



Effectiveness of Solar-Powered Smart School Yard Lights on Energy Efficiency and Lighting Quality

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ABSTRACT

The development of renewable energy, particularly Solar Power Plants (PV), requires a reliable, real-time, and easily accessible electrical energy monitoring system to ensure optimal system performance. This study aims to design and implement an Internet of Things (IoT)-based electrical energy monitoring system for PV using the NodeMCU ESP32 microcontroller, the PZEM-004T sensor for measuring electrical parameters, and the Node-RED platform as the data visualization interface. The developed system is designed to monitor voltage, current, power, energy, frequency, and power loss in real time, and then display the data in the form of numerical values, graphs, and indicators on a dashboard accessible through a local network. The research method includes hardware design, software development (sensor reading, data processing, and communication), integration with Node-RED, and system testing on a small-scale PV installation. The test results show that the system is capable of monitoring electrical parameters in a stable and responsive manner. Variations in sunlight intensity were found to affect the current and power produced by the solar panels, whereas the inverter output voltage tended to remain within normal operating ranges. The Node-RED dashboard display was considered informative and helpful for users in monitoring and analyzing PV performance. Based on these results, it can be concluded that the IoT-based electrical energy monitoring system designed in this study functions well and is feasible for application in residential or educational-scale PV installations. The system still has the potential for further development through cloud service integration, the addition of environmental sensors, and enhancements to data analysis features and user interface design.

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1. INTRODUCTION

Electricity is a fundamental necessity for humans in fulfilling their energy needs. One alternative energy source that can be used to generate electricity is solar energy, which is a new and renewable energy resource. The development of solar power plants (PV) in this context is highly

urgent and needs to be advanced. To optimize the utilization of PV as an alternative energy source, a monitoring device is required to observe the performance of the system [1]. With the increasing use of PV, an effective monitoring system is needed to ensure optimal performance and efficient energy utilization.

However, in the present day, monitoring is still commonly performed manually by conducting direct inspections at the location where the solar cells are installed. This method is certainly neither effective nor efficient when continuous monitoring of solar cells is required. Since environmental conditions are constantly changing, it becomes difficult to determine the performance of solar cells at a specific location without understanding variations in solar radiation intensity and other related parameters. To evaluate the performance of a solar panel, it is necessary to measure its output power. Such measurements can be performed using a multimeter; however, this method has several limitations, including the inability to perform continuous monitoring. Therefore, this study requires a software-based system capable of automatically recording the output data of solar panels, enabling more effective measurement results and simplifying the monitoring process for researchers in assessing solar cell performance [2][3].

NODE-RED also allows users to create their own custom nodes. Connectors or wires link one node to another, indicating the flow of data or the logic sequence of the program. Users create connections by clicking and holding on the output of a node, then dragging the wire to the input of the desired node. Once the flow is completed, NODE-RED executes the workflow accurately [4].

The purpose of this study is to design and implement an IoT-based electrical energy monitoring system for solar power plants (PV) using NODE-RED, which is capable of providing accurate data and enabling users to control the system remotely. This research aims to address the previously identified problems and improve energy-use efficiency. The benefits of this study are both theoretical and practical. Theoretically, the study is expected to contribute to the advancement of knowledge in the fields of renewable energy and IoT technology. Practically, the system developed in this research can assist users in monitoring and managing electrical energy consumption more efficiently, as well as reducing operational costs associated with the use of electrical energy from PV.

2. METHOD

This study employs a quantitative method because it aligns with the research objectives, namely to develop, test, and evaluate a measurement instrument based on numerical and objective data. The quantitative approach emphasizes the collection of numerical data through standardized instruments, which are then analyzed statistically to answer research questions or test hypotheses systematically and objectively [5], [6]. The use of this method enables the researcher to carry out a series of instrument development procedures, such as construct formulation, blueprint preparation, content and construct validity testing, as well as reliability testing, ensuring that the resulting instrument is accurate, consistent, and feasible for use [7], [8]. In addition, the structured and standardized characteristics of quantitative research—supported by clearly documented procedures—make the findings easier to replicate and compare with similar studies, thereby enhancing the reliability and external validity of the results obtained [9], [10]. The following is the flowchart of the device workflow that I have developed.

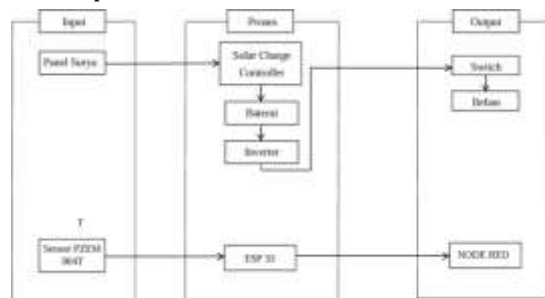


Figure 1. FlowChart Tool Work

Figure 1 above shows the block diagram of an Internet of Things (IoT)-based electrical energy monitoring system that uses a solar panel as the main energy source. The system is divided into three main sections: input, process, and output. In the input section, the energy source comes from the solar panel, which converts sunlight into electrical energy. This electrical energy is then supplied to the

process section, consisting of a solar charge controller, battery, and inverter. The solar charge controller functions to regulate the current and voltage from the solar panel to ensure proper battery charging. The energy stored in the battery is then used by the inverter, which converts direct current (DC) into alternating current (AC) that can be used by the load.

To monitor electrical parameters, the system is equipped with a PZEM-004T sensor that measures voltage, current, power, and energy consumption. Data from this sensor is sent to the ESP32 microcontroller, which acts as the central unit for data processing and communication. The ESP32 then transmits the data to the NODE-RED platform to be accurately visualized through a web-based interface. In the output section, the electrical current from the inverter is controlled through a switch before being supplied to the load. This system enables efficient and accurate monitoring of energy consumption while also providing control over the load through a digital interface.

The wiring configuration that I have designed to interconnect all components is as follows:



Figure 2. Equipment Circuit Schematic



Figure 3. Tool Design

Table 1. Component Testing

No	Component Name	Test Data			
		Damage	Trouble	Not Successful	Successful
1.	Panel Surya	-	-	-	✓
2.	Solar Charge Controler (SCC)	-	-	-	✓
3.	Baterai	-	-	-	✓
4.	Miniature Circuit Breaker (MCB) AC	-	-	-	✓
5.	Miniature Circuit Breaker (MCB) DC	-	-	-	✓
6.	Inverter DC To AC	✓	✓	-	-
7.	ESP32	-	✓	-	✓
8.	Stepdown DC LM2596	✓	✓	-	✓
9.	Modul PZEM-004T Beserta Sensor	-	✓	-	✓
10.	Terminal Block	-	-	-	✓
11.	Jumper Cables	✓	-	-	✓
12.	NODE-RED	-	✓	-	✓
13.	Light 20Watt	-	-	-	✓
14.	Arduino IDE	-	-	-	✓

3. RESULT DAN ANALISIS

This research was tested in the researcher’s residential environment by designing and implementing an Internet of Things (IoT)-based electrical energy monitoring system utilizing the NodeMCU ESP32 as the microcontroller, the PZEM-004T sensor module for measuring electrical parameters, and the Node-RED platform as the medium for data visualization [11], [12]. The system developed is capable of performing real-time data acquisition from the solar panel, including measurements of voltage, current, power, and generated electrical energy, as has been widely implemented in household energy monitoring systems and solar generator applications using the ESP32 and PZEM-004T modules [10], [4]. Furthermore, the measurement data are automatically transmitted via Wi-Fi to a local server or cloud platform and visualized through a Node-RED dashboard, allowing users to monitor energy consumption and production in real time and analyze historical data for system performance evaluation [13], [6].



Figure 4. Photovoltaic (PV)

3.1. PZEM-004T Sensor Testing

The following table presents the testing results of the PZEM-004T sensor based on the measurement data obtained when the system was tested using a 20-watt LED lamp as the load. The measured voltage of 227.6 V indicates that the household power supply was stable and within the standard voltage range of the electrical grid. The measured current of only 0.04 A shows that the load used was relatively light, which is consistent with the characteristics of energy-efficient LED lamps. The active power reading of 9.7 W demonstrates that the sensor was able to measure the load's power consumption accurately, although the value is lower than the lamp’s rated power due to efficiency factors and the non-linear characteristics of the load.

The measured frequency of 58.8 Hz indicates that the system operated under stable conditions, although it is slightly above the nominal value of 50 Hz. Meanwhile, the recorded power loss value of 0 W shows that no significant power losses were detected during the test. Based on these results, it can be concluded that the PZEM-004T sensor performed well in monitoring electrical parameters under a light-load scenario.

Table 2. PZEM-004T Sensor Testing

No	Parameters Measured	Reading Results	Information
1.	Voltage (Volt)	227,6V	Stable, according to household electricity standards

2.	Current (Ampere)	0,04 A	Low, light load (LED lights)
3.	Power (Watt)	9,7 W	Active, according to measurement results
4.	Frekuensi (Hertz)	58,8 Hz	Stable, although slightly above 50 Hz
5.	Power Loss (Watt)	0 W	No power loss detected

3.2. Testing PV

The testing was conducted from 08:00 to 16:00 under clear weather conditions. The parameters measured were voltage (V), current (A), and power (Watt).

Table 3. Testing PV

Time	Solar Panel Output		Output Inverter			Irradiation Light (W/m ²)
	Voltage (VDC)	Current (ADC)	Voltage (VAC)	Current (AAC)	Power (Watt)	
08.00	19,6	1,39	236	0,03	9,4	6972,0
09.00	19,7	1,62	239	0,03	7,6	9515,0
10.00	19,2	2,03	23,4	0,02	5,9	3905,0
11.00	19,9	2,45	225	0,02	7,9	1064,00
12.15	19,1	0,92	239	0,05	8,6	8700,0
13.00	19,1	0,94	240	0,03	8,6	2720,0
14.00	19,2	0,70	242	0,05	9,8	2524,0
15.00	17,6	0,16	239	0,04	10,8	5727
16.00	17,4	0,14	238	0,04	10	3700

Table 3 From the testing results, it can be observed that the DC voltage of the solar panel ranged from 17.4 to 19.9 V, with the highest current of 2.45 A recorded at 11:00, while in the late afternoon the current decreased significantly to as low as 0.14 A. The inverter's AC voltage remained stable between 225 and 242 V with a current output of approximately 0.02–0.05 A, whereas the inverter's power output fluctuated within the range of 5.9–10.8 W and reached its maximum value of 10.8 W at 15:00. The intensity of sunlight exhibited substantial variation, with the highest value recorded at 9515 W/m² at 09:00 and the lowest at 1064 W/m² at 11:00. Overall, these results indicate that solar irradiance directly influences the current generated by the solar panel. However, the increase in inverter power does not always correlate linearly, as it is affected by energy conversion efficiency and the load conditions of the system.

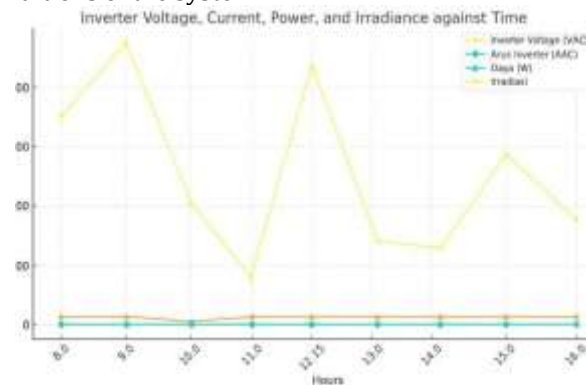


Figure 5. Testing Chart PV

From the graph illustrating the relationship between time and inverter voltage, current, power, and irradiance, it can be concluded that the inverter voltage remains stable within the desired operating range, while fluctuations in output power are primarily influenced by variations in irradiance throughout the day. The data anomaly observed at 10:00 requires further examination or may be excluded from the analysis, as it does not align with the overall measurement trend.

4. DISCUSSION/CONCLUSION

Based on the design, implementation, and testing processes, it can be concluded that the IoT-based PV energy monitoring system utilizing the ESP32, the PZEM-004T sensor, and the Node-RED platform is capable of monitoring voltage, current, power, energy, frequency, and power loss in real time with good stability and accuracy. The DC voltage of the solar panel ranged from 17.4 to 19.9 V, with the highest recorded value of 19.9 V, while the inverter's AC voltage remained stable between 225 and 242 V, with a maximum value of 242 V. The maximum DC current produced by the panel was 2.45 A at 11:00, the inverter's maximum output power reached 10.8 W at 15:00, and the highest solar irradiance was recorded at 9515 W/m² at 09:00. These findings indicate that variations in irradiance significantly influence the current and power generated by the solar panel, whereas the voltage remains relatively stable within its normal operating range. The Node-RED dashboard developed in this system successfully presents data in numerical, graphical, and indicator formats, making it easier for users to monitor PV performance and analyze energy output variations throughout the day. Overall, the designed system is feasible for implementation in household-scale or educational PV installations and has strong potential for further development through cloud-based data storage integration, the addition of environmental sensors, and improvements to the user interface.

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