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Smart Lab Energy – for Real-Time Electricity Consumption Monitoring in The Electronics Engineering Technology Laboratory, Polytechnic State of Lampung

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Abstract. *This study aims to design and implement an Internet of Things (IoT)-based electrical energy monitoring system capable of displaying real-time data in a vocational education laboratory environment. The developed system utilises an ESP32 microcontroller and a PZEM-004T sensor to accurately measure voltage, current, power, and energy parameters. The measurement data are transmitted to a cloud server and visualised through a digital dashboard, allowing users to monitor and analyse energy usage easily. The test results show that the system performs well and produces consistent data compared to manual measurements using a digital clamp meter. The implementation of this system has the potential to improve energy efficiency, reduce power waste, and support the application of a green campus concept in higher education institutions. Moreover, this system can be used as a project-based learning medium to enhance students' competencies in embedded systems, sensors, and IoT-based automation..*

1. INTRODUCTION

Energy efficiency has become an essential issue in line with the rapid development of technology and digitalisation, including in vocational education environments such as the Electronics Engineering Technology Laboratory (TRE) at Polytechnic State of Lampung. This laboratory utilises various practical equipment that consumes significant amounts of electrical energy; however, its management system is still conventional, relying on manual recording. This condition leads to low user awareness regarding energy efficiency and unmeasured electricity consumption patterns in real time. Therefore, a technology-based solution is needed to enhance energy efficiency while providing accurate data to support more innovative and sustainable laboratory management.[1].

In the era of Industry 4.0 towards Society 5.0, the application of Internet of Things (IoT) technology becomes key in creating efficient and adaptive energy management systems. IoT enables real-time power consumption monitoring and data-driven decision making by integrating sensors, microcontrollers, and cloud platforms. Implementing IoT in intelligent building systems can reduce energy consumption by up to 30% and operational costs by 20% through device control optimisation and continuous data analysis [2]. Furthermore, IoT supports integrating various systems such as lighting, temperature, and security, creating an efficient and comfortable environment. These research findings indicate that IoT is relevant to industrial and commercial sectors and has great potential to be implemented in educational environments as part of the effort towards a sustainable, innovative campus.

Based on these considerations, the Smart Lab Energy concept becomes an ideal solution by integrating IoT sensors, microcontrollers, data networks, and machine learning algorithms to monitor and predict electrical power consumption in real time [3]. This system not only serves as a tool for energy efficiency and operational cost savings, but also as an innovative learning medium that supports project-based learning and implementing green campus initiatives at Polinela. Therefore, this research is titled "Smart Lab Energy – Implementation of an Intelligent System for Real-Time Prediction and Monitoring of Electrical Power Consumption in the Laboratory," It aims to develop a system capable of optimising energy efficiency while improving technological literacy among vocational students.

2. LITERATURE REVIEW

2.1 Smart Laboratory

A Smart Laboratory (Smart Lab) is a modern laboratory concept that integrates digital technology, automation, and the Internet of Things (IoT) to create an efficient, safe, and adaptive working environment. In the IoT-based Smart Laboratory System, Banagar and Khattar state that IoT can automate laboratories, helping achieve more effective power consumption, minimize human intervention, and enable easy device monitoring [4].

2.2 Internet of Things in Monitoring Energi

The Internet of Things (IoT) is a technology that enables various electronic devices to connect via the internet to collect, transmit, and analyze data in real time, including for monitoring electrical energy consumption. The implementation of IoT in electrical power monitoring systems allows for the direct measurement of parameters such as voltage, current, and power through the integration of sensors and microcontrollers connected to digital platforms. According to research on IoT-Based Electrical Power Monitoring Systems for Real-Time Energy Consumption Monitoring, the use of NodeMCU and PZEM-004T sensors connected to the Blynk application has proven capable of displaying power consumption and electricity cost data with high accuracy, as well as helping users control electrical loads and improve energy efficiency [5]. Meanwhile, a Three-Phase Power Monitoring System Based on IoT using PZEM-004T sensors and Arduino microcontrollers is also able to display real-time voltage, current, and power data via the Blynk application, with a data transmission range of up to 30 meters and a response time of less than five seconds [6]. Integrating IoT-based monitoring and automatic control systems is essential for innovative, efficient, and sustainable energy management across various sectors, including vocational education laboratories.

2.3 Energy Consumption Prediction System

Energy consumption prediction systems play a crucial role in supporting efficient power usage, especially in educational laboratory environments with high electricity consumption. The government, through the Ministry of Energy and Mineral Resources (ESDM), also continues to promote energy conservation in the education sector, one of which is through the Energy Saving Program in 24 Schools conducted by the Directorate General of New, Renewable Energy, and Energy Conservation (EBTKE) as part of the national effort to save energy in the public sector [7]. Implementing Internet of Things (IoT) technology is a strategic step in creating an energy consumption prediction system capable of real-time monitoring of electrical loads using current and voltage sensors integrated with microcontrollers. This approach is also in line with national energy efficiency policies. It supports the RUPTL 2021–2030 targets of PT PLN (Persero), which emphasize increasing the contribution of new and renewable energy (NRE) to 23% by 2025 and 35% by 2034 [7]. IoT-based energy consumption prediction systems can measure various parameters such as voltage, current, power, and energy while analyzing usage patterns to produce accurate predictions. The integration of NodeMCU ESP8266, PZEM-004T sensor, and DHT11 can measure and display energy data and environmental parameters in real time through the ThingSpeak platform, with an accuracy rate of up to 95–99% [8]. The IoT-based Smart Watt Meter system using Wemos D1R1 and the PZEM-004T sensor can also predict electricity costs online. It is integrated with an Android application to provide more efficient energy usage information [8]. In addition, an IoT system with the PZEM-004T sensor connected to an online dashboard can help users understand power consumption patterns and significantly reduce energy waste.

2.4 Implementation of Intelligent Systems in Educational Environments

Laboratories serve as centres for practice, experimentation, and applied research requiring intelligent systems to monitor power consumption while providing user feedback, fostering energy efficiency awareness and an understanding of modern technology. However, the intensive use of electronic equipment often leads to energy waste and a lack of real-time monitoring. Therefore, implementing systems based on the Internet of Things (IoT), Artificial Intelligence (AI), and automation has become a strategic step toward realizing modern and efficient laboratories. Integrating sensors and microcontrollers (such as Arduino or ESP32) enables monitoring of energy usage, temperature, humidity, and device status, with data transmitted to a server or cloud and visualized through a digital dashboard [9].

The system also enables automatic control, such as cutting off power to unused equipment, adjusting lighting or air conditioning according to laboratory schedules, and sending notifications when power surges occur. In addition to improving technical efficiency, the intelligent system serves as a project-based learning medium in which students are directly involved in the design, programming, and development of monitoring and automatic control systems. This strengthens embedded systems, sensors, automation, and data analytics competencies relevant to industrial needs. Implementing intelligent systems also aligns with government policies on transforming vocational education and campus digitalization, supporting polytechnics as centres of applied innovation and producing highly skilled, work-ready human resources [10].

2.5 Current, Voltage, and Power

Electric current occurs due to the movement of electric charge, measured in coulombs, which flows through a circuit to reach a particular path. The current rate of charge change per unit time is measured in amperes (A). Electric voltage is the difference in potential energy between two points, measured in volts (V), or can be described as joules per coulomb. Electric power is the rate at which energy is absorbed or emitted per second, measured in watts (W) [11].

2.6 Electrical Energy

Electrical energy is a form of energy applied in specific situations. The amount of electrical energy an electrical device uses is calculated by multiplying the electric voltage (V), electric current (I), and other relevant factors. The mathematical equation 1 is as follows [12].

$$P = V \times I \tag{1}$$

P : power in watts (W)
V : voltage in volts (V)
I : electric current in amperes (A)

If we know the current (I) and resistance (R) values in a circuit, we can apply the power formula in another form derived from Ohm's law. Ohm’s law states that the voltage (V) applied to an element in an electrical circuit is proportional to the current flowing through it and inversely proportional to the element's resistance [13].

$$V = I \times R \tag{2}$$

By substituting this equation into the basic power formula, we obtain:

$$P = I^2 \times R \tag{3}$$

This formula indicates that the power absorbed by a component in an electrical circuit is proportional to the square of the current flowing through the element and also proportional to that component's resistance [14]. The following is the calculation of the load used in watt-hours (Wh) using the equation.

$$Wh = \frac{Power\ (w) \times Time\ (s)}{3600} \tag{4}$$

2.7 Dashboard Firebase

The Firebase Dashboard is a data visualisation system integrated with Internet of Things (IoT) devices to monitor real-time electricity consumption. A microcontroller or IoT gateway processes data obtained from current and voltage sensors, and then sends it to a cloud-based storage server. Through the Firebase platform, this data can be presented in graphs, numerical indicators, or interactive charts that are easy for users to understand. Such a system can display energy consumption information accurately and dynamically, facilitating efficient monitoring and analysis of electrical system performance [15]. Integrating Firebase as a cloud-based monitoring dashboard also supports implementing adaptive, transparent, and sustainable IoT systems in energy management within educational laboratory environments [16].

3. RESEARCH METHOD

The method used in this project is quantitative comparative, which compares two or more groups, variables, or specific conditions using numerical data. The primary focus of this method is to identify significant differences between the objects being compared based on quantitative measurements. The quantitative comparative method is highly effective for analyzing changes in electricity consumption before and after the implementation of an Internet of Things (IoT)-based system, as it can objectively demonstrate value differences based on measurable data [17]. This approach is also used to test hypotheses regarding the existence of differences between two or more variables, making the results a reliable basis for data-driven decision making.

In the context of the Smart Lab Energy System project, the quantitative comparative method is used to compare the level of electricity consumption in the laboratory before and after the implementation of the intelligent system based on the Firebest Dashboard. Numerical data obtained from current and voltage sensors is recorded over a specific period, and then statistically analyzed to determine whether there are significant differences in power consumption patterns. The analysis results are expected to visualize energy usage and provide empirical evidence regarding the effectiveness of the developed monitoring and prediction system. In addition, this method can be extended to compare efficiency between laboratory rooms, differences in electricity consumption between peak and off-peak hours, and performance comparisons between the intelligent system and conventional methods. Thus, the quantitative comparative method enables the Smart Lab Energy project to obtain an objective, measurable, and scientific picture of the impact of system implementation on energy savings and efficiency [18].

3.1 Device Flowchart

The system flowchart in Figure 1 illustrates the workflow of the IoT-based Smart Lab Energy system that has been developed. This diagram outlines the process stages, starting with sensor data acquisition and data transmission over the network and ending with the visualization of monitoring results on the dashboard.

Based on Figure 1, the system begins with the initialization of the ESP32 microcontroller, which serves as the main control center. The microcontroller reads voltage, current, power, and energy data through the PZEM-004T sensor. Next, the device connects to the WiFi network and the MQTT broker to ensure that data can be sent to the server. If the connection fails, the system will automatically attempt to reconnect. Successfully transmitted data is processed using Node-RED to parse the JSON format, then stored in a database and re-published to Firebase. The final result of this process is visualized through the monitoring dashboard, allowing users to monitor electricity consumption in real time.

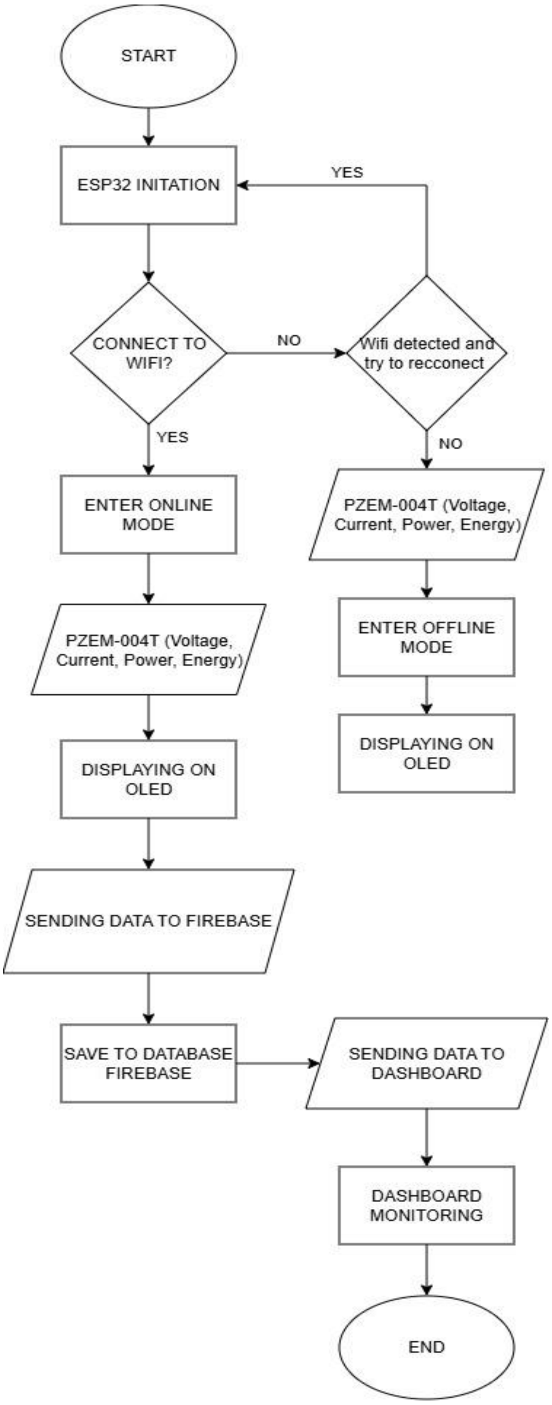

Figure 1 Device Flowchart

3.2 *Wiring Diagram*

The monitoring and control system's design uses the ESP32 Dev Kit V4 as the central controller, which is connected to various supporting components such as relays, the PZEM-004T sensor, adapters, and load sockets. The following figure shows the circuit diagram of the system used.

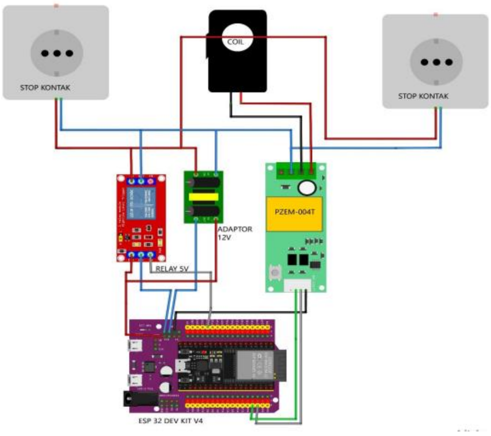

Figure 2 Wiring Diagram

Based on the circuit diagram, the ESP32 Dev Kit V4 is the central controller that receives data from the PZEM-004T sensor to measure voltage, current, power, and electrical energy, as well as from the coil (SCT) to detect current. The ESP32 processes the data obtained and can then be displayed or sent to a monitoring application. In addition, the 5V relay connected to the ESP32 is an automatic switch to control the electric current at the socket, allowing the electrical load to be manually and automatically controlled. A 12V adapter is the main power source for the circuit, and it also supports this system.

3.3 *Block Diagram*

The IoT-based electrical energy monitoring and control system is designed using the ESP32 module as the central controller. Data from various sensors is processed and transmitted over the internet, allowing it to be monitored using the Blynk application. The following figure shows the block diagram of the system used.

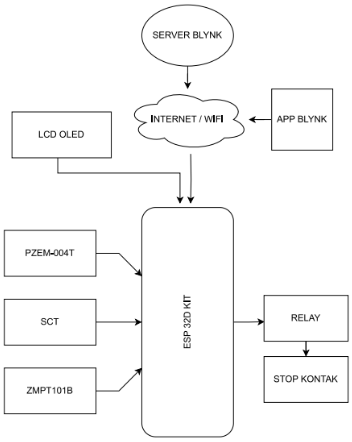

Figure 3 Block Diagram

Based on the block diagram, the ESP32 receives input from several sensors: the PZEM-004T for measuring electrical parameters, the SCT as a current sensor, and the ZMPT101B for measuring AC voltage. The measurement results are displayed on the OLED LCD and sent to the Blynk server for monitoring through the Blynk application. In addition, the ESP32 controls a relay connected to the socket, allowing users to turn electrical loads on or off manually or automatically via the application.

4. RESULTS AND DISCUSSION

Measurements of voltage, current, power, and electrical energy parameters were carried out during the learning period to obtain an overview of the electricity consumption patterns in the Electronics Engineering Laboratory. The results of these measurements are then presented in the form of line charts to facilitate analysis and visually display the relationships between parameters. The following graph presents electricity usage data based on students' computer usage activities in the laboratory.

4.1 Research Results

Observations were conducted for six hours of laboratory activities, from 07:00 to 13:00 WIB, using the PZEM-004T sensor to monitor real-time electricity consumption. The obtained data show voltage, current, power, and energy values change in line with student practicum activities in the Electronics Engineering Technology Laboratory. It was observed that energy consumption in the laboratory varied according to student activities during practicum hours. Between 07:00 and 09:00, current and power values were relatively high (averaging 0.88 A and 111 W). This indicates that during the early hours, most laboratory equipment, such as oscilloscopes, power supplies, soldering irons, and computers, was activated in preparation for practicum activities. Between 10:00 and 11:00, the measured power decreased slightly from 106.5 W to 88.1 W.

This decline indicates that some students had completed their practical work or were only using specific equipment with lighter loads. At 12:00, both current and power dropped to 0 A and 0 W, indicating that no practicum activities were taking place—possibly due to lunch break or a session change. However, the energy value increased slightly from 2.855 kWh to 2.877 kWh due to residual standby power consumption from connected devices.

Table 1 PZEM-004T Sensor Reading Results

Time	Voltage	Current	Power	Energy
7:00	209.2	0.917	116.6	2.43
8:00	210.9	0.867	109.8	2.542
9:00	207.3	0.858	108.1	2.651
10:00	220.5	0.816	106.5	2.758
11:00	220.4	0.664	88.1	2.855
12:00	212.8	0	0	2.877
13:00	212.7	0.549	68.9	2.919

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Subsequently, at 13:00, the current rose again to 0.549 A with a power of 68.9 W, indicating that laboratory activities had resumed, although with lower intensity than in the morning. Overall, the voltage remained stable in the 207–221 V range, reflecting a reliable power supply from the campus electrical network without significant fluctuations. The linear increase in energy shows that the Smart Lab Energy system can record electricity consumption continuously and accurately throughout the observation period.

These results illustrate that electricity usage in the laboratory correlates directly with the schedule and intensity of student practicum activities. The monitoring system based on the PZEM-004T sensor successfully provides representative information on hourly energy consumption patterns, which can later serve as a basis for evaluating energy use efficiency and planning electricity savings on campus.

4.2 Voltage Measurement Results

As shown in Figure 4, the electrical voltage fluctuated from 212 V at 07:00 and increased to a maximum value of 220 V at 10:00. This increase occurred due to learning activities, during which many computers were in use, causing the power supply to become more stable. After 10:00, the voltage gradually decreased, reaching 213 V at 13:00. This decline was caused by a reduction in computer usage intensity after peak hours, resulting in a decrease in electrical load.

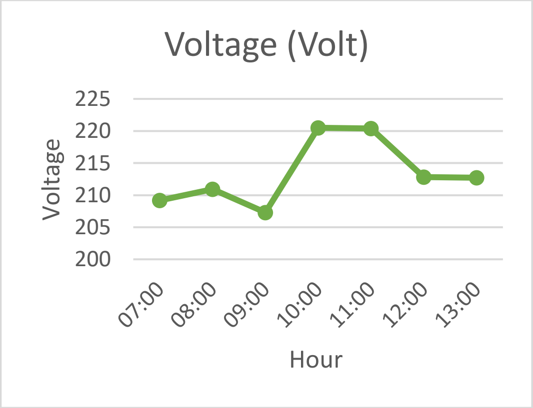

Figure 4 Voltage Measurement Results

4.3 Current Measurement Results

Electric current is measured to determine the amount of load drawn from the electrical network according to learning activities. As shown in Figure 5, the electric current fluctuates in accordance with the intensity of learning activities. At 07:00, the current was recorded at 0.8 A and increased to 1.1 A at 08:00 when more computers were in use. After that, the current gradually decreased to 0.9 A at 11:00. A sharp drop occurred at 12:00, with the current reaching 0 A, indicating that the computers were turned off during the lunch break. Once learning activities

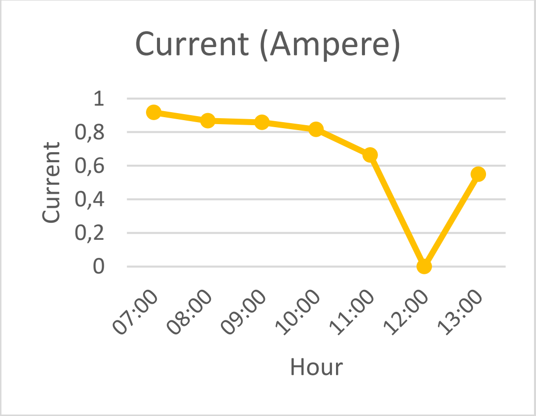

Figure 5 Current Measurement Results

4.4 Power Measurement Results

Electric power is observed to identify changes in electricity consumption according to the number of computers in operation.

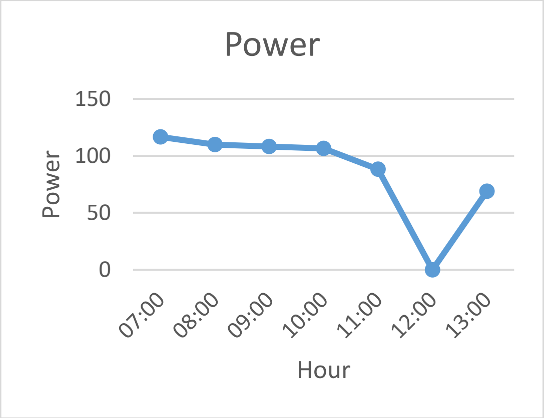

Figure 6 Power Measurement Results

As shown in Figure 6, the electric power undergoes significant changes following the number of computers in use. At 07:00, the power was recorded at 160 W and gradually decreased to 110 W by 11:00. A sharp drop occurred at 12:00, with the power reaching 0 W, indicating that learning activities ceased during the break. After the learning session resumed, the power increased again to 70 W at 13:00, although it was not as high as in the earlier hours.

4.5 Energy Measurement Results

Electrical energy is measured to determine the accumulated power consumption during the learning period in the laboratory.

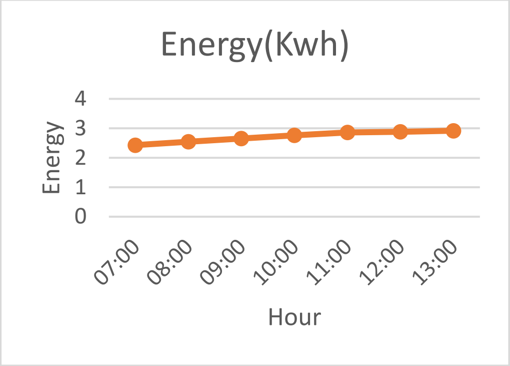

Figure 7 Energy Measurement Results

As shown in Figure 7, the electrical energy displays a consistent upward trend from 2.3 kWh at 07:00 to 2.9 kWh at 13:00. This occurs because energy is cumulative over the duration of use. As learning activities continue and computers remain on, electricity consumption keeps increasing even though current and power may decrease during certain hours.

4.6 Manual Measurement Results Using Digital Clamp Meter

Table 2 Digital Clamp Measurement

Time	Voltage (V)	Current (A)
7:00	201.97	0.874
8:00	215.96	0.907
9:00	202.39	0.827
10:00	221.24	0.798
11:00	209.7	0.671
12:00	221.71	0
13:00	221.22	0.568

Manual measurements using a digital clamp meter were carried out every hour from 07:00 to 13:00 WIB to obtain voltage and current data for the electrical load in the Electronics Engineering Technology Laboratory. These values were compared to the Smart Lab Energy system based on the PZEM-004T sensor.

The observations showed that the measured voltage ranged from 201–221 V, while the load current was between 0.56–0.90 A. The voltage remained relatively stable throughout the observation period, with a slight increase between 10:00 and 13:00, indicating that the power supply from the electrical network was in good condition. The electric current exhibited a fluctuating pattern that followed equipment usage in the laboratory. At 07:00–08:00, the current reached its highest value (around 0.87–0.90 A), coinciding with the start of student practicum activities. Afterwards, the current gradually decreased to 0.67 A at 11:00 and reached 0 A at 12:00, indicating a break in practicum activities. At 13:00, the current rose again to 0.57 A, suggesting that some laboratory activities had resumed.

Overall, the measurements obtained using the digital clamp meter showed a pattern of electricity usage consistent with the readings from the PZEM-004T sensor, with natural variations due to the instantaneous nature of manual measurements. The relatively stable values and absence of extreme spikes indicate that the laboratory's electrical installation operated efficiently and reliably throughout the observation period.

5. CONCLUSION

Based on the results of the design, implementation, and testing of the Smart Lab Energy system, the integration of IoT-based technology using the ESP32 microcontroller and PZEM-004T sensor effectively enables real-time monitoring of electrical energy consumption in the Electronics Engineering Laboratory. The system successfully records and analyzes high voltage, current, power, and energy data accurately, displaying it through a digital dashboard that facilitates continuous supervision and management of power usage. The comparison between IoT-based monitoring results and manual measurements using a digital clamp meter shows consistent outcomes, indicating the system’s reliability and efficiency. Moreover, implementing this intelligent monitoring system reduces unnecessary energy consumption, enhances operational efficiency, and promotes awareness of sustainable energy use among students and academic staff.

This system can be developed further by integrating predictive analytics using machine learning algorithms to estimate energy trends and optimise control functions automatically based on consumption patterns. Such advancements will strengthen the role of innovative laboratories as practical learning media and as real applications of Industry 4.0 technology in educational institutions.

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