Research Article

Clean Energy Innovation in Campus Environment with Small-Scale Wind Power Plants Integrated with IoT

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Abstract: Universities as innovation centers have a strategic role in driving the clean energy transition through the implementation of small-scale wind power plants integrated with IoT. This article analyzes the potential of wind power technology in campus environments, which have an average low wind speed (3–5 m/s) through Savonius-type vertical axis turbines equipped with IoT modules for real-time monitoring of wind speed, wind direction, electrical energy production, and battery status. The results show that this technology is capable of producing 100–200 W of power with a wind energy conversion efficiency to electrical energy of up to 20-30%. The implementation of this technology not only increases energy independence but also becomes a renewable energy education platform for students. Multidisciplinary collaboration between the fields of electrical engineering, mechanical engineering, and informatics engineering is the key to system optimization, while green campus policies can accelerate the adoption of this technology nationally.

Keywords: Renewable energy, IoT, small-scale wind turbines, green campus, energy management.

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Citation: Artanto, D., et.al. (2025). Clean energy innovation in campus environment with small-scale wind power plants integrated with IoT. *Iota*, 5(1), https://doi.org/10.31763/iota.v5i1.881

Academic Editor: Adi, P.D.P
Received: January 14, 2025
Accepted: February 03, 2025
Published: February 28, 2025

Publisher's Note: ASCEE stays neutral about jurisdictional claims in published maps and institutional affiliations.

1. Introduction

The energy crisis and climate change are pushing universities to become pioneers in adopting clean energy. Campuses, with little open space, are ideal locations for implementing small-scale wind power plants. The wind potential in several small campuses in Indonesia has an average wind speed of 3–5 m/s, sufficient for small-scale turbines. The main challenges are wind speed fluctuations and energy conversion efficiency. IoT integration in this system allows real-time monitoring, performance optimization, and adaptive energy management.

This research was developed in Five stages: (1) Planning and analysis of wind energy potential, (2) Design of turbine and IoT systems, (3) Development of monitoring and control systems, (4) Implementation and testing, (5) Data analysis and efficiency optimization.

2. Literature Review

2.1 Comparison with related studies

Several studies have discussed the application of small-scale wind energy in urban and campus environments. For example, a study at Tidar University showed that a small-scale wind power generation system in a high-rise building produces 138.24 W of power with IoT to regulate the flow of energy to the battery and the electricity grid [1]. Wind speed and voltage sensors are connected to the ESP32 microcontroller, enabling automatic control based on real-time data.

Research at Gunadarma University developed efficient and economical small-scale wind turbines for remote areas with low wind speeds in Indonesia [2]. This study used a qualitative approach by analyzing literature related to vertical-axis wind turbines. The results of the analysis indicate that the development of small-scale wind turbines is a sustainable solution to meet energy needs.

Research by Haryanti et al. developed a micro-scale wind power plant using a windmill that rotates a DC generator [3]. The mill has five blades with a length of 75 cm each and uses a fan belt to increase the generator rotation speed. The first test was carried out at a height of 1.46 meters with a wind speed of 4 m/s, producing a voltage of 12.1 V and a power of 60.5 W. The second test at a height of 4 meters with a wind speed of 8 m/s produced a power of 133 W. The results of the study indicate that with the right design, micro-scale wind turbines can be used as a renewable energy source for micropower applications.

Several studies abroad have also developed small-scale wind turbines that can be placed in areas where the wind is not too strong, such as in urban areas and residential areas [4][5][6][7][8][9][10][11][12][13][14]. The development of small-scale wind turbines also supports a green campus environment. Several studies have developed renewable energy generation by combining small-scale wind turbines with solar panels [15][16][17][18][19][20].

The generation of electrical energy also needs to be monitored so that the level of effectiveness and efficiency can be known at all times. Several studies have been conducted on the development of intelligent monitoring using IoT technology, which can monitor energy data generated by the wind turbine from anywhere and at any time [21][22][23][24]2[25].

From the research that has been done above, then the development of small-scale wind turbines was carried out on the campus of Sanata Dharma University, in addition to realizing a green campus environment, also as a learning demonstration media for energy conservation and its utilization. IoT technology was added to be able to monitor wind energy data and electrical energy data generated from anywhere and at any time.

3. Conceptual Framework

As written in the introduction, this research was developed in 5 stages: (1) Planning and analysis of wind energy potential, (2) Sensors and IoT systems, (3) Development of monitoring and control systems, (4) Implementation and Testing, (5) Data analysis and efficiency optimization. The following is a description of each stage.

3.1 Planning and Analysis of Wind Energy Potential

Site feasibility study: Analysis of average wind speed (≥3 m/s), topography, and environmental factors using anemometers or historical weather data. Turbine type selection: Vertical axis turbines are recommended for areas with unstable winds or limited space (such as campuses), while horizontal axis turbines are suitable for areas with strong winds. Figure 1, Figure 2, and Figure 3 show the design of a Savonius vertical shaft-type windmill with 5 blades.

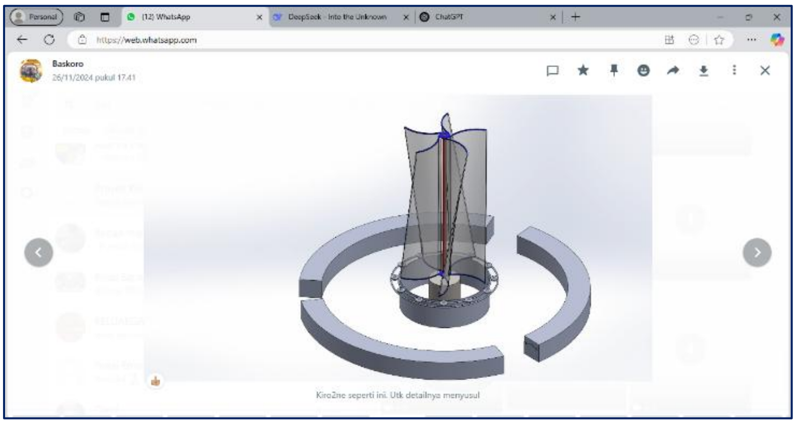

Figure 1. Design of a Savonius-type windmill with 5 blades

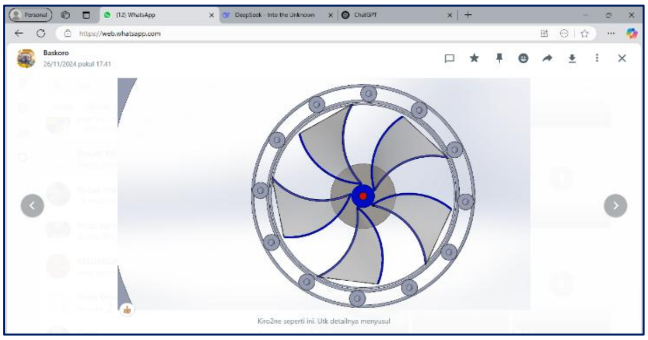

Figure 2. Top view of the windmill design

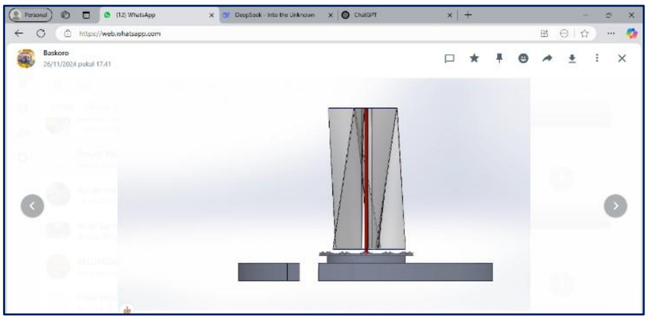

Figure 3. Side view of the windmill design

3.2 Sensors and IoT System Design

Integration of anemometer and wind vane sensors to measure wind speed and direction. IoT system: TTGO-LORA ESP32 for data acquisition and data transmission to the cloud platform (Firebase and ThingSpeak). Figure 4 shows the TTGO LORA ESP32 circuit connected to a wind speed and direction sensor.

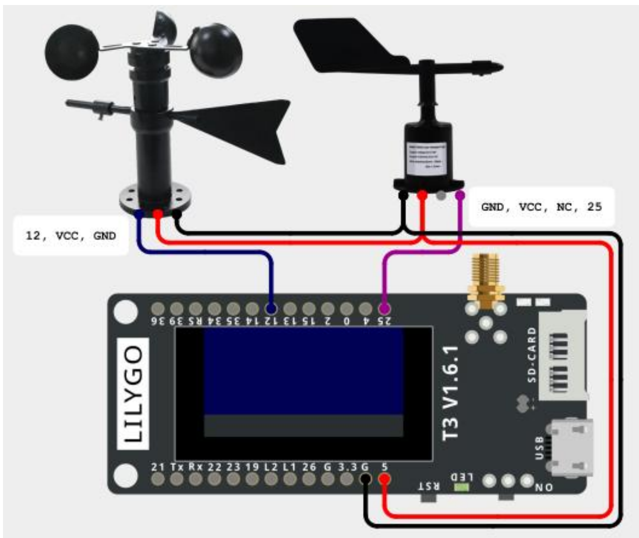

Figure 4. TTGO LORA circuit to monitor wind direction and speed and send it to the cloud.

The use of TTGO-LORA ESP32 here is to provide data transmission communication features in open areas that do not have a Wi-Fi connection. With the LoRA communication protocol, it is possible to send data over long distances via radio waves. The data sent is then received by the second TTGO-LORA ESP32, which is in the room with a Wi-Fi connection. The data is then forwarded to the Cloud via a Wi-Fi connection. Figure 5 shows a diagram of an IoT-integrated wind power plant monitoring system.

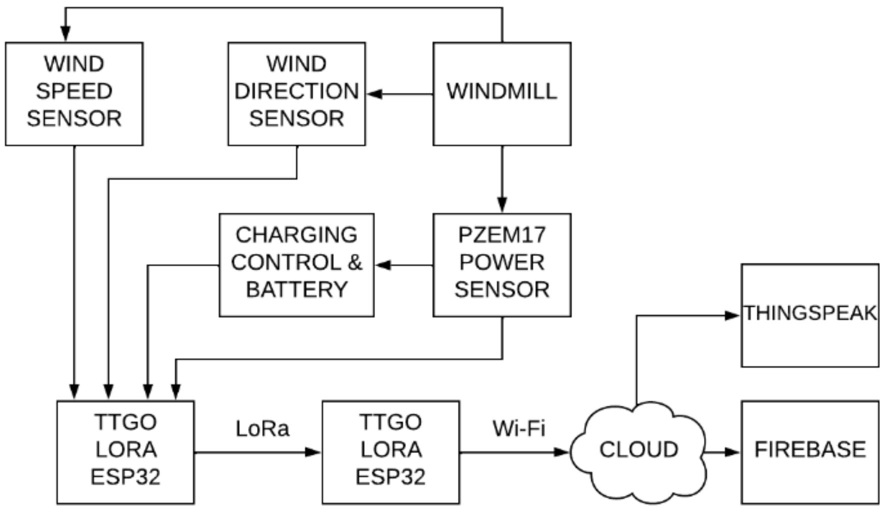

Figure 5. Monitoring system diagram for an IoT-integrated wind power plant

3.3 Monitoring and Control System Development

Supporting sensor: Wind Speed and Wind Direction sensors, PZEM-017 module for measuring DC voltage, current, power, frequency, and energy consumption, and DHT22 for measuring temperature and humidity.

User interface: Web/application-based dashboard using Thingspeak for real-time data visualization such as energy production, battery status, wind speed, and wind direction. Figure 6 and Figure 7 show the screen display from the web dashboard in Thingspeak, which shows wind conditions, wind direction, wind speed, generated electrical power, and battery voltage.

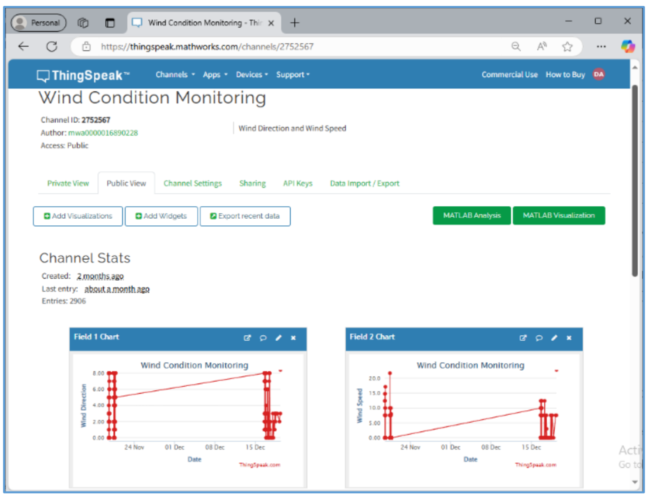

Figure 6. Wind monitoring dashboard: wind speed and direction

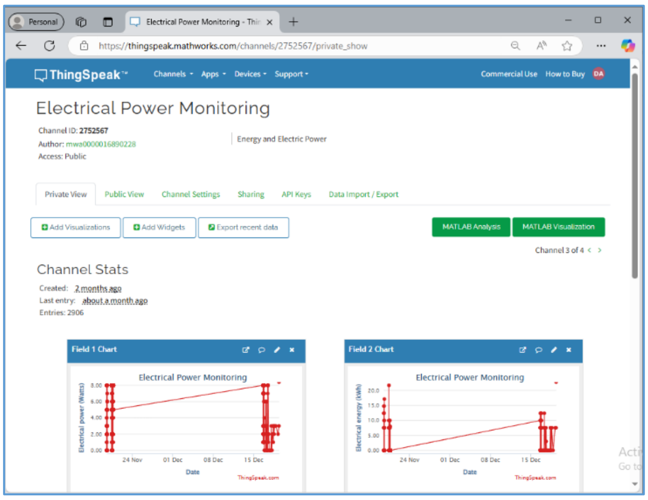

Figure 7. Electrical power monitoring dashboard: electrical power and battery voltage.

3.4 Implementation and Trial Test

Calibration sensor: accuracy of wind speed measurement and electrical parameters. Performance test: Effect of wind speed on output power. The following Table 1 shows the observation of the relationship between wind speed and the electrical power produced.

Table 1. Relationship between wind speed and electrical power generated

Wind speed (m/s)	Power (W)
1	10
2	50
3	80
4	120
5	200
6	285
7	315

3.5 Data Analysis and Efficiency Optimization

Data processing: Use of Firebase to store historical data. Figure 8 shows the Firebase (cloud database) display with JSON data.

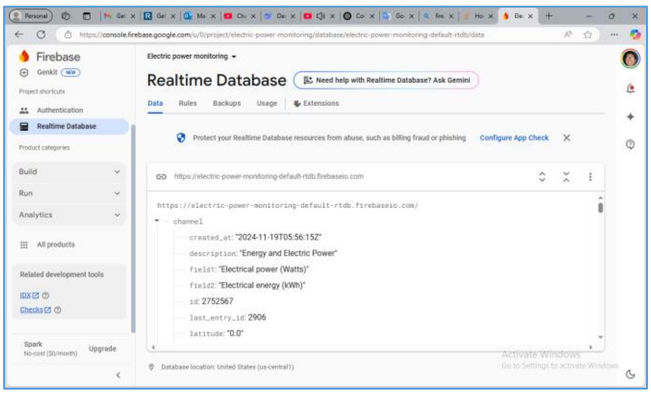

Figure 8. Power monitoring database stored in Firebase

In this study, data storage uses Thingspeak and Firebase services. This is intended to provide a layer of redundancy. If there is a problem with one of the services, the data can still be accessed or managed through the other service. Here Thingspeak is used for real-time data collection and fast visualization, while Firebase is used to store data long-term, which is useful for in-depth analysis and integration with other applications. Regarding data storage, Thingspeak has limited storage capacity, while Firebase offers large capacity, which can be used for long-term data collection.

Regarding data management, Thingspeak offers data visualization and analytical integration for simple data. While for more complex data, Firebase has better data management features. Regarding security, Thingspeak offers basic security, while for higher security it is necessary to use Firebase.

4. Technical Specification

The design of a small-scale wind power plant with the Savonius vertical shaft type has been successfully implemented. Figure 9 shows a 3D design for using a windmill to generate electricity for lighting at night. Furthermore, Table 2 shows the monitoring of electrical energy produced in 72 hours (3 days).

Figure 9. 3D design of a windmill at night as a source of electrical energy for lighting

Table 2. Results of monitoring wind speed data and power and electrical energy produced for 72 hours

Wind speed (m/s)	Power (W)	Hour (h)	Energy (kWh)
0	**0**	3	0
1	10	4	40
2	50	10	500
3	80	20	1600
4	120	15	1800
5	200	12	2400
6	285	5	1425
7	315	3	945
		72	**8,710**

Figures 10 and 11 respectively show graphs of wind speed and electrical power generated for 3 days.

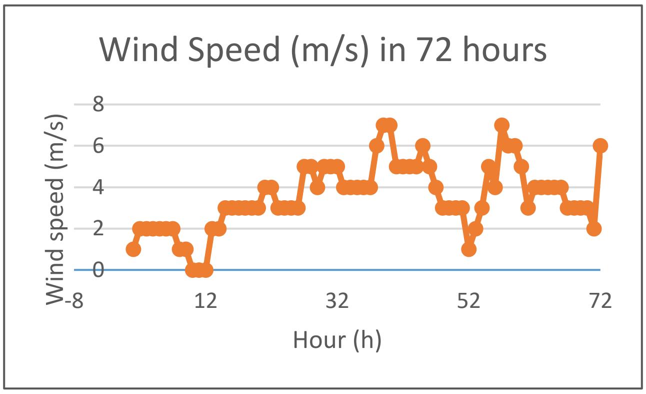

Figure 10. Wind speed (m/s) data graph for 72 hours

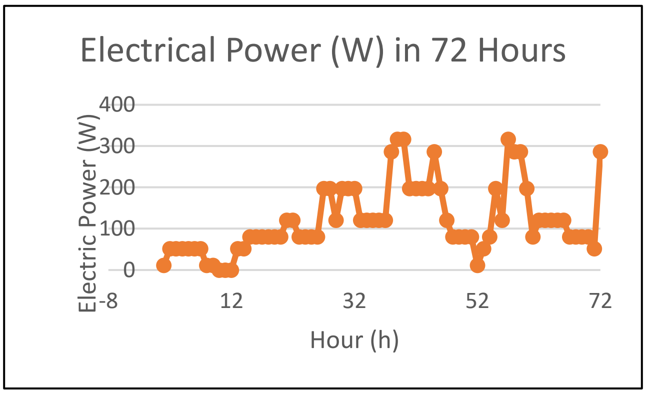

Figure 11. Electrical power (W) data graph for 72 hours

From Table 2 and Figures 10 and 11, it can be seen that the electrical power generated by the Windmill is sufficient to meet the electricity needs for electrical devices that students usually carry, such as laptops, cell phones, etc.

5. Conclusion

The implementation of IoT-integrated small-scale wind power plants on campus not only reduces carbon footprint but also becomes a living laboratory for renewable energy research. With continuous optimization, IoT-integrated small-scale wind power plants have the potential to meet up to 10% of campus energy needs and become a model for the surrounding community. The implementation of IoT-integrated small-scale wind power plants on campus has great potential to support energy sustainability. With IoT-based monitoring, energy efficiency can be improved, so that campuses can reduce dependence on conventional energy sources and adopt a more environmentally friendly green energy model. Future developments include integrating the generation of electrical energy from wind turbines with other environmentally friendly, clean electrical energy generation technologies, such as solar panels, and the addition of air quality sensors, to monitor and maintain safe levels of pollution in the campus environment.

Acknowledgments: This research was conducted by involving technology, art, and literature in a collaborative project, named Kalangwan, which means beauty, with funding support from Sanata Dharma University.

Author contributions: The authors are responsible for building Conceptualization, Methodology, analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, visualization, supervision of project administration, funding acquisition, and have read and agreed to the published version of the manuscript.

Funding: The study was conducted without any financial support from external sources.

Availability of data and Materials: All data are available from the authors.

Conflicts of Interest: The authors declare no conflict of interest.
Additional Information: No Additional Information from the authors.

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