

Prototype of a Mini Wind Turbine for Automatic Charging Based on the Internet of Things (IoT) in the Garden Area of STMIK Kaputama

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Abstract

Lighting in the garden area of STMIK Kaputama Binjai, located on the upper floor of the building, remains very limited and fully dependent on the conventional power supply, making the area uncomfortable and potentially unsafe for use at night. This research aims to design and build a mini wind turbine prototype as an alternative energy source for garden lamps, to develop an automatic charging system that stores wind energy in a battery and switches the lamp on based on a light sensor, and to implement Internet of Things (IoT) technology through the Blynk application for remote monitoring and control. The research was developed using the prototype method, with a system consisting of a vertical axis wind turbine (VAWT) coupled to a 12 V DC generator, a 1N5822 Schottky diode, an LM2596 module, a TP4056 module as the charging controller for an 18650 battery, an XL6009 module as a step-up converter for the LED lamp, a voltage sensor, an INA219 current sensor, an LDR sensor, a relay, and a NodeMCU ESP32 as the main controller. Testing was conducted directly in the garden area of STMIK Kaputama using naturally available wind. The results show that the prototype produced 0.11-2.62 W of power at wind speeds of 1.8-5.3 m/s, the automatic charging system raised the battery voltage by 0.48 V (from 3.62 V to 4.10 V) over three hours, the LDR-based automatic lighting control succeeded in all five lighting conditions (100%), the charged battery powered the lamp for more than six hours, and real-time monitoring via Blynk operated with an average delay of 1.40 seconds with remote ON/OFF control succeeding in 10 out of 10 attempts, supported by an average error of 1.74% for the voltage sensor and 3.06% for the INA219 current sensor. Therefore, the IoT-based mini wind turbine prototype is proven capable of serving as an independent and environmentally friendly alternative energy source for campus garden lighting, although the charging rate is still affected by fluctuations in local wind speed.

Keywords: Automatic charging; Blynk; ESP32; Garden lamp; Internet of Things; Mini wind turbine

1. Introduction

The demand for electrical energy in campus environments continues to increase along with the growth of academic, administrative, and other supporting activities. Electrical energy is required not only in classrooms, laboratories, and offices, but also in public facilities such as campus garden areas. A garden area functions as an open space used by students and the academic community for outdoor activities, so the availability of an adequate lighting system becomes an important aspect in supporting comfort, safety, and the usability of the area, particularly at night.

Based on field conditions, lighting in the garden area of STMIK Kaputama Binjai is still very limited. This condition is caused by the location of the garden on the upper floor of the building, so that a lighting system has not been optimally provided. Insufficient lighting causes the garden area to be less suitable for use at night because it reduces comfort and potentially creates security risks for students and academic staff. In addition, the energy required for lighting still depends on the conventional power supply, while no independent power generation system is available to help meet the energy needs of the garden lamps automatically and sustainably.

Wind energy is one of the renewable energy sources that in principle will not be depleted in the long term. The utilization of wind energy is regarded as a market-ready technology because its technological maturity continues to improve and its development costs are increasingly competitive, although its performance remains strongly influenced by the geographical conditions of the installation site [1]. The utilization of wind energy through a mini wind turbine prototype is considered suitable for producing low-power electrical energy that can be used for light loads such as garden lamps. However, because the electrical energy produced by a wind turbine is affected by changes in wind speed, a voltage and current monitoring system based on the Internet of Things (IoT) is required to determine the operating condition of

the system in real time. IoT technology enables physical objects to record, transmit, and exchange data with minimal manual intervention, so that monitoring and control activities can be carried out more effectively, flexibly, and efficiently [2].

Several previous studies have addressed IoT-based monitoring systems for mini wind power plants. The developed system used a wind turbine, a generator, an INA219 sensor, a DC voltage sensor, a NodeMCU ESP32, an LCD, and the ThingSpeak platform to monitor current and voltage parameters in real time, with a measured power range of approximately 1.25 W to 2.97 W at wind speeds changing from 3.0 m/s to 5.7 m/s [3]. However, that study still focused on monitoring electrical parameters, so it was not specifically directed toward serving as an alternative energy source for garden lighting systems in campus environments. Another study developed an IoT-based charging control system for a wind power plant using an ESP32, an LCD, a website, and a micro SD card as the data storage medium, with monitored parameters including the voltage, current, and power entering the battery [4]. Although it was able to perform real-time remote monitoring, the focus of that study was still limited to the battery charging process rather than the direct application of wind energy as a power source for light loads. In addition, research on an IoT-based monitoring system for a laboratory-scale vortex turbine has also been conducted using an ESP32, an LCD, and an Android application to monitor water discharge, turbine rotation, voltage, and power [5]; however, the research object was a water-flow-based turbine, so it did not address the utilization of wind energy through a mini wind turbine as an alternative energy source for outdoor lighting.

Another study proposed an IoT-based monitoring system for current, voltage, and RPM in a portable wind power plant using an ESP32 and ThingSpeak, while also testing measurement accuracy against a reference instrument [6]. Research on IoT-based monitoring of a horizontal axis wind turbine emphasized that telemetry is required to ensure the turbine operates under safe and optimal conditions, particularly for systems placed in open environments [7]. IoT-based monitoring of wind speed and direction using a Raspberry Pi showed that meteorological parameters can be acquired remotely as supporting data for decision making [8]. In a combined solar panel and wind turbine system, monitoring of voltage, current, and power through the Blynk application showed a solar panel output of approximately 18.2 V with a power of 37.75 W, while the wind turbine produced approximately 12.2 V with a power of 3.6 W [9]. Meanwhile, real-time IoT-based monitoring of a vertical axis wind turbine reported an INA219 sensor error percentage for current readings in the range of 5.1% to 16.6% and a voltage error as low as 1.7% [10]. Other studies applied a relay-based smart auto change to switch the energy source according to the higher voltage [11], as well as the design and development of a wind power plant with an IoT-based battery charging monitoring system [12]. Efforts to control wind turbine output for greater stability have also been examined through the development of a controlled output wind turbine [13].

Based on these studies, a research gap remains, namely the absence of an IoT-based mini wind turbine prototype specifically designed as an alternative energy source for garden lamps at STMIK Kaputama Binjai with the capability of monitoring voltage, current, power, battery capacity, and lamp status in real time together with remote ON/OFF control. Therefore, this research aims to: (1) design and build a mini wind turbine prototype capable of producing electrical energy to power IoT-based garden lamps within the STMIK Kaputama environment; (2) design an IoT-based automatic charging system that can store wind energy in a battery and activate the lamp automatically based on a light sensor; and (3) implement IoT technology through the Blynk application to monitor the turbine condition and battery capacity, and to provide remote ON/OFF lamp control.

2. Research method

This research used the prototype method, a development approach that allows a system to be built and improved iteratively based on feedback from testing results. This approach was chosen so that the developed mini wind turbine prototype functions according to specifications and meets the needs of field usage. The research flow is shown in Figure 1.

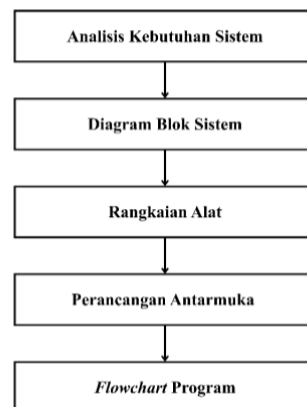


Fig. 1. Research flow

Based on this flow, the first stage is the identification of system requirements for a mini wind turbine prototype capable of performing IoT-based automatic charging. Next, the interface was designed and built using Blynk, connected to hardware such as the NodeMCU ESP32, the voltage sensor, and the DC motor as the core of the system. The constructed prototype was then tested to obtain feedback regarding functionality and interface, so that improvements and refinements could be carried out iteratively until the system worked optimally.

2.1. System requirement analysis

Requirement analysis was conducted to determine the components needed so that the prototype could work effectively. The hardware used includes a DC generator as the main electricity source from the wind turbine, a fan (turbine blade), an acrylic casing, a NodeMCU ESP32 as the main controller, a 0-25 V voltage sensor module, an INA219 current sensor, a 12 V DC motor, an LM2596 module, an XL6009 converter, an 18650 battery, a TP4056 module, a 1N5822 Schottky diode, a relay, and an LED lamp. The software used includes the

Arduino IDE for programming, the Blynk application as the monitoring and control platform, Fritzing for circuit schematic design, and Draw.io for flow diagram creation. The technical specifications of the main hardware are summarized in Table 1.

Table 1. Specifications of the hardware used

No	Component	Electrical specification (voltage and current)	Function
1	DC generator (12 V DC motor)	Nominal voltage 12 V DC; output 0-12 V DC (fluctuating with wind speed); current ± 0.1 -0.5 A depending on load	Main electricity generator driven by the turbine blades
2	Turbine blade (fan)	Mechanical component, no direct electrical specification	Captures wind energy and rotates the generator shaft
3	NodeMCU ESP32	Logic voltage 3.3 V; power supply 5 V; operating current ± 80 -260 mA	Main controller of the IoT-based system
4	Voltage sensor module (FZ0430)	Measurement range 0-25 V DC; supply 3.3-5 V	Reads battery voltage as a capacity indication
5	INA219 current sensor	Bus voltage 0-26 V DC; current measurement up to ± 3.2 A; I2C interface	Measures current and voltage on the load path
6	LM2596 (step-down converter)	Input 4.5-40 V; output 1.25-37 V; current up to ± 2 -3 A	Steps down the generator voltage to ± 5 V for the TP4056 input
7	18650 battery (1 cell)	Nominal voltage 3.7 V (± 4.2 V when full); capacity ± 2000 -2600 mAh	Stores the converted electrical energy
8	TP4056 module	Input 4.5-5.5 V; charging voltage 4.2 V; maximum current 1 A; overcharge, over-discharge, and overcurrent protection	Regulation and protection of battery charging
9	XL6009 module (step-up)	Steps up the battery voltage to a level of 12 V DC	Voltage adjuster for the LED lamp supply
10	12 V LED lamp	Low-power DC load	Garden lighting load

The 12 V DC motor is used as a DC generator driven by the turbine rotor to produce a direct current output. This approach was chosen because the structure of a DC generator is relatively simple and economical, and it is easily integrated with DC-based power conditioning circuits without requiring an AC to DC conversion stage [14], [15]. The 1N5822 Schottky diode is used as a rectifier as well as reverse current protection because it has fast switching capability and a low forward voltage drop [16]. The XL6009 converter functions to adjust the voltage level to match the requirements of the storage system and the load when the source voltage fluctuates [17]. The TP4056 module works with the constant current-constant voltage (CC-CV) method and charges the battery up to a full voltage of 4.2 V with a maximum current of 1 A [18]; the type used is equipped with overcharge, over-discharge, and overcurrent protection, similar to the charging protection function in comparable studies [19]. The 18650 battery was selected as the storage medium because it has good energy density and a practical form for small-scale applications [20].

The 0-25 V voltage sensor module works using the principle of a resistance-based voltage divider, namely reducing the input voltage to a safe level so that it can be read by the ADC pin of the microcontroller [21], [22]. The INA219 sensor is used to monitor current and voltage in an integrated manner through the I2C interface by utilizing shunt voltage and bus voltage measurements [23], [24]. The 12 V LED lamp is positioned as a lighting load as well as a relatively stable test load for evaluating the response of the generation system to loading conditions [25]. The overall working logic of the system is described in the form of a flowchart, namely a diagram that presents the sequence of steps of a process systematically using symbols connected by flow lines [26]. The Blynk application was chosen as the IoT platform because it provides drag-and-drop dashboard creation and is considered easier to operate than similar platforms [27].

2.2. System block diagram

The system block diagram describes the overall flow of energy and data in the designed system, as shown in Figure 2.

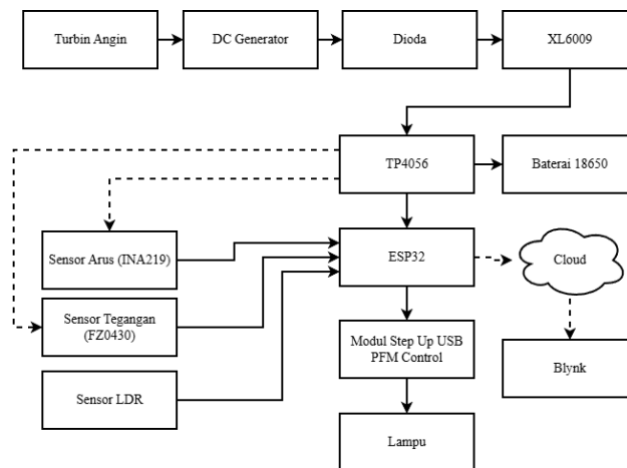


Fig. 2: System block diagram

In general, the system integrates three main processes, namely energy generation from the wind turbine, power storage in the battery, and IoT-based monitoring and control. The electrical energy produced by the DC generator from the turbine rotation is passed through a diode to prevent reverse current, then conditioned before being delivered to the TP4056 module that regulates the charging process of the 18650 battery. The output of the charging module is also used to supply power to the NodeMCU ESP32 as the main controller. The ESP32

receives input from the voltage sensor, the INA219 current sensor, and the LDR sensor, calculates power through the equation $P = V \times I$, and then transmits the data to the cloud so that it can be accessed through the Blynk application. In addition, the ESP32 controls the lamp through a relay and a step-up module, so that the system is able to perform automatic charging as well as real-time load control.

2.3. Circuit design

The circuit design describes the electrical connections between components in detail, covering the power supply path, the sensor signal path, and the load control path, as shown in Figure 3.

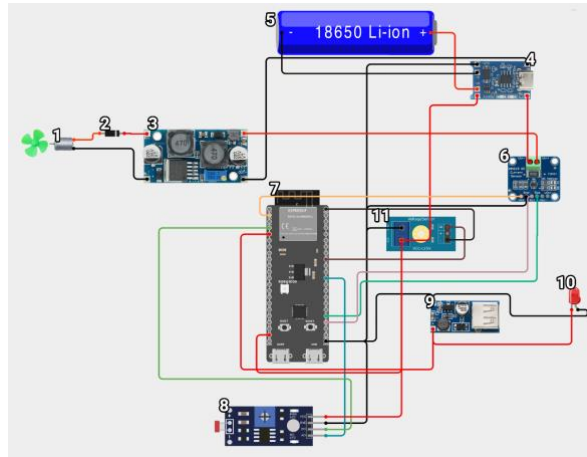


Fig. 3: Circuit design of the device

2.4. System workflow

The workflow of the program embedded in the NodeMCU ESP32 is described through the flowchart in Figure 4. The program begins with sensor initialization and Wi-Fi connection, followed by periodic readings of voltage, current, and light intensity. The power value is calculated from the voltage and current readings, and then the system makes a control decision: if a dark condition is detected, the lamp is turned on; whereas if it is bright, the lamp is turned off. All readings are transmitted to the Blynk application so that users can monitor the system condition and control the lamp remotely.

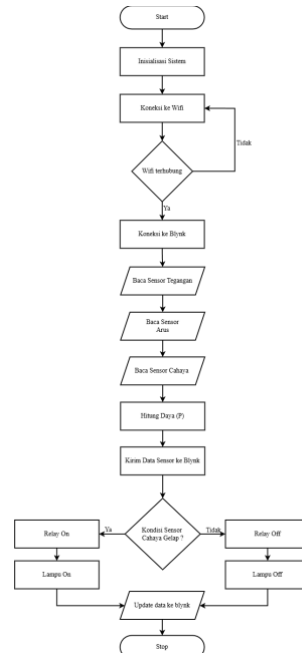


Fig. 4: Program flowchart

3. Result and discussion

3.1. System implementation

3.1.1. Software implementation

The system software was written using the Arduino IDE with the C/C++ programming language. The program uploaded to the NodeMCU ESP32 contains several main functions, namely initialization of the INA219 sensor through I2C communication, reading of the voltage sensor and the LDR sensor through ADC pins, power calculation using the formula $P = V \times I$, relay control logic based on the LDR threshold value, and data transmission to the Blynk server through a Wi-Fi connection using an authentication token. Sensor readings are performed periodically every two seconds, and the results are then sent to the designated Blynk virtual pins.

3.1.2. Hardware implementation

The prototype hardware was assembled by placing vertical axis wind turbine (VAWT) blades on the upper part of the frame, directly coupled to a DC generator (12 V DC motor) as the electricity generating component. The generator output is connected sequentially to a 1N5822 Schottky diode as reverse current protection, an LM2596 module as a step-down converter to a level of +5 V, and a TP4056 module that regulates the charging of the 18650 battery. The XL6009 module is placed on the battery output path to step up the voltage to a level of 12 V as the supply for the LED lamp. All electronic components are placed inside an acrylic casing to protect them from the weather while also facilitating circuit inspection. The overall assembled prototype is shown in Figure 5.

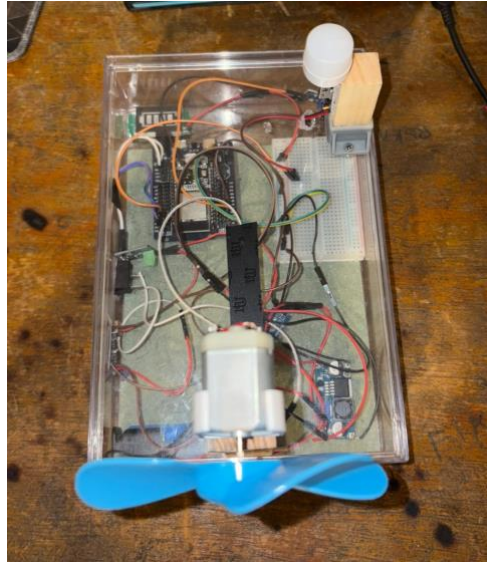


Figure 5. Assembled mini wind turbine prototype

3.1.3. Blynk application interface implementation

The monitoring and control interface was implemented using the Blynk application on a smartphone. The Blynk dashboard consists of widgets displaying the input voltage, input current, power, and battery voltage values, chart widgets displaying voltage and current graphs in real time, LDR threshold and ambient condition indicators, a lamp status indicator, and an ON/OFF control button for manual mode. Each widget is connected to the virtual pin corresponding to the program on the ESP32, as shown in Figure 6.

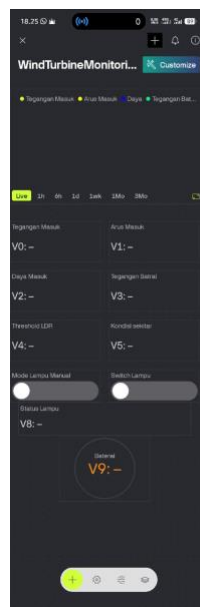


Figure 6. Blynk application dashboard display

3.2. System testing

System testing was carried out in the garden area of STMIK Kaputama Binjai using the natural wind speed available at the location. The tests included testing of the wind turbine output, the accuracy of the voltage and current sensors, the battery charging process, automatic lamp control based on the LDR sensor, manual control through the Blynk application, real-time monitoring, battery endurance in powering the lamp, and a comparison of battery charging between a USB Type-C charger and the wind turbine.

3.2.1. Battery charging test

Battery charging testing aims to determine the ability of the system to store the energy converted by the wind turbine into the 18650 battery automatically through the TP4056 module. The test was conducted for three hours during the day with an average wind speed of 3.8 m/s, starting from a battery voltage of 3.62 V. During the charging process, the red LED indicator on the TP4056 module was lit as a sign that

charging was in progress. The battery voltage was recorded every 30 minutes through the Blynk application. The test results are presented in Table 2.

Table 2. Battery charging test results

No	Time (minutes)	Battery voltage (V)	Increase (V)
1	0	3.62	–
2	30	3.74	0.12
3	60	3.84	0.10
4	90	3.92	0.08
5	120	3.99	0.07
6	150	4.05	0.06
7	180	4.10	0.05

Based on Table 2, the battery voltage increased from 3.62 V to 4.10 V, or by 0.48 V, over three hours of charging. The rate of voltage increase tended to decrease as the battery voltage approached 4.2 V, which is consistent with the characteristics of the CC-CV charging method of the TP4056 module. During the charging process, the TP4056 module worked well in keeping the charging process safe without excessive heat on the battery cell. These results show that the automatic charging system from wind energy has functioned according to the design, although the charging rate is highly dependent on wind availability at the location.

3.2.2. LDR sensor and automatic lamp control test

This test aims to ensure that the system can turn the lamp on and off automatically based on ambient light intensity. The LDR ADC threshold value was set at 2000, where an ADC value below the threshold is categorized as a dark condition. The test was conducted under five different lighting conditions with the results presented in Table 3, while the testing condition in the dark state is shown in Figure 7.

Table 3. LDR sensor and automatic lamp control test results

No	Light condition	LDR ADC value	Relay status	Lamp status	Remarks
1	Bright (daytime)	3450	OFF	Off	As expected
2	Cloudy	2650	OFF	Off	As expected
3	Dusk	1750	ON	On	As expected
4	Night	820	ON	On	As expected
5	Total darkness (covered)	310	ON	On	As expected



Fig. 7: Automatic lamp test under dark conditions

Based on Table 3, all test conditions produced results consistent with the program logic. The lamp was off under bright and cloudy conditions because the ADC value was above the threshold, and it was on under dusk, night, and total darkness conditions. Thus, the automatic lamp control function based on the light sensor worked with a success rate of 100%.

3.2.3. Real-time monitoring test on the Blynk application

This test aims to determine the reliability of transmitting voltage, current, power, and lamp status data from the ESP32 to the Blynk application. The test was conducted by comparing the time of value changes on the Arduino IDE Serial Monitor with the time of value updates on the Blynk application display. The monitoring graph in the application is shown in Figure 8, while the test results are presented in Table 4.



Fig. 8. Voltage and current monitoring graph on Blynk

Table 4. Data transmission delay test results to Blynk

No	Observed parameter	Delay (seconds)	Remarks
1	Voltage	1.3	Data transmitted
2	Current	1.5	Data transmitted
3	Power	1.4	Data transmitted
4	Lamp status	1.1	Data transmitted
5	Voltage (repeat test)	1.7	Data transmitted
Average delay		1.40	

Based on Table 4, all data were successfully transmitted to the Blynk application with an average delay of 1.40 seconds. This delay value is still reasonable for the monitoring needs of a small-scale generation system, so that users can still monitor the condition of the turbine, battery, and lamp in real time without significant obstacles.

3.2.4. Comparison of battery charging using a USB Type-C charger and the wind turbine

This test aims to compare the charging process of the 18650 battery using a standard 5 V USB Type-C charger with charging using the constructed wind turbine. Both tests were conducted on the same battery with an initial voltage of 3.62 V, where charging through the USB Type-C charger was connected directly to the input of the TP4056 module. The battery voltage for both methods was recorded every 30 minutes for three hours, with the comparison results presented in Table 5.

Table 5. Comparison of battery charging using a USB Type-C charger and the wind turbine

No	Time (minutes)	USB Type-C charger voltage (V)	Wind turbine voltage (V)	Difference (V)
1	0	3.62	3.62	0.00
2	30	3.85	3.74	0.11
3	60	4.02	3.84	0.18
4	90	4.12	3.92	0.20
5	120	4.18	3.99	0.19
6	150	4.20 (full)	4.05	0.15
7	180	4.20 (full)	4.10	0.10

Based on Table 5, charging using the USB Type-C charger was faster than charging using the wind turbine. With the USB Type-C charger, the battery reached a full voltage of 4.20 V in approximately 150 minutes, indicated by the change of the LED indicator on the TP4056 module from red to blue. Meanwhile, charging through the wind turbine was only able to raise the battery voltage from 3.62 V to 4.10 V over 180 minutes. This difference was caused by the charging current of the USB Type-C charger being relatively stable at around 1 A according to the maximum capacity of the TP4056 module, whereas the charging current from the wind turbine fluctuated following the wind speed at the test location. Although slower, charging through the wind turbine remains feasible because it utilizes renewable energy that is freely available and operates automatically without requiring grid electricity.

3.3. Discussion of test results

Based on the entire series of tests, the mini wind turbine prototype for IoT-based automatic charging can be declared to function in accordance with the research objectives. A summary of the overall system test results is presented in Table 6.

Table 6. Summary of overall system test results

No	Test item	Result	Conclusion
1	Wind turbine output	Power 0.11-2.62 W at wind speed 1.8-5.3 m/s	Functional
2	Voltage sensor accuracy	Average error 1.74%	Accurate
3	INA219 current sensor accuracy	Average error 3.06%	Accurate
4	Automatic battery charging (TP4056)	Increased 0.48 V in 3 hours	Functional
5	Automatic lamp control (LDR)	Successful in 5 of 5 conditions	Functional
6	Manual control via Blynk	Successful in 10 of 10 attempts	Functional
7	Real-time Blynk monitoring	Average delay 1.40 seconds	Functional
8	Battery endurance	Lamp on for more than 6 hours	Functional
9	Comparison of USB Type-C and wind turbine charging	USB full in ± 150 minutes; turbine increased 0.48 V in 3 hours	Functional

In terms of the research objectives, all formulated problems have been answered through the implementation and testing results. First, the constructed mini wind turbine prototype was proven capable of producing electrical energy from natural wind in the garden area of STMIK Kaputama to power low-power garden lamps. Second, the automatic charging system composed of the Schottky diode, the LM2596, and the TP4056 module was able to store wind energy in the 18650 battery safely, with the XL6009 module stepping up the battery voltage to a level of 12 V for the lamp load, and the LDR sensor was able to activate the lamp automatically under dark conditions with a success rate of 100%. Third, IoT technology based on the Blynk application was successfully implemented to monitor the turbine condition through voltage, current, and power parameters, to monitor battery capacity through battery voltage readings, and to display lamp status in real time while also controlling the lamp remotely.

When compared with previous studies, the power output obtained in this research, namely 0.11-2.62 W at wind speeds of 1.8-5.3 m/s, lies in a range comparable to the monitoring results of a mini wind power plant that reported a power of 1.25-2.97 W at wind speeds of 3.0-5.7 m/s [3], and is lower than the wind turbine output in a solar-wind hybrid system that reached 3.6 W [9]. In terms of measurement accuracy, the average error of the INA219 current sensor in this research of 3.06% is better than previous research that reported current reading errors in the range of 5.1% to 16.6% [10]. This difference indicates that the placement of the sensor on the load path and the two-second sampling period used in this research are sufficient to produce data suitable as a basis for control decision making. The novelty of this research lies in combining the functions of generation, automatic charging, light-sensor-based load control, and real-time monitoring in a single prototype applied directly to the case of campus garden lighting, which has not been found in previous studies that generally stop at the monitoring function.

Nevertheless, several limitations were found during testing. The turbine power output is strongly influenced by fluctuations in natural wind speed at the location, so that the battery charging rate is not always consistent throughout the day. In addition, at wind speeds below 1.8 m/s, the generator output voltage is too low to be utilized by the charging circuit. These limitations are consistent with the characteristics of small-scale wind power generation reported in previous research and can serve as considerations for further system development.

4. Conclusion

1. A vertical axis wind turbine (VAWT) mini wind turbine prototype was successfully designed and built using a 12 V DC generator, a 1N5822 Schottky diode, an LM2596 module, a TP4056 module, an 18650 battery, an XL6009 module, and a NodeMCU ESP32. The prototype was proven capable of producing electrical energy from natural wind in the garden area of STMIK Kaputama with a power output of 0.11-2.62 W at wind speeds of 1.8-5.3 m/s, so that it can be used to power low-power IoT-based garden lamps.
2. The automatic charging system functioned according to the design, in which the TP4056 module was able to store wind energy in the 18650 battery safely with a voltage increase of 0.48 V (from 3.62 V to 4.10 V) over three hours of charging, and the LDR sensor was able to turn the lamp on and off automatically with a success rate of 100% under five lighting conditions. The charged battery was able to power the lamp for more than six hours. Compared with charging using a USB Type-C charger that reached full voltage in approximately 150 minutes, charging through the wind turbine was slower because it depends on wind speed fluctuations, but it remains feasible as a renewable alternative energy source that operates automatically.
3. Internet of Things technology based on the Blynk application was successfully implemented to monitor the turbine condition through voltage, current, and power parameters, to monitor battery capacity through battery voltage readings, and to display lamp status in real time with an average data transmission delay of 1.40 seconds, supported by voltage sensor accuracy with an average error of 1.74% and INA219 current sensor accuracy with an average error of 3.06%, as well as remote ON/OFF lamp control that succeeded in 10 out of 10 attempts.

Future research is recommended to improve the turbine blade design or to use a generator with lower starting torque so that the turbine can still produce sufficient voltage at wind speeds below 1.8 m/s, to increase the energy storage capacity by arranging several battery cells in parallel, to combine the wind turbine with other energy sources such as solar panels (hybrid) so that the charging process becomes more consistent, and to develop monitoring features such as battery condition notifications and historical data storage in a database.

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