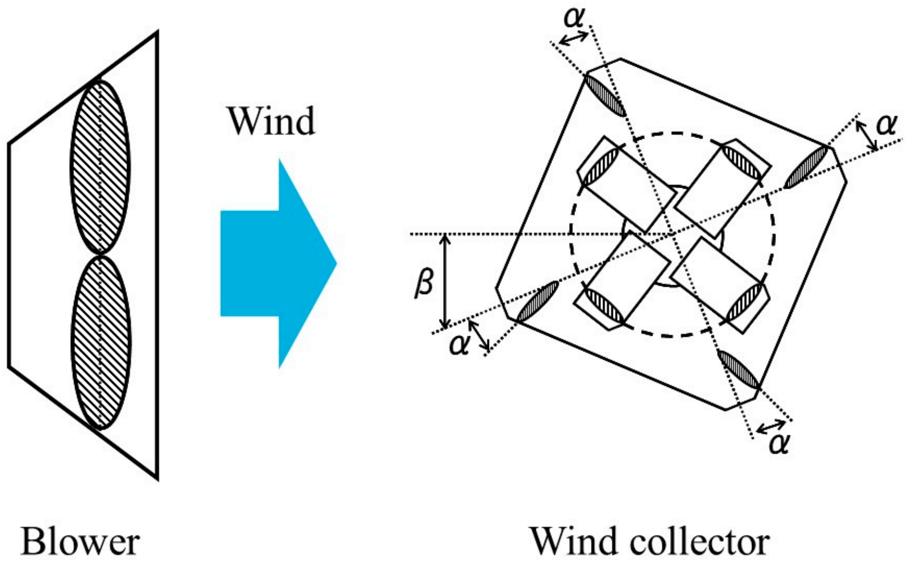



**Figure 5.** System configuration.

The mounting angle α of the wind collector plate represents the angle relative to the wind inflow direction. The position β indicates the angle between the center axis of the wind turbine and the arrangement of the wind collector plate. The mounting angles α of the wind collector plate were set to 0° and 22.5°, and the positions β were set to 0° and 22.5°, respectively. To confirm the basic wind collection effect, an experiment was conducted at constant wind speeds of 6, 8, and 10 m, and the wind speed was reproduced using a large fan. In Experiment 1, a wind turbine was not introduced, and an anemometer was installed on the rotation axis of the wind turbine to measure the wind speed and confirm the effectiveness of the wind collector alone. The experimental setup is illustrated in Figure 6. The wind collector plate of the wind collector had a structure that enabled simple changes in the angle, and a small vertical-axis wind turbine with a rated power of 40 W was used as the wind turbine.

**Figure 6.** Appearance of experiment.

In Experiment 2, an experiment was conducted on the power generation characteristics owing to the difference in the installation angle and the position of the wind collector when using only the wind collector, when the number of blades of the small vertical-axis wind turbine was three and four, respectively, using the circuit configuration shown in Figure 7. As shown, the system comprised a wind collector, small wind power generator, rectifier circuit, and load resistor (150 Ω). Consequently, the power generated at the load end after passing through the rectifier circuit was measured.

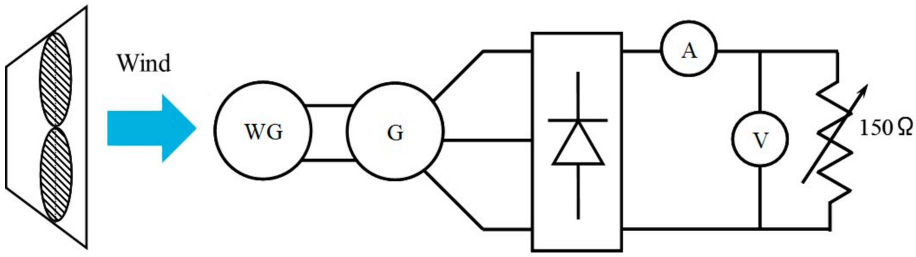



**Figure 7.** Circuit configuration.

### *3.1. Wind Speed Characteristics When Wind Collector Is Installed*

To confirm the fundamental characteristics of the wind collector alone, measurements were performed on the change in wind speed depending on the installation angle and position of the wind collector plate at constant wind speeds of 6, 8, and 10 m/s. The experimental results in Figure 8 show the rate of increase in wind speed achieved by installing a wind collector, relative to the wind speed input to the wind turbine. The calculations are based on considering the input wind speeds (6 m/s, 8 m/s, and 10 m/s) as 100%. As is evident, the introduction of the wind collector increased the wind speed on the rotation axis of the wind turbine. At wind speeds of 8 and 10 m/s, the introduction of the wind collector increased the wind speed by 130–140% compared with the wind turbine alone, thereby confirming the effectiveness of the wind collection effect.

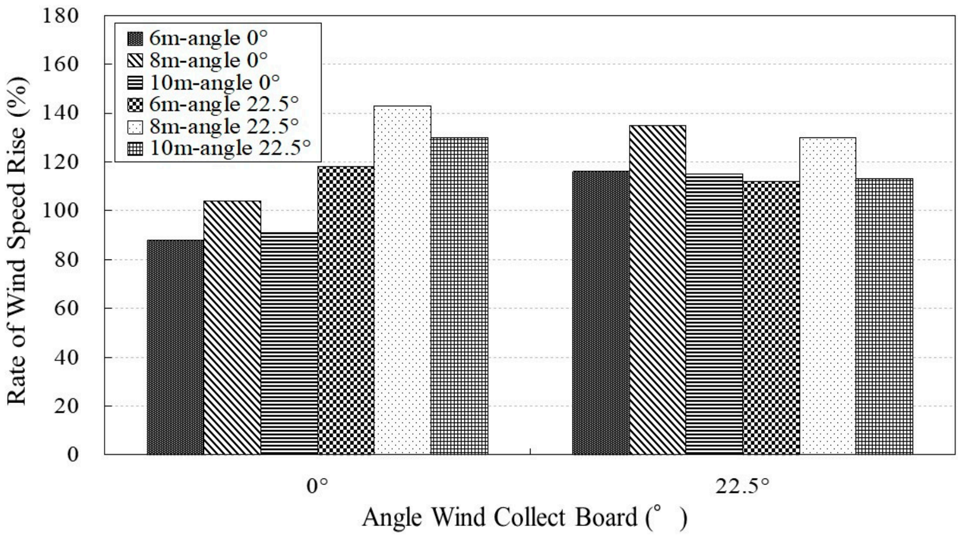



**Figure 8.** Wind speed characteristics.

### *3.2. Power Generation Characteristics When Wind Collector Is Installed*

Power generation was measured by changing the installation angle and position of the wind collector plate when the wind speed was constant at 6, 8, and 10 m/s and a wind turbine was installed in the wind collector. The experimental results are shown in Figures 9 and 10. Figures 9 and 10 show the power generation characteristics based on the installation angle of the wind collector plate for each wind speed and number of blades when the wind collector positions were 0° and 22.5°, respectively. In addition, the rate of increase when the wind collector was installed for the case when the power generation of the wind turbine alone was set to 100% is depicted. As is evident, when the installation angle of the wind collector plate was 0°, the power generation reached 146% for the number of blades of three. Moreover, it increased to a maximum of 172% with four blades. In addition, when the number of blades was four, a stable rotation speed and stable power generation were realized at both installation angles of the wind collector plate of 0° and 22.5°.

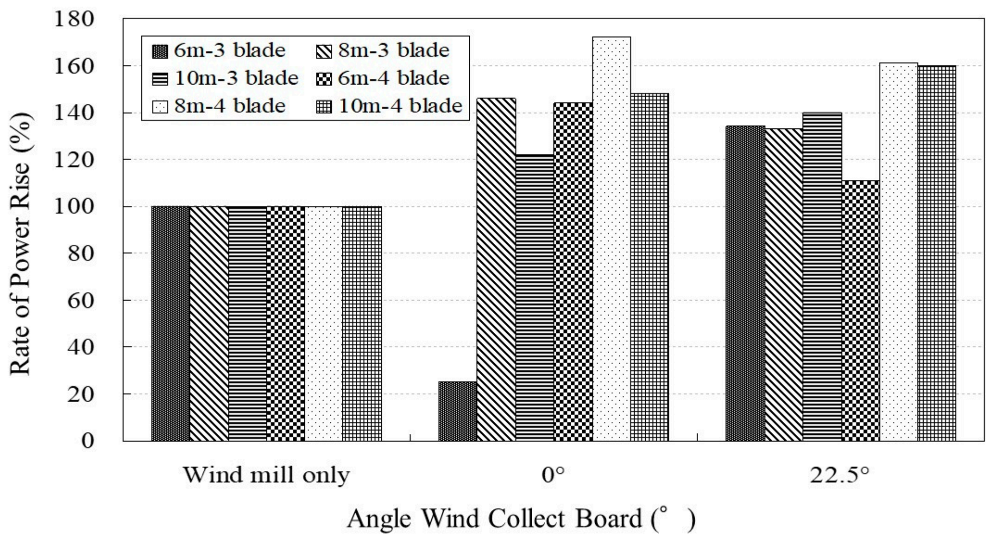



**Figure 9.** Power characteristics at β = 0° position.

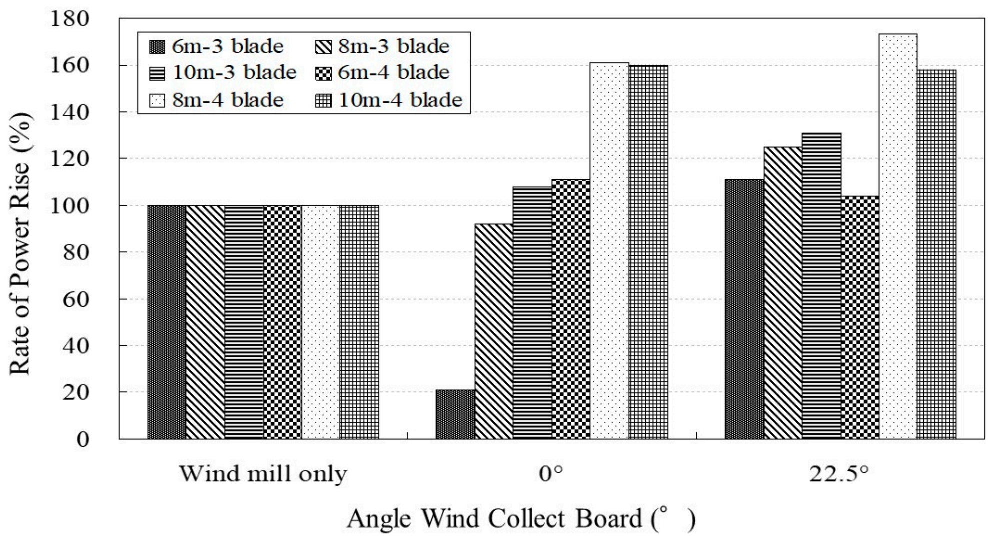
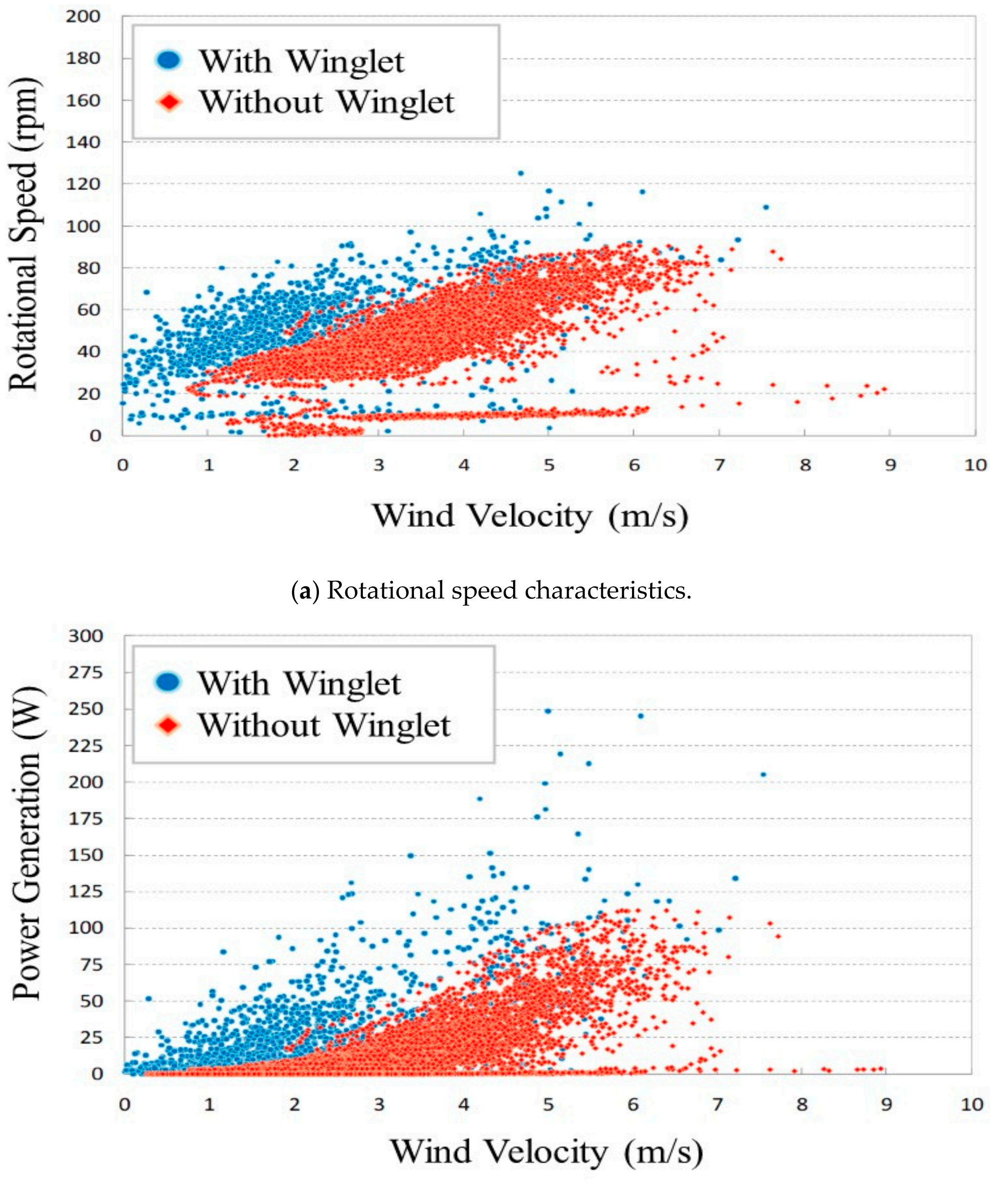



**Figure 10.** Power characteristics at β = 22.5° position.

Thus, the number of blades of the wind turbine to be installed in this wind collector was four. Further, the installation angle of the wind collector plate at 22.5° was better than that at 0° in terms of both the rotation speed and power generation, and thus, 22.5° was optimal. Therefore, it was inferred that the wind collection effect could be expected even at low wind speeds by introducing a wind collector into a small vertical-axis wind turbine, and the effectiveness of introducing a wind collector was confirmed. In this study, the wind speed characteristics in the wind collector for a small vertical-axis wind turbine and the power generation characteristics when the wind collector was introduced into the small vertical-axis wind turbine with three and four blades were compared. In terms of the wind speed characteristics, an increase of 130–140% was confirmed. Meanwhile, in terms of the power generation characteristics, the maximum increase was 172% when the number of blades was four, and the effectiveness of introducing a wind collector was confirmed.

## 4. Field Test of Wind Collection Effect

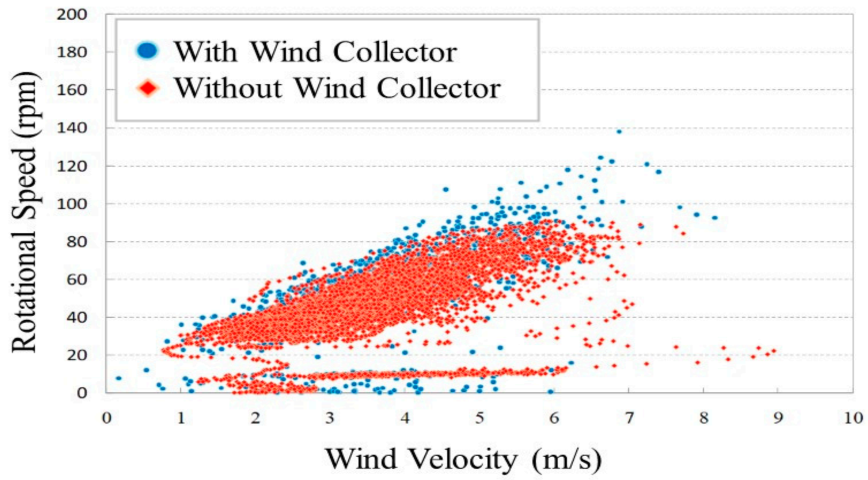
Field tests were conducted after installing the winglets shown in Figure 4 and after introducing the wind collector. The test results were compared based on the presence or absence of winglets and wind collector. The field test results are shown in Figures 11–13. The circuit configuration is shown in Figure 14. The sampling time for the field tests was set to 3 s, and the test results were graphed using the average values over a one-minute period.



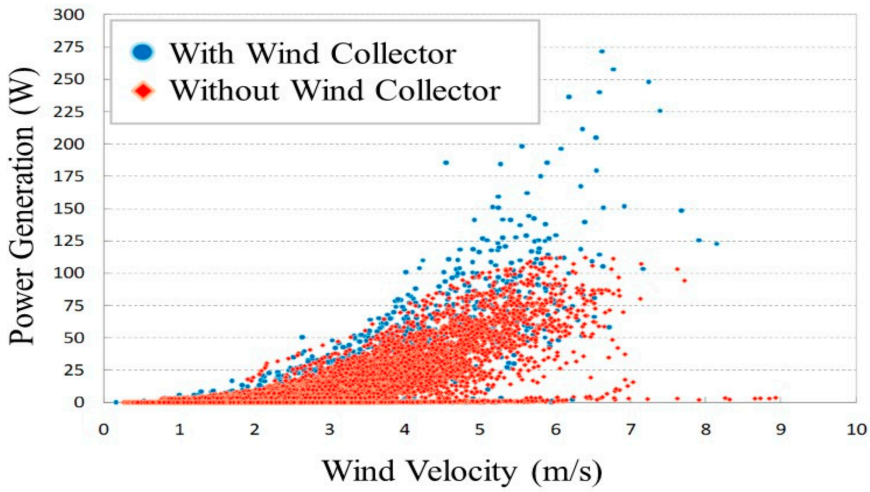

(**a**) Rotational speed characteristics.

(**b**) Power generation characteristics.

**Figure 11.** Experiment result (winglet).

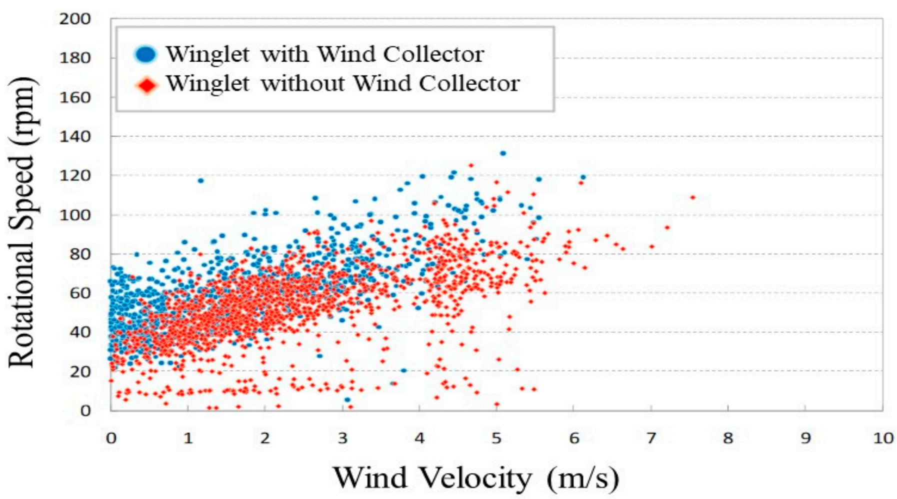



(**a**) Rotational speed characteristics.



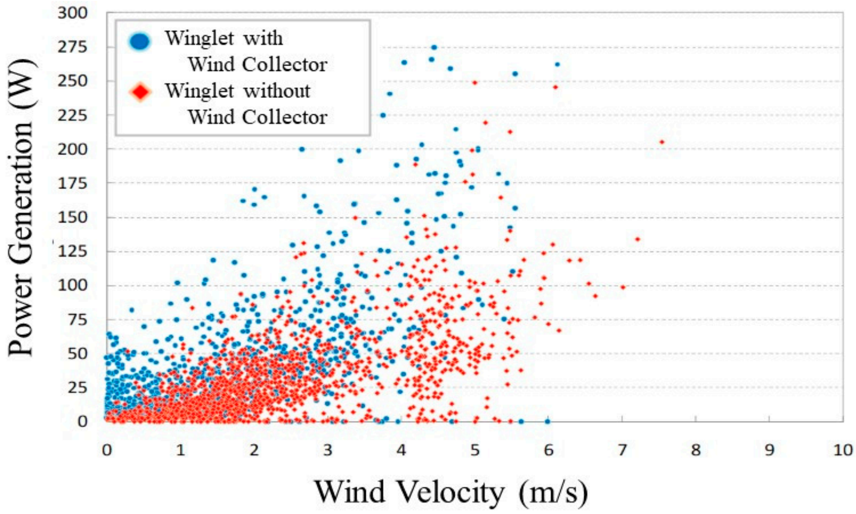

(**b**) Power generation characteristics.

**Figure 12.** Experiment result (wind collector).




(**a**) Rotational speed characteristics.

**Figure 13.** *Cont.*




(**b**) Power generation characteristics.

**Figure 13.** Experiment result (winglet and wind collector).

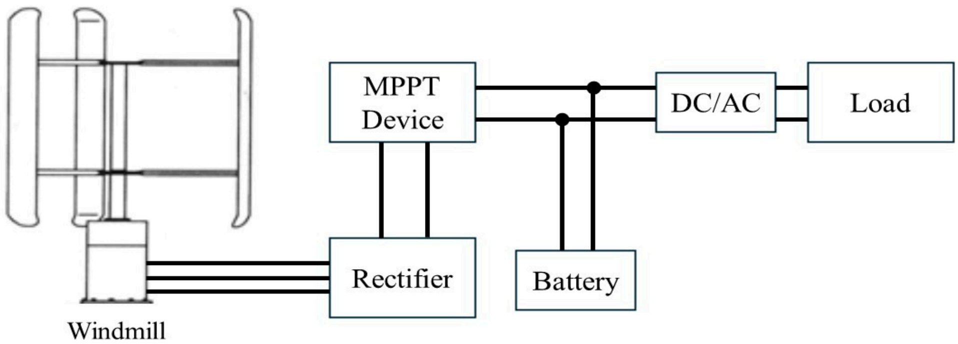



**Figure 14.** System configuration.

Figure 11 presents a comparison of the conventional straight-blade vertical-axis wind turbine with the winglets, Figure 12 presents comparisons with the wind collector, and Figure 13 presents comparisons with the winglet-equipped wind turbine alone with the wind collector. The rotation speed and power generation characteristics are illustrated. By comparing Figure 11a,b for the same wind speed range, it was confirmed that the winglets were higher than the straight blades alone. The introduction of winglets increased rotational speed and power generation, particularly at low wind speeds.

A comparison of Figure 12a,b for the same wind speed range confirmed that the wind collector yielded higher values overall than the use of straight blades alone. Moreover, a high rate of increase was confirmed, particularly at high wind speeds.

A similar comparison of Figure 13a,b shows that the introduction of the winglets facilitated increased rotation speed and power generation, even in low-wind-speed regions; however, the introduction of the wind collector yielded higher values overall. These field test results confirmed the effectiveness of introducing winglets and wind collectors.

Figure 14 shows the experimental circuit for the field test. The output of the wind generator is connected to the MPPT device through a rectifier. An energy storage device is connected to the connected DC bus bar. The load is powered as an AC load through DC/AC.

## 5. Conclusions

This study confirmed the effectiveness of winglets and wind concentrators in vertical-axis wind turbines. The test results confirmed that by introducing winglets and wind concentrators, higher values could be obtained in terms of the rotation speed and generated power compared to straight-blade wind turbines. Chapter 2, "Wind Energy Characteristics", explains the basics of wind energy conversion and highlights the importance of optimization, introducing the performance-enhancing effects of winglets and wind collectors. Consequently, it was confirmed that the wind after the wind turbine flowed without being dispersed, unlike the inflow wind. Section 3 describes the development of wind collectors. Tests were conducted to examine the installation angle and position of the wind collector plate. Satisfactory results were obtained at a wind collector plate installation angle of 22.5°. Section 4 describes field tests conducted using winglets and a wind collector on a small vertical-axis wind turbine. Consequently, the effectiveness of introducing the proposed winglets and wind collector was confirmed. In the future, we aim to analyze more data and examine the effects of each case within low and high wind speed ranges.

**Author Contributions:** Conceptualization, T.H. and K.Y. methodology, T.H. and K.Y.; validation, T.H. and K.Y.; formal analysis, T.H. and K.Y.; investigation, T.H. and K.Y.; resources, T.H. and K.Y.; data curation, T.H. and K.Y.; writing—original draft preparation, T.H. and K.Y.; writing—review and editing, T.H. and K.Y.; visualization, T.H. and K.Y.; supervision: T.H. and K.Y.; project administration, T.H. and K.Y. All authors have read and agreed to the published version of the manuscript.

**Funding:** Funded by Eco-electric Power Research Center, Aichi Institute of Technology, Japan.

**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. United Nations Public Information Center. What are the Sustainable Development Goals (SDGs). Available online: https://www.unic.or.jp/activities/economic_social_development/sustainable_development/2030agenda/ (accessed on 2 September 2024).
2. Ushiyama, I. *Wind Energy Reader*; Ohmsha, Ltd.: Tokyo, Japan, 2005.
3. Seki, K.; Ushiyama, I. *Vertical Axis Wind Turbines*; Power-sha, Ltd.: Tokyo, Japan, 2008.
4. Ushiyama, I.; Mino, M. *Handbook of Small Wind Turbines*, 5th ed.; Power-sha, Ltd.: Tokyo, Japan, 2004.
5. Horiuchi, K.; Seki, K. Flow analysis of Straight wing Vertical Axis Type Wind Turbine for Power Generation. *IEEJ Trans. PE* **2003**, *123*, 1488–1494. [CrossRef]
6. Tokuyama, H.; Ushiyama, I.; Seki, K. The performance and Wind Tunnel Test of Aerofoils for Small Wind Turbine Generating Systems. *IEEJ Trans. PE* **2003**, *123*, 208–215. [CrossRef]
7. Hata, Y.; Uchida, T.; Ohya, Y.; Karasutani, T. Numerical simulation of the flow around a wind turbine with a flanged diffuser. In Proceedings of the 31st Symposium on Wind Energy Utilization JWEA, Tokyo, Japan, 2009; pp. 372–374.
8. Ying, C.; Wang, W.; Yu, J.; Li, Q.; Yu, D.; Liu, J. Deep learning for renewable energy forecasting: Ataxonomy, and systematic literature review. *J. Clean. Prod.* **2023**, *384*, 135414. [CrossRef]
9. Chang, G.; Lu, H.; Chang, Y.; Lee, Y. An improved neural network-based approach for short-term wind speed and power forecast. *Renew. Energy* **2017**, *105*, 301–311. [CrossRef]
10. Famoso, F.; Oliveri, L.M.; Brusca, S.; Chiacchio, F. A Dependability Neural Network Approach for Short-Term Production Estimation of a Wind Power Plant. *Energies* **2024**, *17*, 1627. [CrossRef]
11. Ushiyama, I. *Fundamentals of Wind Energy*; Ohmsha, Ltd.: Tokyo, Japan, 2005.
12. Hosoe, T.; Kamiya, T.; Yukita, K.; Goto, Y.; Ichiyanagi, K.; Kusakabe, T. High-Efficiency Utilization of Wind Power Generator Using the Wind Collector. *IEEJ Trans. Power Energy* **2006**, *126*, 308–314. [CrossRef]
13. Fujimoto, K.; Ichikawa, T.; Yukita, K.; Goto, Y.; Ichiyanagi, K.; Idobata, Y.; Ishigaki, K.; Maruyama, K. A study of Wind Collect Effect with Vertical Axis Wind Power Generation (part 1)—Wind collector. *JSME* **2009**, *14*, 29–30.

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