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Performance Analysis of an IoT-Based Smart Energy Meter for Real-Time Monitoring of Electrical Energy Consumption

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ABSTRACT

This study presents the performance analysis of an IoT-based Smart Energy Meter designed for real-time monitoring of electrical energy consumption. The system utilizes a NodeMCU ESP8266 microcontroller integrated with two PZEM-004T modules and PZCT-02 current sensors to measure voltage, current, power, and energy from multiple electrical loads. The measured data is transmitted to the Blynk platform, enabling real-time monitoring through a smartphone application. The performance of the system was evaluated by comparing the measurement results with a standard multimeter, resulting in average errors of 0.447% for voltage, 1.704% for current, and 1.844% for power, indicating good measurement accuracy. Experimental results under different load conditions show that higher power loads lead to significantly increased energy consumption and operational cost, where a 32 W load consumes approximately 0.038 kWh compared to 0.006 kWh for a 5 W load within the same duration. Overall, the system demonstrates reliable performance and provides an effective solution for real-time energy monitoring and management in household applications.

INTRODUCTION

The rapid growth of electrical energy consumption in residential sectors has increased the importance of efficient monitoring systems. The widespread use of electrical appliances in households contributes significantly to rising energy demand, which directly impacts electricity costs. However, conventional energy meters are generally limited to measuring total energy consumption without providing detailed or real-time information to users. This limitation reduces user awareness of energy usage patterns and makes it difficult to identify inefficient consumption. Therefore, the development of an advanced monitoring system is required to support more effective energy management (Afandi, 2025; Wulandari et al., 2025)

The advancement of Internet of Things (IoT) technology has enabled the integration of electrical measurement systems with real-time communication platforms. IoT-based smart energy meters allow users to monitor electrical parameters such as voltage, current, power, and energy consumption remotely through mobile applications. This capability improves accessibility and enables users to make better decisions regarding energy usage. Several studies have shown that IoT-based systems can enhance monitoring performance and provide more efficient energy management solutions (Muralidhara et al., 2020; Saleem et al., 2022)

In addition, the implementation of smart energy monitoring systems often involves the use of sensors and microcontrollers to ensure accurate data acquisition. Previous studies have demonstrated the effectiveness of combining sensors such as PZEM-004T with microcontrollers for real-time monitoring applications (Yasa et al., 2023; Dahlan et al., 2025). These systems are typically integrated with communication platforms to allow data transmission and visualization in real time

Various research efforts have been conducted to develop IoT-based energy monitoring systems with improved performance and functionality. Some studies have focused on system design and monitoring capabilities (Andrianto et al., 2024; Chong et al., 2025), while others have emphasized real-time data processing and communication reliability (Garcés et al., 2025; Munoz et al., 2024). Furthermore, the integration of monitoring and control systems in household applications has also been explored, showing the potential of IoT in improving energy efficiency and system usability (Farid & Salahuddin, 2024). Despite these developments, challenges still remain, particularly in achieving accurate measurements, maintaining system stability, and monitoring multiple loads simultaneously

Based on these considerations, this study aims to evaluate the performance of an IoT-based Smart Energy Meter in monitoring electrical energy consumption in household appliances. The analysis focuses on measurement accuracy as well as the behavior of energy consumption under different load conditions. The outcomes of this research are expected to provide insights into the effectiveness of IoT-based monitoring systems and contribute to the development of more reliable energy management solutions.

RESEARCH METHODS

The experimental procedure was systematically designed to evaluate the performance and reliability of the developed smart energy monitoring system under various load conditions. In this study, the testing process was conducted using four different lighting loads with nominal power ratings of 5 W, 11 W, 18 W, and 32 W. Each load was tested separately to ensure that the system response to each power level could be clearly observed and accurately analyzed. During the experiment, electrical parameters including voltage, current, power, energy consumption, and estimated cost were continuously monitored and recorded. The data collection process was carried out at predetermined time intervals, starting from 5 minutes up to 80 minutes, in order to examine the variation and stability of the measured parameters over time. This approach allows for a more comprehensive understanding of how energy consumption evolves under different load conditions.

All experiments were performed under normal indoor environmental conditions with a stable and consistent power supply to minimize external disturbances that could affect the measurement results. Furthermore, to assess the accuracy and validity of the developed system, the measurement results obtained from the smart energy meter were compared with those obtained from a standard reference instrument, namely a multimeter. In addition, the collected data were further processed and analyzed to determine the percentage error between the two measurement methods. This analysis was conducted to evaluate the level of accuracy and reliability of the proposed system. Moreover, the results were also used to observe the pattern of energy consumption and cost estimation for each load variation, providing deeper insights into the system's performance in practical applications.

The flowchart presented in Figure 1 illustrates the operational sequence of the proposed IoT-based smart energy monitoring system developed using the ESP8266 and integrated with the Blynk application for real-time monitoring.

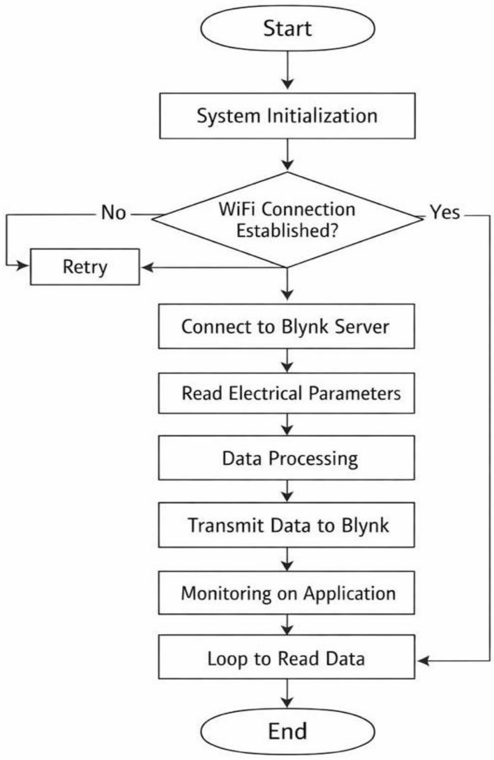

Figure 1. Flowchart of the Proposed System

The process begins with system initialization, where all hardware components and communication modules are configured. The system then attempts to establish a WiFi connection. If the connection fails, the system will retry until a stable connection is achieved. Once connected, the system proceeds to communicate with the Blynk server. After successful connection, the system continuously reads electrical parameters such as voltage, current, and power from the sensors. The acquired data is then processed before being transmitted to the Blynk application. The results are displayed in real time, allowing users to monitor electrical consumption remotely. This process runs in a continuous loop to ensure consistent and up-to-date monitoring.

The system architecture is shown in Figure 2.

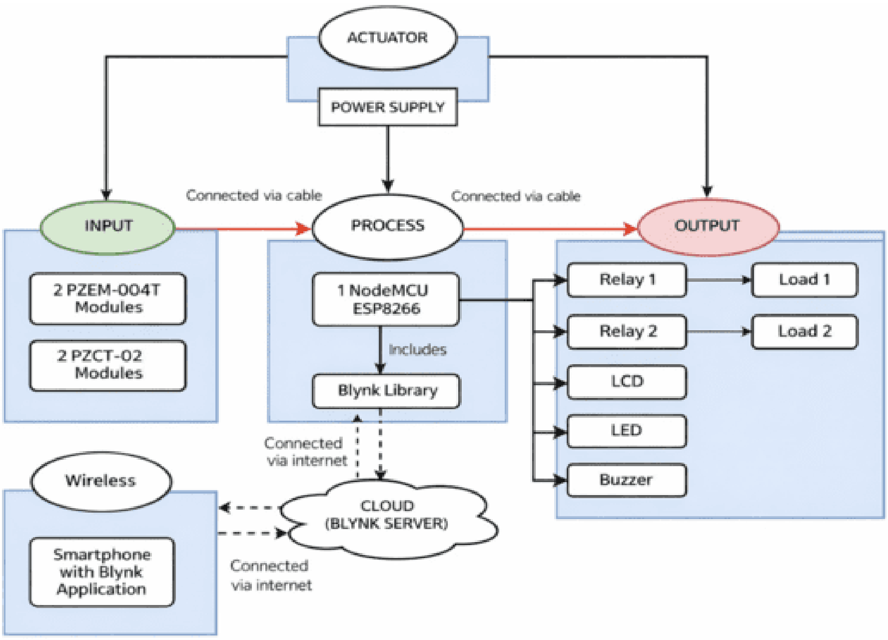

Figure 2. IoT-Based Smart Energy Meter System Block Diagram

The block diagram in Figure 2 illustrates the overall operation of the IoT-based Smart Energy Meter system, which consists of three main parts: input, process, and output. In the input section, the system utilizes two PZEM-004T modules and two PZCT-02 current sensors to measure electrical parameters from two different loads. The measured data is then transmitted to the processing unit.

Based on the system block diagram, the detailed circuit design of the proposed Smart Energy Meter is presented in Figure 3.

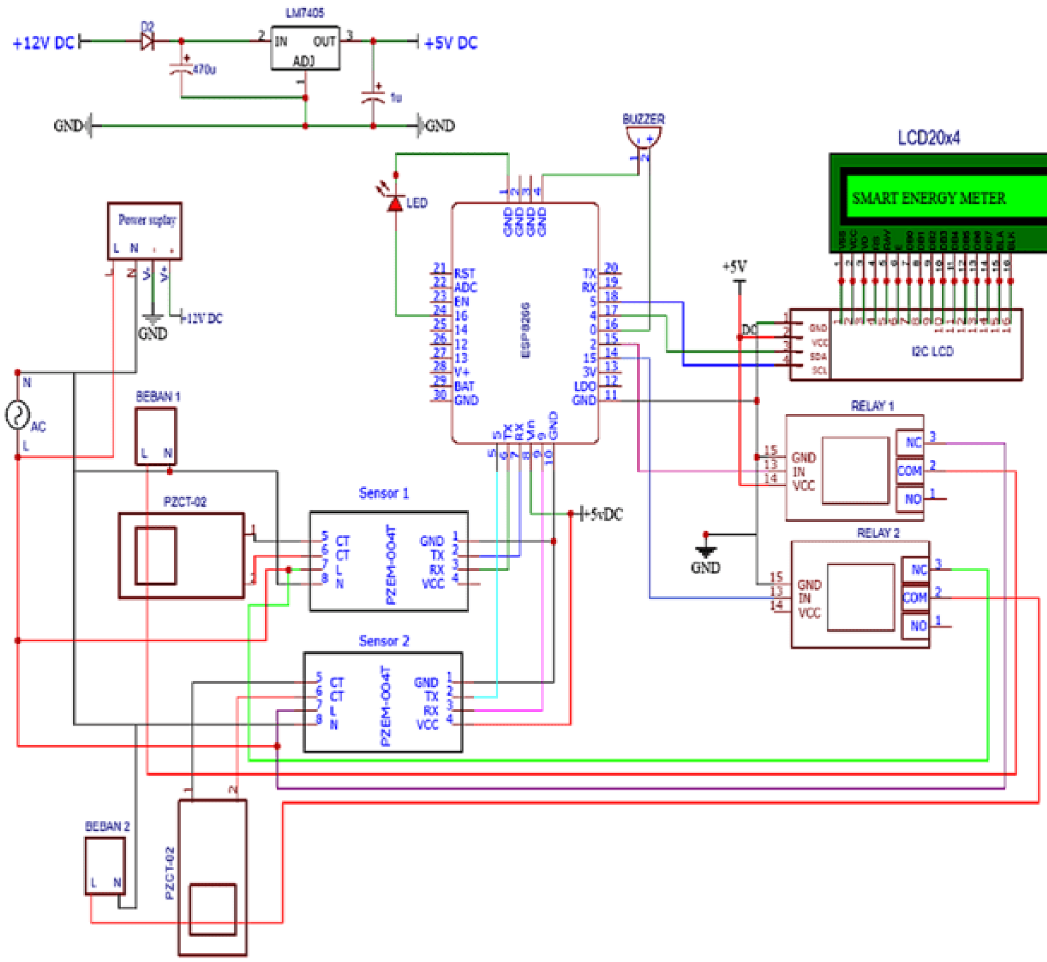

Figure 3. Schematic Diagram of the Smart Energy Meter System

The circuit diagram of the IoT-based Smart Energy Meter system illustrates the interconnection between the main components, including the NodeMCU ESP8266, two PZEM-004T modules, two PZCT-02 current sensors, relay module, LCD, LED, and buzzer. The PZEM-004T modules and PZCT-02 sensors are used to measure voltage, current, power, and energy from two different electrical loads, and the measured data is transmitted to the NodeMCU as the central processing unit. The microcontroller processes the data and communicates with the Blynk platform via a WiFi connection to enable real-time monitoring through a smartphone. Additionally, the relay module is used to control the loads, while the LCD displays the measured parameters locally, and the LED and buzzer function as system status indicators. Overall, the circuit design supports efficient data acquisition, processing, and real-time energy monitoring.

The physical design of the device is shown in Figure 4.

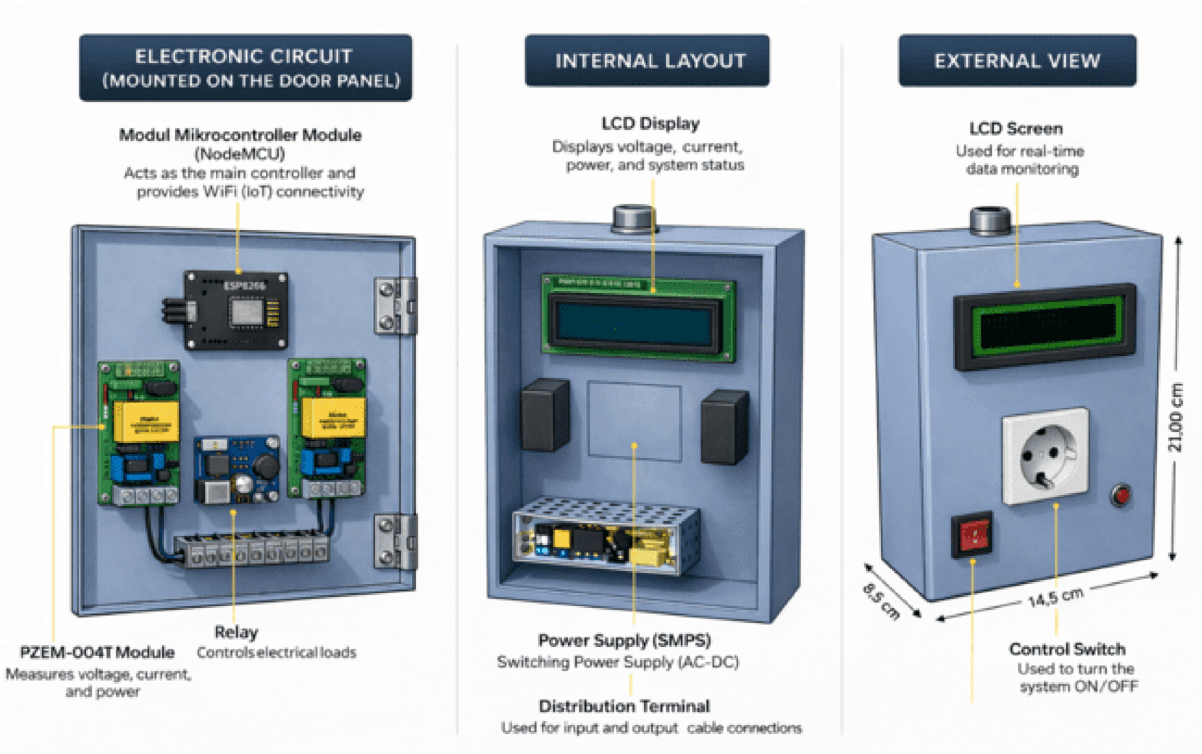

Figure 4. Physical Design of the Smart Energy Meter

To illustrate the system performance in real time, the monitoring interface on the mobile application is presented in Figure 5.

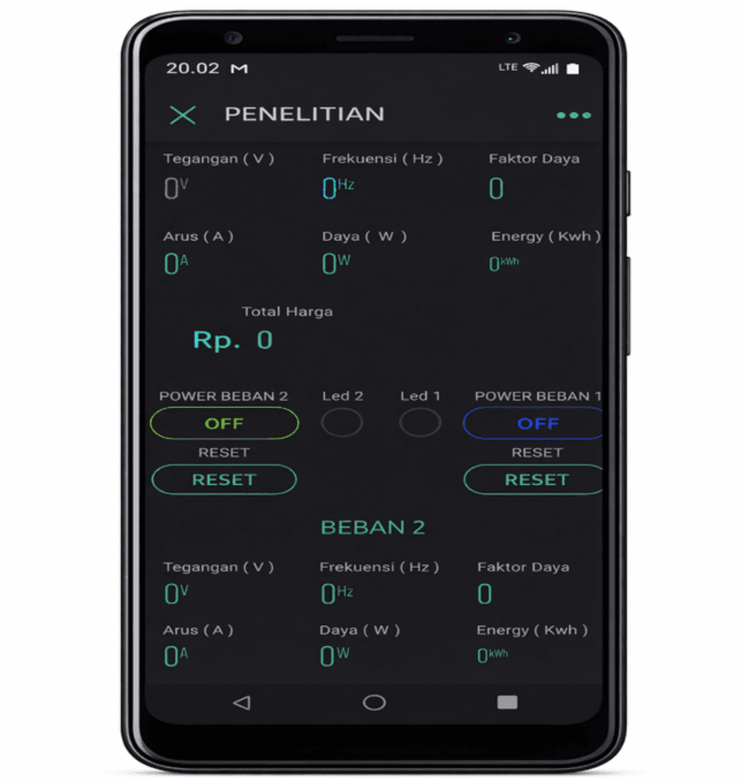

Figure 5. Blynk Application Interface

RESULTS AND DISCUSSION

The implementation of the developed Smart Energy Meter system is shown in Figure 6. The figure illustrates the complete realization of the system, including the electronic circuit mounted on the door panel, the internal layout of the components, and the external appearance of the device. The electronic circuit integrates key components such as the microcontroller, measurement modules, and relay units, which are responsible for data processing and load control. The internal layout shows the arrangement of the power supply, wiring system, and supporting components to ensure stable operation and proper connectivity. Meanwhile, the external view presents a compact enclosure equipped with an LCD display, control switch, and output socket, allowing users to monitor and control the system easily.

Figure 6. Implementation of the Smart Energy Meter System

Measurement Performance Evaluation

The performance of the developed Smart Energy Meter system was evaluated by conducting a series of measurements using the proposed device under controlled testing conditions. The tests were carried out using lighting loads with different power ratings, namely 5 W, 11 W, 18 W, and 32 W lamps, in order to observe the system performance under varying load conditions and to assess its response to different levels of electrical consumption. The measurement results obtained from the developed system were then compared with those measured using a standard multimeter as a reference instrument to determine the level of accuracy and reliability of the system. In addition, this comparison aims to validate the capability of the proposed system in providing real-time monitoring data with acceptable precision. The comparison results are presented in Table 1.

Table 1. Measurement Comparison Results

Load	Voltage Design (V)	Voltage Multi (V)	Error V (%)	Current Design (A)	Current Multi (A)	Error I (%)	Power Design (W)	Power Multi (W)	Error P (%)
Lamp 5W	224.8	226.4	0.707	0.040	0.050	2.000	5.0	4.9	2.041
Lamp 11W	220.6	222.5	0.854	0.064	0.063	1.587	10.8	10.4	3.846
Lamp 18W	218.5	218.4	0.046	0.134	0.136	1.471	19.5	19.4	0.515
Lamp 32W	219.6	219.2	0.183	0.205	0.213	3.756	31.1	30.8	0.974
Average			0.447			1.704			1.844

Based on the results presented in Table 1, the measurement values obtained from the developed system are relatively close to those measured using the multimeter for all load variations. The voltage measurements show very small deviations with an average error of 0.447%, indicating high measurement accuracy. Meanwhile, the current measurements exhibit slightly higher variations with an average error of 1.704%, which may be influenced by sensor characteristics and load conditions. In terms of power measurement, the system demonstrates good performance with an average error of 1.844%, as the calculated power is directly affected by both voltage and current values. Overall, the results indicate that the developed system is capable of providing reliable measurements with acceptable accuracy for real-time energy monitoring applications.

Although the experimental results show that the developed Smart Energy Meter is capable of measuring electrical parameters with relatively low error values, several factors may contribute to the observed measurement deviations. The average error values obtained for voltage, current, and power indicate that the system has acceptable accuracy; however, minor discrepancies still occur due to practical measurement conditions. One of the main factors affecting measurement accuracy is the limitation of the PZEM-004T sensor, which may experience sensitivity variations and calibration differences when measuring low current values, particularly in low-power loads such as the 5 W lamp. In addition, fluctuations in the input voltage from the power supply can influence the stability of the measurement results. Although the experiments were conducted under relatively stable conditions, small variations in voltage can lead to differences in current and power readings. Another contributing factor is the response time of the system, where delays in data acquisition and transmission may cause slight inconsistencies between the measured values and the reference instrument. Furthermore, environmental factors such as temperature and electrical noise may also affect sensor performance and signal accuracy.

Energy Consumption Analysis Under Different Load Conditions

The analysis of energy consumption was carried out using the developed Smart Energy Meter system to observe the behavior of electrical energy usage under different load conditions over time. In this study, two types of lighting loads with power ratings of 5 W and 32 W were used to represent low and high power consumption levels. Measurements were conducted at different time intervals to evaluate the variation in electrical parameters, energy consumption, and operational cost. The electricity cost was calculated based on the applicable electricity tariff of Rp 1,444 per kWh, as determined by the national electricity provider. The results of this analysis are presented in Table 2.

Table 2. Energy Consumption Comparison of 5W and 32W Lamps

Time (min)	V (5W)	I (5W)	P (5W)	Energy (kWh)	Cost (Rp)	V (32W)	I (32W)	P (32W)	Energy (kWh)	Cost (Rp)
5	224.6	0.031	5.1	0.000	0	219.7	0.131	32.4	0.002	2.888
10	225.0	0.030	5.1	0.001	1.444	220.1	0.132	32.2	0.005	7.22
15	224.7	0.030	5.0	0.001	1.444	219.4	0.130	32.2	0.007	10.108
20	225.2	0.029	5.0	0.001	1.444	220.3	0.134	32.1	0.010	14.44
30	224.9	0.029	4.9	0.002	2.888	220.0	0.132	32.1	0.015	21.66
40	224.5	0.029	4.9	0.003	4.332	219.2	0.131	32.0	0.019	27.436
50	225.1	0.029	4.9	0.003	4.332	220.4	0.133	29.8	0.024	34.656
60	224.8	0.029	4.9	0.004	5.776	219.8	0.132	29.8	0.029	41.876
70	225.3	0.028	4.7	0.005	7.220	220.5	0.134	29.8	0.035	50.54
80	224.7	0.028	4.7	0.006	8.664	219.6	0.131	29.8	0.038	54.872

Based on the results obtained at various time intervals, the power consumption of the 32 W lamp consistently ranges between approximately 29.8–32.4 W, while the 5 W lamp remains within 4.7–5.1 W, indicating stable system performance with minimal fluctuations. In terms of energy consumption, the 32 W lamp reaches approximately 0.038 kWh within 80 minutes, whereas the 5 W lamp only reaches around 0.006 kWh, showing that the higher power load consumes about 6–7 times more energy. This difference is also reflected in the operational cost, where the 32 W lamp incurs up to Rp54.87, while the 5 W lamp only costs around Rp8.64 within the same duration. The relatively small variations in voltage, current, and power values indicate that the developed system has good stability and consistency in real-time measurements. Furthermore, the integration of the IoT-based system enables users to monitor energy consumption and estimated costs directly through a smartphone, providing an effective solution for efficient energy management.

For better understanding of the energy consumption characteristics, the results are presented graphically in Figure 7.

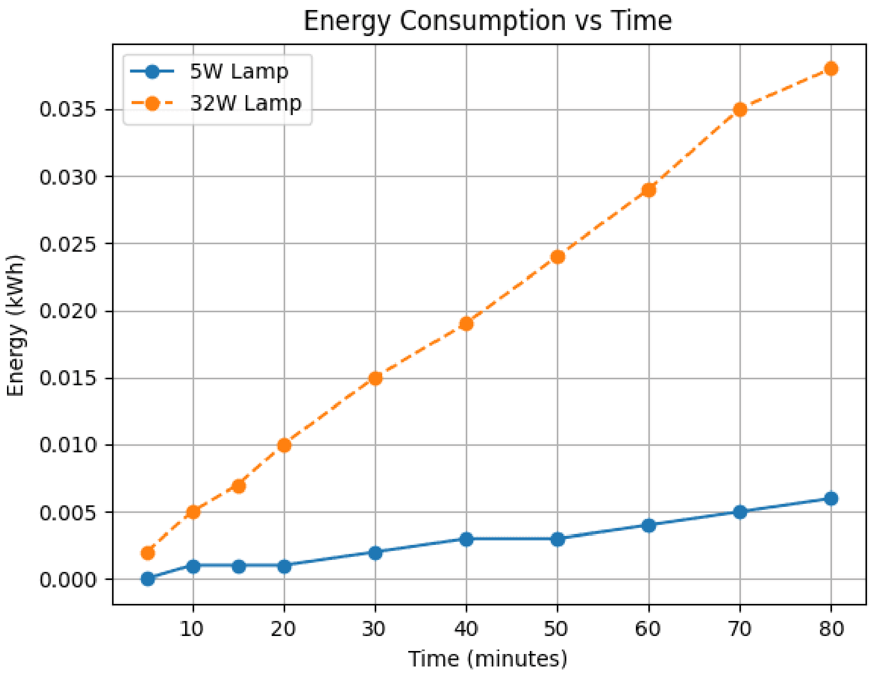

Figure 7. Energy Consumption Comparison of 5 W and 32 W Lamps Over Time

As shown in Figure 7, the energy consumption of both lamps increases with time; however, the rate of increase differs significantly between the two loads. The 32 W lamp exhibits a much steeper growth curve compared to the 5 W lamp, indicating faster energy accumulation due to its higher power rating. In contrast, the 5 W lamp shows a gradual and relatively stable increase in energy consumption over time. The gap between the two curves becomes more pronounced as time progresses, highlighting the significant difference in energy usage between low-power and high-power loads. Additionally, minor irregularities in the curves reflect real measurement conditions, suggesting that the system captures practical variations rather than ideal linear behavior. Overall, the graph confirms that energy consumption is strongly influenced by both load power and operating duration.

When compared with previous studies, the performance of the proposed system is consistent with similar IoT-based energy monitoring systems that utilize low-cost sensors, where small measurement errors are still considered acceptable for household applications (Muralidhara et al., 2020; Saleem et al., 2022). The integration of IoT technology in this system provides an additional advantage by enabling real-time monitoring and user accessibility, which has also been highlighted in prior research (Garcés et al., 2025; Munoz et al., 2024).

The real-time monitoring interface of the system on the Blynk application is presented in Figure 8.

Figure 8. Real-Time Monitoring Interface of the Smart Energy Meter System

As shown in Figure 8, the real-time monitoring interface of the Smart Energy Meter system successfully displays key electrical parameters, including voltage, current, power, energy consumption, and estimated cost through the Blynk application. The interface allows users to observe the differences in energy usage between multiple loads in a clear and accessible manner. The displayed data reflects the actual measurement results obtained from the system, indicating that the communication between the hardware and the mobile application operates effectively. Furthermore, the ability to monitor energy consumption and cost in real time provides significant advantages for users in managing and optimizing electrical energy usage. Overall, the implementation demonstrates that the developed system is capable of functioning as an efficient and reliable IoT-based energy monitoring solution for practical applications.

However, the system still has several limitations. The current implementation is limited to monitoring a small number of loads and relies on a stable internet connection for real-time data transmission. In addition, the system does not include advanced data storage or long-term analysis features, which may be necessary for more comprehensive energy management. Future improvements may focus on enhancing measurement accuracy through better calibration methods, expanding the number of monitored loads, and integrating data logging and advanced analytics features.

CONCLUSION

This study demonstrates that the developed IoT-based Smart Energy Meter is capable of measuring electrical parameters such as voltage, current, and power with satisfactory accuracy when compared to a standard multimeter. This is supported by the average error values of 0.447% for voltage, 1.704% for current, and 1.844% for power. In addition, the system shows stable performance across different load conditions. The energy consumption analysis further reveals that higher power loads result in significantly greater energy usage and operational cost over time. For instance, the 32 W lamp consumes approximately 0.038 kWh within 80 minutes, while the 5 W lamp only consumes about 0.006 kWh, indicating that the higher power load requires around 6–7 times more energy under similar conditions. This difference is also reflected in the operational cost, where the 32 W lamp produces substantially higher expenses compared to the 5 W lamp.

In terms of research contribution, this study provides an implementation and performance evaluation of an IoT-based energy monitoring system using low-cost components, including the NodeMCU ESP8266 and PZEM-004T sensor. The study also contributes by presenting an analysis of measurement accuracy and energy consumption behavior under different load conditions, which can serve as a reference for future developments of similar systems. Future work may focus on improving measurement accuracy, integrating data logging and advanced analytics, and expanding the system to support a wider range of electrical loads and larger-scale monitoring applications.

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