IoT-BASED ENERGY METERING SYSTEM FOR THREE PHASE POWER SUPPLY

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ABSTRACT
This study presents an Internet of Things (IoT)-based solution for monitoring and measuring various electrical parameters in a three-phase power system. The system is intended to address the problem of lack of real-time remote monitoring and processing of energy consumption data usually associated with the conventional digital metering system being used in Nigeria's power distribution networks. The three-phase energy meter was built with the ESP32 Wi-Fi-enabled microcontroller, which processes input signals from ZMPT101B and ACS712 sensors connected to each phase. These sensors enable acquisition of voltage and current data used for computation of instantaneous power and energy consumption per phase. The energy data for each of the phases are streamed wirelessly via the internet to the Google Sheets platform using a Google Service Account and Goggle Sheets Application Programming Interface (API), enabling seamless real-time cloud-based data logging capability. The system was tested under varying load conditions and the results demonstrated the system's ability in capturing records of all the electrical parameters of interest for all three phases with overall energy measurement accuracy of 99.1%, average latency of 7ms and system availability of 100%. The system therefore offers high level of accuracy, reliability, scalability, security and user friendliness.

Keywords: Internet of Things (IoT), Three-Phase energy metering, Real-Time Monitoring, Google Sheets.

1. INTRODUCTION

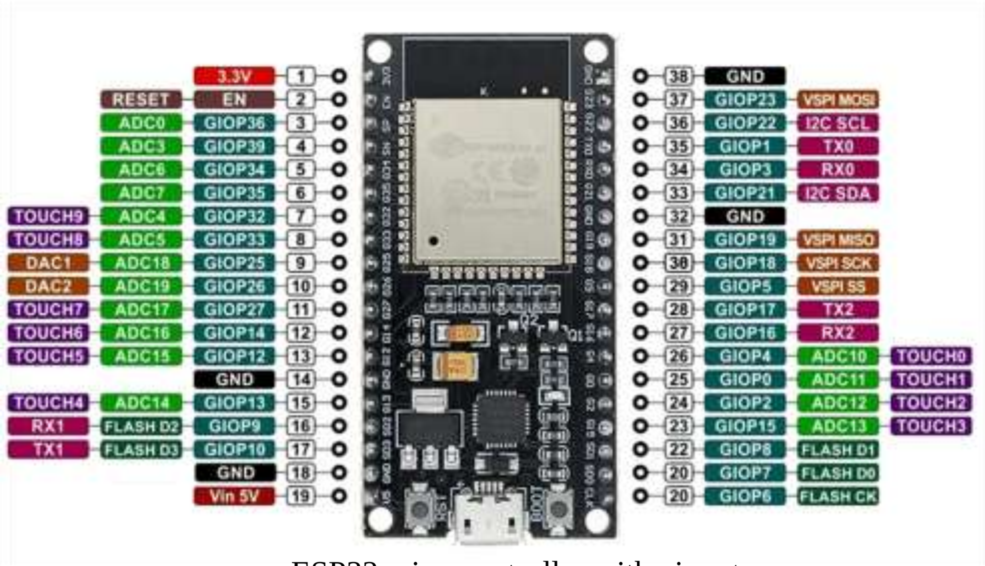
The increasing global reliance on electrical energy for domestic, commercial and industrial activities has emphasized the need for improved energy usage monitoring and management. Energy wastages and poor management of energy is one of the problems facing the power sector globally. The increasing demand for energy and the global call for sustainability has made efficient energy management a critical area of research (Usoro *et al.*, 2025). As power distribution networks expand and energy costs rise, consumers and utility providers seek more intelligent tools for monitoring, analysing and optimizing electricity consumption. The development and implementation of smart metering technologies have gained momentum as a replacement for traditional analog metering systems. Although analog energy meters are being phased out in most urban areas in Nigeria, they are still widely used in rural areas (Iloh, 2020). Analog energy meters present several limitations which include lack of automated data logging, inability to support remote access to measurement data and minimal integration with analytical tools. Most importantly, they do not provide real-time feedback which makes it difficult for users to respond promptly to consumption spikes, system failures, or abnormal usage patterns. This creates inefficiencies in energy consumption and impairs effective energy conservation strategies (Usoro *et al.*, 2025).
Advancements in microelectronics and embedded systems coupled with the evolution of the Internet of Things (IoT) have revolutionized how electrical parameters are monitored. IoT-based smart metering systems offer real-time tracking, remote access, improved data granularity and integration with cloud platforms for advanced analytics (Munoz *et al.*, 2022). These systems are particularly valuable in settings that require multi-phase energy monitoring such as medium- to large-scale enterprises, estate facilities, and power-distribution boards in industrial complexes. Various other attempts have been made to develop IoT-based energy management systems target practical benefits such as convenience, speed, and accurate information (Srun *et al.*, 2024; Salman *et al.*, 2016).

This study presents the design and implementation of an IoT-based, three-phase energy metering system using a Wi-Fi-enabled microcontroller and Google Sheets platform. The system is designed to measure voltage, current, power and energy on each phase and transmit the data in real-time to a remote cloud-based interface. Through the use of low-cost components and open-source software tools, this solution balances affordability with technical performance. Its aim is to support smart energy usage, enable more efficient diagnostics, and facilitate proactive energy management in three-phase systems.

2. METHODOLOGY

2.1 Materials

The key hardware materials used in this work are ACS712 current sensors, ZMPT101B voltage sensors, ESP32 microcontroller, 16x4 LCD, MTN Mi-Fi modem (serving as the internet gateway) and relays. The key software materials used are Arduino IDE and Google Sheets app. Figure 1 shows the pictures of some of the key hardware components used in developing the energy meter prototype.



ESP32 microcontroller with pinouts

ACS 712 Pinouts

ZMPT101B

16x4 LCD

Figure 1: Some of key components used in developing the energy meter prototype

2.2 Methods

2.2.1 Mathematical Modelling for Energy Calculation

The energy measurement algorithm involves the use of sensed current and voltage signals to compute power consumption over a specified period of time. Thus, the mathematical model was developed sequentially by:

(i) Calculating the current sense by the ACS712

(ii) Calculating the voltage sensed by the ZMPT101B
(iii) Calculate power by multiplying the current and voltage values
(iv) Calculate the energy consumption by integrating power obtained over a period of time.

(a) Mathematical model for Current Sensing

For each phase, the equation for determining the current sensed by the ACS712 is given by:

$$I_{\emptyset} = \frac{V_{out} - V_{zero}}{K_c} \qquad (1)$$

Where,
$I_{\emptyset}$ is the load current being measure
V_{out} is the ACS712 output voltage
V_{zero} is the zero current output voltage ($3.3V \div 2$ for)
K_c is the sensitivity of sensor

The digital equivalent of the analog value of the sensor output, V_{out} is determined using (2)

$$V_{out} = \frac{Raw\ Value}{ADC\ Resolution} \times V_{ref} \qquad (2)$$

Where,
Raw value = the ADC reading
ADC resolution = 4096 (for 12-bit ADC of ESP32)
V_{ref} = 3.3V (for ESP32 pins)

(b) Mathematical Voltage Sensing

For each phase, the voltage is measured using the **ZMPT101B voltage sensor** and follows the equation:

$$V_{\emptyset} = V_{sense} \times K_v \qquad (3)$$

Where,
$V_{\emptyset}$ = Phase voltage being measured
V_{sense} = ZMPT101B sensor output voltage
K_v = Calibration factor for ZMPT101B

The digital equivalent of the analog value of the voltage sensor output, V_{sense} is determined as in (2) above:

$$V_{sense} = \frac{Raw\ Value}{ADC\ Resolution} \times V_{ref} \qquad (4)$$

(c) **Calculation of Active Power**

The measured power for each phase is calculated using (5):

$$P = V_{\emptyset} \times I_{\emptyset} \times cos\emptyset \qquad (5)$$

Where,

$cos\emptyset$ = power factor

For the combined three phase power calculation, (6) is used:

$$P = \sqrt{3} \times V_{\emptyset} \times I_{\emptyset} \times cos\emptyset \qquad (6)$$

(d) **Energy Consumption Calculation**

Energy consumption is computed by integrating power over time using (7) as in (Iloh, 2020):

$$E = \frac{1}{1000}\int_0^t Pdt$$

$$= \frac{1}{1000}\int_0^t V_{\emptyset} I_{\emptyset} cos\emptyset dt \qquad (7)$$

E = energy consumed in kilowatt-hour (kWh)
P = power in watts
$V\emptyset$ = root mean square voltage in volts
$I\emptyset$ = root mean square current in amperes
$\emptyset$ = power factor of the supply
t = time in seconds

2.2 System Architecture

The architecture of the developed IoT-based three-phase energy metering system is structured around three major functional layers: the sensing layer, the processing layer, and the communication layer. Each layer plays a distinct role in enabling accurate data acquisition, efficient processing, and seamless remote data access and visualization. The synergy among these components ensures that the system operates reliably under diverse load conditions, offering real-time monitoring capabilities with minimal latency.

(a) Sensing Layer

The sensing layer is responsible for acquiring real-time voltage and current signals from each of the three phases of the electrical supply. For voltage measurement, ZMPT101B voltage sensors are employed. The sensors are chosen for their precision, compact size, and isolation capabilities which makes them suitable for continuous monitoring of AC voltage in embedded systems. For current measurement, ACS712 Hall-effect current sensors are utilized. These sensors convert the magnetic field induced by current flow into a proportional voltage signal. The combined setup captures instantaneous voltage and current values for each phase and translates them into analog signals compatible with microcontroller input. The sensors are carefully calibrated to minimize error and ensure safe operation within the expected electrical range (Kumar & Pandey 2024).

(b) Processing Layer

At the heart of the system is the ESP32 microcontroller which is a versatile and powerful SoC (System-on-Chip) that handles signal processing, control logic, and communication tasks. It is equipped with multiple analog-to-digital converters (ADCs) to read the analog outputs from the sensors. The ESP32 processes these signals to derive electrical quantities such as root mean square (RMS) voltage and current, active power (P), and energy consumption (E) using in-program formulae. Signal conditioning and averaging techniques are implemented to filter out noise and ensure stable readings. The processing layer also handles threshold comparisons and can support future integration of control algorithms like load balancing or demand-side management (El-Khozondar *et al.*, 2024).

(c) Communication Layer

The processed data is then prepared for transmission using the ESP32's integrated Wi-Fi module, which provides the gateway for internet connectivity. The communication layer utilizes HTTPS protocols to securely transmit data to a preconfigured Google Sheets using a Google service account Google Sheets API. This method allows for persistent cloud storage, enabling both historical data analysis and real-time visualization. The architecture supports bidirectional communication capabilities which can be expanded to include remote control functions such as relay activation or shutdown of loads in future versions. This layer ensures that users can access the system from any location using standard web-enabled devices (Onay *et al.*, 2023).

The architecture provides flexibility which allows the system to be modified with minimal hardware changes. This adaptability makes the design suitable for deployment in various environments from individual residences to larger industrial settings. The block diagram of the developed system is shown in figure 2 while figure 3 shows the system's high-level model.

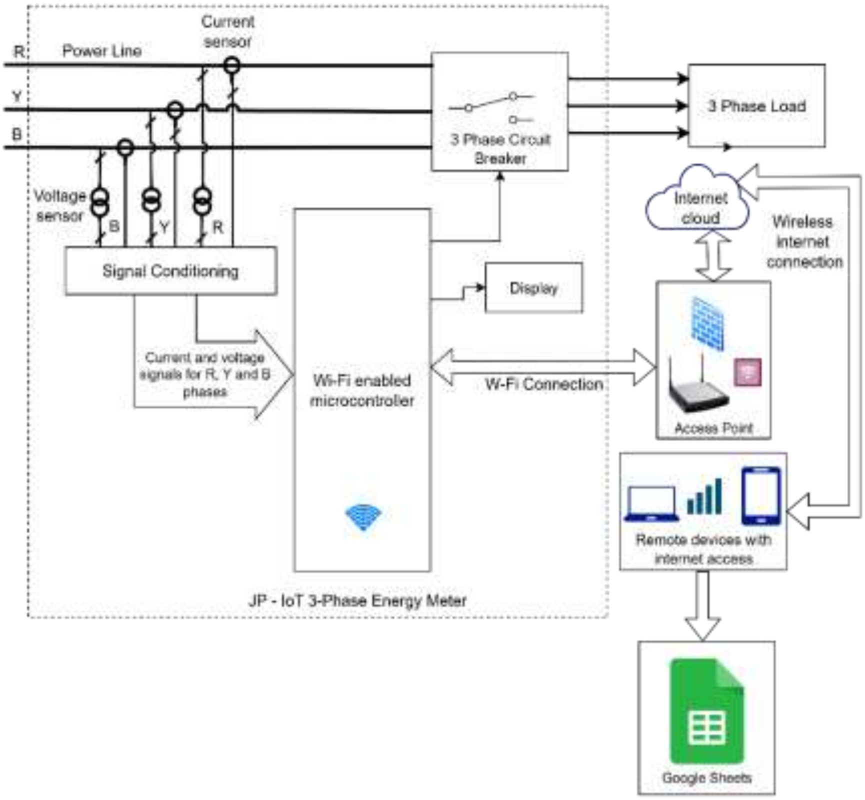


Figure 2: Block diagram of the IoT-based three-phase energy monitoring system.

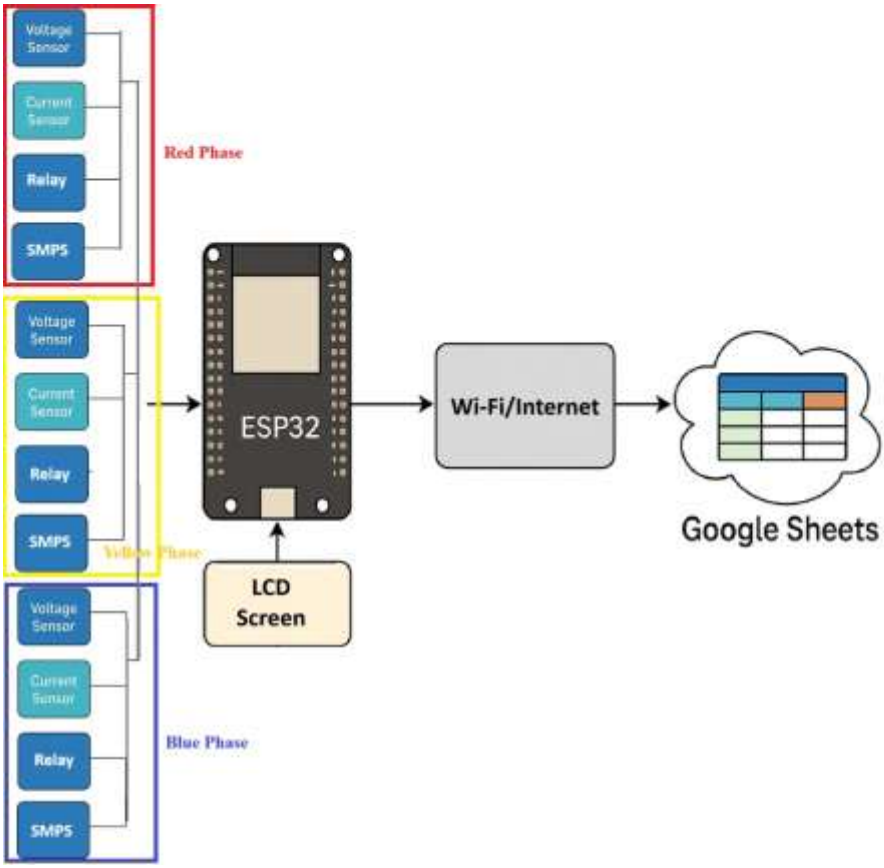


Figure 3: High-level system model showing hardware, cloud, and user interface integration.

2.3 Software Implementation

The software implementation forms the operational core of the energy metering system, ensuring that the hardware components interact seamlessly and deliver accurate data in real time. Development of the firmware was carried out using the Arduino Integrated Development Environment (IDE) which was chosen for its ease of use, extensive library support and compatibility with the ESP32 microcontroller. The firmware is designed to execute a sequence of tasks critical to the accurate measurement and transmission of electrical parameters. These tasks are implemented as modular functions that enhance readability, maintainability and performance:

(a) **Reading analog input values:** The ESP32 continuously samples analog voltage and current signals from the ZMPT101B and ACS712 sensors. These signals are read through the analog-to-digital converter (ADC) channels. Sampling is carried out at regular intervals to ensure consistent data acquisition, and buffering techniques are used to mitigate transient noise.

(b) **Calculating instantaneous and average values:** Once the raw signals are captured, the firmware computes the root mean square (RMS) values of voltage and current for each phase. Instantaneous power is calculated by multiplying voltage and current values at each sampling point. These instantaneous values are then averaged over fixed time windows to derive stable real-time readings. Energy consumption is computed as the integration of power over time, updated periodically.

(c) **Use of Google Sheets Interface:** To set up the google sheets platform for the system, a Google Service account was created and Google Sheets API key generated following similar procedure used in (randomnerdtutorials.com, n.d.). The processed electrical parameters are organized into structured strings formatted for compatibility with Google Sheets. Each set of readings includes a timestamp and phase identifiers. The data were prepared for secure HTTPS transmission to a Google Sheets. This step ensures proper alignment and labelling of data columns in the cloud for accurate visualization and logging. (Ahmed & Rizvi 2024). Conditional formatting was applied to highlight critical thresholds such as over-voltage or over-current conditions. These visual cues make it easier for users to detect and respond to abnormal operating conditions promptly. The use of Google Sheets as the visualization platform ensures reliability, scalability, and low implementation cost. Moreover, it provides room for future enhancements, such as integrating Google Data Studio for more advanced analytics or automated notifications via email or SMS when critical conditions are detected. Through this dashboard, the system transforms raw sensor readings into actionable insights, empowering users to make informed energy management decisions.

(d) **Managing Wi-Fi connectivity:** A key aspect of the firmware is its ability to establish and maintain a stable Wi-Fi connection. Upon startup, the ESP32 connects to a predefined wireless network. If a disconnection occurs, the system detects the loss of connectivity and attempts automatic reconnection. This is done without user intervention which ensures continuous data updates without interruption (Saleem *et al.*, 2023).

Error-handling routines were also implemented to handle edge cases such as sensor reading failures or network latency. The firmware is also structured to allow future upgrades, including integration of MQTT for broader IoT interoperability or implementation of OTA (Over-The-Air) updates for system maintenance. The software acts as the bridge between physical measurements and digital insight which enables a robust and user-friendly smart metering experience. The Sequence Diagram of the Developed System is shown in figure 4.

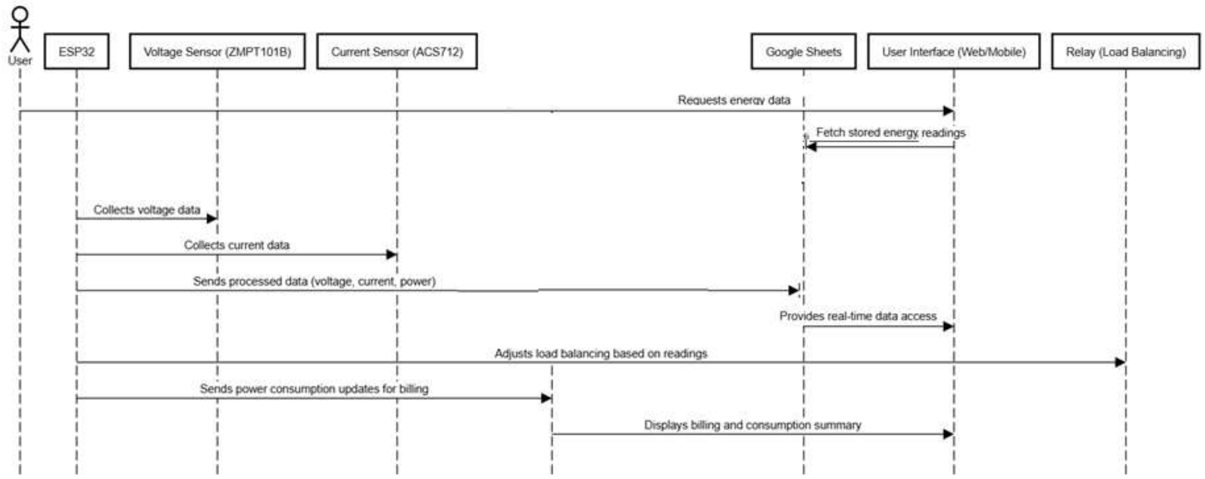
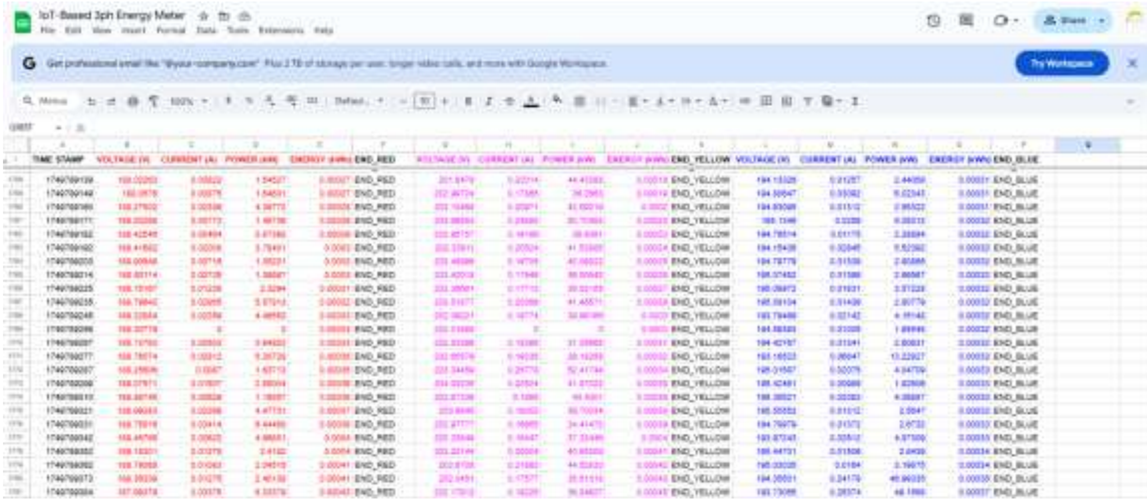


Figure 4: Sequence diagram illustrating the data acquisition and cloud update process.

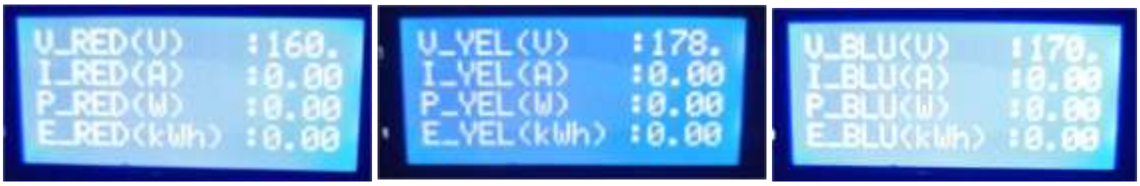
3. RESULTS AND DISCUSSION

(a) Dashboard and Visualization

To ensure that the data collected by the system is easily accessible and meaningful to users, a dynamic dashboard was developed using Google Sheets in combination with Google Apps Script. This cloud-based solution provides real-time updates of electrical parameters which makes it possible to monitor energy usage trends as they unfold. The dashboard automatically receives new data entries through secure HTTPS communications initiated by the ESP32 microcontroller. Each update includes time-stamped records of voltage, current, power, and energy readings for all three phases. To enhance data comprehension, multiple types of visual aids such as line graphs, bar charts, and pie charts could be embedded within the spreadsheet. Screenshot samples of the Google Sheets display and the LCD display are shown in figure 5.



(a) Screenshot sample of the Google Sheets dashboard



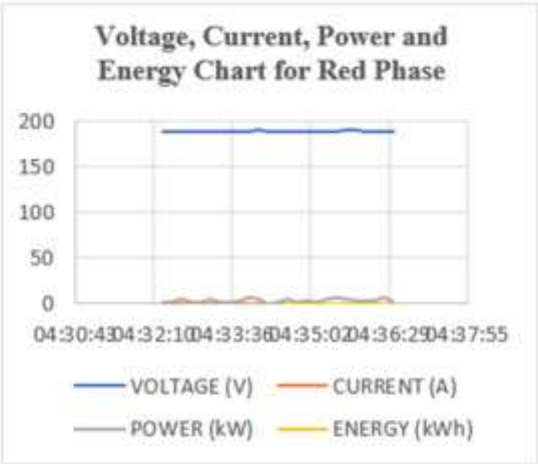
(b) Photo samples of measurement on energy meter LCD display for the three phases

Figure 5: Pictures of the samples of Google Sheets (a) and LCD displays (b)

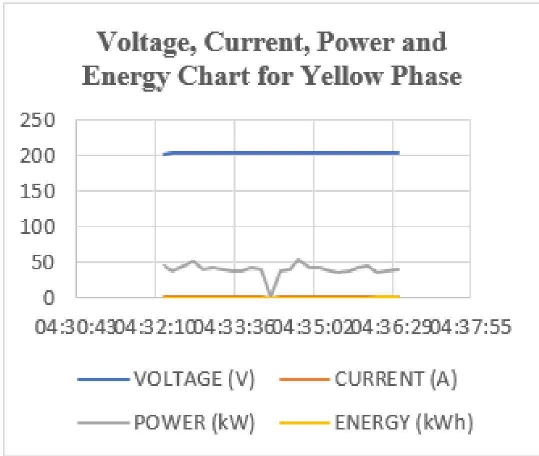
These visualisation components allow users to quickly identify patterns, spot anomalies, and understand consumption behaviour at a glance. A major feature of the dashboard is its accessibility. Users can connect to the Google Sheets dashboard from any remote device with internet access, including smartphones, tablets, and laptops/desktop computers provided they have access to platform. The user interface is intuitive, requiring no specialized software or technical expertise. Data is organized into properly labelled columns and rows, and historical logs can be easily downloaded for offline analysis or reporting purposes (Mazandarani & Smith 2023).

(b) Phase-wise Testing and Results

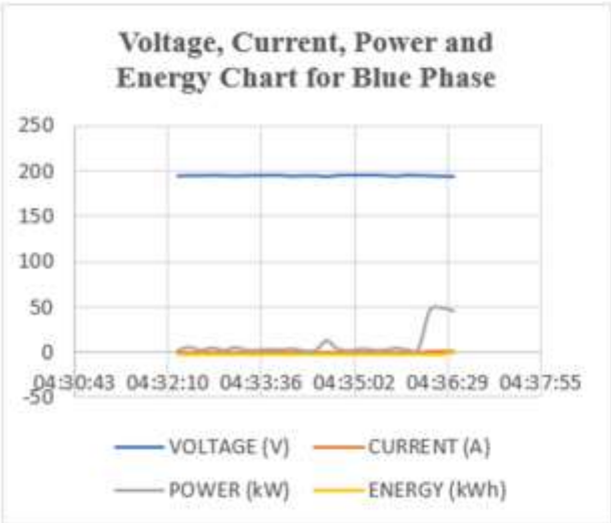
To evaluate the performance and reliability of the developed IoT-based three-phase energy metering system, the system was tested under varying load conditions. The Energy meter was connected to a three-phase load board and measurements from each of the phases were captured both from the LCD of physical prototype and from the google sheets platform. The samples of results for the voltage, current, power and energy measurements obtained are shown in figures 6 (a), (b), (c) and (d). Note that (d) shows the combined results of the voltages for the three phases. Such phase-wise results can also be generated for each of the other parameters (current, power and energy).



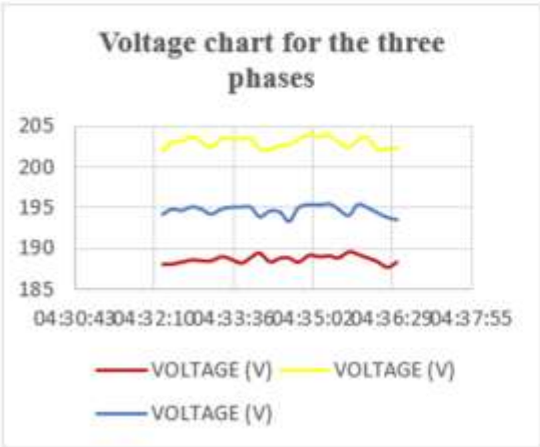
(a) Red Phase



(b) Yellow Phase



(c) Blue Phase



(d) Combine three phase results

Figure 6: Results of voltage, current, power and energy measurements plotted from google sheets data for each of the phases (a), (b), (c) and (d).

(c) System Performance Evaluation Results

The system evaluation focuses on assessing the overall performance, reliability, and responsiveness of the IoT-based three-phase energy metering system. This includes evaluating core metrics such as energy measurement accuracy, data transmission latency, system availability, and security. These metrics reflect the system's operational capacity in real-world environments and its readiness for practical deployment. The evaluation was conducted under varying load and network conditions to ensure robustness. The results validate the effectiveness of the hardware-software integration in delivering accurate and real-time energy monitoring.

Table 1: Performance Evaluation Metrics Used

Metric	Definition	Measurement Tool
Accuracy	Percentage of correct energy readings compared to standard measurement devices	Multimeter / Test energy meter
Latency	Time delay between data sensing and cloud/dashboard update	Timestamp logging or ping test
Availability	Uptime or system responsiveness over a given period	Uptime counter / Device watchdog log
Security	Measures the system's protection against data breach or unauthorized access	Manual security checklist & penetration test

Table 2: Performance Results

Metric	Expected Value	Measured Value	Criteria Met (Yes or No)
Accuracy (%)	≥ 95%	99.1%	Yes
Latency (ms)	≤ 10 ms	7 ms	Yes
Availability (%)	≥ 95%	100%	Yes
Security (%)	≥ 95%	100%	Yes

(i) Evaluation Method of the Accuracy Test: The results of the accuracy of the system were computed using the following formula:

$$Accuracy = \left(1 - \frac{|Reference\,Value - System\,Value|}{Reference\,Value}\right) \times 100 \quad (8)$$

(ii) Latency Test: Latency refers to the time delay between when a sensor records a value and when that value is displayed or stored (e.g., in a cloud database or dashboard). It is typically measured in **milliseconds (ms)**. For the system tested, the latence value was determined using (9).

$$Latency = Timestamp_{Received} - Timestamp_{Generated} \quad (9)$$

Where:

$Timestamp_{Generated}$ = Time when the ESP32 or sensor captured the reading

$Timestamp_{Received}$ = Time when the data is logged in Google Sheets or received at the dashboard.

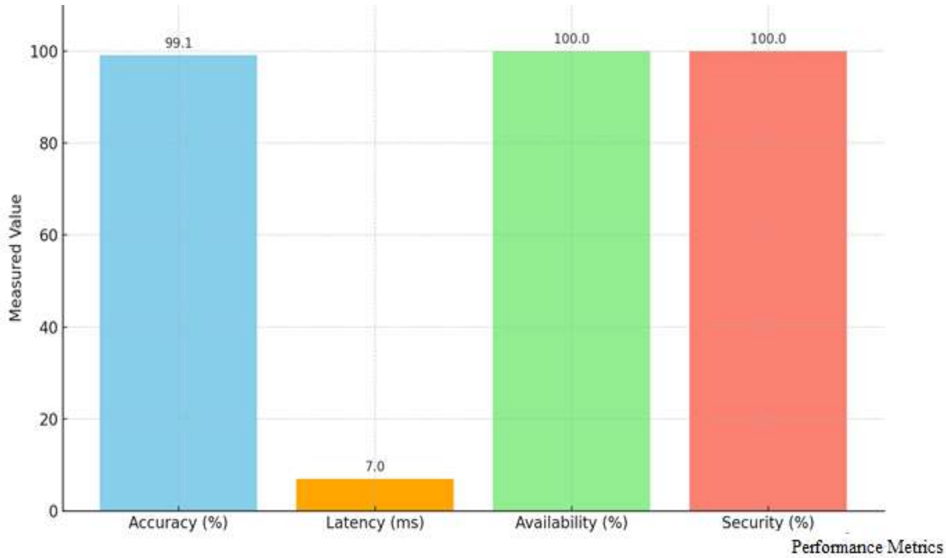


Figure 7: System level performance metrics

(d) **Physical Construction of the Developed System:** The photos of the developed prototype are shown in figure 8.

Figure 8: Physical hardware construction of the developed system

(e) **Discussion**

The results of this work demonstrated that a cost-effective IoT-based can be developed for multi-phase energy monitoring system with a level of accuracy and reliability suitable for practical applications. In contrast to many commercial smart metering systems, which often come with high procurement and maintenance costs, the proposed solution utilizes open-source tools, low-cost sensors, and the readily available ESP32 microcontroller to deliver a robust alternative.
By integrating these accessible technologies, this research bridges the gap between affordability and performance making smart energy monitoring more attainable for households, small businesses, and utility companies developing economies.

Despite these achievements, several limitations were noted during testing and deployment. One key issue is the susceptibility of sensor readings to electrical noise, particularly in environments where heavy inductive loads are present. This noise can lead to minor fluctuations in measurement accuracy. To address this, future designs should incorporate better shielding techniques, signal filtering algorithms, or the use of industrial-grade sensors with enhanced noise immunity.

Another challenge observed was occasional delays in data transmission caused by Wi-Fi connectivity interruptions. While the firmware's auto-reconnection mechanism minimized downtime, these network fluctuations could still impact real-time data visibility. Future system enhancements could involve implementing dual-channel communication strategies, such as combining Wi-Fi with GSM or LoRa networks, to provide backup connectivity and ensure higher system resilience. The developed system lays a strong foundation for affordable, scalable, and reliable energy monitoring solutions. With targeted improvements, it holds significant potential for broader adoption in smart homes, smart grids, and energy management systems.

4. CONCLUSION

The development and successful implementation of an IoT-based three-phase energy metering system have been achieved through a combination of low-cost hardware, open-source software, and modern communication technologies. The system fulfilled the core objective of enabling real-time monitoring of key electrical parameters, including voltage, current, power and energy consumption across all three phases. By leveraging cloud integration through Google Sheets, the system provides users with a convenient, accessible platform for monitoring and analysing energy usage over time. This platform not only empowers end-users to monitor their energy consumption but also provides utilities and facility managers with an effective tool for decision-making and resource optimization

This solution proves particularly suitable for deployment in a wide range of environments, from residential homes to small industries and office buildings. In these settings, gaining detailed insight into energy consumption patterns is crucial for promoting energy efficiency, reducing operational costs, and facilitating preventive maintenance. By offering a cost-effective alternative to the more expensive commercial metering systems, this work makes smart energy management more accessible to a broader audience. This study can be extended to include a centralized energy metering solution for multiple loads thereby minimizing the number and cost of energy meters needed for servicing the loads separately.

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