

An IoT-Based Implementation with Node-RED for Real-Time Monitoring and Early Warning of Laboratory Energy Consumption via Telegram

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Abstract – Accurate and responsive monitoring of electricity consumption plays an important role in improving energy management in educational buildings. However, most existing IoT-based energy monitoring systems primarily emphasize data visualization and lack lightweight early warning mechanisms that can be easily deployed using existing kWh meters in laboratory environments. This study develops an Internet of Things (IoT)-based kWh meter monitoring system that provides real-time early warning notifications when room-level electricity consumption exceeds a predefined threshold. The system was implemented in two laboratories and integrates Modbus RTU for data acquisition, MQTT for data transmission, Node-RED for data processing and visualization, and SQLite as a lightweight local database. Automatic Telegram notifications are triggered when the measured active power exceeds 2000 W. Experimental results demonstrate stable real-time data acquisition with a 30-second polling interval, where voltage and frequency remain within nominal standards, active current and power reflect actual load conditions, and the power factor remains close to 1. The proposed system is intended as a practical monitoring and early warning solution rather than an energy optimization tool. Although the evaluation is limited to two laboratory environments and employs a static threshold configuration, the proposed architecture offers a simple, effective, and replicable IoT-based early warning framework that can be extended to larger-scale deployments in future work.

Keywords – Internet of Things; Modbus RTU; MQTT; Node-RED; Energy Monitoring.

I. INTRODUCTION

MONITORING electricity consumption in a building is essential for understanding energy usage patterns in each room. Such monitoring enables the classification of rooms based on their electricity consumption levels, ranging from low to high. This classification offers valuable insights for developing energy-saving strategies, including limiting or regulating electricity usage, thereby enhancing overall energy efficiency across the building.

Currently, every building on campus, including the Politeknik Negeri Banjarmasin, is equipped with a kWh panel to monitor electricity consumption. These panels typically utilize digital meters that display key parameters, including voltage (R, S, T), power, current, and power factor. Although the kWh panels are capa-

ble of providing local information, the data is typically used only for internal monitoring and has not yet been integrated into a broader system [1]. This condition limits the distribution of energy monitoring information across buildings. Furthermore, installing kWh panels in each room is also necessary to distinguish electricity consumption at a finer level [2], which is particularly important in state university environments where budget management and utilization must be carried out efficiently.

On the other hand, most campuses, including the Politeknik Negeri Banjarmasin, already have internet infrastructure that covers almost the entire campus area. This infrastructure creates opportunities for the application of the Internet of Things (IoT) in energy monitoring systems. IoT enables devices such as kWh meters installed in various locations to be connected within an integrated system, allowing them to communicate over the internet and thereby improving the effectiveness of electricity monitoring [3–5]. Although this technology has been widely implemented in industrial and

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commercial sectors, its adoption in campus environments in Indonesia remains limited. Moreover, with the implementation of efficiency policies by the central government, public universities are encouraged to use electricity more efficiently, making the management and monitoring of energy consumption increasingly important.

Several previous studies have developed IoT-based energy monitoring systems. For example, [6] developed an IoT-based kWh meter monitoring system with a web interface that integrates a map for visualization. While the system was able to display real-time measurement data, it was limited to a single measurement point. Another study [7] proposed a Green IoT framework integrating LoRaWAN and edge-level anomaly detection for campus energy monitoring. Although efficient, this approach requires dedicated infrastructure such as LoRaWAN gateways. Similarly, [8] designed an IoT-based platform for monitoring electrical parameters and environmental conditions using the TCP/IP protocol; however, the system did not implement automatic alerts for energy consumption spikes. A related study [9] developed an IoT-based electricity meter but focused on the design of the meter itself rather than integrating existing meters into a centralized monitoring system. In addition, [10] employed SQL Server as a database solution, which requires additional installation and configuration, making it less practical for laboratory environments or small-scale facilities. Furthermore, [11] discussed data retrieval from RS-485 implemented energy meters for industrial monitoring but did not address real-time notification mechanisms.

In contrast to these studies, the present research proposes an IoT-based energy monitoring system that integrates existing kWh meters with Node-RED, the MQTT (Message Queuing Telemetry Transport) protocol, and SQLite as the database. The system is designed to enable real-time monitoring, web-based visualization, and automatic notifications via Telegram when energy consumption exceeds a defined threshold, with a case study at Building K of Politeknik Negeri Banjarmasin.

The main contributions of this research are three-fold. First, this study develops and validates a real-time

IoT-based energy monitoring system using existing kWh meters, demonstrated through deployment in two separate laboratory environments. Second, it proposes a lightweight end-to-end architecture integrating Modbus RTU, MQTT, Node-RED, and SQLite to support continuous data acquisition, processing, and visualization. Third, it implements a real-time, threshold-based notification mechanism via Telegram that enables timely operator response to excessive electricity consumption.

This approach results in an efficient multi-room monitoring model that can be replicated in other facilities while facilitating operators in taking timely action against sudden increases in electricity usage.

Fig. 1 illustrates the overall conceptual framework of the proposed IoT-based energy monitoring and early warning system. The framework demonstrates the integration of legacy power metering infrastructure with modern IoT communication and monitoring technologies. The PM1200 kWh meter provides electrical parameter measurements that are retrieved via Modbus RTU communication through an ESP32-based gateway device. The ESP32 transmits the acquired data to an MQTT broker, enabling distributed data communication using a publish–subscribe architecture.

Node-RED acts as the central processing unit that performs data parsing, visualization, storage, and notification triggering. Measurement data is stored locally using SQLite to ensure system reliability and low deployment complexity. The processed data is visualized through a web-based dashboard for real-time monitoring, while threshold-based early warning notifications are delivered via Telegram messaging. This integrated framework enables efficient, scalable, and cost-effective electricity monitoring for laboratory environments.

II. RESEARCH METHODS

The research method employs a design and development approach to build an Internet of Things (IoT)-based energy monitoring system in the Microprocessor Laboratory and the Instrumentation and Measurement Laboratory at Politeknik Negeri Banjarmasin. The system is designed to read electricity consumption data from the kWh meter device (Schneider PM1200) [12] installed on the electrical panel, using an ESP32 microcontroller [13] as the processor and data transmitter.

Data acquisition is carried out through the Modbus RTU communication protocol, and the collected data is periodically transmitted via MQTT, a lightweight publish–subscribe protocol widely used for connecting sensor devices over a network [14–16]. Node-RED, a flow-based programming platform for developing applications that collect, process, and visualize data

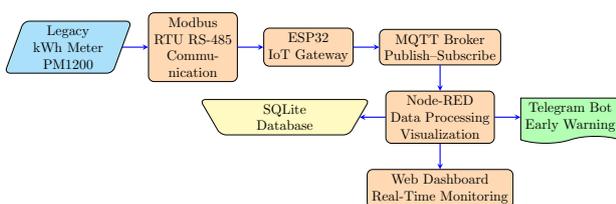


Figure 1: Conceptual Framework of IoT-Based Energy Monitoring and Early Warning System

[17], acts as a client subscribing to relevant topics from the broker to receive and process the data.

When the system detects that electricity consumption exceeds a predefined threshold, it automatically sends a notification to designated users via a Telegram bot [18]. The threshold parameter used in this study is the active power measured by the Schneider PM1200 kWh meter.

i. System Architecture Design

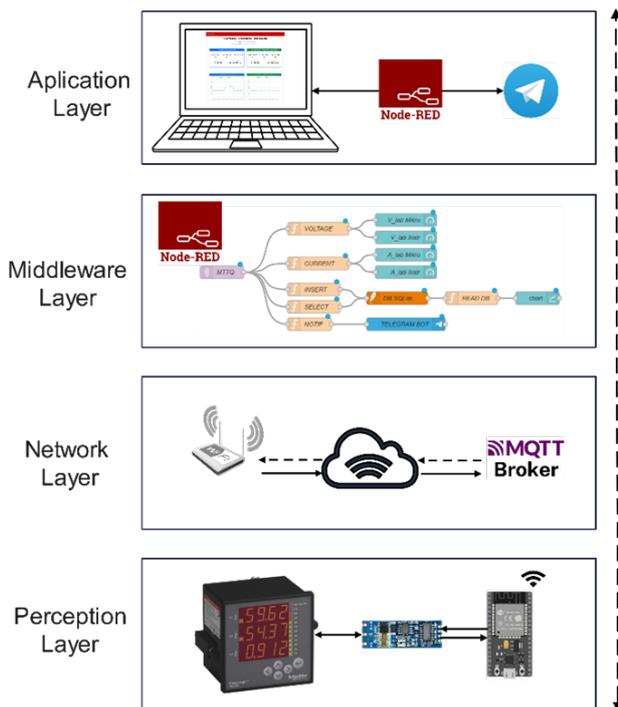


Figure 2: IoT System Architecture for Monitoring kWh Meters Based on Modbus RTU, MQTT, and Node-RED

The developed system follows an IoT architecture consisting of four layers: perception, network, middleware, and application, as illustrated in Fig. 2. In the perception layer, an ESP32 device is connected to a power meter via an RS-485 interface to periodically read electricity consumption data. The ESP32 then transmits this data to an MQTT broker through the campus internet connection, which functions as the Internet gateway.

At the network layer, the data published by the ESP32 is forwarded to a cloud-based MQTT broker. Node-RED, running on either a laptop or Raspberry Pi, subscribes to this broker to receive the data. Within the middleware layer, Node-RED processes the data and presents it in the form of a web-based dashboard.

Additionally, Node-RED is configured to send automatic notifications to users through the Telegram Bot API whenever electricity consumption exceeds a

predefined threshold. This notification mechanism represents the application layer, providing direct real-time interaction with end users.

ii. Data Communication Flow

In this system, the ESP32 microcontroller functions as a Modbus master that polls data from the Schneider PM1200 kWh meter, which acts as a Modbus slave, via the RS-485 interface using the Modbus RTU communication protocol. The parameters retrieved from the PM1200 include total active energy, voltage, and current, which serve as the primary data for monitoring electricity consumption.

The Schneider PM1200 is a commercially available and factory-calibrated kWh meter; therefore, this study does not aim to evaluate sensor calibration accuracy. Instead, the validation focuses on system-level performance, including reliable data acquisition, correct data transmission via MQTT, and consistent integration and visualization within the Node-RED-based IoT monitoring framework.

The ESP32 performs periodic polling by reading specific register addresses according to the device's user manual. Once the data is obtained, the values are encapsulated in JavaScript Object Notation (JSON) format. JSON is chosen because it is lightweight, human-readable, efficient for handling large datasets, and widely supported across various platforms such as Node-RED, making data parsing straightforward [19]. The JSON-formatted data is then transmitted to Node-RED via the MQTT protocol.

This process runs continuously to ensure that monitoring data is always updated in real time. Data acquisition is carried out by accessing Modbus registers based on individual parameter addresses listed in the user manual [20]. These registers define the address, data type, and unit required to interpret the measurement values. The main register addresses used in this system are presented in Table 1.

Table 1: Main Register on Schneider PM1200 Read by ESP32

No	Parameter	Register Address
1	VLL (Line to Neutral Voltage)	3911
2	I_avg (Current Average)	3913
3	W_total (Active Power, Total)	3903
4	PF_avg (Power Factor Average)	3907
5	Frequency	3915

The measurement parameters from the PM1200 are stored in two 16-bit Modbus registers that must be combined into a single 32-bit floating-point value in Little Endian format. For example, the VLN parameter

(line-to-neutral average voltage) is located at register address 3911, as summarized in Table 1. Since the data spans two registers, the reading is performed starting from register 3910 (offset -1) and 3911 simultaneously. Register 3910 contains the least significant bits (LSB), while register 3911 contains the most significant bits (MSB).

These two registers are then combined in Little Endian order to form a 32-bit floating-point value representing the measured parameter. The merging of the two registers into a 32-bit number is expressed in Equation (1).

$$\text{rawData} = (\text{Register}_{MSB} \ll 16) | \text{Register}_{LSB} \quad (1)$$

The raw data shown in Equation (1) is subsequently converted into a 32-bit floating-point number according to the IEEE-754 standard [21], using either data type casting or bitwise interpretation. This conversion enables the system to correctly interpret the two registers as a single floating-point value corresponding to the measured physical parameter.

iii. Data Processing and Storage

The data transmitted by the ESP32 via the MQTT protocol is received by Node-RED running on the server side. Node-RED functions as a real-time data processing platform. Once the data is received, Node-RED parses the JSON payload to extract parameter values such as voltage, current, active power, and other related variables. Each parsed data record is then stored locally using an SQLite database.

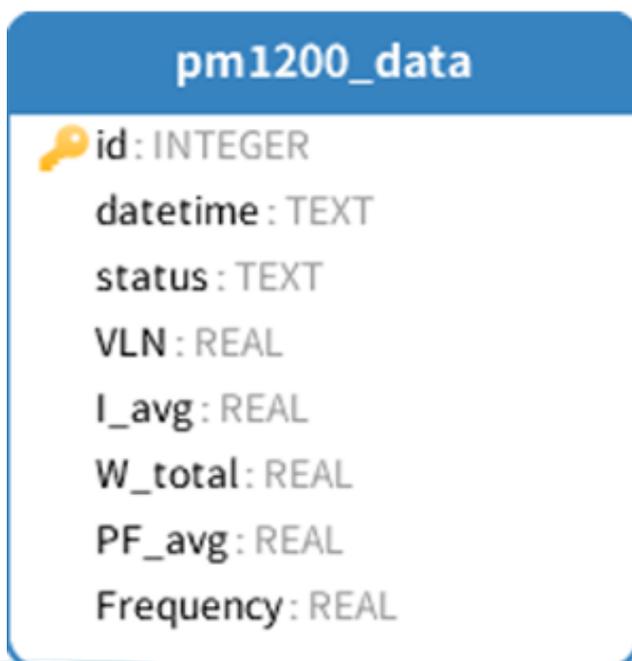


Figure 3: Table Schema Diagram

The database schema used in the system is illustrated in Fig. 3. The choice of SQLite is based on its simplicity, as it does not require additional server installation, is lightweight, and can be directly integrated into the Node-RED workflow [22]. The data is stored in a single main table consisting of columns such as *id* (primary key), *datetime* (measurement timestamp), and key measurement parameters such as total active power, line-to-neutral voltage, average current, average power factor, and frequency. The data displayed on the Node-RED dashboard is retrieved from the SQLite database based on the most recent updates.

iv. Research Procedure

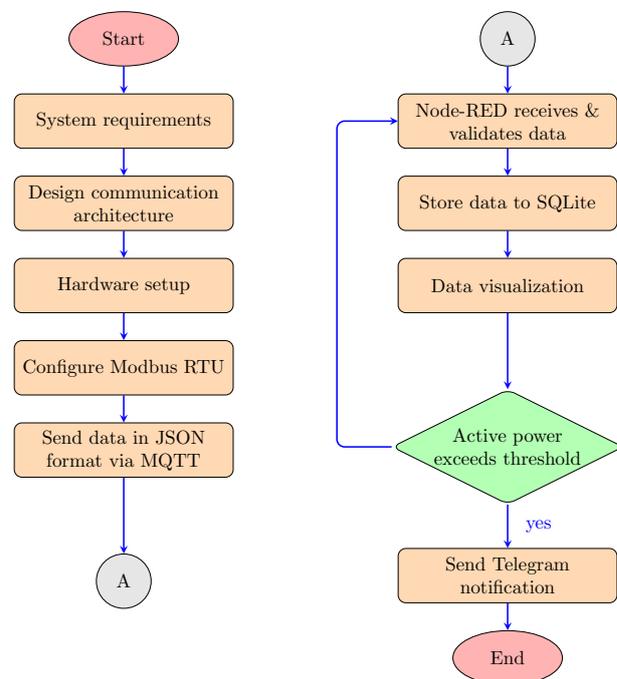


Figure 4: Research Procedure Flow Diagram

The research procedure is illustrated in Fig. 4. The procedure begins with a system requirements analysis followed by the design of the communication architecture between the PM1200 kWh meter, the ESP32 microcontroller, and the Node-RED server. Once the architecture is defined, the next stage involves configuring the hardware, including the ESP32 microcontroller and supporting devices.

Following the hardware setup, Modbus RTU communication is established between the PM1200 and ESP32 via a TTL-to-RS-485 module. The acquired data is packaged in JSON format and transmitted using the MQTT protocol. Node-RED is programmed to receive, process, and store the data into the SQLite database.

Additionally, Node-RED displays the measure-

ment parameters on a dashboard and continuously monitors the active power value by comparing it to a predefined threshold. If the active power exceeds this threshold, the system automatically sends a notification to the designated user via a Telegram bot. Otherwise, no notification is triggered.

III. RESULTS

To evaluate the developed system, experiments were conducted in the Microprocessor Laboratory and the Instrumentation and Measurement Laboratory, both located in Building K of Politeknik Negeri Banjarmasin. Data were collected from the kWh panels installed in each room. The measured total active power served as the reference for the system to trigger notifications via Telegram.

i. Data Acquisition Result

The real-time acquisition of kWh meter parameters was successfully displayed through the Node-RED dashboard, as shown in Fig. 5. The monitored parameters include line-to-neutral voltage (VLN), average current (I_{avg}), total active power (W_{total}), average power factor (PF_{avg}), and frequency. These results demonstrate that the designed system is capable of continuously collecting and presenting measurement data in real time.

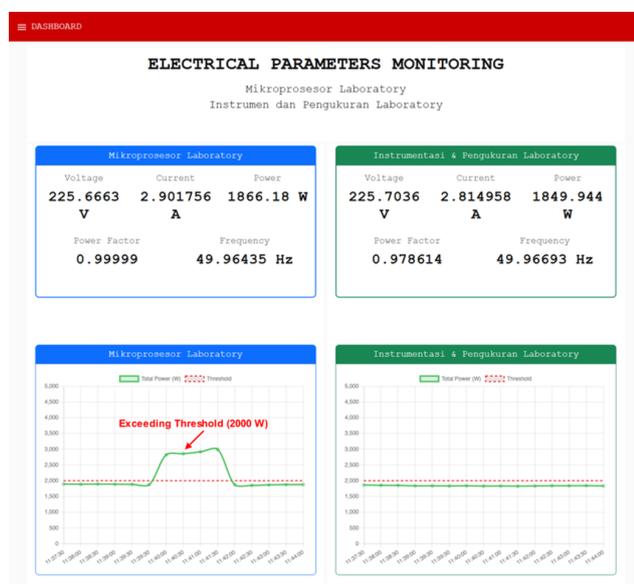


Figure 5: Node-RED Dashboard for Energy Monitoring

Furthermore, the active power measurement results indicate that the measured values exceeded the 2000 W threshold as the electrical load increased, as illustrated by the threshold line in Fig. 5. The 2000 W threshold was defined as an operational reference based on typical laboratory load characteristics and safety considerations, rather than statistical optimization or

predictive modeling. This static threshold was used to demonstrate the functionality of the early warning mechanism and can be adjusted to accommodate different usage profiles or operational requirements in future implementations. When the threshold is exceeded, the system automatically generates a notification via Telegram.

ii. Notifications via Telegram

Node-RED is configured to send messages via the Telegram Bot API whenever power consumption exceeds the 2000 W threshold. Each message includes the location, timestamp, and consumption value, as illustrated in Fig. 6. Notifications are triggered when the measured parameters, such as current or active power, surpass the predefined threshold. This function demonstrates the system's reliability in supporting early detection. The integration enhances user connectivity with the system, ensuring that users receive timely updates without the need for continuous dashboard monitoring.

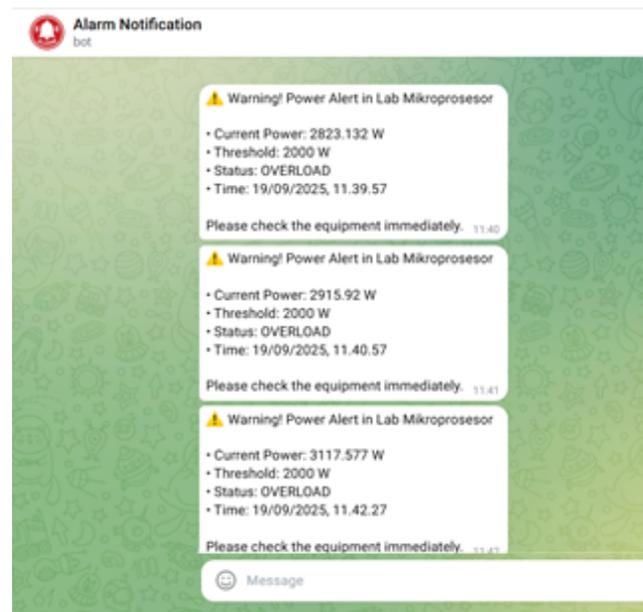


Figure 6: Screenshot of Notification on Telegram

iii. Descriptive Analysis of Measured Data

The descriptive analysis of measurement parameters from the kWh meter in the Microprocessor Laboratory is presented in Fig. 7. The line-to-neutral voltage (VLN) remained relatively stable with a median of approximately 226 V. The average current (I_{avg}) was around 2.9 A, with several outliers indicating transient load spikes. The total active power (W_{total}) showed a wider distribution with outliers exceeding 3000 W, reflecting peak load conditions. The average power factor (PF_{avg}) approached 1.0, indicating high energy

efficiency. Meanwhile, the system frequency remained consistent at around 50 Hz with very small variations, in line with nominal standards.

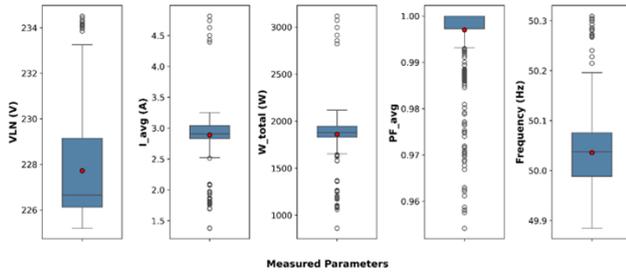


Figure 7: Boxplots of kWh Meter Measurement Parameters in the Microprocessor Laboratory

In comparison, the descriptive statistics from the Instrumentation and Measurement Laboratory are shown in Fig. 8. The line-to-neutral voltage (VLN) was highly stable with a median of about 226 V. The average current (I_{avg}) remained steady at approximately 2.79 A with minimal variation. The total active power (W_{total}) had a median of 1837 W, with no significant load spikes observed. The average power factor (PF_{avg}) was close to 1, suggesting optimal energy efficiency. The system frequency also remained stable at 50 Hz with negligible variation, consistent with the nominal grid standard.

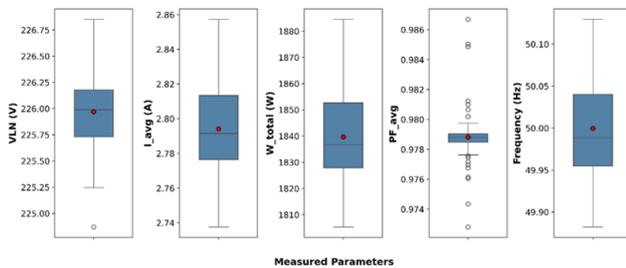


Figure 8: Boxplots of kWh Meter Measurement Parameters in the Instrumentation and Measurement Laboratory

IV. DISCUSSION

The research results demonstrate that the developed energy monitoring system operated as designed under the experimental conditions. The system evaluation was conducted under normal network operating conditions using the existing campus internet infrastructure. The robustness of the system against network failures, communication delays, or packet loss was not explicitly tested and is therefore considered beyond the scope of this study.

The system was evaluated under natural laboratory operating conditions during routine activities, without

applying controlled or systematic variations of electrical loads. Consequently, the observed load fluctuations reflect typical daily usage patterns rather than predefined experimental scenarios.

The data analysis in this study is intentionally limited to descriptive statistics, as the primary objective is to validate the functionality and operational behavior of the proposed IoT-based monitoring and early warning system. This approach is sufficient to demonstrate data stability, load variation patterns, and threshold exceedance events.

Data from kWh meters in two different laboratories were successfully acquired via Modbus RTU, transmitted using MQTT, and visualized in real time using a Node-RED dashboard. The system was also capable of sending automatic Telegram notifications when total power consumption exceeded the predefined 2000 W threshold. Stable data acquisition was observed with a polling interval of 30 seconds, and all Modbus registers were consistently read and transmitted under normal operating conditions.

These findings indicate that a Node-RED-based IoT architecture can function effectively as both a real-time monitoring platform and an operational early warning mechanism for electricity consumption across multiple laboratory environments. To further position the proposed system within existing IoT-based energy monitoring research, a quantitative comparison with previous works is presented.

i. Quantitative Comparison with Previous Works

To evaluate the performance and practical contribution of the proposed system, a quantitative comparison was conducted against several related IoT-based energy monitoring studies. The comparison focuses on key system characteristics, including monitoring capability, communication protocol, database implementation, real-time notification support, and deployment complexity. The comparison results are summarized in Table 2.

As shown in Table 2, most previous studies focused primarily on data visualization and cloud-based monitoring. For example, the system developed in [6] provided real-time monitoring but was limited to a single measurement location and did not implement automatic alert mechanisms. Meanwhile, [7] introduced a Green IoT architecture capable of multi-room monitoring using LoRaWAN and anomaly detection. However, this approach requires dedicated gateway infrastructure, increasing deployment cost and system complexity.

Similarly, the system proposed in [8] implemented multi-parameter monitoring using TCP/IP communication but lacked automated early warning capabilities.

Table 2: Quantitative Comparison with Previous IoT-Based Energy Monitoring Systems

Study	Communication Protocol	Database Type	Real-Time Notification	Multi-Room Monitoring	Infrastructure Complexity
[6]	HTTP/Web-Based	SQL Database	No	Single Point	Medium
[7]	LoRaWAN + Edge Processing	Cloud Database	Limited	Multi-Room	High
[8]	TCP/IP	Cloud Storage	No	Multi-Room	Medium
[9]	IoT Embedded Meter Design	Not Specified	No	Single Point	Medium
[10]	Cloud-Based IoT	SQL Server	No	Multi-Room	High
Proposed System	Modbus RTU + MQTT	SQLite (Local)	Yes	Multi-Room	Low

Table 3: System Performance Metrics

Metric	Measurement	Result	Description
Polling Interval	30 seconds	(stable)	Consistent data acquisition interval from PM1200 meter
Data Acquisition Success Rate	100%	during testing	All Modbus registers were successfully read under normal conditions
Notification Latency	≈ 1–3 seconds		Delay between threshold exceedance and Telegram notification
System Availability	Continuous operation	during testing	No service interruption observed during laboratory monitoring

The work presented in [9] emphasized the design of an IoT-based energy meter, focusing more on hardware development rather than integration with existing meters. In addition, [10] implemented a cloud-based smart meter system using SQL Server, which provides robust data storage but requires additional server configuration and maintenance.

In contrast, the proposed system combines Modbus RTU and MQTT communication to enable reliable real-time data acquisition while maintaining low infrastructure complexity. The use of SQLite enables lightweight local data storage without requiring additional database servers. Furthermore, the integration of Telegram-based notification provides a direct and responsive early warning mechanism that is not commonly implemented in previous studies.

From a deployment perspective, the proposed architecture demonstrates improved practicality by sup-

porting multi-room monitoring while maintaining low implementation complexity. This balance between functionality and deployment simplicity represents a key advantage of the proposed system for educational and small-scale facility environments.

ii. System Performance Metrics Comparison

To further evaluate system performance, several operational metrics were analyzed, including polling interval stability, data acquisition success rate, notification response latency, and system availability. These metrics provide quantitative insight into the reliability of the proposed IoT monitoring architecture.

The performance evaluation results are summarized in Table 3. The polling interval stability refers to the consistency of data acquisition timing from the kWh meter, while notification latency represents the time required for the system to send alerts after threshold exceedance.

As presented in Table 3, the system maintained stable real-time monitoring performance under normal network conditions. The notification latency remained low due to the lightweight MQTT publish–subscribe communication mechanism. These results indicate that the proposed architecture is suitable for operational early warning monitoring applications.

iii. Scalability Evaluation

Scalability is an important factor in IoT-based monitoring systems, particularly for campus or multi-building deployments. The proposed system architecture supports scalability through MQTT-based communication and modular Node-RED workflow design.

The scalability characteristics of the proposed system compared with conventional monitoring architectures are summarized in Table 4. The comparison evaluates scalability based on device integration capability, network traffic efficiency, and deployment flexibility.

As shown in Table 4, the publish–subscribe architecture enables flexible integration of additional monitoring nodes without significant system redesign. This architecture allows the system to scale efficiently from laboratory-level deployment to building- or campus-level monitoring systems.

iv. Cost Efficiency Analysis

Cost efficiency is a critical consideration in implementing IoT monitoring systems, especially in educational institutions with limited infrastructure budgets. The proposed system emphasizes the use of open-source software and commercially available hardware to reduce deployment costs.

Table 4: Scalability Comparison of IoT Monitoring Architectures

Aspect	Conventional Monitoring	Proposed IoT Architecture
Device Integration	Limited to fixed monitoring nodes	Supports multiple distributed kWh meters
Communication Model	Point-to-point communication	Publish-subscribe MQTT communication
System Expansion	Requires major re-design	Supports modular and incremental expansion
Network Efficiency	Higher bandwidth consumption	Optimized bandwidth usage via MQTT

The cost efficiency comparison between the proposed system and conventional monitoring approaches is presented in Table 5. The comparison considers hardware requirements, software licensing, and operational maintenance complexity.

Table 5 shows that the proposed system significantly reduces deployment and maintenance costs by utilizing lightweight microcontrollers, open-source software platforms, and existing network infrastructure. This cost efficiency makes the proposed architecture particularly suitable for small- and medium-scale monitoring applications.

Overall, the quantitative evaluation across performance metrics, scalability, and cost efficiency demonstrates that the proposed IoT-based monitoring system provides a balanced trade-off between functionality, reliability, and deployment practicality.

v. Security and Reliability Considerations

Security and reliability are critical aspects of IoT-based monitoring systems, particularly when the system is deployed across distributed environments and connected through public or campus networks. The proposed monitoring architecture incorporates several basic security and reliability measures to ensure stable system operation and data integrity during normal operating conditions.

From a communication security perspective, the MQTT protocol supports authentication mechanisms through username and password credentials, which were implemented in the system to restrict unauthorized access to the MQTT broker. In addition, network access to the Node-RED server is limited within the campus network environment to reduce exposure to external threats. Although end-to-end encryption using Transport Layer Security (TLS) was not implemented

in the current system configuration, MQTT supports secure communication through TLS, which can be incorporated in future system deployments to enhance communication security.

Data reliability is supported through the publish-subscribe architecture of MQTT, which enables asynchronous communication between devices and ensures message delivery consistency under stable network conditions. The polling mechanism implemented in the ESP32 ensures that Modbus register readings are performed periodically and systematically. The successful reading and transmission of Modbus data during system operation indicate stable communication between the PM1200 kWh meter, ESP32 microcontroller, and Node-RED server.

Furthermore, the use of SQLite as a local embedded database enhances system reliability by allowing data storage independent of external database servers. This approach reduces system vulnerability to external server failures and minimizes dependency on cloud-based storage services. The local storage mechanism also enables faster data retrieval for real-time dashboard visualization.

Table 5: Cost Efficiency Comparison

Component	Conventional Monitoring	Proposed IoT Monitoring System
Data Processing Platform	Proprietary SCADA or monitoring software	Node-RED (Open Source)
Database System	Dedicated SQL Server	SQLite (Embedded Database)
Communication Infrastructure	Dedicated monitoring network	Existing campus internet network
Hardware Controller	Industrial gateway devices	ESP32 microcontroller
Deployment Cost	High	Low
Maintenance Complexity	Moderate to High	Low

Despite these reliability advantages, the system currently does not include advanced fault tolerance mechanisms such as automatic reconnection strategies during network interruptions, data buffering during communication failures, or redundant communication paths. The robustness of the system under adverse network conditions, including packet loss, latency variation, or broker disconnection, was not evaluated and remains a limitation of this study.

From an operational reliability standpoint, the system demonstrated continuous monitoring performance during laboratory operation, with stable data acquisition and notification delivery under normal network conditions. However, long-term reliability testing un-

der varying environmental and network conditions has not yet been performed.

Future system development may enhance security by implementing TLS-based encrypted MQTT communication, token-based authentication, and role-based access control for dashboard monitoring. Reliability improvements may include data buffering mechanisms, automatic broker failover strategies, and redundant monitoring nodes to support high-availability monitoring architectures.

Overall, although the current system implements fundamental security and reliability measures sufficient for laboratory-scale deployment, further enhancements are required to support large-scale and mission-critical monitoring environments.

vi. Practical Deployment and Real-World Impact

The proposed IoT-based energy monitoring system demonstrates practical applicability for real-world deployment, particularly in educational institutions and laboratory environments that require efficient electricity consumption management. The system was designed using commercially available hardware and open-source software platforms, enabling straightforward replication and deployment without requiring specialized infrastructure.

From an operational perspective, the system improves energy monitoring efficiency by providing real-time visibility of electricity consumption at the room level. This capability enables laboratory managers and technical staff to identify abnormal power usage patterns and respond promptly to potential overload conditions. The automatic Telegram-based notification mechanism reduces reliance on manual monitoring, thereby improving operational responsiveness and reducing the risk of equipment damage caused by excessive electrical loads.

In the context of campus energy management, the proposed monitoring framework supports data-driven decision making by providing continuous historical consumption records. These records can be utilized to analyze usage patterns, evaluate laboratory energy performance, and support planning for load balancing or scheduling optimization. The ability to monitor electricity consumption across multiple laboratories also supports the implementation of smart campus initiatives and sustainability-oriented energy management programs.

The use of lightweight hardware such as the ESP32 microcontroller and embedded database solutions such as SQLite significantly reduces deployment cost and maintenance complexity. This characteristic makes the system particularly suitable for small- and

medium-scale institutions that require monitoring solutions with limited technical resources. Furthermore, the modular architecture allows incremental expansion to additional monitoring locations without requiring major system redesign.

Beyond laboratory environments, the proposed system architecture can potentially be applied to other facility types, including classrooms, office buildings, and industrial training facilities. The flexibility of MQTT-based communication and Node-RED workflow programming enables integration with additional sensors or control devices, supporting the development of broader smart building monitoring ecosystems.

From a sustainability perspective, improved monitoring and early detection of abnormal electricity consumption contribute indirectly to energy conservation and operational efficiency. By enabling timely corrective actions, the system supports institutional efforts to reduce unnecessary energy waste and improve overall electricity utilization efficiency.

Although the system demonstrates strong practical deployment potential, large-scale implementation across multiple buildings requires additional considerations, including network infrastructure scalability, centralized data aggregation strategies, and enhanced cybersecurity mechanisms. Addressing these aspects represents an important direction for future research and real-world deployment optimization.

Overall, the proposed system provides a practical, scalable, and cost-effective solution that bridges legacy power metering infrastructure with modern IoT-based monitoring technologies, supporting the transition toward smart and energy-efficient facility management.

The main contribution of this study lies in the integration of Modbus RTU, MQTT, Node-RED, and SQLite into a simple yet effective end-to-end energy monitoring framework. Unlike prior works that primarily focus on visualization and data logging, this study incorporates a real-time, threshold-based notification mechanism to enable timely operator response to sudden increases in electricity consumption.

While the proposed architecture demonstrates a practical and extensible framework for laboratory energy monitoring, this study has several limitations. The system was validated only in two laboratories, employed a statically defined notification threshold, and did not evaluate network robustness under failure conditions. In addition, the alert mechanism is currently limited to the Telegram platform. These limitations indicate opportunities for future work, including large-scale deployment, adaptive thresholding, and comprehensive network performance evaluation.

Future research may address these limitations by

incorporating adaptive threshold mechanisms based on machine learning-based anomaly detection, conducting controlled load variation experiments, evaluating network performance under adverse conditions, and expanding notification delivery to multiple platforms.

V. CONCLUSION

This study presents an IoT-based energy monitoring system that integrates Modbus RTU, MQTT, Node-RED, and SQLite to enable real-time data acquisition, visualization, and early warning notifications for electricity consumption in laboratory environments. The system successfully acquired and transmitted kWh meter data from two laboratories with a stable polling interval of 30 seconds and reliably generated Telegram notifications when total active power exceeded the pre-defined 2000 W threshold, demonstrating consistent operational performance under normal network conditions.

From a broader perspective, this work contributes to the field of IoT-based energy monitoring by demonstrating that a lightweight, flow-based architecture can function not only as a monitoring tool but also as an operational early warning mechanism without requiring complex infrastructure or proprietary platforms. Practically, the system reduces the need for continuous manual supervision by providing automated notifications, supporting timely responses to abnormal energy usage in laboratory settings. Academically, the study provides a replicable reference architecture for integrating legacy power meters into modern IoT frameworks using open-source tools.

Nevertheless, this study has several limitations. The system was validated only in two laboratories, the notification threshold was statically defined, and network robustness under failure conditions was not evaluated. These limitations indicate opportunities for future research, including adaptive thresholding using machine learning-based anomaly detection, controlled load variation experiments, network performance evaluation, and deployment at a larger multi-building scale with multi-platform notification support.

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