Sustinere
Journal of Environment and Sustainability
Volume 8 Number 3 (2024) 397-407

Print ISSN: 2549-1245 Online ISSN: 2549-1253
Website: https://sustinerejes.com E-mail: sustinere.jes@uinsaid.ac.id

RESEARCH PAPER

Electrical power monitoring system for solar power plants based on the Internet of Things

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Article history:
Received 10 October 2024 | Accepted 31 October 2024 | Available online 30 December 2024

Abstract. The objectives of this research are: first, to develop an electrical power monitoring system for solar power plants based on the Internet of Things; second, to evaluate the performance of this tool; and third, to assess the contribution of this tool to support the achievement of the SDGs. The development method involves three stages: analysis, design, and development. The development process was carried out at the off grid solar power plant house in Magelang, Indonesia. The measuring instruments used for testing included a multimeter and an ammeter. Testing adhered to International Electrotechnical (IEC) standards. The analysis technique employed was quantitative descriptive analysis, involving the calculation of averages and percentages. The results are as follows. First, the Internet of Things-based electrical power monitoring system for solar power plants consists of several components, including the PZEM 004T sensor, NodeMCU Wi-fi module, adapter, and I2C Liquid Crystal Display (LCD). This system is capable of monitoring current, voltage and electrical power in real time, both locally and remotely. Second, the test results demonstrate that this tool performs well, with an average deviation of less than 5%. Specifically, the deviations for voltage, current, and power measurements are 0.49%, 2.15%, and 1.09%, respectively. Third, this tool provides significant value by enhancing the performance and sustainability of solar energy systems, thereby contributing significantly to global efforts in achieving Sustainable Development Goals.

Keywords: Solar power plants; Electrical power monitoring system; Internet of Things; Renewable energy

1. Introduction

Indonesia, being located directly on the equator, enjoys sunshine throughout the year. The geographical advantage provides significant potential for harnessing renewable energy sources, particularly solar energy, which can be utilized extensively as a source of electrical power. Solar energy, being the largest and main energy source for sustaining life, present an ideal alternative for renewable energy solution. One alternative approach to utilizing renewable energy is through solar energy conversion into electrical energy. Solar Power Plants are a prominent example of this application offering a sustainable and effective means in generating electricity. This aligns with the United Nations' Sustainability Development Goals (SDGs), which is emphasizes the importance of ensuring access to clean, affordable, reliable and modern energy, alongside the urgency of addressing climate change. The adoption and expansion of solar energy solutions not only support

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DOI: https://doi.org/10.22515/sustinere.jes.v8i3.442

sustainable development but also contribute to global efforts in mitigating environmental challenges.

This Solar Power Plant harnesses energy from sunlight, which is absorbed by solar panels. This energy is then stored in a storage battery and subsequently converted into electrical energy (Lewis, 2016). Not all of the electrical energy generated by solar panels is directly consumed by electronic devices, a portion is stored in a battery use during nighttime or power outages (Lai & McCulloch, 2017). The battery is rechargeable, making it highly efficient for use in solar module systems (Li, Liu et al., 2017).

Indonesia's oil reserves were estimated to be depleted within 12 years as of 2015, depending on the reserve-to-production ratio at that time. Similarly, natural gas reserve is expected to run out in 33 years, while coal reserves may last for 82 years (Nasruddin et al., 2016; Deendarlianto et al., 2020). The high energy demand is not matched by production capacity, leading to shortages. Consequently, nearly all countries, including Indonesia, are striving to develop energy from new and renewable energy sources (Presidential Regulation of Republic of Indonesia No 22 Year 2017).

The development of renewable energy technology for the industrial sector is advanced significantly, especially in the utilization of solar thermal energy (Li, Zhu et al., 2017). Despite the availability of various modern tools to support solar power plant operations, many users still rely on manual equipment, such as traditional measuring instruments. The increasing demand for technological solution arises from the need to address human limitations and other challenges. Technology, fundamentally created and developed by humans, aims to simplify tasks and improve efficiency. By leveraging Internet of Things (IoT) technology, it is possible to connect humans with devices and platforms via the internet, enabling more seamless and automated interactions (Nusa, 2015).

Based on observations at the Off-Grid Solar Power Plant House in Ngluwar, Magelang, Indonesia, several issues were identified. First, the equipment used to measure voltage, current, and power is not yet automated. Second, the measurement process is still carried out manually, often without even using analog measuring instruments for voltage, current, and power measurements. The manual process requires significant effort and considerable time, increasing the likelihood of errors during measurements and resulting in inefficiencies. Such inaccuracies and wasted time can be mitigated by replacing manual measuring instruments with an automated system. This would enable the measurement process to be monitored remotely via a smartphone connected to the internet (Aggista, 2020). The electrical parameters to be monitored include voltage, current, and power.

These electrical quantities from the fundamental basis for other electrical measurements. Voltage represents the attractive force between two positive and negative charges separated by a certain distance. While potential difference is often expressed in joules per coulomb, the International System of Unit (SI) defines voltage in volts (V). Current refers to rate of change of charge flowing per unit of time. Electric power, on the other hand, measures the amount of electrical energy transferred every second, equivalent to joules per second. According to Parhan (2013), electrical power is defined as the ability or capacity to perform work or transfer energy.

Therefore, it is necessary to design a device capable of monitoring electrical power with a system that can be connected to the internet. This monitoring system measures voltage, current, and power using a PZEM 004T version 3 sensor. The device will be integrated with a smartphone application, enable user to easily access and control the hardware anytime and anywhere with an internet connection. The objectives of this research are as follows. First, to develop hardware and software devices for an Internet of Thing (IoT)-based electrical power monitoring system in solar power plants. Second objective is to evaluate the performance of IoT-based electrical power monitoring devices in solar power plants. Third, to assess the role of this tool in support the achievement of SDGs, especially in promoting energy efficiency and sustainability

2. Literature review

2.1. Previous research

Relevant research regarding the development of an electric power monitoring system that has been carried out previously includes the following. Real time electrical energy consumption monitoring system using microcontroller. Nusa (2015) designed a tool to monitor electrical energy consumption, utilizing a step-down transformer to measure source voltage. To measure load current, an ACS712 current sensor and an ATmega 328 microcontroller were used to process data from the necessary parameters and obtain electrical energy consumption values. The results were displayed on a 20 x 4-character LCD to provide information to electricity users, through this system did not yet incorporate the IoT.

Android-based electrical energy usage monitoring tool using PZEM-004T module. Habibi et al. (2017) designed a tool to monitor three-phase kWh meters using an Arduino microcontroller and a web-based SMS gateway. This tool measures the current of a three-phase kWh meter, stores the current value data in a database, and displays it on the web. It can also send short messages to cell phones if one of the current phases on the kWh meter is missing or leaking. However, this energy monitoring device still relies on SMS to send data to the web, which can deplete credits quickly due to repeated SMS usage.

Electrical energy measurement based on PZEM-004T. This device was designed by Anwar et al. (2019) to monitor electrical energy using the PZEM-004T sensor, which include sensors for current, voltage, and phase difference. Additionally, it utilizes an Arduino Mega 2560 microcontroller for the control system, although it does not yet incorporate IoT.

Other studies regarding the development of IoT-based solar power plant monitoring tools include the solar energy monitoring system using IoT developed by Patil et al. (2017). Research on solar power monitoring systems using IoT was also carried out Katyarmal et al. (2018), Rani et al. (2023), and Gopal et al. (2020). These four studies all focused on developing IoT- based monitoring tools for solar power plants. Based on the advantages and disadvantages of previous research, this study aims to develop an electric power monitoring system for solar power plants based on the IoT.

2.2. Sustainable Development Goals (SDGs)

The SDGs are a global initiative consisting of 17 goals, which include the eradication of poverty, taking action against climate change, and ensuring access to clean and affordable energy (Halkos & Gkampoura, 2021). Among these goals, SDG 7 and SDG 13 are particularly relevant to development of PV panels: SDG 7 (clean and affordable anergy) and SDG 13 (taking action against climate change}.

SDG 7 aims to ensure access to affordable, reliable, and modern energy for all. In this context, solar PV (McCollum et al., 2017) has significant potential in the transition to clean energy, particularly in developing countries where conventional energy sources are often scare. SDG 13 demands urgent action against climate change and its impacts. The adoption of renewable energy technology, such as PV panels, will be a key part of global efforts to mitigate climate change (Abbasi et al., 2024).

2.3. Solar power plant (SPP)

Solar power plant (Solar Photovoltaic) is a power plant that converts sunlight into electrical energy through solar cells (photovoltaic), which transform solar photon radiation into electricity. The SPP used in this research is an off-grid type, meaning it is an electricity generation system that relies solely on solar energy as its only source of electrical power, independent from and not connected to the Perusahaan Listrik Negara (PLN) electricity network. The electrical energy produced by the solar panels can be used directly to meet the load's electricity needs, while any excess energy is stored in a battery for use as backup power. The supporting components include the Solar Panel Module, Solar Charge Controller (SCC), Direct Current (DC) to Alternating Current (AC) inverter, and battery (Lubis, 2007). The off-grid solar power plant is illustrated in Figure 1.

2.4. Solar power plant (SPP)

Monitoring is the process of measuring, recording, collecting and processing information used to make decisions in project management (Bakti, 2018). In this research, a monitoring system tool was used to measure several electrical quantities, such as electric current in Amperes (A), electric voltage in Volts (V), and electric power in Watts (W). With this monitoring tool, the amount of electricity used, including current, voltage, and power, will be determined, allowing it to be used for various purposes, such as monitoring electrical load conditions, controlling electrical equipment, and making efforts to save electricity usage, among others.

2.5. Internet of Things

IoT is a concept or program where an object has the ability to transfer or transmit data over a network without the assistance of computers and humans. According to Sulistiyo (2021), the IoT is a computing concept that envisions a future where every physical object can be connected via the internet by identifying itself to other devices. IoT systems work with objects in the form of sensors, which have the ability to collect information, read data, and communicate wirelessly with other sensors. This information is then transmitted via the internet as a means of wireless communication, after which the data is stored in the cloud or a data center. IoT-based platforms can access this stored information and display it via the application, depending on the type of data to be shown.

3. Methodology

The research method used for this study is analysis, design, development and testing (see Figure 2). The stages of the model are as follows. Analysis, this stage aims to identify the needs for devices required by society. Design, this stage focuses on designing the devices, including both the hardware and the software programs to be used. Development, the stage involves improving pre-existing tools to create an effective and efficient device. Testing, the devices developed are tested to determine whether they function as whether they function and perform well.

3.1. Need analysis

At the analysis stage, the data presented is obtain from observations at the Solar Power Plant House in Ngluwar, Magelang, Jawa Tengah, Indonesia. The measuring instruments currently used to operate manually, requiring the Solar Power Plant operator to measure voltage, current, and electrical power manually. This manual process is time-consuming and energy-intensive. To

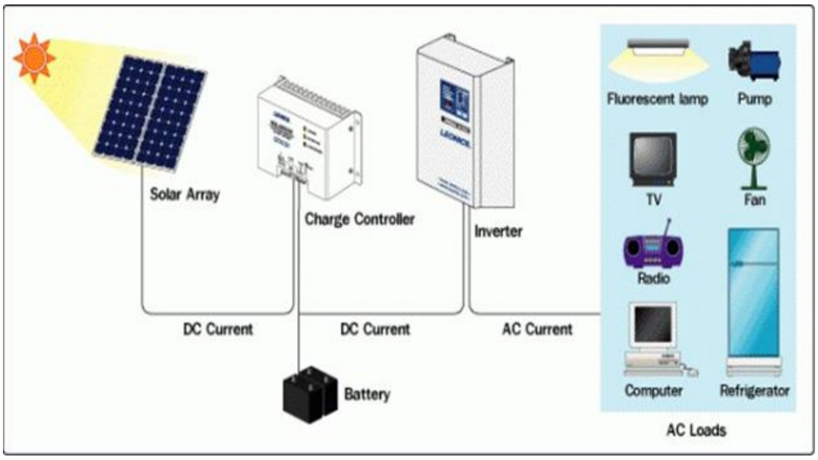

Figure 1. Off-grid solar power plant (Salas, 2017)

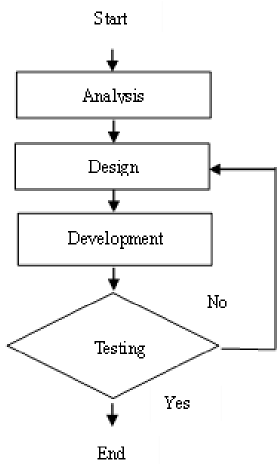

Figure 2. Research stage flowchart

address this issue, a device is needed to facilitate quicker and more efficient measurements. Therefore, there is a need to develop an IoT-based electrical quantity monitoring device to simplify and streamline the measurement process.

3.2. System design

3.2.1. Device work principle

Figure 3 shows a flowchart of how the IoT-based Solar Power Plant Monitoring System operates. The begins when the device is powered on by connecting it to a power source and an adapter. Next, the NodeMCU processes the input data from the PZEM-004T sensor readings. The Blynk platform processes the data once the hotspot and smartphone are connected to the internet, and the results are displayed on the LCD. The system continuously monitors the load being measured.

3.2.2. System block diagram

Figure 4 is a block diagram of the device to be developed. It consists of the main component, NodeMCU, which functions as a Wifi module to connect to the Blynk application. The PZEM 004T is used to measure electrical parameters such as voltage, current, and electric power. Additionally, an LCD is included to display the data from these electrical parameters.

3.2.3. Electronic design

This design aims to simplify the installation process of the tool's components. System block diagram and electronic design are presented in Figure 4 and Figure 5. The electronics circuit uses the NodeMCU ESP3266 as the main component, functioning as a Wifi module to connect to the Blynk application. The PZEM-004T is used as a sensor to measure electrical parameters such as voltage, current, and power. Additionally, an LCD is included to display the data from these electrical parameters. The following are the results of the electronic design diagrams.

3.2.4. Mechanical design

Mechanical design is created to determine the physical form of the tool, including both the control box (Figure 6) and its mechanics components (Figure 7). This design uses an X6-type box to house the components. The size and shape are planned to accommodate the dimensions of the component. The design was created using CorelDRAW X8.

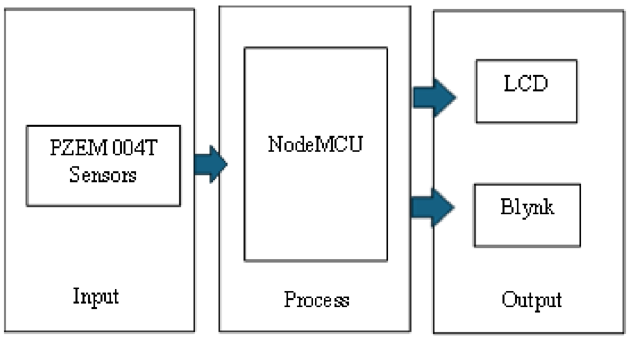

Figure 4. System block diagram

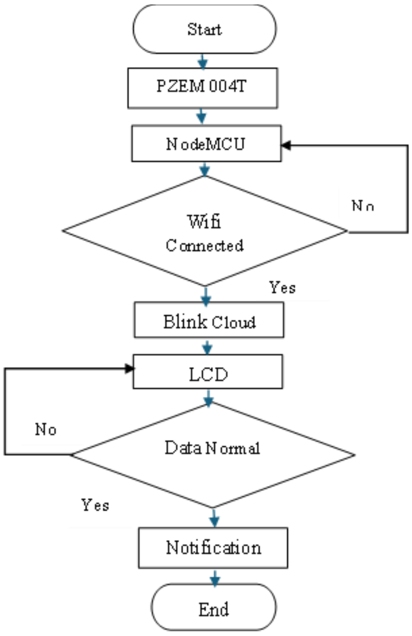

Figure 3. Device work principal flowchart

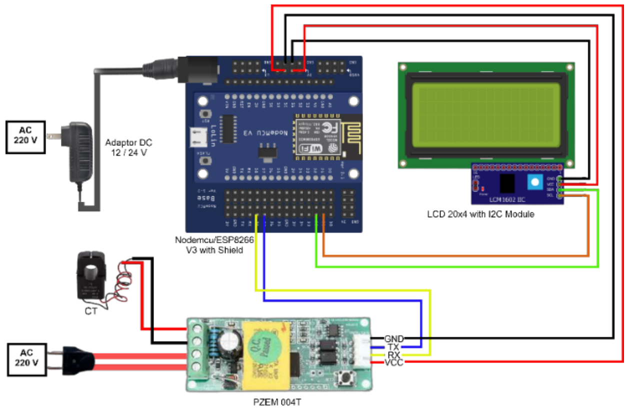

Figure 5. Electronics design

4. Results and discussion

4.1. Hardware development

The design stage for developing the tool's requirements marks the initial stage of the tool realization process. During the planning stage, an analysis is conducted to identify the number and types of tools needed. Once the function of each component is determined, the circuit is designed, as shown in the electronic circuit diagram (Figure 5). This includes identifying which components will serve as inputs and which will ack as outputs, facilitating the assembly process. The Figure 8 is an illustration of the component wiring circuit installed in the component box. The components inside the box include a NodeMCU ESP8266, which serves as a WiFi module to connect to the Blynk application, a PZEM-004T sensor for measuring electrical parameters such as voltage, current, and power, and an LCD display to show the data from these electrical measurements.

4.2. Software development

The development of software for the electrical power monitoring system in solar power plants based on the IoT involves coding microcontroller using Arduino IDE software. The Figure 9 and 10 show the results of the software development process.

4.3. Testing results

Data collection for testing the Electric Power Monitoring System in Electric Power Plants was carried out at the Off Grid Power Plant House, Ngluwar, Magelang, Jawa Tengah, Indonesia. The

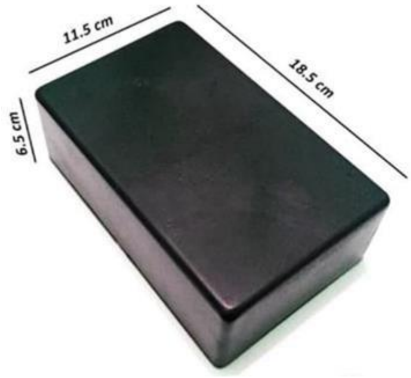

Figure 6. Box design

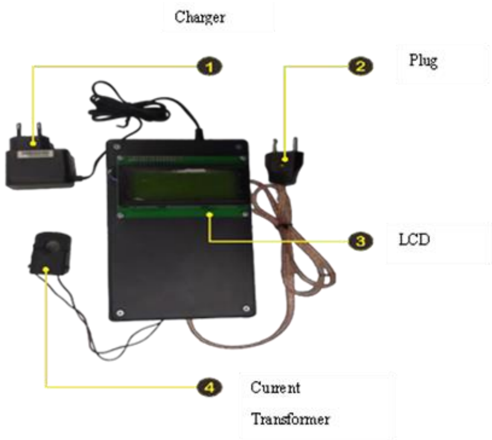

Figure 7. Device design

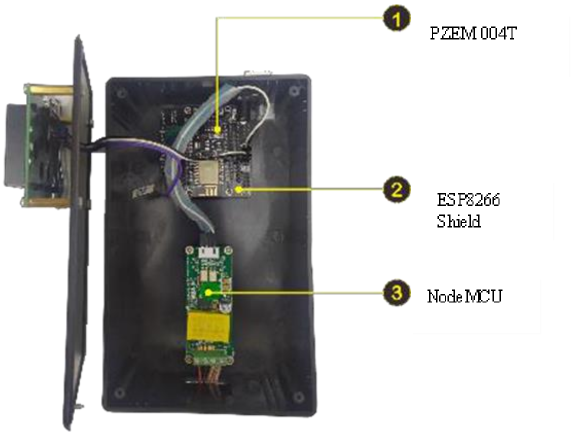

Figure 8. Development of hardware

purpose was to evaluate the performance of each component and the device as a whole. Testing was performed by collecting six data samples from each sensor reading at 5-minute intervals. The aim was to obtain valid data, ensuring the device functions as expected and meets its objectives. The testing included functional testing of components such as NodeMCU, PZEM 004T sensor, LCD, and I2C, all of which are found to function properly. Additionally, performance testing was conducted as follows.

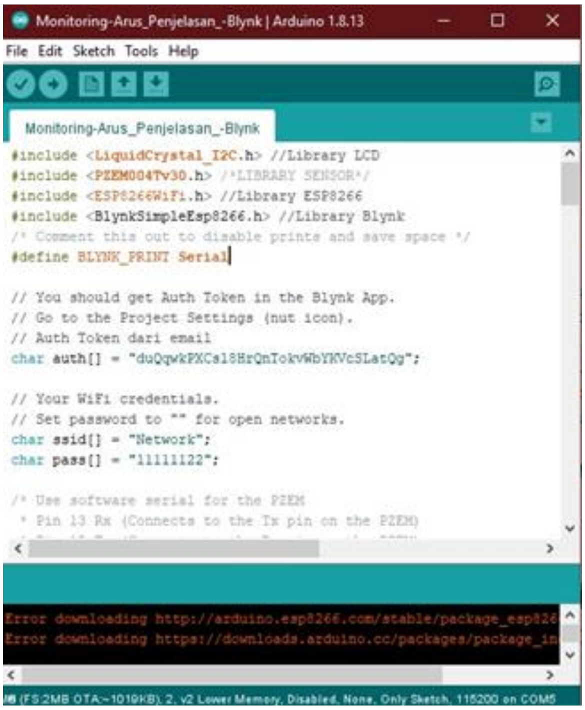

Figure 9. Software development by Arduino IDE

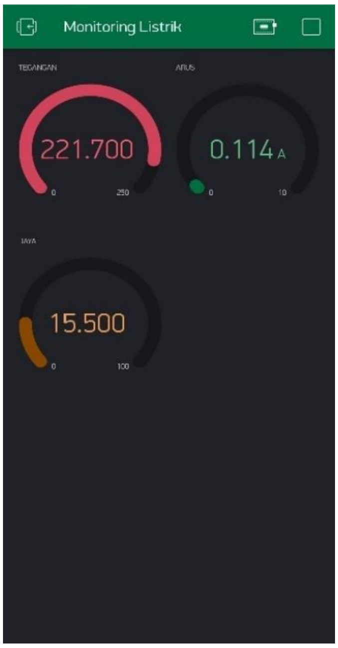

Figure 10. Blynk application appearance

4.3.1. Voltage measuring testing

The results obtained from voltage testing revealed the highest error in the third experiment, with an error value of 1.27% at a 12W lamp load. The overall average error in the sensor experiment was 0.49%. Several factors could contribute to measurement errors, including: first, environmental conditions such as temperature, humidity and air pressure, which can affect the measurement results (Wang et al., 2015). Second, environments with significant electromagnetic interference (EMI), such as proximity to other electronic equipment, which can affect sensors or monitoring devices, especially if the device is sensitive to EMI (Driessen et al., 2019). If We look at the characteristics of class 4 measuring instruments, this prototype voltage sensor can still be used as a reference for carrying out voltage measurements because the average error is below 5%. The Voltage measurement test results are summarized in Table 1.

4.3.2. Electric current measuring testing

The results obtained from current testing found the highest error in the second experiment with an error value of 3% with a lamp load of 9 W and the overall average error in the sensor experiment was 2.15%. The current measurement error is greater than the voltage measurement error. If We look at the characteristics of class 4 measuring instruments, this prototype voltage sensor can still be used as a reference for carrying out voltage measurements because the average error is below 5%. The electric current measurement test results are summarized in Table 2.

4.3.3. Electric power measuring testing

The results obtained from the PZEM 004T power sensor readings when compared with the wattmeter measuring instrument produce data with differences that are not much different. The biggest error was 1.49% at a light load of 7 W and the overall average error in the sensor experiment was 1.09%. If we look at the characteristics of class 4 measuring instruments, this prototype voltage sensor can still be used as a reference for carrying out voltage measurements because the average error is below 5%. The electric power measurement test results are summarized in Table 3.

Table 1. Voltage measurement test results

Load (W)	Voltmeter (V)	LCD (V)	Diff (V)	Error (%)	Result
Lamp 7W	221	221.50	0.50	0.22	Meet Standard
Lamp 9W	221	221.90	0.90	0.40	Meet Standard
Lamp 12W	219	221.80	2.80	1,.27	Meet Standard
Lamps 7 & 9W	221	221.50	0.50	0.22	Meet Standard
Lamps 7 & 12W	222	221.60	0.40	0.18	Meet Standard
Lamps 9 &12 W	220	221.40	1.40	0.63	Meet Standard

Table 2. Current test results

Load (W)	Ammeter (A)	LCD (A)	Diff (A)	Error (%)	Result
Lamp 7W	0.050	0.051	0.001	2.00	Meet Standard
Lamp 9W	0.065	0.067	0.002	3.00	Meet Standard
Lamp 12W	0.082	0.084	0.002	2.43	Meet Standard
Lamps 7 & 9W	0.111	0.113	0.002	1.80	Meet Standard
Lamps 7 & 12W	0.126	0.128	0.002	1.58	Meet Standard
Lamps 9 &12 W	0.142	0.145	0.003	2.11	Meet Standard

Table 3. Electric power test results

Load (W)	Wattmeter (W)	PZEM (W)	Diff. (W)	Error (%)	Results
Lamp 7W	6,70	6,80	0,10	1,49	Meet Standard
Lamp 9W	8,90	8,83	0,07	0,78	Meet Standard
Lamp 12W	11,20	11,30	0,10	0,89	Meet Standard
Lamps 7 & 9W	15,60	15,40	0,20	1,28	Meet Standard
Lamps 7 & 12W	17,90	17,70	0,20	1,11	Meet Standard
Lamps 9 &12 W	20,10	19,90	0,20	0,99	Meet Standard

4.3.4. Internet of Things performance

In testing the Internet of Things (IoT) system on the prototype, it was found that: First, the time interval for sending data from the device to the Blynk application on the smartphone had a time interval that was in accordance with the program, namely 2000 mS or 2 seconds. Second, data collection on sensors uses real-time data collection and via an internet connection. Third, IoT connections are only used in places that can be reached via an internet connection. These parts were research result/ findings displayed as words, tables, figure, and photographs.

4.4. Discussion

The developed monitoring tool supports SDGs by monitoring and measuring of the performance of Solar Power Plant systems in real time. It supports in: First, using the precise measurement of voltage, current, and power, the systems can be optimized for increasing the efficiency of renewable energy utilization. In addition to this, the data collected from here helps the stakeholders understand the consumption pattern and undertake any adjustment that may be considered necessary to maximize the output of energy (Harrison et al., 2010). Second, it encourages the use of renewable energy, hence reducing dependence on fossil sources-a key factor in the bid for cleaner and more available energy (Kabeyi & Olanrewaju, 2022). Third, the study aids in supporting technological innovation with the use of IoT in monitoring solar PV systems and, therefore, acts as a driver for wide application of modern technology in effectiveness and operational efficiency promotion in the energy sector (Ahmad & Zhang, 2021). Fourth, energy infrastructures, with advanced monitoring tools, shall be more responsive to existing needs and challenges: cope better with changes in energy demand (Omer, 2008).

5. Conclusion

Based on the results of this this study, it can be concluded that this device functions as intended and meets the desired specifications. The findings from the testing phase can be summarized as follows.

This monitoring tool features the capability to measure electrical parameters, including voltage, current, and power. It is equipped with an IoT feature, allowing real-time monitoring of measurement result through the Blynk application on a smartphone. The system comprises a NodeMCU ESP8266, a shield, an LCD with I2C, a PZEM-004T sensor for measuring electrical quantities, and a project box to house and protect the components.

Performance testing showed that the voltage measurement had an average error of 0.49%, the current measurement an average error of 2.15%, and the power measurement an average error of 1.09%. These results demonstrate that the device measures voltage, current, and power accurately and effectively, comply with IEC Standard No. 13B-23, which requires measurement error to be below 5%.

The innovation introduced by this system provides an effective and efficient solution for enhancing the sustainability of renewable energy systems. It also contributes to the achievement of Sustainable Development Goals (SDGs), particularly in the areas of clean and affordable energy, fostering innovation, and addressing climate change.

Based on the results of the final project, several shortcomings have been identified. Therefore, further development of this tool is recommended to enhance its functionality and performance. From the discussion of test results and tool limitations, it is evident that a dedicated local server should be developed to enable data to be displayed and accessed via smartphones or websites. Additionally, the application interfere is currently quite basic and requires improvement to enhance usability and visual appeal. Future research could focus on expanding the capabilities of this monitoring tool, making it applicable to other sectors reliant on renewable energetic systems, such as agriculture and industry. This would broaden its benefits and contribute further to sustainability efforts.

Acknowledgment

The authors, from the Electrical Education Department, Faculty of Engineering, Universitas Negeri Yogyakarta, prepared this journal article based on the research report on the electric power monitoring system for solar power plants utilizing the Internet of Things. This research was conducted as part of a Faculty of Engineering program at Universitas Negeri Yogyakarta in 2021

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