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End-to-End Performance Evaluation of an IoT-Based Smart Energy Meter through Accuracy and Quality of Service Analysis

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ABSTRACT

This research is motivated by the increasing need for accurate and real-time electrical energy monitoring systems to support energy usage efficiency. The purpose of this study is to develop an Internet of Things (IoT)-based electrical energy monitoring system capable of measuring and transmitting data in real-time. The system is designed using a PZEM-004T sensor integrated with an ESP32 microcontroller and the Firebase cloud platform for data storage and visualization via a web dashboard. Performance evaluation is conducted through an analysis of measurement accuracy and network quality of service (QoS). Accuracy analysis is performed using Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) parameters, while network QoS analysis is conducted by measuring latency, Received Signal Strength Indicator (RSSI), and Signal-to-Noise Ratio (SNR). Test results show that the system has a low error rate, with a voltage MAE value of 0.136%, current of 1.130%, and power of 1.190%, as well as a voltage RMSE of 0.181%, current of 1.217%, and power of 1.275%. With an average latency of 19.50 ms, an RSSI of -33.50 dBm, and an SNR of 66.50 dB, the system demonstrates reliable network QoS. Overall, these results indicate that the system is capable of providing accurate and stable performance for real-time energy monitoring applications. The integration of measurement accuracy and reliable network QoS in a single IoT-based system ready for practical implementation is the main contribution of this research.

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1. INTRODUCTION

Energy efficiency is a fundamental aspect of modern infrastructure sustainability. Recent studies indicate that optimizing energy consumption in buildings, such as high-rise hotels, depends not only on physical building envelope renovations but also on smart energy system management [1]. On the other hand, the transformation towards smart grids demands real-time transparency of energy consumption data [2], and data integration from the user side is key to grid stability [3].

The emergence of the Internet of Things (IoT) has become one of the main drivers in the development of energy management systems [4]. In line with this, various smart energy management architectures have been continuously developed. One of its applications is the utilization of LoRaWAN technology in standalone photovoltaic systems [5]. In addition, smart monitoring systems for renewable energy sources have also been developed and validated in both simulated and real-time environments [6], [7]. More broadly, the integration of IoT in grid management has proven to be effective in improving energy efficiency [8].

At the implementation level, device cost remains the biggest challenge for mass adoption. Solutions based on economical microcontrollers such as the ESP32 and the PZEM-004T sensor have now become a standard in low-cost metering research [9]. The effectiveness of this sensor has been validated and proven capable of providing precise power measurement accuracy for controlling electricity usage [9], [10], [11], and it has been implemented for simple home automation [12], [13].

Recent studies have extensively explored the use of low-cost sensors and cloud platforms such as Firebase for energy monitoring [14], [15]. Furthermore, combinations of similar sensors and platforms have also been applied to a broader range of IoT applications, from disaster mitigation [16], smart greenhouses [17], and attendance systems [18], to critical environments that demand precise network timing [19]. However, the majority of these studies tend to focus primarily on device-level measurement accuracy or general system functionality.

Although network performance aspects have been discussed within the context of broader IoT architectures [20], [21], research that simultaneously evaluates hardware accuracy and end-to-end Quality of Service (QoS) in low-cost smart energy meter systems remains underexplored. Therefore, this research focuses on the end-to-end performance evaluation of an IoT-based Smart Energy Meter by comprehensively linking device-level measurement accuracy with network performance metrics, thereby providing a more holistic evaluation of system reliability.

2. METHOD

2.1. Research Design

The system is designed using the ESP32 module as the main processing unit. This selection is based on the study by Espinosa-Gavira et al. [22], which characterized the ESP32's performance as highly reliable for synchronized sensor networks. The PZEM-004T v3 sensor is used to acquire electrical parameters, following the method applied by Adrian et al. [23] for real-time data acquisition. The employed data logger architecture adopts a flexible open-source concept that enables early error detection [24].

This research utilizes an experimental approach to evaluate the performance of the IoT-based electrical energy monitoring system in terms of measurement accuracy and network Qos. The research stages include: (1) system design and implementation, (2) measurement accuracy testing, and (3) QoS performance evaluation.

2.2. System Architecture

Figure 1 illustrates the overall system architecture. The developed system consists of three primary layers: the data acquisition layer, the communication and processing layer, and the cloud and user interface layer. The data acquisition layer utilizes the PZEM-004T v3.0 sensor to measure electrical parameters, specifically voltage, current, and power. The measurement data is then processed by the ESP32 microcontroller at the communication layer and transmitted via a Wi-Fi network to the Firebase Realtime Database. Furthermore, the data is visualized in real-time through a Flutter Web-based interface. Data transmission is executed periodically every 5 seconds to maintain an optimal balance between system responsiveness and bandwidth utilization efficiency.

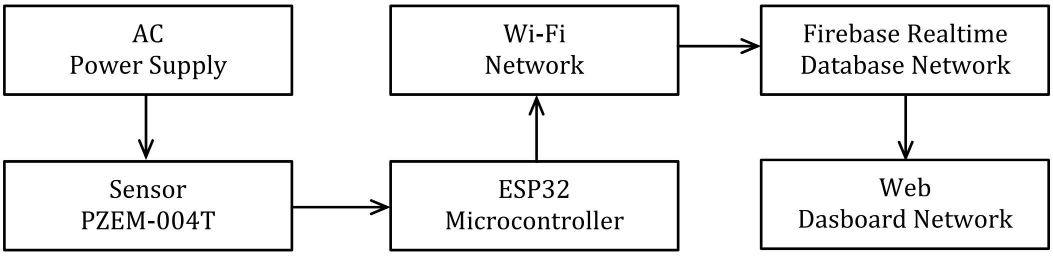

Figure 1. End-to-end architecture of IoT-based energy monitoring system.

2.3. System Configuration and Experimental Setup

The equipment used consists of a PZEM-004T v3.0 sensor, an ESP32 microcontroller, the Firebase Realtime Database platform, and a Flutter Web-based user interface. A calibrated digital multimeter is utilized for comparison purposes. Testing is conducted on resistive loads, specifically lamps with varying power ratings, to ensure the consistency of the measurement conditions. The communication network employs 2.4 GHz Wi-Fi, with the distance between the device and the access point ranging from 5 to 10 meters. The test configuration and device interconnections are illustrated in Figure 2. Meanwhile, the components utilized, their types or models, and their primary functions are detailed in Table 1.

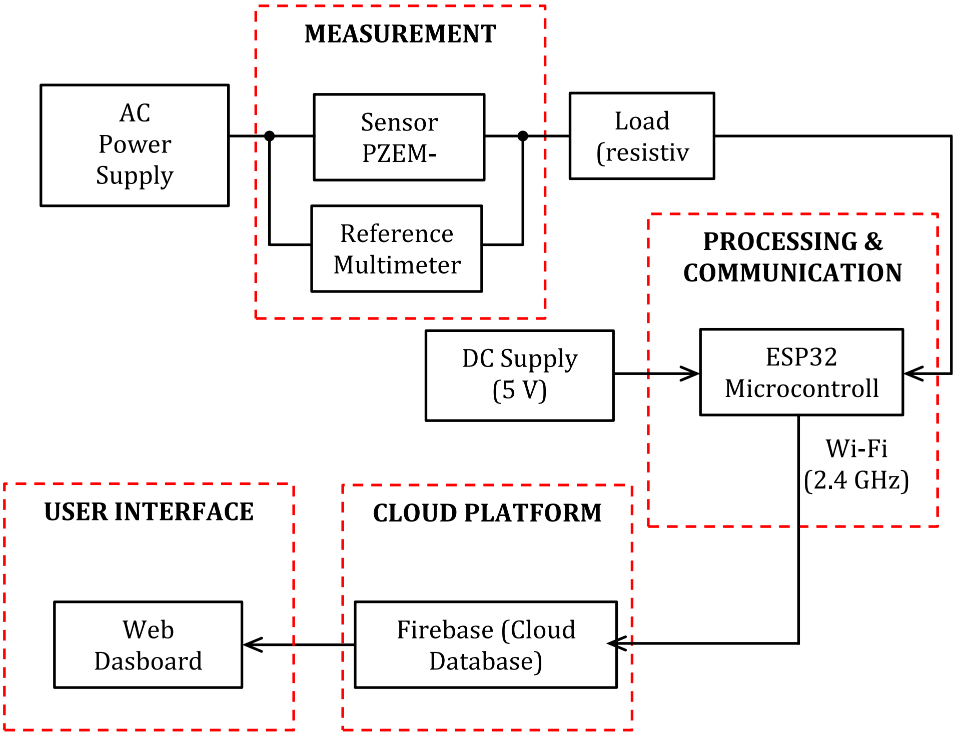

Figure 2. Experimental setup for IoT-based energy monitoring system.

Table 1. Components used, types/models, and their main functions.

Component	Type/Model	Main Function
Sensor	PZEM-004T	Measures electrical parameters (voltage, current, power, energy).
Microcontroller	ESP32	Processes sensor data and transmits data to the server via Wi-Fi.
Electrical Load	Incandescent/LED lamp	Serves as the test object for electrical energy consumption.
Power Supply	220 V AC	Provides electrical energy for the system and the load.
Reference Multimeter	Fluke 115 True RMS Digital Multimeter	Measures electrical parameters for comparison (ground truth).
Communication Network	Wi-Fi 2.4 GHz	Serves as the data transmission medium from the ESP32 to the server/cloud.
Cloud Platform	Firebase	Stores and manages monitoring data in real-time.
User Interface	Web Dashboard	Displays real-time energy monitoring data to the user

2.4. Data Collection Procedure

Data collection is conducted simultaneously using the developed system and a reference measurement instrument, namely the Fluke 115 True RMS Digital Multimeter. The Fluke 115 was employed as the ground-truth reference, possessing a stated basic DC voltage accuracy of 0.5% + 3 counts and an AC voltage/current accuracy of 1.0% + 3 counts. To ensure the reliability of the results as a benchmark, the instrument was recently calibrated according to standard procedures prior to the experiment. Although the PZEM-004T sensor inherently provides the capability to measure accumulated energy (kWh), this study focuses specifically on evaluating the accuracy of instantaneous parameters, namely voltage (V), current (A), and power (W). This focus was chosen to better assess the system's real-time monitoring capabilities and its immediate response to load changes without the compounding variables of time-accumulated metrics. The data are periodically transmitted by the ESP32 to a database and subsequently displayed on the user interface in real-time.

2.5. Measurement Accuracy Evaluation

To provide a more comprehensive evaluation of the system's performance, measurement accuracy is assessed through statistical metrics, specifically the mean absolute error (MAE) and root-mean-square error (RMSE) [20]. Both MAE and RMSE are calculated relatively and expressed as percentages. The MAE percentage is calculated using the following equation:

$$\mathrm{MAE} = \frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}\left|\frac{\mathrm{S_i} - \mathrm{M_i}}{\mathrm{M_i}}\right| \tag{1}$$

meanwhile, the RMSE percentage is calculated using the following equation:

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}\left(\frac{\mathrm{S_i} - \mathrm{M_i}}{\mathrm{M_i}}\right)^2} \tag{2}$$

where N is the number of data points.

2.6. Network QoS Evaluation

Network QoS is evaluated using three main parameters: latency, received signal strength indicator (RSSI), and signal-to-noise ratio (SNR). Measurements are conducted while the system operates in real-time at specific time intervals. The average, maximum, and minimum values are utilized to analyze system stability [10]. The units, definitions, and measurement objectives of these three parameters are presented in Table 2.

Table 2. Units, definitions, and measurement objectives of latency, RSSI, and SNR.

Parameter	Unit	Definition	Measurement Objective
Latency	ms	The time delay required for data to travel from the device to the server/cloud.	To assess the system's response speed in real-time data transmission.
RSSI	dBm	The signal strength received by the device from the Wi-Fi network.	To evaluate the network connection quality in terms of signal strength.
SNR	dB	The ratio between signal strength and noise in the communication channel.	To assess signal quality against interference (noise).

2.7. Data Analysis, Validity, and Research Limitations

The obtained data are analyzed quantitatively through the following stages: (1) calculating the MAE and RMSE for voltage, current, and power; (2) analyzing the distribution and stability of the network QoS; and (3) comparing the results with IoT system performance standards found in the literature.

The validity of the results is maintained by utilizing a calibrated reference measurement instrument and ensuring consistent testing conditions. However, this study has several limitations, namely that the testing is exclusively conducted on resistive loads, the system's performance relies on the quality of the local Wi-Fi network, and it does not yet include implementation on a multi-node scale.

3. RESULT AND DISCUSSION

3.1 Measurement Accuracy

Table 3 presents the measured voltage, current, and power values using the SEM and a multimeter. On the other hand, by utilizing (1) and (2), the MAE values for voltage, current, and power are presented in Table 4. It can be observed that the MAE values for the voltage, current, and power are 0.136%, 1.130%, and 1.190%, respectively, while their RMSE values are 0.181%, 1.217%, and 1.275%, respectively. These results indicate that the developed system, namely the SEM, possesses a high level of accuracy, particularly in voltage measurement, due to its extremely small deviation from the reference measurement instrument (multimeter). This high accuracy indicates that the integration of the PZEM-004T sensor with the ESP32 microcontroller is capable of producing stable and reliable measurements, as also reported in previous studies [9], [22].

Table 3. Measured voltage, current, and power values using the SEM and a multimeter.

Voltage (V)		Current (A)		Power (W)	
SEM	Multimeter	SEM	Multimeter	SEM	Multimeter
218.8	218	0.305	0.300	66.734	65.400
220.8	220	0.118	0.120	26.054	26.400
221.3	221	0.305	0.300	67.497	66.300
222.2	222	0.305	0.300	67.771	66.600
219.5	219	0.210	0.208	46.095	45.552
220.2	220	0.145	0.144	31.929	31.680
221.0	221	0.310	0.308	68.510	68.068
222.5	222	0.200	0.198	44.500	43.956
223.0	223	0.290	0.288	64.670	64.224
219.8	220	0.150	0.149	32.970	32.780
220.7	221	0.305	0.300	67.314	66.300
221.5	221	0.320	0.318	70.880	70.278
222.0	222	0.120	0.119	26.640	26.418
223.2	223	0.250	0.248	55.800	55.304
224.0	224	0.305	0.300	68.320	67.200

Table 4. The MAE values for the voltage, current, and power.

Parameter	MAE (%)	RMSE (%)
Voltage	0.136	0.181
Current	1.130	1.217
Power	1.190	1.275

The difference in error values among voltage, current, and power indicates distinct measurement characteristics. The current and power parameters exhibit relatively higher MAE and RMSE values compared to voltage. This is due to the sensitivity of current measurement to load fluctuations, as well as error propagation in power calculation resulting from the multiplication of voltage and current. A similar phenomenon has also been reported in IoT-based energy monitoring systems, stating that power measurement errors tend to be larger due to the accumulation of errors from their constituent parameters [12], [15].

When compared to the MAE, the RMSE values for voltage, current, and power are consistently higher. This indicates that the occurring error variations are not dominated by extreme outliers. In other words, the error distribution can be categorized as stable, and therefore, it can be stated that the system possesses good performance consistency under various operational conditions. This stability is a crucial indicator in IoT-based real-time monitoring systems, particularly in energy management applications [6], [24].

The system's error rate, which is close to 1%, demonstrates competitive—if not superior—performance compared to similar systems. In general, such systems exhibit error rates ranging from 1% to 3% [10], [11], [15]. These results indicate that the proposed system is not only feasible for real-time energy monitoring but also provides sufficient accuracy for advanced energy consumption analysis. With a low error rate and well-controlled error distribution, the system can be considered a reliable and efficient IoT-based electrical energy monitoring solution.

3.2 Network QoS Analysis

The measurement results of the network QoS parameters, specifically latency, RSSI, and SNR, were obtained over a 30-minute period with data acquisition at 5-minute intervals. A summary of their maximum, minimum, and average values is presented in Table 5. Quantitatively, the latency values range from 10.32 ms to 28.03 ms, with an average of 19.50 ms; the RSSI values range from −42.87 dBm to −25.18 dBm, with an average of −33.50 dBm; and the SNR values range from 57.13 dB to 74.82 dB, with an average of approximately 66–67 dB. These values indicate that the system possesses a good network QoS, particularly for real-time monitoring-based IoT applications that require low delay and stable connectivity [7], [20], [22].

Table 5. A summary of their maximum, minimum, and average values of QoS parameters.

Parameter	Minimum	Maximum	Average
Latency (ms)	10.32	28.03	19.50
RSSI (dBm)	-42.87	-25.18	-33.50
SNR (dB)	57.13	74.82	66.50

Figure 3 illustrates the latency, RSSI, and SNR graphs over a 30-minute period. These graphs confirm the aforementioned statistical results while also providing additional information regarding temporal dynamic patterns. In the latency versus time graph, fluctuations are visible with several spikes approaching the maximum value; however, the majority of the data remains within the 15–25 ms range. In the context of IoT systems, latency below 50 ms is generally categorized as excellent for wireless-based monitoring applications [20], [23]. In other words, the obtained results have demonstrated that the system is capable of maintaining high responsiveness.

In terms of signal quality, the RSSI versus time graph exhibits a relatively stable value distribution within the range of −30 to −40 dBm. This indicates that the signal falls into the strong signal category. This value signifies that the system operates under good network conditions with a low packet loss rate [8], [11], [14]. This consistency is further reinforced by the SNR values, which are at a high level (> 57 dB). These SNR values demonstrate that the received signal is far more dominant compared to the noise. In wireless communication systems, an SNR above 20 dB is already considered adequate [9], [12]. Therefore, it can be concluded that the values obtained in this study indicate an excellent network QoS.

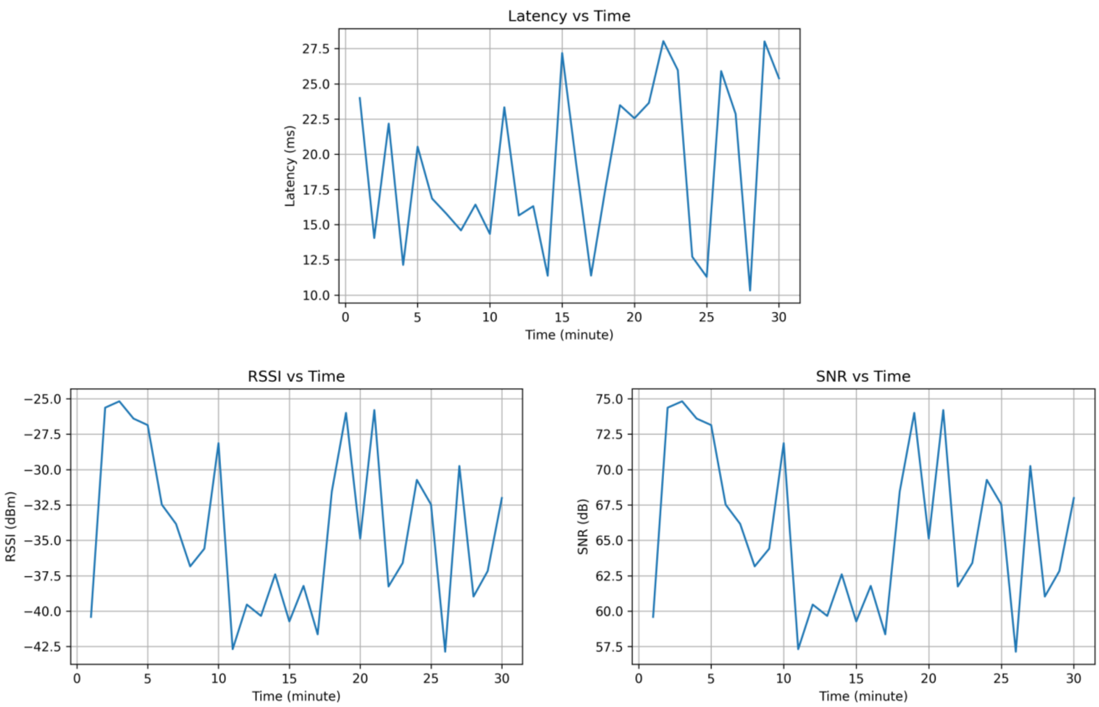

Figure 3. Latency, RSSI, and SNR versus time over a 30-minute period.

Furthermore, the graphical analysis reveals a correlation among the parameters. A decrease in RSSI tends to be followed by a reduction in SNR, and under certain conditions, it contributes to an increase in latency. This relationship aligns with wireless communication theory, which states that channel quality (determined by RSSI and SNR) directly affects transmission delay and data reliability [12], [18], [20]. Although fluctuations are present, the occurring changes are relatively minor and do not cause a significant degradation in the network QoS.

By combining the statistical analysis from the table and the visual patterns from the graphs, it can be concluded that the system possesses a consistent, stable, and reliable QoS. The graphs serve as a validation of the numerical results while simultaneously providing a deeper understanding of the system's behavior over time. These findings align with previous studies indicating that the combination of low latency, strong RSSI, and high SNR constitutes a primary indicator of successful IoT-based monitoring system implementation [14], [18], [22].

3.3 Overall System Performance Analysis

Overall, the developed system demonstrates good performance in terms of measurement accuracy and network QoS. The relatively low MAE and RMSE values indicate that the system is capable of measuring electrical parameters with a minimal error rate. When compared to previous studies, the obtained error values fall within a competitive range. This demonstrates that the developed system possesses adequate performance, making it feasible for real-time energy monitoring applications [14], [22].

From a communication perspective, the network QoS parameters indicate that the system has low latency (< 30 ms), an RSSI within the strong signal category, and a high SNR. This combination indicates that the system is capable of maintaining stable connectivity with good data transmission quality. These results align with IoT network performance standards, which state that low latency and high signal quality are primary indicators of a successful wireless network-based monitoring system [12], [20].

The graphical analysis reveals that although fluctuations occur at several measurement points, these variations are not significant and do not affect the overall system performance. This indicates that the system possesses a good level of robustness against network dynamics. Furthermore, the correlation among RSSI, SNR, and latency indicates that communication channel quality directly affects transmission delay, as reported in previous studies [12], [18].

Nevertheless, this study still has limitations, particularly regarding the testing conditions, which were conducted in an environment with a relatively stable network quality. Therefore, the system's performance under more dynamic network conditions or with high levels of interference needs to be further evaluated.

Considering the aspects of accuracy, communication stability, and performance consistency, the developed system can be categorized as a reliable solution for IoT-based energy monitoring. The main contribution of this study lies in the integration of a monitoring system that is not only accurate in measurement but also possesses stable communication performance, thereby supporting practical implementation on a larger scale.

4. CONCLUSION

This study has successfully developed an IoT-based electrical energy monitoring system using an ESP32, which is capable of performing real-time measurements and data transmission with high accuracy and good communication quality. The test results demonstrate that the system has a low error rate, with MAE values of 0.136% (voltage), 1.130% (current), and 1.190% (power), as well as RMSE values of 0.181%, 1.217%, and 1.275%. In terms of communication, the system exhibits reliable performance with an average latency of 19.50 ms, an RSSI of around −33.50 dBm (strong signal category), and an SNR of approximately 66.50 dB.

This integration of high measurement accuracy and communication stability demonstrates that the proposed system possesses competitive performance compared to IoT-based energy monitoring systems in previous studies. Thus, this system has the potential to be practically implemented for real-time electrical energy consumption monitoring. In the future, this research can be expanded through testing under more dynamic network conditions and the integration of data-driven analytical features to enhance energy consumption prediction and optimization capabilities.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

REFERENCES

[1] L. S. Riantini et al., “Energy Efficiency Analysis of Building Envelope Renovation and Photovoltaic System in a High-Rise Hotel Building in Indonesia,” *Buildings*, vol. 14, no. 6, 2024.

[2] H. O. Garcés et al., “Development of an IoT-Enabled Smart Electricity Meter for Real-Time Energy Monitoring and Efficiency,” *Electronics*, vol. 14, no. 6, pp. 1–36, 2025.

[3] Z. Javid, I. Kocar, W. Holderbaum, and U. Karaagac, “Future Distribution Networks: A Review,” *Energies*, vol. 17, no. 8, pp. 1–45, 2024.

[4] M. Aiello, “IoT architectures: from data to smart systems,” *Front. Internet Things*, vol. 1, pp. 1–5, 2022.

[5] W. A. Jabbar, S. Annathurai, T. A. Tajul, and M. F. Mohd Fauzi, “Smart energy meter based on a long-range wide-area network for a stand-alone photovoltaic system,” *Expert Syst. Appl*., vol. 197, p. 116703, 2022.

[6] C. K. Rao, S. K. Sahoo, and F. F. Yanine, “Development of intelligent smart energy monitoring systems for renewable energy source using Proteus-8 environment and validated with experimentation,” *J. Electr. Syst. Inf. Technol*., vol. 12, no. 1, 2025.

[7] D. M. Atia, H. T. El-Madany, Y. Atia, and M. B. Zahran, “Real-Time Implementation of Energy Management for Photovoltaic/Battery/Diesel Hybrid System Based on LabVIEW,” *Int. J. Renew. Energy Res*., vol. 12, no. 2, pp. 1105–1116, 2022.

[8] N. S. Madhuri et al., “IOT integrated smart grid management system for effective energy management,” *Meas. Sensors*, vol. 24, p. 100488, 2022.

[9] K. A. Yasa et al., “IoT-based Electrical Power Recording using ESP32 and PZEM-004T Microcontrollers,” *J. Comput. Sci. Technol. Stud*., vol. 4, pp. 1–7, 2023.

[10] T. H. Rangkuti and M. Martiano, “Design of IoT Based Electrical Parameter Monitoring System using NodemCu V3 and PZEM-004T V3 Sensor,” *Tsabit J. Comput*., vol. 2, no. 1, pp. 1–8, 2025.

[11] W. Ahmad, D. Widiatmoko, and F. Kholid, “Design of Electrical Energy Monitoring System Using NodeMCU ESP8266 and PZEM-004T for Power Usage Control,” *Fortech*, vol. 5, no. 1, pp. 10–18, 2024.

[12] A. Veerraju, A. Adil, and S. Naik, “Electrical Energy Monitoring and Home Automation Using IoT,” *Int. J. Innov. Sci. Res. Technol*., vol. 5, no. 10, pp. 1020–1023, 2020.

[13] Syafii, A. Luthfi, and A. Y. A. Rozzi, “Design of raspberry pi web-based energy monitoring system for residential electricity consumption,” *Int. Conf. Inf. Technol. Syst. Innov*., pp. 192–196, 2020.

[14] J. E. B. Monton, J. T. Dellosa, and R. N. Mendoza, “IoT-Based Energy Monitoring System (IBEMS) for Optimizing Power Consumption in University Facilities,” 8th *Int. Artif. Intell. Data Process. Symp*., 2024.

[15] A. I. Shirol, A. Jali, and A. A. Patil, “Sustainable IoT Architecture for Real-Time Water Quality Assessment Using ESP-NOW Communication,” *Int. J. Sci. Technol*., vol. 16, no. 2, pp. 1–6, 2025.

[16] A.U. Nawawi et al., “Development of the Android Application for the Landslide Disaster Mitigation Real-time System based on Firebase Server and OneSignal,” *J. Elektron. dan Telekomun*., vol. 24, no. 2, p. 129, 2024.

[17] I. Fathi, “An IoT Based Low-Cost Smart Greenhouse Monitoring System Using ESP8266 and Firebase for Real-Time Environmental Control,” *Int. J. Adv. Nat. Sci. Eng. Res*., vol. 5, no. 5, pp. 268–286, 2025.

[18] M. F. A. M. Noor et al., “Development of Employee Attendance Management System using Flutter,” *J. Comput. Res. Innov*., vol. 8, no. 2, pp. 1–10, 2023.

[19] C. Megías, V. Vázquez, E. Ros, M. Cappelli, and J. Díaz, “Ethernet-based timing

system for accelerator facilities: The IFMIF-DONES case," *Comput. Networks*, vol. 233, 2023.

[20] P. O. Ayeni and O. C. Adesoba, "IoT-based home control system using NodeMCU and Firebase," *J. Edge Comput.*, vol. 4, no. 1, pp. 17–34, 2025.

[21] P. Venkadesh, S. V Divya, and N. Vishal, "Smart Dustbin using ESP32 for Waste Management," *IRO J. Sustain. Wirel. Syst.*, vol. 6, no. 4, pp. 309–317, 2024.

[22] M. J. Espinosa-Gavira et al., "Characterization and Performance Evaluation of ESP32 for Real-time Synchronized Sensor Networks," *Procedia Comput. Sci.*, vol. 237, pp. 261–268, 2024.

[23] M. Adrian et al., "Real-Time Data Acquisition With Esp32 for IoT Applications Using Open-Source Mqtt Brokers," *Proc. Manuf. Syst.*, vol. 19, pp. 61–68, 2024.

[24] M. L. M. Amorim et al., "Open-Source Data Logger System for Real-Time Monitoring and Fault Detection in Bench Testing," *Inventions*, vol. 9, no. 6, 2024.