Design and Implementation of an IoT-Based 3-Phase Electricity Usage Monitoring System: Case Study at Geophysics Station Class I Sleman, Yogyakarta

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Article Info

A B S T R A C T

Efficient electrical energy management is increasingly important in supporting the sustainability of institutional operations and national budget efficiency policies. This study presents the design and implementation of an Internet of Things (IoT)-based 3-phase electricity usage monitoring system implemented at the Sleman Class I Geophysical Station, Yogyakarta. This system integrates a PZEM-004T energy sensor, an ESP32 microcontroller, a 16x2 Liquid Crystal Display, and a W5500 Ethernet module to acquire, process, and transmit real-time electrical parameters, including voltage, current, and kWh. A local network topology is implemented to ensure stable data transmission to a MySQL-based database server, which allows storing data according to a predefined table structure. A web-based user interface is developed to visualize real-time measurements, historical graphs, and electricity cost estimates. Several features are also developed. System evaluation is conducted by comparing the developed instrument with the official PLN kWh meter. Statistical analysis shows an average difference of 0.021 kWh with a standard deviation of 0.02132 kWh. The linear regression results show a slope of 1.000349, an intercept of −3.589572, and a coefficient of determination (R²) of 0.9999988, indicating a near-perfect linear correlation. Error metrics including MAE (0.01934 kWh), RMSE (0.02696 kWh), and MAPE (0.0001885%) confirm the high accuracy and precision of the system. Therefore, the proposed system is reliable for real-time internal energy monitoring and supports data-driven electricity usage optimization.

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1. INTRODUCTION

Electrical energy usage in a building needs to be monitored and integrated to improve operational efficiency, optimize load management, and support data-based energy conservation strategies in smart building systems [1]. Internet of Things (IoT) is a technology paradigm that connects various physical devices through an internet network, enabling the process of collecting, exchanging, and analyzing data in real-time to support intelligent and automated systems has become very relevant [2]. The success of implementing IoT in electricity monitoring systems is demonstrated through the ability to acquire real-time energy consumption data, increase the accuracy of load analysis, and optimize energy management in smart building environments [3]. This approach also contributes to achieving long-term energy efficiency through adaptive control and dynamic response to changing electricity consumption patterns [4].

The application of microcontrollers in smart buildings acts as a control center in IoT systems to acquire sensor data, process information locally, and send data to monitoring platforms to increase the efficiency and automation of building energy management [5]. ESP32 implementations are very commonly used due to their built-in Wi-Fi capabilities that support wireless connections in Internet of Things (IoT) applications [6] and can transmit data via various communication protocols [7][8]. The PZEM-004T module is a digital-based electrical energy sensor that is capable of acquiring comprehensive electrical parameters including voltage, current, active power, energy, power factor, and frequency via serial communication, making it widely used in electrical monitoring systems [9][10][11]. The exchange of data between microcontrollers and sensors employs various communication protocols—such as UART, I2C, SPI, and Wi-Fi—selected based on system requirements including data rate, distance, power consumption, and hardware compatibility in Internet of Things (IoT) applications [12][13].

In an effort to improve the efficiency of national budget utilization, the Government of Indonesia has issued Presidential Instruction (Inpres) Number 1 of 2025 concerning Expenditure Efficiency in the Implementation of the State Budget (APBN) and Regional Budget (APBD) for the 2025 Fiscal Year. This Presidential Instruction mandates all ministries, government agencies, and local governments to conduct budget reviews and implement expenditure savings, with a targeted efficiency of IDR 306.69 trillion, consisting of IDR 256.1 trillion from ministries/agencies' expenditures and IDR 50.59 trillion from intergovernmental transfers to regions [14]. As part of the Meteorology, Climatology, and Geophysics Agency (BMKG), the Class I Sleman Geophysical Station Technical Implementation Unit (UPT) Yogyakarta is obligated to support this budget efficiency policy. One concrete action that can be taken is to optimize the use of electrical energy through an effective electricity usage monitoring system, because real-time energy monitoring allows the identification of inefficiencies and supports optimal energy management strategies and cost reductions [15].

In practice, electricity usage monitoring is done manually using conventional kWh meters located far from the office operational building, making it less efficient and seems to drain energy and time if done periodically and routinely, as well as hindering electricity load analysis and slowing down decision making related to energy savings. This research aims to develop a 3-phase electricity usage monitoring system that is able to record, process, and display electricity usage data in real-time. This system is expected to help the Class I Sleman Geophysical Station Technical Implementation Unit (UPT) in monitoring electricity usage more effectively, supporting the identification of wasteful electricity loads, and increasing budget efficiency in accordance with central government directives.

2. RESEARCH METHOD
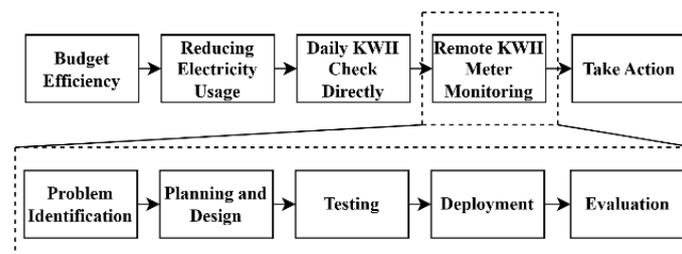### 2.1 Conceptual Framework and Methodology

Figure 1. Conceptual Framework and Methodology

The Class I Geophysical Station in Sleman, Yogyakarta, is required to manage its resources more efficiently and measurably. One sector focused on efficiency is electricity usage. One initial step implemented was to record electricity usage (kWh) every morning by directly observing the readings on the PLN electricity meter. However, the location of the main panel, which is quite far from the operational building, presents a challenge. Therefore, an automated system is needed to record electricity usage periodically. With real-time electricity usage information available, all employees can make quick and informed decisions about energy conservation.

The process begins with the identification and analysis of problems related to the limitations in monitoring daily electricity usage in real-time due to the distance of the PLN main panel from the operational area. From this analysis, system requirements are formulated. The next stage is system planning and design, which includes hardware selection and software design. After the design stage, the system enters the prototype testing phase. The success of the prototype forms the basis for full system implementation or deployment within the UPT environment. During the evaluation stage, the results of electrical energy readings from the device are compared with reference data from the PLN kWh meter and will be analyzed further.
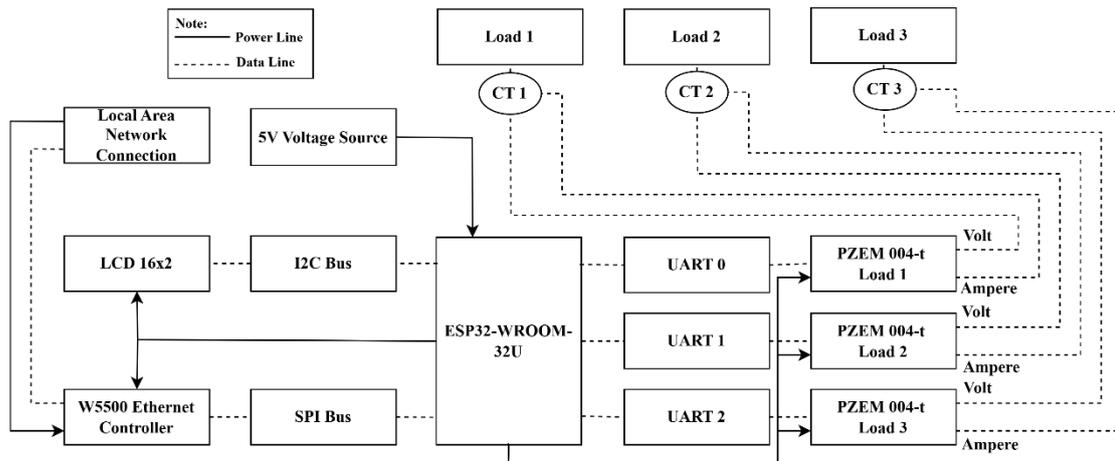
2.2 Design of Hardware

Figure 2. Design of Hardware

In this electricity usage monitoring system, the connection between devices is carried out by considering the data communication needs and the interface protocol used. The PZEM-004T sensor communicates with the ESP32 using the UART (Serial) protocol, while the W5500 Ethernet module is connected via the SPI interface. In addition, the 16x2 I2C LCD is connected to the ESP32 using the I2C protocol. The pin selection on the ESP32 is adjusted to avoid conflicts between devices and to maintain communication efficiency. All devices are connected to a stable power supply from the 5V adapter and 3.3V regulator available on the ESP32, to maintain the stability of the system. With this systematic wiring arrangement, the system is able to acquire and transmit electricity measurement data accurately and in real-time via a LAN network to a local server.

2.3 Data Communication Topology

Figure 3. Data Communication Topology

The system developed in this research applies a local network topology as a data transmission medium between devices. The main device of the system is equipped with a W5500 Ethernet module, configured with a dynamic IP address on the local network with the format 192.168.1.x. This device is physically connected using a UTP cable to a network switch installed in the Graha Building. The switch has a direct connection to the central router of the office network, which functions as a data traffic controller and IP addressing in the LAN network. Another switch located in the Operational Room is also connected to the same router, thus allowing other devices, including the target PC which has a static IP of 192.168.1.95, to be able to receive data directly from the microcontroller through the same communication line.

2.4 Calculation of 3-Phase

The PZEM-004T sensor module installed on each load path (L1, L2, L3) only provides basic data in the form of voltage, current, and energy usage (kWh) per phase. To obtain a representation of the overall 3-phase system, aggregate calculations are performed using a microcontroller-based computing method.

The 3-phase voltage (V_{3ph}) is calculated using the Root Mean Square (RMS) method from the 3-phase voltages with the equation:

$$V_{3ph} = \sqrt{(V_1)^2 + (V_2)^2 + (V_3)^2} \tag{1}$$

Where V_1, V_2, and V_3 are the voltages on phases L1, L2, and L3 respectively.

The 3-phase current (I_{3ph}) is calculated adaptively based on the current availability conditions on each phase. The system applies conditional logic to calculate the average current only from active phases (value greater than zero), so that the calculation results remain representative even in the presence of unbalanced loads or inoperative phases. If all three phases are active, the 3-phase current is calculated as the arithmetic average of the three phases:

$$I_{3ph} = \frac{I_1 + I_2 + I_3}{3} \tag{2}$$

However, if only two phases are active, the 3-phase current is calculated from the average of both phases, and if only one phase is active, then the current value is directly used as I_{3ph}. If all phases are inactive, then I_{3ph} is set to zero.

The total 3-phase energy usage (kWh_{3ph}) is obtained by adding up the energy usage of the three phases and the initial energy value that was previously recorded:

$$kWh_{3ph} = kWh_1 + kWh_2 + kWh_3 \tag{3}$$

This calculation method allows the system to provide a comprehensive picture of 3-phase load conditions in real-time, while accommodating load imbalances that commonly occur in industrial and commercial electrical installations.

2.5 Design of Database

The database design for this research system is modular and structured to support the recording, monitoring, and analysis of electricity usage on an hourly, daily, and monthly basis, as well as displaying estimated electricity rates. This database uses the MySQL database management system and consists of several core tables, each with its own relationships and functions. Table 1 is a description of the main components in the database design.

Table 1. Design of Database

Tables	Information
data_kwh	Raw data storage center for electrical energy measurements on the PZEM-004t
data_jam_kwh	Record hourly electricity usage in kWh per hour.
data_harian_kwh	Records total daily electricity consumption calculated based on the accumulation of hourly consumption.
data_bulanan_kwh	An aggregation of daily data that stores the total number of kWh consumed each month.
baseline_kwh_harian	Stores initial kWh consumption data at the beginning of the day based on date.
tarif_terkini	Information on current electricity rates per kWh.
tarif_listrik_data	Record the electricity rates charged per day.
batas_kwh	Stores the daily consumption limit value determined as the electricity usage threshold.

2.6 User Interface

The user interface design for this web-based electricity usage monitoring information system was carried out using a modular and structured approach, using Visual Studio Code (VSCode) as the primary text editor. The programming languages used include HTML, CSS, JavaScript, and PHP, with integration with MySQL as the database management system (DBMS). This website is designed to present real-time and historical electricity measurement data, complete with visualizations and electricity rate calculations based on energy usage. The website consists of several main files, each with a specific role in data presentation and processing. This structure follows the principle of separation of concerns to separate the interface display, business logic, and database manipulation.

3. RESULTS AND DISCUSSION

Figure 4. Deployment Hardware and Software

The deployment phase aims to fully implement and integrate the system in a predetermined real-world environment. Deployment is carried out in stages, encompassing physical device installation, software system installation, and data communication network configuration. Installation is carried out with attention to occupational safety, electrical standards, and system reliability. All sensor and measurement system connections are protected using a waterproof and dustproof (IP65) panel enclosure to ensure long-term operational reliability. The average data transmission delay from the research instrument to the target PC data

receiver is only 2 seconds (for example, data scheduled to be sent at 12:00 is received and recorded at 12:00:02). The successful integration of hardware and software systems enables comprehensive data acquisition and processing.

The system acquires electrical parameters through the PZEM-004T sensor, performs 3-phase calculations, and transmits the data to a target PC via a network communication protocol. All acquired data is processed based on predefined logic to make it more meaningful and used in highly useful features for users such as electricity usage alerts, data aggregation, and electricity bill estimation. The data is then systematically stored in a MySQL database according to a predefined table structure, ensuring data integrity and accessibility for long-term analysis. The visualization interface presents multiple layers of information. To increase flexibility and support further analysis, reporting, and administrative documentation, all data pages and tables are equipped with a data export feature that allows users to download records in CSV format for further processing or archiving purposes.

Figure 5. Dashboard Website

The developed web-based dashboard serves as a real-time interface that displays the latest voltage, current, and electricity usage (kWh) measurements for each phase (L1, L2, and L3), as well as aggregated results from the 3-phase calculations. The system continuously updates measurement data transmitted from embedded devices, allowing users to observe the latest electricity conditions. In addition to numerical indicators, the dashboard provides line graph visualizations for each parameter, depicting the temporal trends of 3-phase voltage, current, and electricity usage. This graphical representation serves as an analytical tool to support pattern recognition, load behavior evaluation, and anomaly detection in the electricity system. Furthermore, the platform includes a daily electricity consumption feature that displays the total kWh used on the current day. This feature is integrated with a configurable threshold mechanism, allowing administrators to define consumption limits. When daily usage exceeds a predetermined threshold, the system provides an alert indication, thus supporting proactive energy management and strengthening institutional electricity efficiency control strategies.
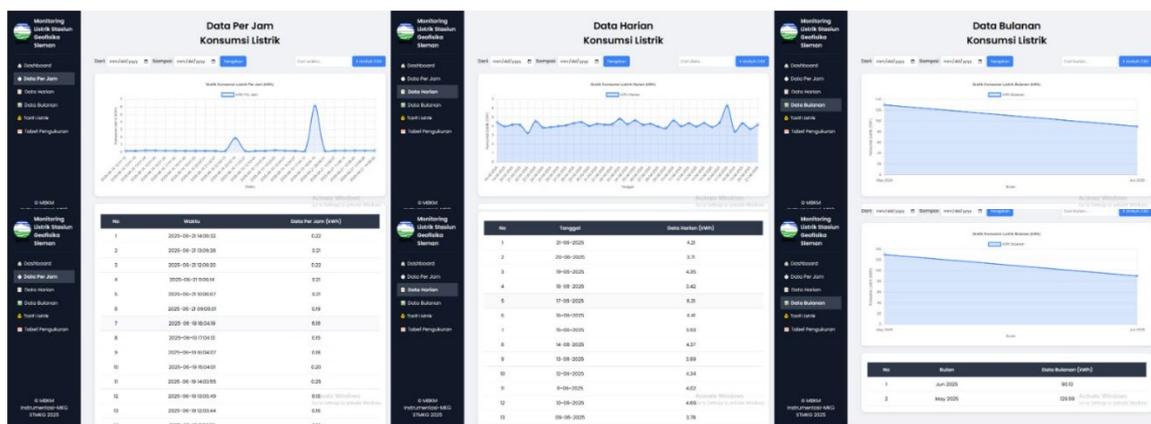

Figure 6. Electricity Usage Per Hour, Per Day, and Per Month

The user interface also presents structured electricity usage data in hourly, daily, and monthly formats as a hierarchical aggregation of recorded energy measurements. Hourly consumption data is obtained by calculating the difference between the cumulative kWh reading in the current hour and the kWh value recorded in the previous hour, thus representing the actual energy usage in a one-hour interval. Daily consumption data is generated by summing all hourly usage values recorded in the same calendar day, providing a comprehensive representation of total daily electricity demand. Furthermore, monthly consumption data is derived from the aggregation of total daily consumption within the same month, enabling broader trend analysis and long-term evaluation of energy usage patterns. This multi-level aggregation structure ensures data consistency across multiple time scales and facilitates detailed and strategic analysis of electricity consumption behavior.

Figure 7. Electricity Bill Estimate and Measurement Table

The designed research system also includes a feature to estimate the projected electricity bill in Indonesian Rupiah (IDR) that must be paid by the institution each month, which is an aggregation of the estimated daily electricity usage bill. This estimate is calculated based on the total 3-phase electricity usage (kWh_{3ph}), which is multiplied by the applicable electricity tariff according to the subscribed power category and the institution's building contract scheme. Tariff data determined by the government is stored in the system database and can be updated according to applicable regulatory policies, ensuring that the calculated cost estimates remain relevant and accurate when policy changes occur. In addition, the platform provides a comprehensive measurement table containing all recorded entries, including voltage, current, power, and energy parameters across all phases, thus enabling transparent data tracking and detailed review of each electrical parameter measurement.

Table 2. Data Evaluation

Timestamp	Instrumen Research	Data PLN	Gap
2025-06-18 13:51	10229,72	10229,71	0,01
2025-06-18 16:15	10230,25	10230,24	0,01
2025-06-21 08:07	10240,65	10240,67	0,02
2025-06-21 16:47	10242,45	10242,43	0,02
2025-06-24 09:01	10254,76	10254,68	0,08
2025-06-25 12:01	10260,68	10260,69	0,01
2025-06-29 12:14	10278,85	10278,84	0,01
2025-06-30 09:10	10282,34	10282,33	0,01
2025-07-02 14:22	10290,20	10290,18	0,02
2025-07-05 10:05	10302,49	10302,47	0,02
Mean of Gap			0,021

System evaluation is conducted to test the reliability and accuracy of the data by comparing it to the primary reference source, namely the official PLN meter. The process involves manual recording by taking photographs of both devices simultaneously or within a very short time interval. The obtained data is then compared in tabular form to identify differences in values, which are then analyzed to quantitatively evaluate system performance. This difference represents the magnitude of the deviation between the instrument reading and the primary reference. After all the data has been compared, a simple statistical analysis is performed to obtain the average difference across all observations.

Based on the results of processing several comparative data, it was found that the difference in kWh readings between the monitoring device and the PLN meter was generally very small. The average error from all observation points was 0.021 kWh. This value indicates that the designed monitoring device has a very good level of accuracy, in accordance with the PZEM 004t sensor specifications for energy readings with a tolerance value of ±0.5%. With a deviation that is relatively low and acceptable in the context of non-commercial energy monitoring. This accuracy is quite representative for the needs of internal energy consumption monitoring and can be a valid basis for evaluating the efficiency of daily and monthly electricity use.
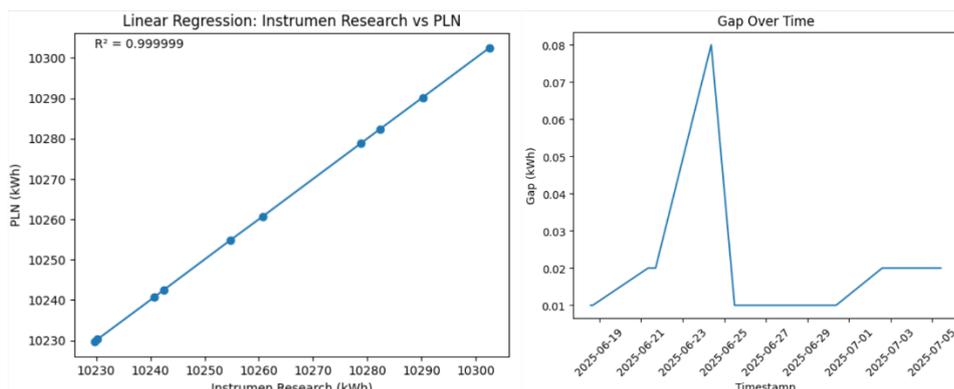
Figure 8. Measurement Data Analysis

Based on the results of statistical analysis of measurement data between research instruments and PLN reference meters, a Mean Gap value of 0.021 kWh with a standard deviation of 0.02132 kWh was obtained, which indicates that the average measurement difference is very small and the variation is relatively low. The maximum Gap value is 0.08 kWh and the minimum is 0.01 kWh, so that practically the measurement error is very low. The results of linear regression modeling show a Slope of 1.000349 and an Intercept of −3.589572, which indicates an almost ideal linear relationship between research instruments and PLN. The coefficient of determination (R^2) value of 0.9999988 confirms that almost all variations in instrument data can be explained by PLN reference data, which means the model's suitability level is very high. In addition, the MAE value of 0.01934 kWh, RMSE of 0.02696 kWh, and MAPE of 0.0001885% further strengthens that the system error rate is very small and is in the very low decimal order. Overall, these results indicate that the developed IoT-based monitoring system has a very high level of accuracy and precision and is suitable for use as a reliable electricity consumption monitoring system.

4. CONCLUSION

This research successfully designed and implemented an IoT-based 3-phase electricity usage monitoring system capable of acquiring, processing, and transmitting real-time electrical parameters with high accuracy and reliability. The development of this system was motivated by the operational need of the Class I Geophysical Station in Sleman, Yogyakarta, to manage electricity consumption more efficiently, as manual daily recording from a remotely located PLN main panel was time-consuming and inefficient. Through systematic stages consisting of problem identification, requirement analysis, hardware and software design, prototype testing, and full deployment, an automated monitoring solution was successfully realized to provide periodic and real-time electricity usage information for data-driven decision-making. The system reliably acquires voltage, current, and energy data from each phase using PZEM-004T sensors, processes the measurement data within the ESP32 microcontroller, and transmits the data via Ethernet (LAN) communication to a centralized database server. The implemented database logic supports multi-level aggregation (hourly, daily, and monthly), electricity usage thresholds, and automated tariff-based cost estimation.

Statistical validation against the official PLN reference meter demonstrates a mean gap of 0.021 kWh with a standard deviation of 0.02132 kWh, indicating very small measurement deviations and low variability. The maximum and minimum observed gaps were 0.08 kWh and 0.01 kWh, respectively, which remain within acceptable tolerance limits for non-commercial monitoring applications. Linear regression analysis produced a slope of 1.000349 and an intercept of −3.589572, reflecting an almost ideal linear relationship between the developed instrument and the reference meter. The coefficient of determination (R^2) of 0.9999988 confirms an extremely high level of agreement, while error metrics including MAE (0.01934 kWh), RMSE (0.02696 kWh), and MAPE (0.0001885%) further demonstrate the system's precision and stability. Overall, the proposed system is highly reliable for real-time internal electricity monitoring and effectively supports data-driven energy efficiency strategies aligned with institutional budget optimization policies.

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