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Monitoring Of Household Electricity Usage Based On The Internet Of Things

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ABSTRACT

The increasing demand for energy efficiency in the digital era has accelerated the adoption of Internet of Things (IoT)-based technologies in household electricity management. This study presents the design and implementation of an IoT-based real-time electricity monitoring system using the ESP32 microcontroller and PZEM-004T sensor, integrated with the Blynk application for remote access. The system measures voltage, current, power, energy consumption, and cost, displaying data on both an LCD and a mobile interface. Experimental testing involved household appliances such as fans and rice cookers under individual and combined usage, with measurements taken at 15-minute intervals. The results demonstrated strong agreement between theoretical calculations and real-time data, with the measured values slightly higher due to the dynamic nature of electrical loads. The system achieved a low average error rate of 0.17%, with a maximum error of 0.30%. These findings confirm the accuracy and reliability of the system, supporting its potential for enhancing user awareness, improving billing precision, and contributing to sustainable energy use in smart home applications.

Keywords
IoT-Based Energy Monitoring, ESP32, PZEM-004T Sensor, Blynk Application, Smart Home Electricity Management

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INTRODUCTION

In today's digital era, the demand for energy efficiency and the automation of electrical systems is steadily increasing. Alongside rapid technological advancement, the Internet of Things (IoT) has emerged as a pivotal solution for developing smarter and more efficient electrical power monitoring systems. IoT facilitates real-time monitoring of electrical parameters, automated data processing, and remote control of electrical devices—features that are highly beneficial across both household and industrial applications [1]. Global power consumption persists in its upward trajectory. The International Energy Agency (IEA) reported that worldwide power demand surged by 6% in 2021, marking the most significant annual growth in decades. This increase has heightened the demand for technology advancements in energy monitoring and conservation. IoT-based monitoring solutions provide real-time surveillance and regulation of energy consumption. Numerous studies indicate that these systems can decrease electricity use by as much as 15%, mainly by enhancing user awareness and promoting more responsible energy practices [2].

The primary components of an IoT-based power monitoring system typically include sensors, microcontrollers, and a data communication interface. Sensors such as the PZEM-004T, ACS712, and current transformers (CT) are commonly used to measure key electrical parameters, including voltage, current, active power, and cumulative energy consumption [3]. Microcontrollers like the ESP32 and NodeMCU are widely adopted due to their built-in Wi-Fi and Bluetooth capabilities, as well as their compatibility with various cloud-based services [4]. Integration with web-based or mobile interfaces enables real-time data visualization. Platforms such as Blynk, Thingspeak, and Node-RED offer user-friendly dashboards along with features for push notifications via messaging apps like Telegram or WhatsApp [5][6]. Additionally, these systems can be linked with smart home devices to support automated control.

In testing the electrical power monitoring system in boarding rooms based on the Internet of Things (IoT) using the ACS712 current sensor and the ZMPT101b voltage sensor, it showed accurate results with an average error value of 0.02% for the voltage sensor, 0.14% for the current sensor, and 0.22% for power measurements. These results indicate that the system has good performance and can be relied upon for monitoring electricity usage [7][8]. Meanwhile, the IoT-based remote electricity consumption monitoring system in real time on the Ubidots interface using the same sensor produced an average accuracy level of 97.56% which can display data in the form of graphs and tables [9].

The application of the PZEM-004T sensor in IoT-based electrical power monitoring systems has demonstrated a high level of accuracy, with an average error rate of approximately 0.34% [10][11][12][13]. In comparison, systems employing the ZMPT101B voltage sensor and the ACS712 30 A current sensor typically yield measurement deviations within the range of 3–5% [14][15]. Other commonly used sensors for electrical power monitoring include current transformers (CT) and the SCT-013 current sensor, both of which have been widely utilized in similar implementations [13][16].

In prior studies, the Blynk application has been adopted for various IoT-based monitoring systems. For example, Blynk was utilized to monitor electrical power in a solar power plant project [17], while in smart home systems, it proved effective in enabling remote lighting control with improved precision and energy efficiency [18]. Beyond electricity monitoring, Blynk has also been used in other applications, such as tracking temperature and pH levels during cocoa bean fermentation processes [19], demonstrating its versatility and adaptability across diverse use cases.

METHOD

Materials and Equipment

The components used in this study include both hardware and software elements essential for building the IoT-based power monitoring system are as follows:

1. Power Source: 220V AC household voltage.
2. CT Transformer (Current Transformer): Measures AC current by producing a signal proportional to the current.
3. PZEM-004T Sensor: Measures voltage (V), current (A), active power (W), and energy (kWh).
4. ESP32 Microcontroller: Processes measurement data and transmits it via Wi-Fi.
5. LCD : Displays real-time data locally.
6. Blynk Application (Mobile App): Provides remote monitoring interface.
7. Laptop (with Arduino IDE): Used to program the ESP32 microcontroller.
8. Android Smartphone: Receives and displays data from Blynk in real-time.
9. Electric fan and rice cooker

The power source is the input to this device, the PZEM-004T sensor performs measurements, the ESP32 microcontroller processes and sends data via Wi-Fi to a server or cloud platform, and users can monitor power consumption via a mobile application or LCD. The system flowchart is presented in Figure 1.

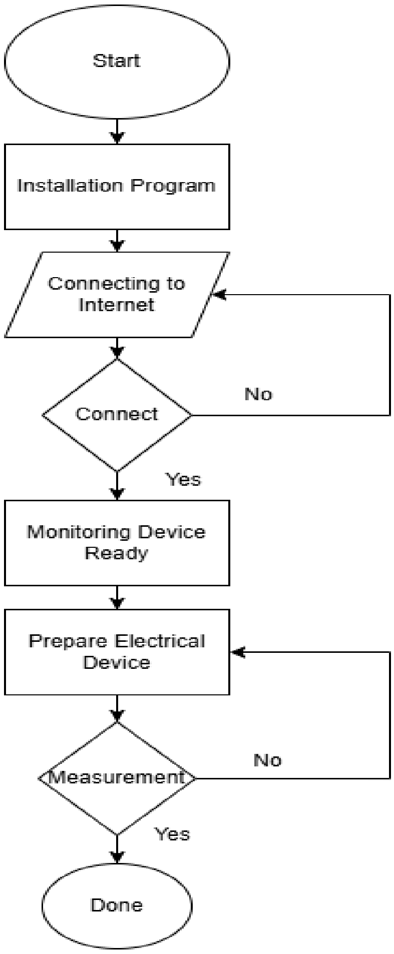

Figure 1. System Flowchart

This method facilitates efficient and real-time oversight of residential electricity usage. The principal power source being monitored is a 220V AC supply. This voltage is introduced into the system for analysis. A Current Transformer (CT) sensor is utilized to quantify the electrical current traversing the circuit. The CT sensor produces an analog signal that is proportionate to the measured current, which is subsequently transmitted to the following modules for processing. The PZEM-004T functions as the primary power sensor module, tasked with detecting essential electrical parameters such as voltage, current, active power, and total energy usage. This module acquires inputs from the CT sensor and the AC voltage line, subsequently relaying the processed measurements to the ESP32 microprocessor. The ESP32, a microcontroller with integrated Wi-Fi and Bluetooth functionalities, serves as the primary control unit. It processes data from the PZEM-004T and displays the results on an LCD screen, while concurrently transmitting them to the Blynk mobile application for remote monitoring. The LCD (Liquid Crystal Display) component presents real-time data, including voltage, current, power, and more parameters obtained from the PZEM-004T. To assess the system's effectiveness, typical household electrical appliances—namely an electric fan and a rice cooker—are utilized as test loads. Figure 2 illustrates the comprehensive system block diagram.

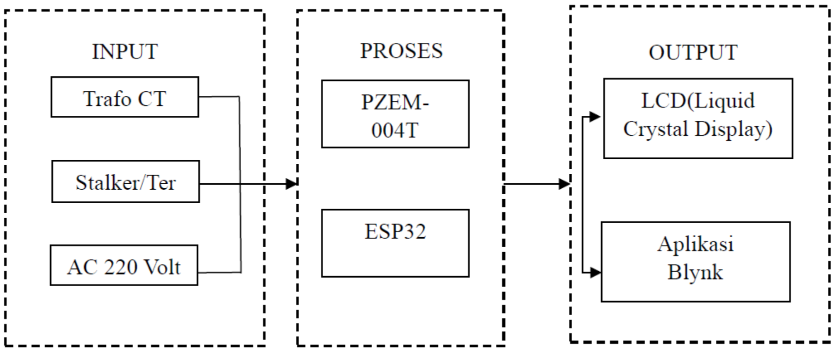

Figure 2. Block Diagram

Blynk App Blynk is an IoT platform that allows controlling and monitoring devices over the internet using a smartphone app. In the context of this diagram, the data processed by the ESP32 will be sent to the Blynk app so that users can monitor electrical conditions in real time remotely.

Data Collection Procedures

The system's operation commences by linking the ESP32 microcontroller to a laptop using a USB cable. The laptop and the Android smartphone must be linked to the same internet network to facilitate synchronization with the Blynk program. Upon connecting the smart plug to an electrical outlet, the system is primed to assess the electrical load. The ESP32 is programmed with the Arduino IDE before deployment. Upon successful software upload, the ESP32 connects to the Blynk application, enabling real-time data monitoring. Upon successful connection of the Blynk application and the system entering standby mode, the measurement of electrical appliances, including electric fans, rice cookers, and comparable household equipment, may begin. The measurement session occurred from 10:00 AM to 1:00 PM to guarantee consistent and ideal circumstances.

The parameters monitored include voltage (V), current (A), power (W), energy consumption (kWh), and the associated cost (in Rupiah). Each test load was measured in real time at six time intervals: 15 minutes, 30 minutes, 45 minutes, 60 minutes, 75 minutes, and 90 minutes. Theoretically, the power calculation use the formula voltage multiplied by current (Equation 1), calculation for energy (Equation 2), calculations for costs (Equation 3) and calculation for %error (Equation 4).

$$P = V \times I \qquad (1)$$

$$E = \frac{P \times t}{1000} \qquad (2)$$

$$Cost = E \times Rp. 1{,}444.70/kWh \qquad (3)$$

$$\%error = \frac{(measured - theoretical)}{theoretical} \times 100\% \qquad (4)$$

After the load is measured, we can see the results produced through the I2C LCD display and on the Blynk application on the Android phone can be seen in Figure 3.

Figure 3. Blynk Application Display

RESULT AND DISCUSSION

Results

The power monitoring device that has been assembled can be seen in Figure 4. After assembly, the power monitoring device is tested to determine whether it functions properly in terms of both hardware and software.

Figure 4. Power Monitoring Device

During testing, the device is connected to the internet and to the smartphone's Wi-Fi so that data can be sent and received by the device. The application used for data reading is the Blynk app, which has been downloaded on an Android device. Blynk is used to connect the server and client, enabling the device to send and receive data from the system. With the Blynk app, the desired data can be viewed from anywhere as long as there is an internet connection [18]. Once successfully connected, the display of electrical power measurements in the Blynk application can be seen in Figure 5 below.

Figure 5. Display Of Electrical Power Measurements

In this study, electrical power was measured both theoretically and directly using an IoT-based power monitoring device. The load used consists of a fan and a rice cooker, and their electrical power is measured over a period of 45 minutes, as shown in Figure 6.

Figure 6. Measuring Rice Cooker Electrical Power

Table 1 presents the theoretical calculations of electrical energy consumption for three usage scenarios: a fan, a rice cooker, and both devices used together. The data includes time intervals of 15, 30, and 45 minutes, with parameters such as voltage (V), current (A), power (Watt), energy (kWh), and estimated cost (Rp) for each case.

Table 1. Theoretical Calculations

Device	Time (Minute)	Voltage (V)	Current (A)	Power (Watt)	Energy (kWh)	Cost (Rp)
Fan	15	220	0.25	55	0.013	19.86
	30	220	0.25	55	0.027	39.73
	45	220	0.25	55	0.041	59.59
Rice Cooker	15	220	0.23	50.6	0.012	18.28
	30	220	0.23	50.6	0.025	36.55
	45	220	0.23	50.6	0.037	54.83
Fan and Rice Cooker	15	220	0.54	118.8	0.029	42.91
	30	220	0.54	118.8	0.059	85.82
	45	220	0.54	118.8	0.089	128.72

In the single-load testing scenario using an electric fan, the system registered a stable voltage of 220 volts and a constant current of 0.25 amperes, yielding a consistent power usage of roughly 55 watts. With the extension of running duration, energy consumption escalated progressively from 0.013 kWh at 15 minutes to 0.041 kWh at 45 minutes. The rise in energy use resulted in a cost increase from Rp. 19.86 to Rp. 59.59. The rice cooker worked at 220 volts, with a current draw of 0.23 amperes, resulting in a power consumption of 50.6 watts. The energy consumption during this assessment varied from 0.012 kWh to 0.037 kWh during a duration of 15 to 45 minutes, resulting in expenses between Rp. 18.28 and Rp. 54.83. When both devices were operated concurrently, the system registered a total current of 0.54 amperes, resulting in a cumulative power usage of 118.8 watts. Energy consumption escalated from 0.029 kWh at 15 minutes to 0.089 kWh at 45 minutes, with corresponding prices increasing from Rp. 42.91 to Rp. 128.72. The results illustrate the precision and responsiveness of the IoT-based monitoring system in recording real-time power consumption across diverse load circumstances.

Based on Table 2, the real-time monitoring data from the Blynk application, recording the electricity consumption of three usage scenarios: a fan, a rice cooker, and a combination of both devices. Measurements were taken at time intervals of 15, 30, and 45 minutes. The recorded parameters include voltage (V), current (A), power (Watt), energy consumption (kWh), and cost (Rp).

During the fan testing procedure, the system documented voltage variations ranging from 229 to 231 volts, accompanied by a consistent current of 0.27 amperes. This led to power usage varying between 61.83 and 62.37 watts. As the length extended, energy consumption escalated from 0.015 kWh to 0.046 kWh, resulting in expenses ranging from Rp. 22.33 to Rp. 67.58. The rice cooker exhibited voltage measurements ranging from 223 to 231 volts, with a current demand of 0.28 amperes. The resultant power consumption varied from 62.44 to 64.68 watts. Energy consumption ranged from 0.015 to 0.048 kWh, with corresponding prices increasing from Rp. 22.55 to Rp. 69.78. When the fan and rice cooker operated concurrently, the total current rose to 0.57 amperes, with power consumption recorded between 128.82 and 129.96 watts. In this configuration, energy consumption peaked at 0.097 kWh over a 45-minute period, incurring expenditures of Rp. 140.20. The results demonstrate the system's sensitivity and precision in monitoring heightened loads and their immediate effects on energy usage and expenses in real-time.

Table 2. Blynk Application Monitoring

Device	Time (Minute)	Voltage (V)	Current (A)	Power (Watt)	Energy (kWh)	Cost (Rp)
Fan	15	229	0.27	61.83	0.015	22.33
	30	229	0.27	61.83	0.030	44.66
	45	231	0.27	62.37	0.046	67.58
Rice Cooker	15	223	0.28	62.44	0.015	22.55
	30	231	0.28	64.68	0.032	46.72
	45	230	0.28	64.4	0.048	69.78
Fan and Rice Cooker	15	228	0.57	129.96	0.032	46.94
	30	226	0.57	128.82	0.064	93.05
	45	227	0.57	129.39	0.097	140.20

Discussion

From the data measurements above, a difference was found in the energy results between direct measurement using the power monitoring device and theoretical calculation. The direct measurement showed a higher energy value compared to the theoretical calculation, as shown in Figure 7.

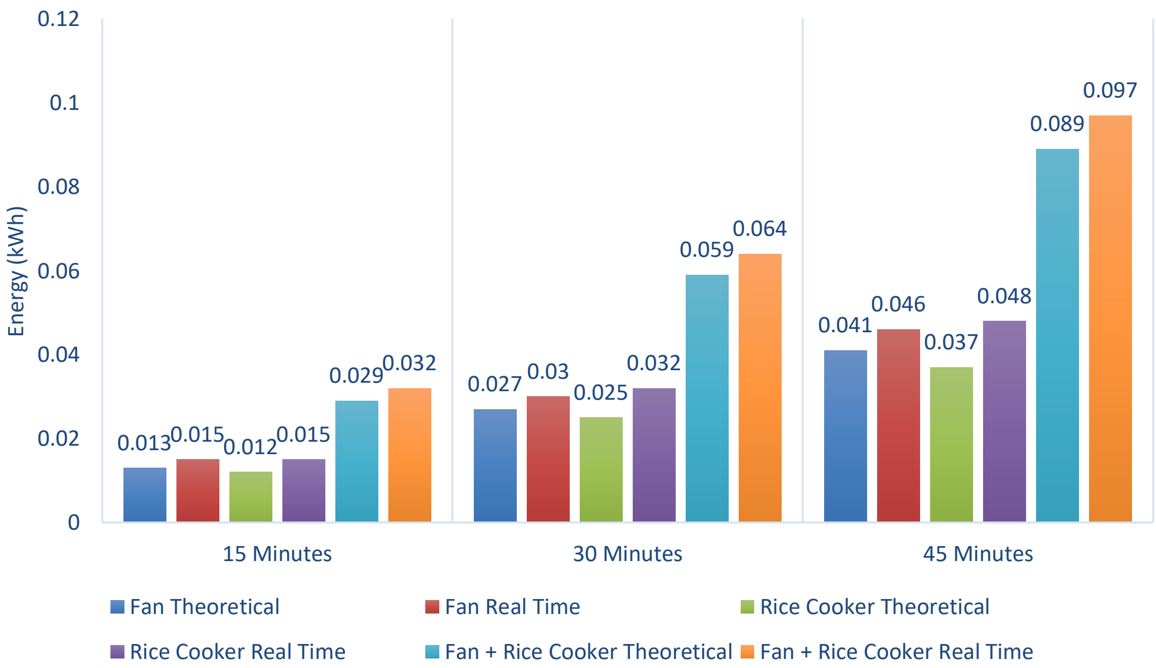

Figure 7. Energy Measurement Chart

From the measurement results above, the average percentage error for each experimental variable measured was 0.17%. Where previous research obtained an average error percentage of 0.34%[10-13]. The largest percentage error occurred are 0.30% during the measurement of the rice cooker at 45 minutes. The percentage error for each measurement can be seen in Table 3.

Table 3. %error of electrical power measurement

Device	Time (Minute)	error (%)
Fan	15	0.15
	30	0.11
	45	0.12
Rice Cooker	15	0.25
	30	0.28
	45	0.30
Fan and Rice Cooker	15	0.10
	30	0.08
	45	0.09

Based on the results presented, the energy values obtained through direct measurement using the Blynk application were consistently higher than those derived from theoretical calculations. This discrepancy is primarily attributed to the dynamic nature of electrical loads in real-world scenarios. Several contributing factors can affect measurement accuracy, including component tolerances, power losses, power factor variations, and voltage or current fluctuations [20][21][22]. Similar differences were also observed in the power and cost measurements, highlighting that IoT-based monitoring systems are capable of accurately capturing real-time energy consumption while enabling more precise billing and predictive cost estimation.

Theoretical analysis remains valuable as a baseline for estimating energy costs and interpreting the power consumption behavior of household appliances under both individual and combined usage. These insights are essential for supporting energy-saving strategies and informed planning—particularly in smart home environments or IoT-driven energy monitoring systems.

CONCLUSION AND RECOMMENDATION

Conclusion

This study successfully developed an IoT-based electricity monitoring system utilizing the ESP32 microcontroller and the PZEM-004T sensor to measure voltage, current, power, energy consumption, and cost in real time. Measurement data were displayed both locally via an LCD and remotely through the Blynk mobile application. The experimental results demonstrated strong alignment between actual measurements and theoretical calculations, with error values ranging from 0.08% to 0.30%, and an average error of just 0.17%. These findings confirm the system's high accuracy and reliability across various household appliances. Equipped with an intuitive user interface and remote monitoring capabilities, the system presents a practical and user-friendly solution for household energy management. Beyond providing real-time insight into electricity usage, it enhances user awareness and facilitates more responsible energy behavior. Ultimately, this system supports long-term energy-saving initiatives and contributes to the advancement of smart home technologies and sustainable energy practices.

Recommendation

Future research should focus on improving the system by including machine learning algorithms that can forecast energy consumption patterns and autonomously identify irregularities. Such developments would facilitate more proactive and astute energy management. Furthermore, enhancing the system's interoperability to accommodate multi-phase power topologies and a wider array of domestic appliances will augment its versatility and practical utility. Subsequent research may investigate the incorporation of solar energy monitoring to enhance hybrid energy systems, merging grid-based electricity with renewable energy sources for a more sustainable and flexible power management strategy.

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