A Wireless Sensor Network Prototype System for Management of Wind and Solar Hybrid Energy Sources at The State Polytechnic of Malang

Amartya Salsabiila Putri Wicaksono[1], Mochammad Junus [2*], Abdul Rasyid[3], Adzikirani Adzikirani[4]

1,2,4 Digital Telecommunication Network Study Program, Department of Electrical Engineering, State Polytechnic of Malang, 65141, Indonesia.
3 Telecommunication Engineering Study Program, Department of Electrical Engineering, State Polytechnic of Malang, 65141, Indonesia

[1]amartya.putri@gmail.com, [2]mochammad.junus@polinema.ac.id, [3]abdul.rasyid@polinema.ac.id, [4]adzikirani@polinema.ac.id

***Abstract*—Electrical energy plays a vital role in various aspects of life, including the education sector. At the State Polytechnic of Malang, electricity is primarily generated by coal burning, which poses environmental challenges. This study proposes a hybrid power generation system utilizing renewable energy sources, specifically wind and solar energy, with a battery as the storage medium. However, the unstable energy output from these sources can lead to overcharging. To address this issue, an energy management system was developed using a Wireless Sensor Network (WSN) integrated with a microcontroller to monitor and manage energy from both sources. The system comprises two nodes and one server. Each node includes a wind turbine, solar panel, sensors, relays, switches, a microcontroller, and wireless transmission devices to transmit data to the server, enabling real-time monitoring through a web-based interface. Test results demonstrate that the system effectively prevents overcharging, achieving a 100% success rate.**

Keywords*— *Battery Management, Energy Management System, Hybrid Power Generation, Overcharge Protection, Renewable Energy, Wireless Sensor Network

I. INTRODUCTION

Electrical energy is a fundamental aspect of human life and plays a crucial role in supporting economic activities, education, and technological development. Ensuring the availability of sufficient, affordable, and environmentally friendly electrical energy is essential to improving societal welfare while simultaneously addressing carbon emissions and climate change challenges [1], [5]. The transition from fossil-based energy to renewable energy sources has therefore become a global priority.

At the State Polytechnic of Malang (Polinema), electrical energy demand is still fully supplied by the national electricity company (PLN), with a significant portion of the electricity generated from the Paiton Coal-Fired Power Plant (CFPP). Although CFPPs are capable of producing large amounts of electricity, they suffer from several drawbacks, including dependence on non-renewable coal resources, high operational and investment costs, and substantial greenhouse gas emissions that contribute to global warming and environmental degradation [5], [7]. These limitations highlight the need for cleaner and more sustainable energy alternatives within educational institutions.

Hybrid renewable energy systems have emerged as an effective solution for achieving a balanced and sustainable energy supply. By combining two or more renewable energy sources, hybrid systems can improve power reliability and reduce dependence on fossil fuels. Several recent studies have reported that hybrid solar–wind energy systems are more reliable than single-source renewable systems, particularly in public and educational facilities, due to their ability to compensate for the intermittent nature of solar irradiation and wind speed variations [1], [4], [5].

The city of Malang possesses considerable wind energy potential, with average monthly wind speeds ranging from 2.7 m/s to 5 m/s, making wind turbines a viable, cost-effective, and environmentally friendly energy source [11]. In addition, Indonesia has substantial solar energy potential, estimated at approximately 200,000 MW, which can be harnessed using photovoltaic panels to convert sunlight into electrical energy [5]. The combination of wind and solar energy therefore represents a promising approach for renewable energy utilization at Polinema.

Despite their advantages, both wind and solar energy sources are highly dependent on environmental conditions, which can cause fluctuations in power generation. To ensure stability and continuity of electricity supply, energy storage systems are required. Batteries are commonly used as storage media; however, improper charging management, such as overcharging, can lead to overheating, reduced battery lifespan, and potential system failure [6], [14]. Consequently, effective energy management and monitoring systems are essential to maintain battery health and ensure safe operation.

This research builds upon previous work conducted by Junus, Wijayanti, and Hidayati (2021) entitled "Wireless

*Corresponding author

Sensor Network for Monitoring Windmills at State Polytechnic of Malang." Their study developed a prototype monitoring system for wind turbine energy sources at Polinema using a Wireless Sensor Network (WSN), enabling real-time monitoring of voltage, turbine rotation speed, and wind speed through a web-based interface [2].

In this study, a prototype energy management system is designed and developed to perform automatic energy source switching between wind turbines and solar panels based on real-time monitored data obtained through a WSN. The WSN system incorporates sensing, controlling, and communication capabilities to simplify condition monitoring and system management. A star point-to-point topology is implemented due to its simplicity, fast data transmission, and ease of deployment [2], [11].

The proposed energy-switching mechanism detects conditions in which the combined charging current from both renewable energy sources exceeds the maximum allowable battery charging threshold. When this condition occurs, the system automatically disconnects the energy source with the higher output to prevent battery overcharging. The prototype consists of two sensor nodes and one server. Each node integrates a wind turbine, solar panel, sensors, relays, switches, a microcontroller, and wireless communication modules to enable real-time data transmission. The server comprises a mini-PC and wireless transmission equipment, allowing data to be stored in a database and visualized through a web-based platform in real time [6], [15], [18]. This research aims to enhance energy efficiency, reliability, and sustainability at Polinema through the integration of renewable energy sources and an intelligent energy management system.

II. METHOD

A. The System Block Diagram

The system block diagram illustrates the overall system design, comprising two sensor nodes connected to a server using the NRF24L01 wireless communication module. The data processed on the server can be monitored in real time via a web interface. The system block diagram is presented in Figure 1.

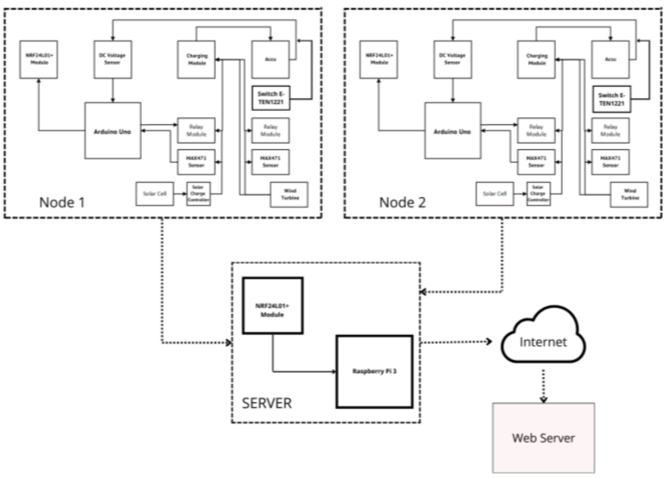

Figure 1. System Block Diagram

The system design is divided into two main components: the sensor nodes, which act as data transmitters, and the server, which functions as the data receiver. The sensor nodes transmit monitoring data, including current and voltage values, to the server using the NRF24L01 module. The server then processes this monitoring data, making it accessible on the web server in real time through an internet connection. The block diagram of the sensor nodes is shown in Figure 2, while the block diagram of the server is depicted in Figure 3.

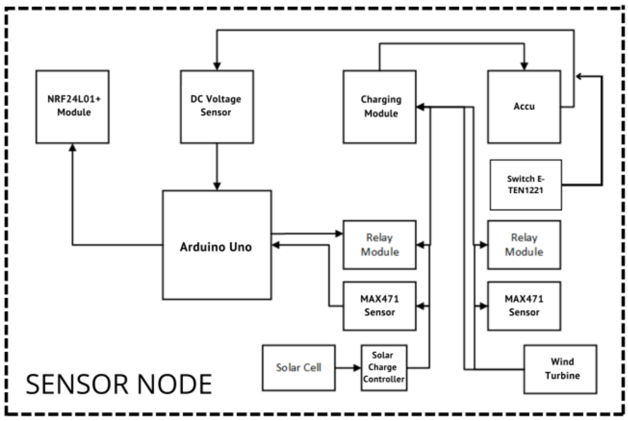

Figure 2. Block Diagram of Sensor Node

The proposed system comprises two sensor nodes, each consisting of a mini wind turbine, a solar panel, an MAX471 sensor, a relay module, an E-TEN1221 switch, a DC voltage sensor, a charge controller, a battery, an Arduino Uno microcontroller, and an NRF24L01 wireless communication module.

Each sensor node is equipped with a microcontroller, voltage and current sensors, relays, and wireless communication modules. The sensors continuously monitor the electrical output of the wind turbine and solar panel. Relays are used as switching devices to connect or disconnect energy sources based on control decisions. Similar hardware configurations have been widely applied in WSN-based renewable energy monitoring systems to ensure reliable sensing and control functions [6], [11], [20].

The server side consists of a mini-PC integrated with a wireless communication module. The server functions as a data receiver, processor, and storage unit. All monitored data are stored in a database and displayed through a web-based interface for real-time visualization and analysis, following common practices in IoT-based energy monitoring systems [15], [19].

A relay module is utilized as an automatic switch. If the combined current from the wind turbine and solar panel exceeds the threshold, the Arduino Uno sends a command to the relay to disconnect the power source with the highest current value to prevent overcharging. The monitoring results are transmitted to the server, where they are managed and stored in a database before being displayed on a web interface in real-time. Additionally, the E-TEN1221 switch functions as an on-off control for the system.

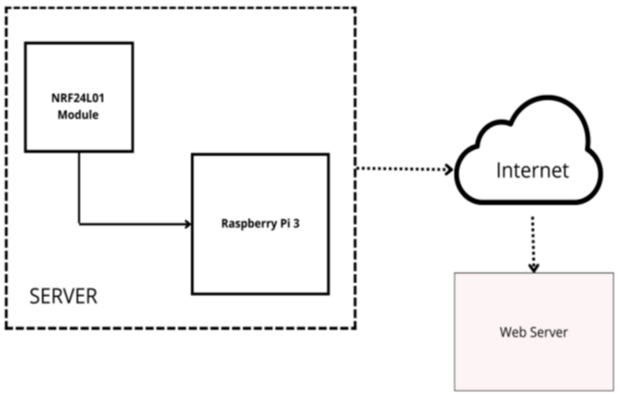

Figure 3. Block Diagram of Server

The server consists of a Raspberry Pi, a mini-computer capable of processing data, and an NRF24L01 wireless communication module. In this system, the Raspberry Pi serves as the local server. Upon power connection, the first step is to initialize the channel IDs for both the sender and receiver to ensure that the data is transmitted to the correct destination. Each sensor node is assigned a unique address. The next step is to initialize a static IP address for accessing the database and web server via an internet connection. The communication system between the sensor nodes and the server utilizes the NRF24L01 module, which enables wireless data transmission and reception.

This system employs a wireless sensor network (WSN) with a star topology. In the star topology, each sensor node has a point-to-point communication channel only with a central device, the server, and the nodes do not communicate directly with each other. Once a sensor node collects data, it sends the data to the server. The communication mode used is simplex, where the sensor node's sole task is to transmit data, while the server's task is to receive it. The delay measurement is performed by comparing the data transmission time at the sensor node with the data reception time as the server.

B. The System Workflow

The node sensor workflow is shown in figure 4. System testing is conducted to evaluate monitoring accuracy, communication reliability, and energy switching performance. Parameters such as data transmission stability, response time, and system behavior under varying environmental conditions are observed. The evaluation methodology follows established practices in hybrid renewable energy and IoT-based monitoring research to ensure objective assessment and reproducibility [4], [16], [17], [19].

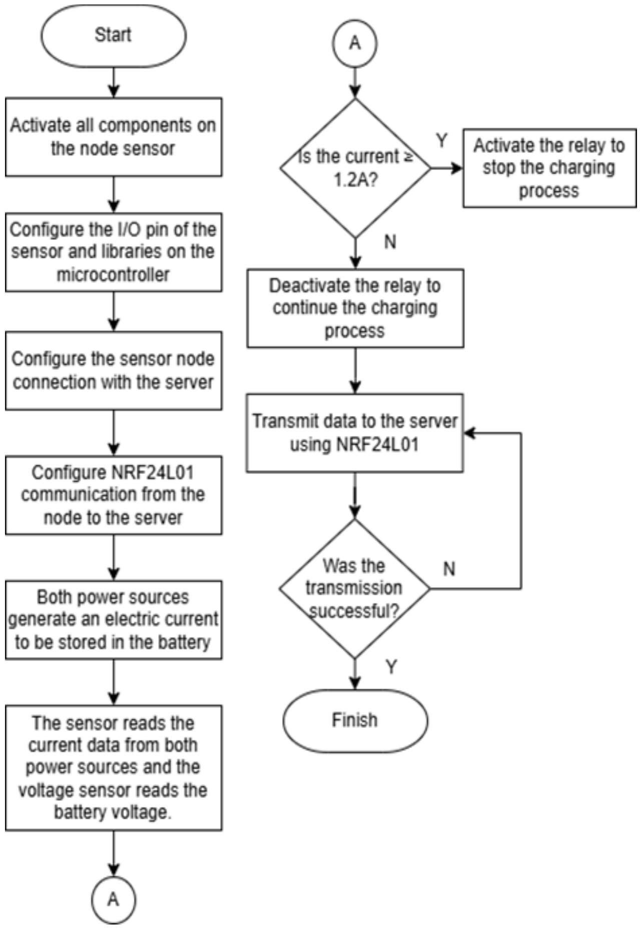

Figure 4. Node Sensor Workflow

Figure 4 illustrates the workflow of node sensor. The workflow begins with activating the device by switching the lever to the ON position, ensuring all components within the sensor node are powered on and connected. Subsequently, the input and output configurations for the sensors, as well as the necessary libraries, are set up within the microcontroller. The next step involves defining unique IDs for each sensor node and establishing a connection between the sensor node and the server. Once the connection is successfully established, the wireless communication module, NRF24L01, is configured to transmit data from the sensor node to the server. In this setup, the NRF24L01 module functions as a transmitter.

Following this, the two energy sources connected to each sensor node, a wind turbine prototype and a mini solar panel, generate electricity to be stored in the battery. The current sensor then measures the current from both energy sources, while the voltage sensor reads the battery voltage. The microcontroller subsequently calculates the total current derived from the two energy sources. If the total current exceeds 1.2A, the microcontroller sends a command to the relay to disconnect the energy source with the higher current. Once the total current no longer exceeds the battery charging limit, the microcontroller sends another command to the relay to resume the charging process.

The system continuously updates the data and transmits it to the server, as shown in figure 5.

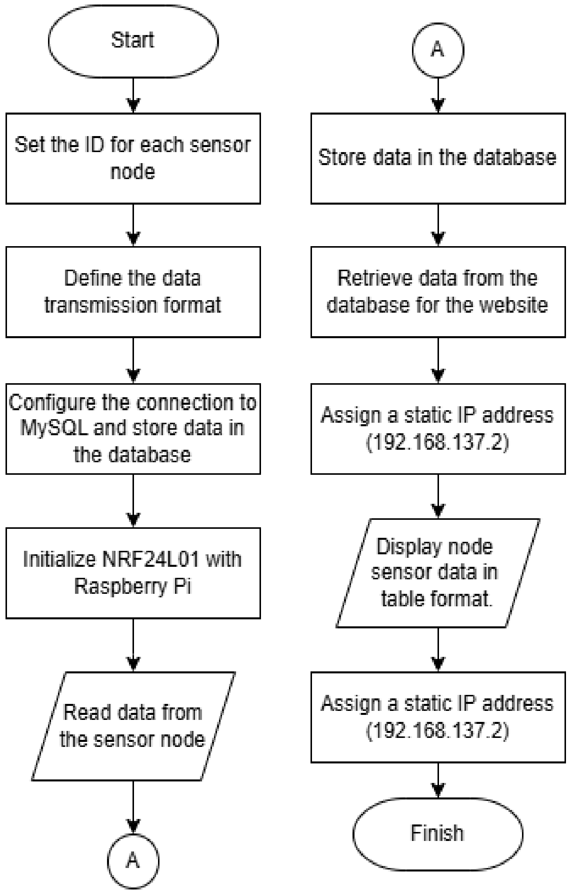

Figure 5. Server Workflow

The method section of this study explains the workflow of the server system, as depicted in Figure 5. The process begins with assigning unique IDs to each sensor node, followed by defining the data transmission format. Subsequently, the system establishes a connection with MySQL to configure data storage within the database. Wireless communication is then initialized by integrating the NRF24L01 module with the Raspberry Pi, allowing the system to read data from the sensor nodes.

Once the data is acquired, it is stored in the database and later retrieved for display on the web server. To facilitate access, a static IP address (192.168.137.2) is assigned to the web server. The system then presents the sensor node data in a tabular format and displays the charging status alongside the battery health condition on the web server. This workflow ensures an efficient process for data acquisition, management, and visualization.

C. The Web Application Design

In this study, the web application was utilized to facilitate the monitoring of the energy management system at Politeknik Negeri Malang. The design is shown in Figure 6.

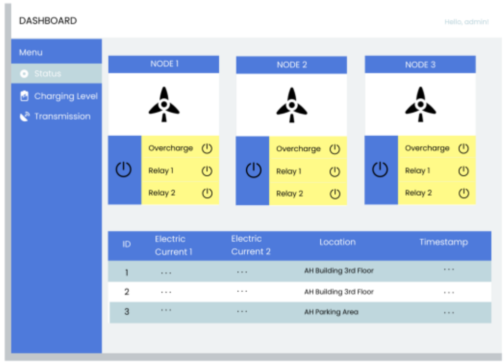

Figure 6. Web Application on Status Menu

Figure 6 illustrates the design of the web interface used in this study to facilitate the monitoring of the energy management system at Polinema. The Status Menu provides real-time information on charging status (overcharging or normal), the activity status of the relay module (active or inactive), and current monitoring data from both energy sources for each sensor node. The Charging Menu displays battery voltage values and health status, while the Transmission Menu shows the average node transmission rate per second, serving as a performance test for wireless communication between nodes and the server.

D. Module Implementation

Each sensor and supporting component on the sensor node is connected to an Arduino Uno as the microcontroller, as shown in Figures 9 and Figure 10.

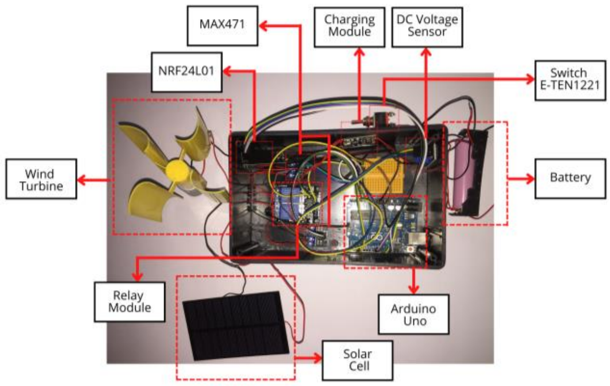

Figure 7. Implementation of Displays in Sensor Node Module

Figure 8. Implementation of the external view of the Sensor Node Module

The server consists of a Raspberry Pi and the NRF24L01 wireless communication module. Each component is connected according to the designed pin configuration. The implementation of the server, assembled into a module, is shown in Figure 11.

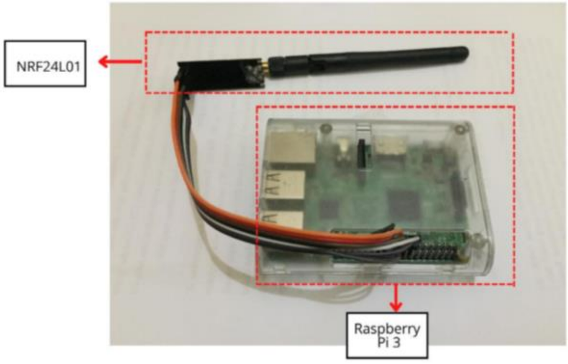

Figure 9. Implementation of Server

E. *Web Application Implementation*

The web server is used to facilitate users in monitoring the hybrid solar-wind energy management system. The server utilizes a local server, which requires a connection to the Raspberry Pi. The implementation of the web server is shown in Figure 10.

Figure 9. Implementation of Web Application

The status menu displays the sensor node and monitoring results. Each sensor node has four parameters: Battery Charging, Status, Solar Panel Relay, and Wind Turbine Relay. The Battery Charging parameter, indicated by a yellow power symbol, signifies that the charging process is ongoing. When the battery is fully charged, the status will display "Battery Full" with a green power symbol. The Status parameter, shown with a green power symbol and labeled "Normal," indicates that the charging process is functioning normally. If overcharging occurs, the power symbol will turn red, and the status will change to "overcharging." The Solar Panel Relay and Wind Turbine Relay parameters, indicated by green power symbols and labeled "close," show that the energy source relays are in the closed state or connected to the battery and actively charging. When the system halts charging, the power symbol will turn red, and the relay status will change to "open.".

III. RESULTS AND DISCUSSION

A. *Sensor Accuracy Test*

This sensor accuracy test was conducted to evaluate the accuracy of the MAX471 sensor and the DC voltage sensor by comparing their readings to a multimeter.The test results for the MAX471 sensor are presented in Table 1, while the results for the DC voltage sensor are shown in Table 2.

TABLE I
MAX471 SENSOR ACCURACY TEST RESULT

Measurement No.	Current on Sensor	Curret on Multimeter	Difference	Error (%)
1	0,47	0,50	0,03	0,06
2	0,49	0,50	0,01	0,02
3	0,52	0,55	0,03	0,05
4	0,55	0,55	0,00	0,00
5	0,59	0,60	0,01	0,01
6	0,61	0,60	0,01	0,01
7	0,63	0,60	0,03	0,05
8	0,67	0,70	0,03	0,04
9	0,70	0,70	0,00	0,00
10	0,74	0,75	0,01	0,01

Based on the testing results of the MAX471 sensor, the test results indicate an error percentage of 0.024% with a sensor accuracy rate of 99.97%.

TABLE II
DC VOLTAGE SENSOR ACCURACY TEST RESULT

Measurement No.	Current on Sensor	Curret on Multimeter	Difference	Error (%)
1	12,15	12,20	0,05	0,004
2	12,16	12,20	0,04	0,003
3	12,17	12,20	0,03	0,002
4	12,19	12.20	0,01	0,0008
5	12,20	12,20	0,00	0,000
6	12,21	12,20	0,01	0,0008
7	12,22	12.20	0,02	0,001
8	12,23	12,20	0,03	0,002
9	12,25	12,30	0,05	0,004
10	12,30	12,30	0,00	0,00

Based on the test results, the error value obtained was 0.001%. This error could be attributed to the presence of ripple or resistor losses in the sensor. The success rate of the DC voltage sensor is 99.9%.

B. *Connection Testing*

The connection testing between each sensor node and the server was conducted to evaluate the communication performance of the WSN using Arduino Uno and NRF24L01 as the transmitter and Raspberry Pi 3 with NRF24L01 as the receiver. The testing employed a point-to-point topology. Data transmission success rates were tested 10 times at predefined distances of 30, 50, 70, and 100 meters. The evaluated parameter was transmission delay at each distance. The success rate of data transmission was classified based on the ITU-T G.144 delay standard.

TABLE III
COMMUNICATION TEST RESULTS OF SENSOR NODE DISTANCE TO SERVER

Distance (meter)	Average Delay (ms)	Classification
30	60	Good
50	80	Good
70	120	Good
100	340	Fair

Based on Table 3, it can be concluded that the WSN demonstrates good performance up to 70 meters with minimal delay, but experiences increased delay at longer distances.

C. Management Energy System Testing

The energy management system was tested by applying it to the sensor node, monitoring current and voltage data, and reviewing results stored in the database and displayed on the web server. Results are shown in Tables 4 and 5.

TABLE IV
SYSTEM TESTING RESULT ON NODE 1

No	Date/ Time	I1	I2	V	I Total	Battery	Status	Relay 1	Relay 2
1	2022-09-02 10:28:04	0,55	0,51	11,94	1,06	C	N	1	1
2	2022-09-03 10:34:10	0,63	0,65	11,94	1,28	C	OC	1	0
3	2022-09-04 10:17:18	0,80	0,76	11,98	1,56	C	OC	0	1
4	2022-09-05 10:22:02	0,48	0,52	12,2	1	F	N	1	1
5	2022-09-06 10:29:09	0,53	0,67	12,0	1,20	F	N	1	1
6	2022-09-07 10:36:16	0,63	0,59	11,96	1,22	C	OC	0	1
7	2022-09-08 10:20:24	0,77	0,76	11,94	1,53	C	OC	0	1
8	2022-09-09 10:37:27	0,82	1,01	11,95	1,83	C	OC	1	0
9	2022-09-10 10:25:31	0,92	0,81	11,95	1,73	C	OC	0	1
10	2022-09-11 10:30:27	0,72	0,64	11,96	1,36	C	OC	0	1

Table IV presents the results of system performance evaluation during the energy management and monitoring process. The table summarizes the measured electrical parameters and system responses under different operating conditions. From the data shown, it can be observed that the proposed system is able to monitor voltage and current values from both the wind turbine and solar panel in a stable and consistent manner, indicating reliable sensing and data acquisition performance.

The results in Table IV also demonstrate the effectiveness of the energy switching mechanism. When the combined charging current approaches or exceeds the predefined battery charging threshold, the system successfully performs source disconnection to prevent overcharging. This behavior confirms that the implemented control logic operates as intended and contributes to maintaining battery safety and system reliability. Overall, the data presented in Table IV indicate that the proposed WSN-based energy management system is capable of supporting efficient and safe operation of the hybrid solar–wind power system.

TABLE V
SYSTEM TESTING RESULT ON NODE 2

No	Date/ Time	I1	I2	V	I Total	Battery	Status	Relay 1	Relay 2
1	2022-09-02 10:28:04	0,56	0,48	11,94	1,04	C	N	1	1
2	2022-09-03 10:34:10	0,64	0,59	11,94	1,23	C	OC	0	1
3	2022-09-04 10:17:18	0,78	0,72	11,96	1,5	C	OC	0	1
4	2022-09-05 10:22:02	0,55	0,67	11,95	1,22	C	OC	1	0
5	2022-09-06 10:29:09	0,69	0,73	11,95	1,42	C	OC	1	0
6	2022-09-07 10:36:16	0,58	0,84	11,96	1,42	C	OC	1	0
7	2022-09-08 10:20:24	0,70	0,68	11,96	1,38	C	OC	0	1
8	2022-09-09 10:37:27	0,56	0,49	12,0	1,05	F	N	1	1
9	2022-09-10 10:25:31	0,55	0,62	12,0	1,17	F	N	1	1
10	2022-09-11 10:30:27	0,59	0,60	11,98	1,19	C	N	1	1

Explanation:
I = Current
V = Voltage
C = Charging
F = Full
N = Normal
OC = Overcharge

The testing was conducted daily over a period of 10 days, within the time range of 10:00 to 11:00 AM. The data was then displayed on the web, as shown in Figure 10.

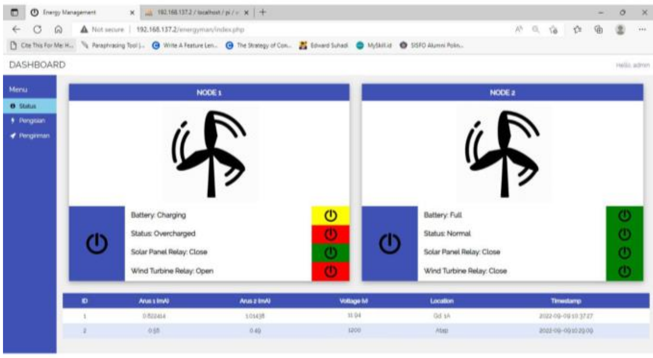

Figure 10. Monitoring Data Display on the Web

The test results show that the system operates as intended, despite low input current and voltage due to the use of mini turbines and solar panels. During charging, if the current exceeds 1.2 A, the system detects overcharging and disconnects the higher current source by activating a relay. A '1' in the relay column indicates the relay is active, while '0' means it is inactive. When the battery is fully charged, the web server displays "full" and the device can be turned off. Thus, charging time depends on the initial battery voltage, with higher voltage leading to faster charging. All monitoring data is stored and displayed on a web server in real-time. Figure 10 shows the charging conditions. Node 1 experiences overcharging, triggering relay 2 to disconnect the wind turbine's current. Node 2, with a voltage of 12 V, shows the battery is fully charged.

D. The System's Efficiency Testing

The system's efficiency was tested by comparing overcharge levels and battery health during charging with and without the energy management system. The tests were conducted over two weeks during daylight hours, considering weather conditions. Results are shown in Table 6 and Table 7.

TABLE VI
TEST RESULTS WITHOUT THE ENERGY MANAGEMENT SYSTEM

Measurement No.	Current on Sensor	Curret on Multimeter	Difference	Error (%)
1	12,15	12,20	0,05	0,004
2	12,16	12,20	0,04	0,003
3	12,17	12,20	0,03	0,002
4	12,19	12.20	0,01	0,0008
5	12,20	12,20	0,00	0,000

In Table 5, observations indicate that over 10 days of testing, overcharging occurred 5 times, resulting in a decrease in battery health from 100% to 87%. This decline is attributed to the manual charging process, which lacks an automatic control system to regulate the charging current entering the battery.

TABLE VII
TEST RESULTS WITH THE ENERGY MANAGEMENT SYSTEM

Measurement No.	Current on Sensor	Curret on Multimeter	Difference	Error (%)
1	12,15	12,20	0,05	0,004
2	12,16	12,20	0,04	0,003
3	12,17	12,20	0,03	0,002
4	12,19	12.20	0,01	0,0008
5	12,20	12,20	0,00	0,000

In Table 6, observations show that during 10 days of testing, no overcharging occurred, and battery health remained stable at 100%. This demonstrates that, without an energy management system, overcharging occurs, leading to a decline in battery health. In contrast, the implementation of an energy management system effectively prevents overcharging and maintains battery health.

IV. CONCLUSION

Based on the background, problem formulation, implementation, testing, and discussion, the system was developed with two sensor nodes and one server using a point-to-point WSN topology. It utilizes the MAX471 current sensor, a DC voltage sensor, Arduino Uno, Raspberry Pi 3, and the NRF24L01 wireless module. Monitoring data is processed by the server and displayed in real-time on the web. The MAX471 sensor showed a 0.024% error, while the DC voltage sensor had a 0.001% error, indicating high accuracy. The optimal communication range is between 30-70 meters. The energy management system effectively prevented overcharging and maintained battery health, unlike uncontrolled charging, which reduced battery lifespan. Development recommendations include implementing larger wind turbines and solar panels, adding error or overcharge notifications, and expanding tests with additional nodes and improved topologies.

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