E-ISSN: 111 – 2716 P-ISSN: 3026 – 8214
MPRI-JAAER | INTERNATIONAL JOURNAL OF APPLIED & ADVANCED ENGINEERING RES.
VOL. 13 NO. 5 JULY, 2026

DESIGN AND IMPLEMENTATION OF AN IOT-BASED SMART ENERGY METER WITH REAL-TIME MONITORING AND MATLAB-BASED DATA ANALYTICS

DANJUMA, I. M.; ASIH, M.; GARBA, S. S.; AKABE, I. D.; & USMAN, A.

Department of Electrical/Electronic Engineering, Faculty of Engineering and Technology, Nigerian Defence Academy, Kaduna, Nigeria.

Corresponding Author: ibrahimakabe4@gmail.com

DOI: https://doi.org/10.70382/mejaaer.v13i5.060

Abstract

Conventional electricity metering systems are limited by their inability to provide real-time monitoring, remote access, and accurate information on energy consumption, which in turn reduces the efficiency of energy management and billing processes. This study aimed to design and implement an Internet of Things (IoT)-based smart energy meter capable of real-time monitoring and MATLAB-based data analytics. A prototype development methodology was adopted, using an ESP32 microcontroller integrated with ACS712 current and ZMPT101B voltage sensors, an LCD module, Wi-Fi communication, and the Blynk cloud platform. Electrical parameters were measured under varying load conditions and transmitted wirelessly for remote monitoring, while MATLAB was used to analyse and visualise the collected data. The developed system successfully measured voltage, current, power, and energy consumption, with recorded values of approximately 220 V, 0.40–1.20 A, 88–264 W, and 0.088–0.264 kWh, respectively. The graphical outputs clearly illustrated voltage stability, load variation, instantaneous power consumption, and cumulative energy usage, thereby improving users' ability to monitor electrical energy in real time. Although slight measurement deviations caused by sensor calibration, signal noise, and network dependence were

Keywords: Energy Management, ESP32, IoT, MATLAB Analytics, Real-Time Monitoring, Smart Energy Meter

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observed, the system demonstrated reliable performance throughout the testing period. The findings indicate that integrating IoT technology with cloud communication and MATLAB analytics provides a practical, low-cost, and scalable solution for intelligent energy monitoring. The study concludes that the proposed system offers significant improvements over conventional metering systems by enabling continuous monitoring, remote access, and informed energy management. Future work should focus on improving sensor calibration, incorporating artificial intelligence for predictive energy analysis, supporting three-phase installations, and providing offline data storage to further enhance system reliability and scalability.

Introduction

The increasing demand for efficient energy management and digital power systems has accelerated the adoption of smart energy meters that integrate sensing, communication, and computing technologies to enable real-time monitoring and data-driven decision making (Rind et al., 2023). This technological advancement offers two principal benefits: improved energy efficiency and more effective monitoring of electricity consumption. As the number of electronic components in commercial and residential settings grows dramatically, accurately measuring their power consumption has become a major concern, especially since many of these devices operate on relatively low electricity levels. Accurate measurement and analysis of energy consumption provide the foundation for improving the efficiency of electrical systems. Baseline energy consumption data enable engineers to identify inefficiencies, optimize energy utilization, and support the design of intelligent energy management solutions (Ben Dhaou, 2023; Rind et al., 2023).

A smart energy meter (SEM) is an electronic device that measures and records parameters such as electric energy consumption, voltage, current, power factor, and frequency (Muqeet et al., 2023; Kabeyi & Olanrewaju, 2023). Smart meters transmit this operational data to consumers, providing clearer insight into their daily consumption patterns, and to electricity suppliers for remote system monitoring, fault detection, and automated billing. These meters typically record electrical energy parameters in near real time and transmit the collected data at predefined intervals. Smart meters support two-way communication between consumers and utility providers, enabling remote monitoring, demand-side management, and improved grid operation. This advanced metering infrastructure (AMI) differs fundamentally from traditional Automatic Meter Reading (AMR) systems, which

primarily support one-way communication and limited remote functionality (Rind et al., 2023). AMR supports only one-way, remote data collection primarily for billing, whereas AMI establishes a continuous bidirectional communication link between the meter and the supplier.

Conventional electricity metering systems are widely used in many distribution networks, yet they fall short in providing real-time, accurate, and remotely accessible energy consumption data. These systems typically rely on manual readings or one-way Automatic Meter Reading (AMR) schemes, which limit timely visibility of load behavior and reduce the efficiency of billing, monitoring, and fault-detection processes. As electricity demand grows and modern loads become more dynamic, these shortcomings continue to undermine the reliability and transparency of energy management systems (Rind et al., 2023; Muñoz et al., 2022).

The evolution of electrical energy metering systems has progressed significantly over the past decades, moving from conventional electromechanical meters to advanced smart metering solutions. Traditional meters, which rely on rotating discs and manual reading, are limited by their inability to provide real-time data and their susceptibility to human error and energy theft (Ohanu et al., 2024).. de Sousa (2023) highlighted that smart meter development has progressed through three main stages: mechanical meters, electronic meters, and intelligent IoT-based meters, with each stage improving measurement accuracy and automation capability. With the advancement of digital electronics, electronic energy meters replaced analog systems, offering improved accuracy and reliability. However, these systems still required manual data collection, limiting their efficiency in large-scale applications (Nikpour, 2023).

Recent studies emphasize the use of microcontrollers with integrated wireless communication capabilities to simplify system architecture. These systems eliminate the need for external communication modules, reducing cost and improving reliability (Mohapatra, 2025). Voltage and current sensing technologies demonstrate an essential role in smart metering systems. Isolated sensing modules are widely used to ensure safety while maintaining measurement accuracy. Proper calibration is necessary to reduce errors caused by noise and environmental factors (Hakim Firdaus , 2024; Ben Dhaou , 2023).

The emergence of the Internet of Things (IoT) has significantly transformed energy monitoring systems by enabling seamless connectivity between devices and cloud platforms. IoT-based smart meters provide real-time monitoring, data logging, and remote accessibility, thereby enhancing energy management and efficiency (Garcés et al., 2025). Choudhary (2024) defined IoT as a paradigm where physical devices are interconnected to enable seamless data exchange and intelligent decision-making. More recent smart energy studies confirm that IoT improves energy efficiency through real-time monitoring and predictive analytics in residential and industrial systems (Nikpour ,

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2023). The researchers further emphasized that IoT-based energy management systems integrate sensing, communication, and computation layers to optimize energy consumption in smart environments.

Early smart metering systems commonly relied on GSM and radio frequency (RF) communication for remote data transmission. Although these technologies improved automated meter reading, they were often associated with higher communication costs, limited scalability, and increased infrastructure requirements. Recent developments have shifted towards Internet of Things (IoT)-based architectures using Wi-Fi-enabled ESP32 platforms, which provide cost-effective, real-time monitoring and cloud connectivity (Almasri et al., 2024). Modern smart meters enable demand response, load balancing, and improved grid reliability through real-time data acquisition, two-way communication, and advanced monitoring capabilities. Recent studies have shown that IoT-enabled smart metering architectures enhance system scalability, remote accessibility, and operational efficiency, making them an important component of modern smart grid infrastructure (Alsafran et al., 2025; Ben Dhaou, 2023).

Smart energy meters are fundamental components of modern smart grid systems, enabling bidirectional communication between consumers and utility providers. This capability facilitates efficient energy distribution, demand response, remote monitoring, and overall system optimization through Advanced Metering Infrastructure (AMI) (Ratshitanga et al., 2023). The integration of IoT technologies in smart meters has opened new possibilities for real-time data analytics, predictive maintenance, and intelligent energy management (Rind et al., 2023). Several studies have proposed IoT-based energy metering systems using various technologies. Almasri et al. (2024) proposed a smart energy meter using ESP8266 and Blynk, which enabled real-time monitoring and control of energy consumption. Sathya et al. (2024) presented a Raspberry Pi-based smart energy meter that integrates Internet of Things (IoT) technology and Python-based processing for real-time acquisition, monitoring, and analysis of electrical energy consumption. El-Khozondar et al. (2024) developed an ESP32-based IoT smart energy monitoring system that enabled real-time measurement and wireless transmission of voltage, current, power, and energy consumption through the Blynk platform, while Garcés et al. (2025) implemented an IoT-based electricity meter using ESP32 and Blynk.

Unlike many existing IoT-based smart metering systems that focus primarily on hardware implementation or cloud-based monitoring, the present study integrates real-time sensing, cloud communication, and MATLAB-based analytical visualisation into a single low-cost platform. This integrated approach provides users with both remote access to electrical parameters and enhanced graphical interpretation of energy consumption patterns, thereby supporting more informed energy management decisions.

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Aim and Objectives

Aim: The aim of this study was to design and implement an Internet of Things (IoT)-based smart energy meter for real-time monitoring and MATLAB-based data analytics.

Objectives:

The specific objectives were to: (i) design and construct a smart energy meter using ESP32 microcontroller; (ii) measure electrical parameters including voltage and current; (iii) compute power and energy consumption; (iv) display real-time electrical parameters on an LCD module; (v) transmit data to a cloud platform; and (vi) improve monitoring accuracy and efficiency.

Research Design

The study adopted a prototype development methodology to design and evaluate an Internet of Things (IoT)-based smart energy monitoring system. The proposed system integrated sensing hardware, embedded processing, wireless communication, and cloud-based visualization to measure and report electrical parameters in real time. This study adopted a prototype development and experimental evaluation approach. The developed prototype was tested under controlled laboratory conditions to evaluate its performance in measuring and transmitting electrical parameters in real time.

The proposed architecture minimized hardware complexity because the ESP32 provided built-in wireless connectivity, eliminating the need for separate Wi-Fi modules. Similar architectures have been reported in recent ESP32-based smart metering research. The system comprised four functional units: (i) sensing unit, (ii) processing unit, (iii) communication unit, and (iv) application unit.

Sensing unit

The current sensor was installed in series with the AC line to detect the amount of current flowing through the load. It converted the measured current into an analog voltage signal, which was sent to the GPIO34 analog-to-digital converter (ADC) pin of the ESP32 for processing. At the same time, the ZMPT101B voltage sensor was connected across the AC supply to measure the line voltage. The sensor conditioned and scaled the AC voltage to a safe analog signal level suitable for the ESP32. Its analog output was connected to GPIO35, another ADC-enabled pin on the ESP32.

ACS712 Current Sensor: The ACS712 was a Hall-effect-based current sensor developed by Allegro MicroSystems. It measured both alternating current (AC) and direct current (DC) by converting the magnetic field generated around a current-carrying conductor into a proportional analog voltage. This enabled non-invasive current measurement while maintaining electrical isolation between the sensing circuit and the high-power line.

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ZMPT101B Voltage Sensor: The ZMPT101B was a voltage sensor commonly used in electronic projects to measure alternating current (AC) voltages. It operated based on the principle of voltage transformation and voltage division, using a voltage transformer and a voltage divider circuit to measure AC voltages accurately and provide a proportional output voltage.

Processing unit

The ESP32 microcontroller served as the central processing unit (CPU) of the system. The ESP32 sampled the analog signals from GPIO34 and GPIO35, digitized them using its built-in ADC, and processed the readings to determine electrical parameters such as voltage, current, power, and energy consumption. The ESP32 was a family of low-cost, energy-efficient microcontrollers that integrated both Wi-Fi and Bluetooth capabilities, featuring a Tensilica Xtensa LX6 microprocessor available in dual-core and single-core variants.

Communication unit

The ESP32 incorporated a built-in Wi-Fi module that enabled wireless communication, allowing remote monitoring, data logging, cloud connectivity, and smart billing applications. Measured data could be transmitted to online platforms such as Blynk, ThingSpeak, or Firebase. This capability transformed the conventional energy meter into a smart IoT-enabled device.

Application Unit

The application unit presented information through both a local LCD display and a remote dashboard accessible through the internet. The LCD display provided real-time visualization of all the system parameters. It communicated with the microcontroller through I2C communication protocol using GPIO21 (SDA) and GPIO22 (SCL). The display showed the following parameters: voltage, current, power, energy consumption, and system status.

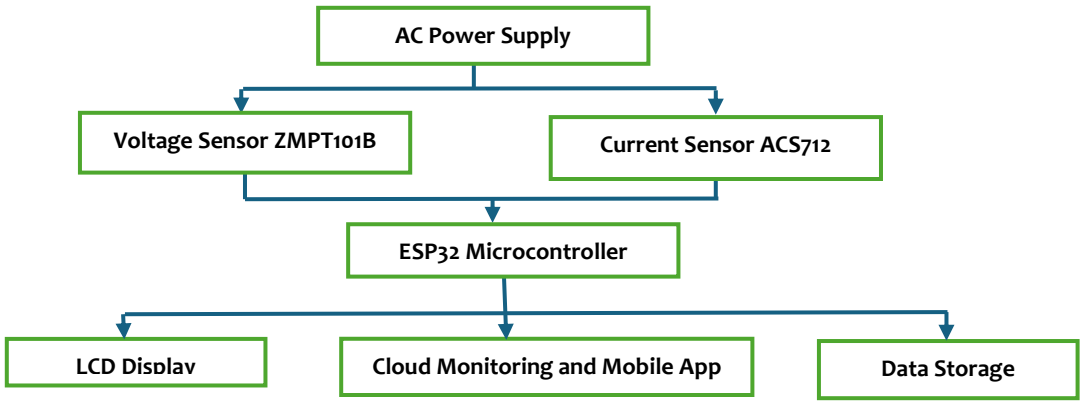


Fig. 1 Block diagram of the proposed smart energy meter

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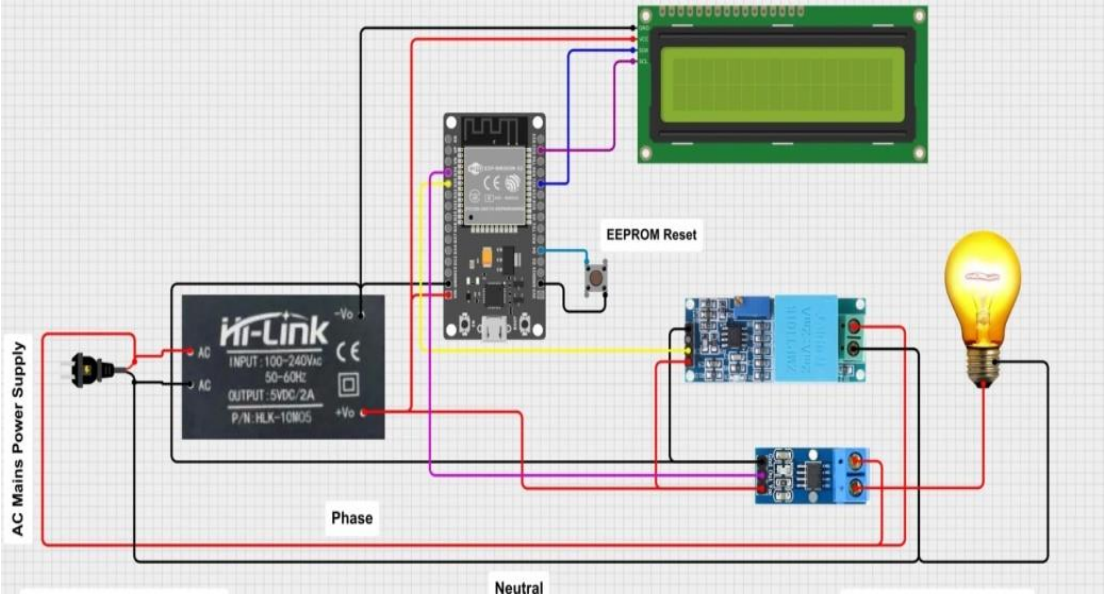


Fig 2: Circuit Diagram of the System Design

Microcontroller Programming

The firmware, written in embedded C++, handled real-time digital signal processing and peripheral execution loops. The firmware configured the microcontroller's internal ADC to sample the conditioned voltage and current waveforms at a high frequency (e.g., 1KHz to 2KHz) to ensure accurate wave tracking. The firmware executed mathematical discrete sampling formulas to compute main electrical metrics:

Root Mean Square Voltage (Vrms) and **Root Mean Square Current (Irms)** were calculated using the sampled values.

Real Power (P) was computed using Equation (1):

$P = V\ x\ I$ ……eqn (1)

Where P = Power (W), V = Voltage (V), I = Current (A)

Energy Consumption was calculated by integrating Active Power over time to yield Kilowatt-hours (kWh):

$E = P \times t$ …… eqn (2)

Where E = Energy (Wh), P = Power (W), and t = Time (hours).

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MATLAB-Based Data Analytics

The MATLAB program provided real-time visualization of the electrical parameters measured by the Smart Energy Meter. The voltage graph illustrated fluctuations in the supply voltage, while the current graph reflected changes in load demand. Instantaneous power was obtained by multiplying the measured voltage and current, providing insight into the real-time power consumption of connected loads. The cumulative energy graph increased continuously with time, representing the total electrical energy consumed in kilowatt-hours (kWh).

MATLAB was selected because of its powerful numerical computing environment, advanced data visualisation capabilities, and suitability for analysing electrical engineering datasets. The software enabled efficient processing of the measured electrical parameters and facilitated graphical interpretation of voltage, current, power, and energy consumption trends.

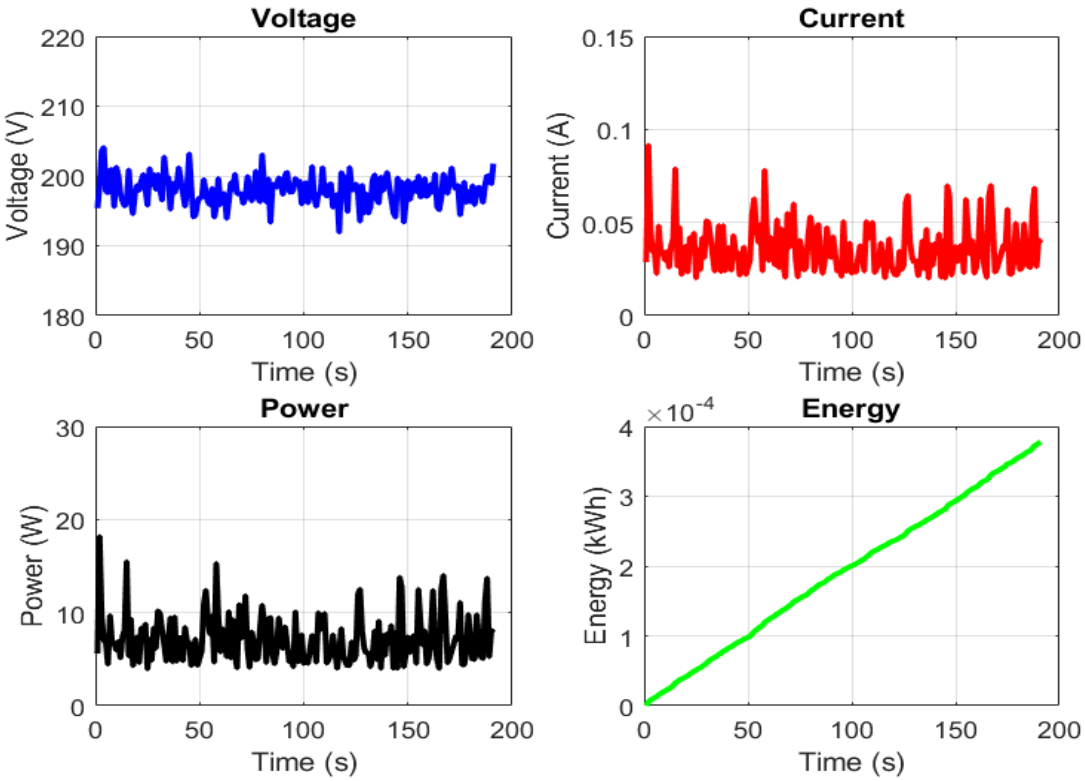


Fig 3: MATLAB Graphs (Voltage vs Time, Current vs Time, Power vs Time, Energy vs Time)

System Flowchart

The system operated by continuously measuring electrical parameters and processing them. The processed data was displayed locally and transmitted to a cloud platform for remote monitoring. The operational sequence was as follows: (i) Initialize ESP32, ADC,

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LCD and WiFi; (ii) Read Voltage (ZMPT101B) and Current (ACS712); (iii) Apply Calibration and Filtering; (iv) Compute RMS Voltage and RMS Current; (v) Compute Power (P) and Energy (E); (vi) Display on LCD; and (vii) Send Data to Cloud.

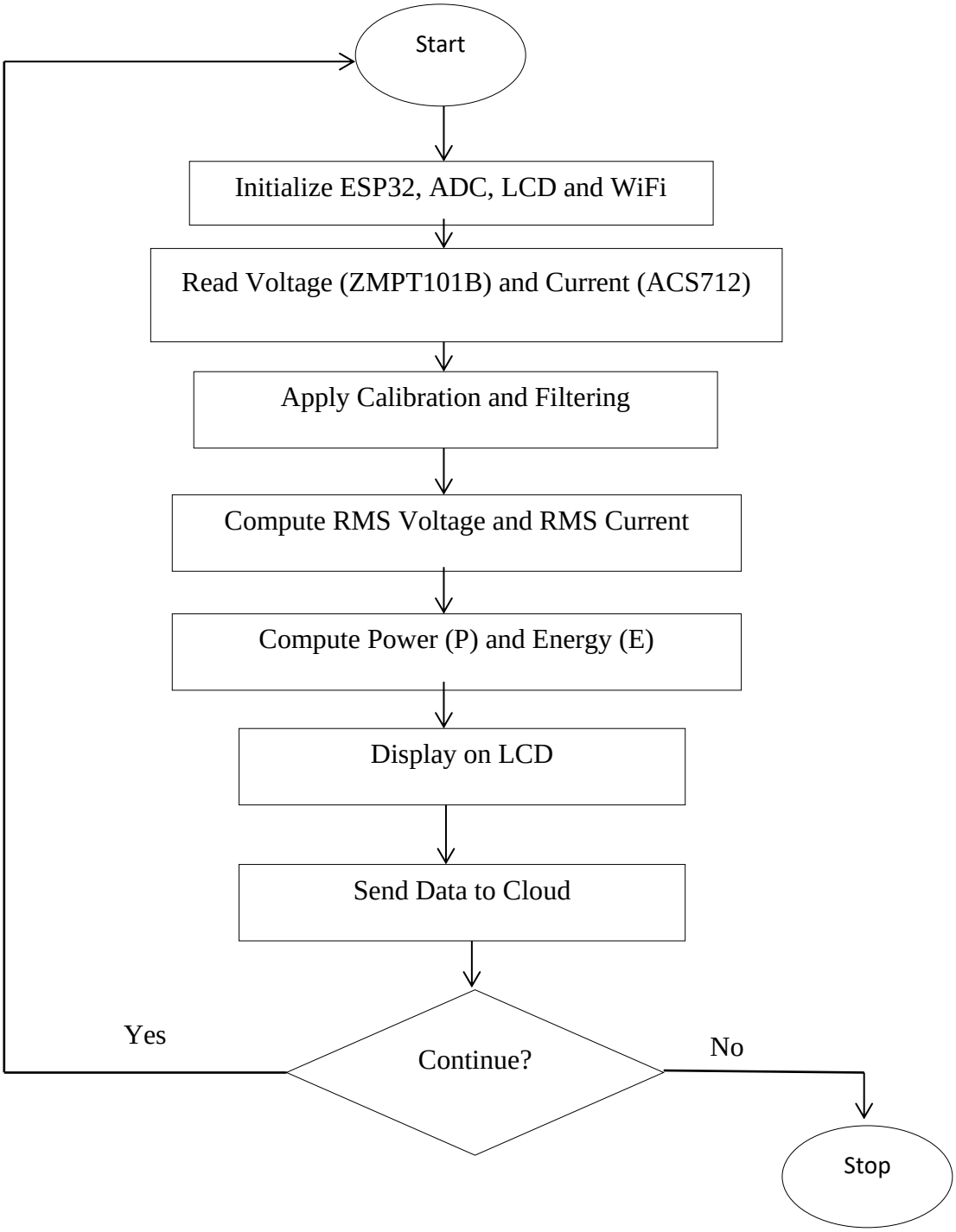


Fig 4: System Flowchart

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IoT Integration and Data Processing

The proposed work was connected through Blynk IoT server for control applications. The status of the connected hardware pins were continuously transmitted to the Blynk server and the smartphone installed with the Blynk App got the ability to read the saved data from the IoT server. The hardware was also controllable from the smartphone through wireless connections with the help of Blynk hardware.

The ESP32 calculated the principal electrical parameters using sampled voltage and current values. The analog signals from sensors were converted to digital values by the ESP32 ADC (12-bit resolution). Calibration factors were applied to obtain actual RMS values. Active power was computed by integrating power over time. A moving average filter was used to reduce noise.

Hardware Specifications

Table 1 presents the hardware components used in the implementation.

Table 1: Hardware Components

Component	Model/Type	Functions
Microcontroller	ESP32	Data acquisition, processing, WiFi communication
Current Sensor	ACS712	Measure AC current using Hall-effect
Voltage Sensor	ZMPT101B	Steps down and isolates AC Voltage for measurement
Display	LCD16X2	Local display of electrical parameters
Power Supply	5V DC	Power ESP32 and sensors

Testing and Results

After completion of the construction, testing was carried out to observe the performance of the circuit. The development of the Smart Energy Meter was divided into distinct, sequential stages spanning hardware synthesis, firmware development, network configuration, and cloud integration.

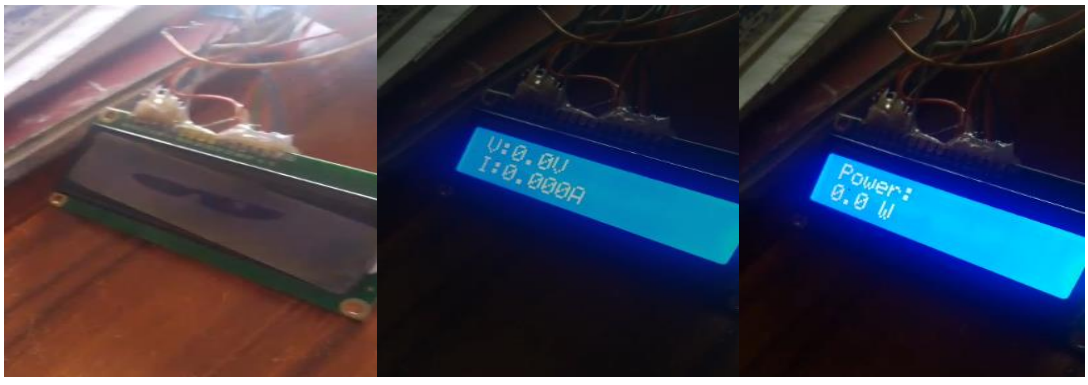


Fig. 5: Experimental Testing of the Developed Smart Energy Meter

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Table 2 presents the results of measured quantities during testing.

Table 2: Measured Electrical Parameters During Experimental Testing

Voltage (V)	Current (A)	Power (W)	Energy (kWh)
220	0.40	88	0.088
220	0.75	165	0.165
220	1.20	264	0.264



Fig. 6: Completed Prototype of the Smart Energy Meter

Discussion

The experimental evaluation demonstrated that the developed IoT-based smart energy meter successfully measured voltage, current, power, and energy consumption while providing continuous real-time monitoring through the ESP32 microcontroller and cloud-based communication platform. The measured electrical parameters remained stable throughout the testing period, indicating that the proposed system is capable of providing reliable data acquisition for residential and small-scale commercial energy monitoring.

The voltage measurements obtained from the prototype closely matched the expected supply values, confirming the effectiveness of the implemented voltage sensing circuit. This finding is consistent with the work of Almasri et al. (2024), who developed an ESP32-based smart energy monitoring system capable of accurately measuring voltage and transmitting real-time data through an Internet of Things (IoT) platform. Similarly, Garcés et al. (2025) reported that IoT-enabled smart electricity meters provide dependable voltage monitoring suitable for intelligent energy management applications. The agreement between the present study and previous investigations confirms that low-cost embedded platforms can achieve measurement accuracy suitable for practical smart metering applications.

Similarly, the current measurements demonstrated satisfactory accuracy under varying load conditions. Accurate current sensing is essential for reliable estimation of electrical power and cumulative energy consumption. The present findings agree with those of Ben Dhaou (2023), who demonstrated that IoT-enabled smart meters continuously monitor electrical current to improve energy management in residential environments. Comparable observations were also reported by Garcés et al. (2025), who highlighted accurate current measurement as a fundamental requirement for reliable smart metering and energy management systems.

The calculated power values followed the expected electrical relationship between voltage and current throughout the experimental period, demonstrating the effectiveness of the implemented computational algorithm. These results are comparable with those reported by Almasri et al. (2024), whose ESP32-based monitoring system accurately determined active power in real time for remote monitoring applications. The close agreement suggests that the developed prototype is capable of producing dependable power measurements while maintaining a relatively simple and cost-effective hardware configuration.

The prototype also successfully accumulated energy consumption data over the monitoring period, enabling continuous tracking of electricity usage. Continuous monitoring of energy consumption provides users with timely information for analysing consumption patterns and improving energy efficiency. This observation supports the findings of Ben Dhaou (2023), who demonstrated that IoT-enabled smart meters enhance energy management through continuous acquisition and visualization of electrical energy data. Likewise, Rind et al. (2023) emphasized that real-time energy monitoring enables both consumers and utility providers to make informed operational decisions that improve energy efficiency and support smart grid development.

The successful transmission of measurement data from the ESP32 module to the cloud platform further demonstrated the effectiveness of the implemented IoT communication architecture. The ability to remotely monitor electrical parameters in real time enhances accessibility, operational efficiency, and user convenience. Similar results were reported by Almasri et al. (2024), who demonstrated reliable wireless transmission of electrical parameters using an ESP32-based IoT monitoring system. In addition, Rind et al. (2023) identified IoT communication as one of the enabling technologies for intelligent smart metering and advanced grid management.

From the perspective of smart grid implementation, the developed prototype demonstrates the practical benefits of integrating IoT technologies into modern electricity metering systems. The combination of real-time monitoring, remote accessibility, and continuous data acquisition supports demand-side management and more efficient utilization of electrical energy. These findings are consistent with Kabeyi

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and Olanrewaju (2023), who identified smart meters as fundamental components of modern smart grid infrastructure because of their ability to support bidirectional communication, demand response, and intelligent energy management. Similarly, Ratshitanga et al. (2023) emphasized that smart metering technologies improve monitoring, automation, and optimization within active electricity distribution systems through advanced communication protocols.

Generally, the performance of the developed prototype compares favourably with recent studies on IoT-enabled smart energy metering systems. The proposed design successfully combines accurate electrical parameter measurement with real-time cloud-based monitoring using an affordable ESP32 platform. Compared with many existing systems, the prototype provides a simple, scalable, and cost-effective solution suitable for residential and small commercial applications. Its capability for continuous monitoring and remote accessibility also demonstrates its potential for integration into future smart grid infrastructures and intelligent energy management systems.

Conclusion

This study presents the design and implementation of an IoT-based smart energy meter that measures voltage, current, power, and energy consumption in real time. By integrating an ESP32 microcontroller with an ACS712 current sensor, a ZMPT101B voltage sensor, MATLAB for analytics, and the Blynk cloud platform, the system enables continuous monitoring, remote access, and graphical visualization of electrical parameters. Experimental results show that the prototype delivers reliable measurements and transmits data effectively for remote monitoring. Compared with conventional electricity meters, the proposed system offers greater visibility into energy consumption, facilitates more informed energy management, and provides a practical, low-cost solution suitable for residential and small commercial applications. While sensor calibration and dependence on network connectivity remain areas for further refinement, the overall performance demonstrates the system's viability for modern smart metering applications.

Limitations of the Study

The developed prototype was evaluated under laboratory conditions using single-phase electrical loads. Consequently, the performance of the system under large-scale industrial environments and varying network conditions was not investigated. In addition, measurement accuracy depended on proper sensor calibration, and continuous cloud connectivity was required for uninterrupted remote monitoring. These limitations provide opportunities for future improvements and broader field validation.

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Recommendations

Future work should focus on refining sensor calibration methods to enhance measurement accuracy across diverse operating conditions. The system should also be extended to support three-phase electrical installations, broadening its applicability to industrial settings. Incorporating artificial intelligence and machine learning algorithms could enable capabilities such as energy demand forecasting, anomaly detection, and predictive maintenance. Additionally, future iterations should integrate local data storage to ensure uninterrupted operation during internet outages and implement robust cybersecurity measures to safeguard transmitted energy data.

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