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(EEE)**

## Affordable Smart Energy Meter with Real-Time Monitoring and Alerts

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## **Declaration**

We, IRADUKUNDA KEVIN JONATHAN, ISHIMWE KAREKEZI Guy Gael, and NDAYISHIMIYE MERCI, students at the University of Rwanda, College of Science and Technology, School of Engineering, Department of Electronics and Telecommunication Engineering, hereby declare that we carried out the work report titled "Affordable Smart Energy Meter with Real-Time Monitoring and Alerts" under the supervision of Mr. Emmanuel HITIYISE. We declare that the work presented in this thesis is entirely our own, except where indicated by reference to the works of others. This work has not been submitted in any other form for any other degree or qualification at any other institution. We understand that plagiarism, whether from published or unpublished sources, may lead to disciplinary action, and we certify that this work does not contain any material that has been accepted for the award of any other degree or diploma.

# Approval and certification

We confirm that this final year project has been carried out at the University of Rwanda, College of Science and Technology, School of Engineering, Department of Electronics and Telecommunication Engineering for the award of the bachelor's degree in Electronics and Telecommunication Engineering under the supervision of Mr. Emmanuel HITIYISE. We also confirm that, to the best of our knowledge, it is our original work. Contributions from other sources have been properly acknowledged.

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# Abstract

The increasing demand for efficient and sustainable energy management has emphasized the need for innovative solutions in energy monitoring. This project, titled "Affordable Smart Energy Meter with Real-Time Monitoring and Alerts," presents the design, implementation, and testing of a low-cost, IoT-based smart energy meter intended for households and small businesses.

The system integrates a PZEM-004T AC energy meter, ESP8266 microcontroller, current and voltage sensors, and a mobile application built on the Blynk IoT platform to provide real-time monitoring, outage notifications, and tamper detection. The collected data is transmitted wirelessly to the cloud, enabling users to remotely monitor and manage their electricity consumption.

Performance evaluation shows that the proposed smart meter delivers accurate readings, ensures fast response times, and provides reliable operation. By empowering users with real-time insights and alerts, this system promotes energy efficiency, cost savings, and supports UN SDG 7. Affordable and Clean Energy in addition to Rwanda's Vision 2050 for sustainable development.

This project demonstrates the feasibility of deploying affordable smart energy solutions to improve energy management, particularly in developing regions.

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# List of abbreviations, acronyms and symbols

IoT	Internet of Things
AC	Alternating Current
PZCT-02	Current Sensor
SCT013	Split Core Transformer
PZEM-004T AC	Energy Meter Module (model PZEM-004T)
ESP8266	ESP8266 Wi-Fi Microcontroller
LCD	Liquid Crystal Display
PC:	Inter-Integrated Circuit
UART	Universal Asynchronous Receiver/Transmitter
GSM	Global System for Mobile Communications
ADC	Analog-to-Digital Converter
API	Application Programming Interface
TLS/SSL	Transport Layer Security / Secure Sockets Layer
MQTT	Message Queuing Telemetry Transport
RESTful	Representational State Transfer (service style)
OTA	Over-The-Air (firmware update)
IIoT	Industrial Internet of Things
AMI	Advanced Metering Infrastructure
AMR	Automated Meter Reading
LoRa	Long Range (radio modulation technique)
LoRaWAN	Long Range Wide Area Network
IEC	International Electrotechnical Commission
GDPR	General Data Protection Regulation
kWh	Kilowatt-Hour
H <sub>0</sub> / H <sub>1</sub>	Null Hypothesis / Alternative Hypothesis
W	Watt
A	Ampere
V	Volt
Mb	Megabyte
Kb	Kilobyte
GDPR	General Data Protection Regulation
ISO	International Organization for Standardization
NIST	National Institute of Standards and Technology
SHA	Secure Hash Algorithm
AT	Attention
HMAC	Ash-based Message Authentication Code
AES	Advanced Encryption Standard
UN -SDGs	United Nations-Sustainable Development Goals

# Chapter 1: General Introduction

The increasing worldwide need for electricity, along with the pressing demand for energy efficiency and sustainability, has driven the swift advancement of smart energy metering systems [1]. While traditional energy meters are effective for basic consumption tracking, they provide limited capabilities for real-time data access, remote monitoring, and dynamic energy management [2]. This shortcoming has underscored the need for intelligent, Internet of Things (IoT)-enabled smart meters that give both consumers and utilities detailed insights into consumption, facilitating optimized usage patterns and cost reduction [3].

Smart meters play a crucial role in contemporary smart grids, enabling bidirectional communication between consumers and service providers [4]. Their capacity to provide detailed data allows for the integration of renewable energy sources, management of demand side, and implementation of dynamic pricing structures [5].

Studies have shown substantial economic and operational advantages when real-time data analytics, big data methodologies, and predictive maintenance are integrated into smart metering systems [6].

Multiple designs have been suggested to upgrade traditional meters with capabilities such as GSM-based communication [7], integration of Arduino and embedded systems [8], and enhanced billing solutions [9].

Additionally, the shift from standalone smart grids to integrated smart energy systems, covering the electricity, heating, and transportation sectors, highlights the critical need for effective energy monitoring technologies [10].

The goal of this project is to create and implement an affordable smart energy meter that allows for real-time monitoring and alerts, utilizing IoT technologies to raise energy usage awareness among households and small businesses. This initiative specifically aligns with Rwanda's Vision 2050 objectives for sustainable development through the incorporation of smart technologies in the energy sector.

## 1.1 Background of project

Smart meters have revolutionized energy management by providing comprehensive consumption data, facilitating energy conservation initiatives, and enabling more accurate billing systems [11]. Early research highlighted the importance of consumer feedback in lowering electricity usage, showing that real-time energy information can greatly impact behavioral change [12].

The first developments in automated energy monitoring relied on wired technologies, but the emergence of wireless communication protocols such as Zigbee and GSM greatly enhanced the range and scalability of smart meters [13]. Projects like Arduino-based prototypes demonstrated the practicality of creating affordable, highly efficient smart meters for residential and small business use [14].

Investigations into IoT applications have pushed innovation further, enabling meters to connect with mobile devices, cloud services, and artificial intelligence for predictive analytics [15]. Successful integration with smart home systems and solar energy management platforms has maximized energy efficiency and cost savings [16].

Implementing big data strategies in smart metering has created new opportunities for predictive maintenance, with models capable of anticipating device malfunctions and optimizing replacement timelines [17]. Furthermore, the principles of Industry 4.0 and the Industrial Internet of Things (IIoT) continue to inspire novel frameworks where energy monitoring, automation, and optimization are thoroughly interconnected [18].

Beyond technological advancements, policy measures and environmental concerns have propelled the worldwide adoption of smart metering solutions. Governments and utility companies are increasingly acknowledging the importance of smart meters in meeting sustainable energy goals and minimizing carbon emissions [19].

Considering the affordability challenges in developing countries, there is a pressing need for smart energy meters that combine advanced technology with cost-efficiency and ease of deployment. This project seeks to address this need by providing a practical IoT-based smart energy meter solution suitable for emerging markets, such as Rwanda.

## 1.2 Problem statement

Traditional energy meters commonly used in households and businesses across Rwanda do not provide real-time monitoring, alerts, or tamper detection features, leading to inefficient energy consumption and unnoticed losses. In the absence of prompt feedback, consumers find it challenging to understand their consumption habits, which results in higher expenses and waste of resources [20].

Furthermore, the lack of tamper detection makes the system vulnerable to unauthorized access, which further places pressure on the energy supply [21]. There is an urgent demand for a cost-effective, IoT-enabled smart energy meter that allows consumers to track their usage in real time, receive alerts about their consumption, and identify irregularities without relying on the utility provider's infrastructure [22].

## 1.3 Motivation

As the demand for electricity in Rwanda increases, users encounter issues such as inefficient energy utilization, insufficient real-time feedback on consumption, and susceptibility to unnoticed wastage. Conventional meters provide minimal control or insight to users, restricting their capacity to effectively manage expenses.

Recent advancements in IoT and cloud technologies allow for cost-effective, real-time monitoring solutions. Driven by the necessity to provide consumers with independent energy management tools, this project suggests an external smart energy meter that improves transparency, encourages efficient energy use, and aligns with the nation's sustainability objectives.

## 1.4 Objectives

### 1.4.1 General objectives

To design and implement an affordable IoT-based smart energy meter that enables real-time monitoring, alerts, and data access for households and small businesses, promoting efficient energy consumption and empowering users to independently manage their electricity usage.

### 1.4.2 Specific objectives

- To develop a system that measures and displays real-time voltage, current, power, and energy consumption.
- To implement an alert mechanism for high energy usage, outages, and possible tampering attempts.
- To enable remote access to energy data via a mobile application and cloud storage.
- To design a tamper detection feature that enhances security and trust in energy usage reporting.
- To ensure the system is affordable, scalable, and user-friendly for low- to middle-income consumers.
- To contribute to Rwanda's goals of promoting sustainable energy use through technology-driven solutions.

## 1.5 Hypothesis

The project thesis is guided by the following null and alternative hypotheses:

H<sub>0</sub>: The implementation of a smart energy meter with real-time monitoring and alert features does not significantly improve user energy management and consumption efficiency.

H<sub>1</sub>: The implementation of a smart energy meter with real-time monitoring and alert features significantly improves user energy management and consumption efficiency.

# Chapter 2: Literature Review

## 2.1 Overview of Smart Energy Meters

The development of energy systems has been profoundly impacted by rising demand, scarce resources, and the necessity for more intelligent energy infrastructure [23]. Smart energy meters serve as a crucial advancement in this era, substituting conventional meters with digital devices that facilitate two-way communication between consumers and utility companies. These meters allow for accurate billing, immediate usage monitoring, and enhanced integration with the grid. The transition to smart metering is not solely a technical transformation but also a strategic initiative, aimed at improving energy distribution and minimizing waste [23].

## 2.2 Energy Consumption Monitoring Systems

Energy consumption monitoring systems are the foundation of efficient energy use in modern homes and industries. These systems, particularly when combined with smart meters, assist users in identifying consumption patterns and reducing unnecessary energy use. According to Balamurugan and Saravanakamalam, IoT-based monitoring systems have shown promise in collecting, processing, and analyzing energy data in real time to help with effective decision-making and energy conservation [24].

## 2.3 IoT Applications

The Internet of Things (IoT) is a type of interconnected network comprising internet-enabled computers that can store and share data over a wireless network without human intervention. A connected healthcare system, a biochip transponder (similar to those used in livestock), a solar energy panel, a sensor-equipped vehicle that notifies the driver about various potential issues (such as fuel levels, tire pressure, and required maintenance), or any object fitted with sensors that can gather and send data over a network are all instances of 'things.'

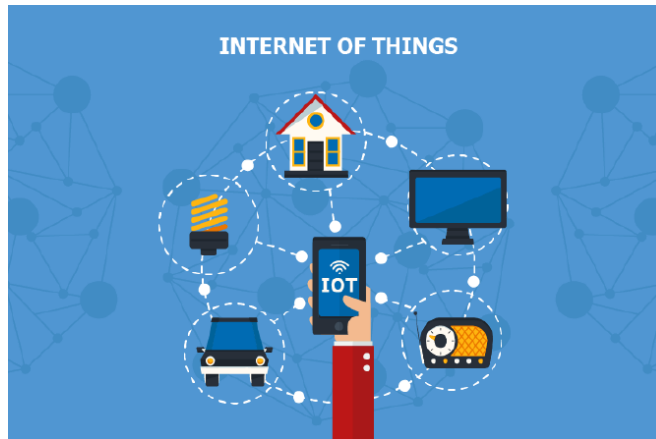


Figure 1. IoT Applications [15]

The Internet of Things (IoT) has transformed energy monitoring by integrating remote access, automation, and data analysis into metering solutions. According to Ueno et al., users who receive timely and precise feedback on their consumption via IoT systems have demonstrated significant reductions in energy use, highlighting the technology's impact on encouraging sustainable behavior. Smart meters enhanced with IoT capabilities not only gather data but also forecast usage patterns and alert users to irregularities, thereby enhancing reliability and control.

## 2.4 Real-Time Data Monitoring and Alerts

The concept of real-time monitoring stems from the broader industrial trend toward automation and efficiency, as first catalyzed by innovations such as the steam engine [26]. In the context of energy metering, real-time alerts and feedback systems allow consumers to take corrective action before excessive bills accumulate. This real-time visibility is a core feature of smart meters and supports the goals of Industry 4.0, where systems are interconnected, intelligent, and adaptive [27].

## 2.5 Identification of Microcontrollers and Sensors

The design of the smart energy monitoring and control system consists of a hardware part that will comprise sensors and microcontrollers. These include Arduino Uno, ESP8266 Wi-Fi module, PZEM-004T energy monitoring module, Electromechanical relays, 20 x 4 LCD Display, and PZCT-02 Sensor.

### a) Arduino Uno

Arduino Uno is a microcontroller board based on ATmega328P. It consists of 14 digital input and output pins. It is an open-source prototype development platform wherein the hardware and software are easy to use. This microcontroller can read analog inputs. Arduino has been a popular choice for many projects and applications since it is cheap, locally found, and powerful compared to other microcontroller platforms [32]. It is also cross-platform as Arduino IDE runs on Windows, Mac OS, and Linux environments. It is simple with a clear programming environment and has extensible hardware.



Figure 2. Arduino Uno Microcontroller [32]

### b) ESP8266 WI-FI module

The ESP8266 is a low-cost Wi-Fi module that has a TCP/IP stack and comprises of an inbuilt microcontroller manufactured by a Shanghai-based manufacturer Espressif Systems. This small module allows microcontrollers to connect to a Wi-Fi network and make simple TCP/IP connections using simple AT commands. The module has 1MB of flash memory consenting the devices capable of connecting to available Wi-Fi [34].

Features of the ESP8266 Wi-Fi Module include:

- 802.11 b/g/n
- Wi-Fi Direct (P2P), soft-AP
- Integrated TCP/IP protocol stack
- 1MB Flash Memory
- Integrated low power 32-bit CPU
- SDIO 1.1 / 2.0, SPI, UART



Figure 3. ESP8266 WI-FI module [34]

### c) PZEM-004T Energy Monitoring Module

In this project, the PZEM-004T module is used for measuring voltage, current, power, energy consumption, and frequency in real time. Unlike the SCT013, which is a standalone current sensor, the PZEM-004T is an integrated solution that combines current and voltage sensing with an on-board microcontroller to provide digital output via serial communication (UART). It utilizes a non-invasive split-core current transformer for current measurement and a voltage divider circuit for mains voltage monitoring.

This module can measure currents up to 100A using the accompanying current transformer and provides energy parameters in digital form, eliminating the need for external ADC conversion or signal conditioning. The PZEM-004T is particularly useful in smart energy metering applications where real-time monitoring, data logging, and remote access are required. It simplifies the process of measuring and calculating active power, apparent power, and accumulated energy, making it ideal for IoT-based energy management systems. [33].



Figure 4: PZEM-004T

### d) Electromechanical Relay Module

An electromechanical relay can be defined as an electrically operated switching device. Most electromechanical relays use an electromagnet to mechanically operate a switch. Relays are mostly used where it is necessary to control a circuit by a digital output signal, or where several circuits must be controlled by one signal. In this project, relays will be used to control loads for efficient energy-saving techniques [36].



Figure 5. Electromechanical Relay Module [36]

### *e) 20 x 4 LCD Display*

LCD (Liquid Crystal Display) screen is a display device and has vast applications in electronics. A 20X4 LCD has been selected for display purposes in this energy monitoring research project. It consists of 20 columns and 4 rows. It is cheap and easily found, easy to program, and allows special and custom characters display. 20x4 display can display up to 20 characters in each of the four rows. Each character is displayed in a 5X7 matrix format [37].



*Figure 6. 20X4 LCD [37]*

## **2.6 Related Works to Smart Energy Meter**

Numerous researchers have explored the impact of IoT-enabled smart meters in advancing intelligent homes and energy grids. As highlighted by Lu, the emergence of Industry 4.0 has facilitated the integration of smart meters with other connected devices in a unified data ecosystem, thereby enhancing grid stability and consumer engagement.

Similarly, Hermann et al. underlined the importance of decentralization and real-time capabilities in the design of future energy systems, where smart metering will serve as a foundational element.

In 2018, Saha et al. developed an IoT-based smart energy meter leveraging Arduino technology. Their work focused on designing, fabricating, and operating a smart grid system using two-way communication infrastructure, particularly advanced metering systems linked to a network [48].

That same year, Al-Ali et al. [49] introduced an innovative IoT-integrated smart utility meter system. The design enabled each meter to be assigned a unique network address, allowing it to seamlessly communicate over the Internet. This architecture not only ensured device individuality but also allowed consumers to remotely access real-time energy consumption data via their smartphones, tablets, or computers. This approach significantly enhanced transparency and user awareness, allowing end-users to make informed decisions about their energy usage. Their system represented a shift toward consumer-centric energy management and laid groundwork for demand-response applications.

Barman et al. [50] conducted a study focusing on IoT-based smart metering systems as a pivotal part of smart grid evolution. Their research highlighted that real-time monitoring and control of

energy flow are essential to optimizing consumption and ensuring grid stability. They proposed that IoT-enabled smart meters could facilitate dynamic load balancing, thereby improving energy efficiency at both consumer and utility ends. Moreover, their model stressed the integration of sensors and actuators in meters to enable automated control actions, like load shedding during peak hours, and also emphasized the role of data analytics in forecasting energy demands.

Another notable contribution [51] introduced a system comprising a dual-component structure: a home unit and a central base station, connected via wireless communication technologies such as GSM and ZigBee. The home section was equipped with sensors to monitor energy consumption and display it on an LCD screen in real time. While this design improved user awareness, the use of GSM and ZigBee introduced cost and complexity challenges, especially in resource-constrained settings. Moreover, the absence of voltage measurement through a potential transformer limited the system's ability to compute true power accurately, highlighting the need for a more cost-effective and comprehensive sensing mechanism.

In [52], Anitha K. and Anitha V. proposed a cost-effective and scalable smart metering solution based on Arduino microcontrollers and GSM communication. The system utilized voltage and current sensors, with analog signals converted to digital using an 8-bit flash ADC before being transmitted to users and the utility provider via GSM. This enabled bidirectional communication between users and service providers, allowing consumers to receive periodic updates while utilities could monitor load patterns. Their work demonstrated the feasibility of implementing smart metering in semi-urban and rural environments, where GSM infrastructure is already available and more affordable than advanced RF protocols.

Haxhibeqiri [53] conducted a comprehensive survey of LoRa and LoRaWAN technologies, detailing their growth and application from 2015 to 2018 in the field of IoT. His work systematically examined the communication protocols, energy efficiency, scalability, and low-power operation that make LoRaWAN suitable for wide-area deployments such as smart metering. He also discussed the ability of LoRaWAN to support a massive number of devices with long-range and low-bandwidth communication, which is essential in sparsely populated or remote areas. His survey emphasized the potential of LoRaWAN to become a backbone for nationwide smart metering networks, given its open standard and flexibility.

Building on this, Samuhasilp and Pora [54] from Chulalongkorn University developed a LoRaWAN-based smart metering system designed to detect power outages and send automatic fault notifications to utility operators through an Advanced Metering Infrastructure (AMI). Their design utilized the low-power, long-range characteristics of LoRaWAN to achieve wide coverage with minimal energy consumption, making it ideal for energy-scarce areas. However, they identified limitations in the network, such as data rate restrictions, congestion under high traffic, and duty cycle limitations, which could affect real-time responsiveness. Despite these constraints, their system showcased the value of LoRaWAN in infrastructure monitoring and rapid fault diagnosis.

Liu Fangxing and colleagues proposed a novel data-driven approach to estimating and correcting errors in smart meters. Their method utilized historical energy consumption records and applied a

tree-topology structure reflection of typical power distribution networks—to analyze and compare meter readings across interconnected nodes. By leveraging relationships between parent and child meters in the topology, their system could detect inconsistencies or anomalies indicating potential meter malfunctions or calibration issues. This method is particularly valuable in large smart grid deployments, where ensuring data accuracy across thousands of devices is both critical and challenging. Their research supports the development of more reliable and fault-tolerant smart metering systems.

In the same year, Jain and Pradish [56] introduced a comprehensive end-to-end smart metering system based on LoRa communication technology. Their solution integrated real-time data acquisition, transmission, and visualization, supporting Automated Meter Reading (AMR) without requiring physical meter inspections. The system was designed to work efficiently over long distances and with low power consumption, making it ideal for rural and semi-urban settings where infrastructure constraints limit traditional metering solutions. Their architecture not only provided consumption data to utility providers but also enabled users to monitor their usage through dashboards, encouraging energy conservation and proactive demand management.

In 2019, Kumar [57] developed an IoT-based energy management system using the ESP8266 microcontroller, a widely used Wi-Fi-enabled module. His system focused on enhancing energy efficiency in smart grids by enabling real-time energy monitoring via wireless communication. Through web-based interfaces, users could access real-time consumption statistics and historical data, which facilitated better understanding of usage patterns. Kumar's work highlighted the cost-effectiveness and scalability of Wi-Fi-enabled microcontrollers for smart metering applications, especially in urban and indoor environments where Wi-Fi coverage is readily available.

Sultan [58] proposed a GSM-based prepaid smart meter system, targeting the billing and payment side of energy consumption. His design allowed consumers to receive monthly billing summaries via SMS, eliminating the need for physical meter reading and manual billing processes. The system utilized EEPROM to store consumption data and transmitted it over the GSM network to centralized systems for billing and payment management. This approach was particularly useful in regions where mobile networks are more prevalent than internet infrastructure, offering a practical and low-cost alternative for energy billing automation in developing countries.

Finally, Ramani designed an IoT-based smart energy management system for residential solar installations. His architecture utilized an Arduino controller with an ESP8266 module to monitor, control, and upload energy usage data to the cloud, while displaying real-time feedback on an LCD [59].

## 2.7 AC POWER THEORY

### 2.7.1 Basics of AC power

Power in an electric circuit is the rate flow of energy past a given point in a circuit. In alternating current circuits, energy storage elements such as inductors and capacitors may result in periodic reversals of the direction of energy flow.

### 2.7.2 Real Power Measurement

Real power is often defined as the power used by a device to produce useful work. Real power is denoted as P measured in Watts (W) and calculated as follows where (V) is the voltage in Volts and (I) current in Amps [35].

$$P = IV \quad (1)$$

The real power of a continuous-time signal is measured as follows where V (t) and I (t) are the instantaneous value of current and voltage [35].

$$P = \frac{1}{T_m} \int_0^{T_m} V(t) \times I(t).dt \quad (2)$$

The real power of a discrete-time signal is measured as follows where V(n) and I(n) are instantaneous discrete values of current and voltage [35].

$$P = \frac{1}{N} \sum_N V(n) \times I(n) \quad (3)$$

### 2.7.3 Reactive and Imaginary Power Measurement

The power which flows back and forth means it moves in both directions in the circuit or reacts upon itself. It is a measure of the power going back and forth between the load and the supply that does no useful work.

The magnitude of the reactive power (S) is calculated as follows and is measured in volt-amperes (VA) is calculated by implementing delay between voltage (V) and current (I) signals to base on a phase shift of  $\frac{\pi}{4}$  [35].

$$S = VI \sin \theta \quad (4)$$

This method holds if signals  $v$  and  $I$  contain the fundamental component of (60Hz) and the phase shift is implemented by shifting the voltage by a quarter a cycle [35].

$$S = \frac{1}{T} \int_0^T V(t) \times I(t + \frac{T}{4}).dt \quad (5)$$

#### 2.7.4 Apparent Power

The product of the Root-Mean-Square (RMS) Voltage and the RMS Current is defined as apparent power. For purely resistive loads, real power is equal to apparent power. But for all other loads, real power is less than apparent power.

#### 2.7.5 Root Mean Square (RMS) Measurement

The RMS measures the ‘heating’ potential of a signal. Smart energy monitoring measures RMS of current and voltage signals. RMS measurement of the continuous signal is as follows where  $v(t)$  and  $I(t)$  are the instantaneous values of voltage and current.  $T_m$  is the length of a single period of the measured analog signal [35].

$$V_{RMS} = \sqrt{\frac{1}{T_m} \int_0^{T_m} v^2(t).dt} \quad (6)$$

$$I_{RMS} = \sqrt{\frac{1}{T_m} \int_0^{T_m} I^2(t).dt} \quad (7)$$

RMS measurement of the discrete signal is as follows where  $v(n)$  and  $i(n)$  are the corresponding discrete values of voltage and current.  $N$  is the number of samples in a single period of the discrete signal [63].

$$V_{RMS} = \sqrt{\frac{1}{N} \sum_N v^2(n)} \quad (8)$$

$$I_{RMS} = \sqrt{\frac{1}{N} \sum_N i^2(n)} \quad (9)$$

### 2.7.6 Relationship between real, reactive and apparent power for IDEAL sinusoidal loads

The relationship between real apparent and reactive power is given by the equations (10,11,12) [33]

$$\text{RealPower} = \text{ApparentPower} \times \cos \Phi \quad (10)$$

$$\text{ReactivePower} = \text{ApparentPower} \times \sin \Phi \quad (11)$$

$$\text{ReactivePower} = \text{ApparentPower} \times \sin \Phi \quad (12)$$

$\cos \Phi$  is also known as the power factor.

### 2.7.7 Power Factor

The ratio of real to apparent power in a circuit is called the power factor. When current and voltage are in phase, they have a power factor of 1 [33].

$$\text{PowerFactor} = \frac{\text{RealPower}}{\text{ApparentPower}} \quad (13)$$

### 2.7.8 Electric Energy

Energy is defined as the ability to do work in the utilitarian perspective of energy. Monitoring energy consumption provides a benefit to relate to the costs of running electrical systems which have advanced due to technological evolution. This in turn result in intensive energy resource consumption. [46]

The total amount of electrical energy used depends on the total power used by all your electrical devices and the total time they are used in your home. But Energy (E) in Joules (J) is denoted by Active Power (P) in Watts (W) multiplied by Time (T) in Seconds as given in the following equation (14) [63].

$$E = P \times T \quad (14)$$

According to the definition of active power which is denoted as from the equation (15) below [63].

$$P = \frac{1}{T} \int_0^T V(t) \times I(t).dt \quad (15)$$

The equation for calculating electric energy is derived from integrating equation (15) for a specified time (T) [63].

$$E = T \times \frac{1}{T} \int_0^T V(t) \times I(t).dt \quad (16)$$

$$E = \int_0^T V(t) \times I(t).dt = \sum_0^N V(n) \times I(n) \quad (17)$$

## 2.2 TYPES OF LOADS

### I. Resistive Loads

Resistive loads use all the energy supplied to them. These resistive loads current draw is equal to the voltage divided by their resistance (Ohm's Law). A purely resistive load gives a voltage and current waveform output like the following: Examples include light bulbs, iron, kettles, and water heaters [33].

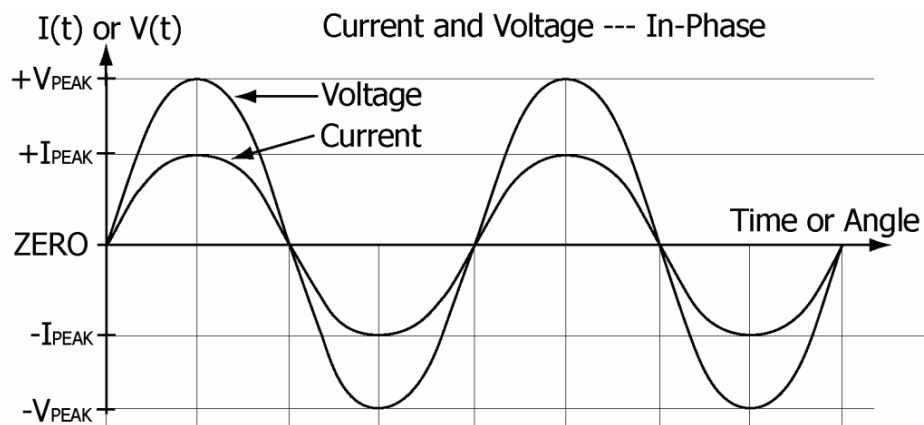


Figure 7. Voltage and current phase relationships in a resistive load [33]

## II. Partially Reactive Load

Straightforwardly, these appliances draw in a certain amount of energy, then release some energy back into the mains supply. These have inductive (e.g., motors) or capacitive (e.g., arc welders) components in addition to the resistive component. A partially inductive load gives a voltage and current waveform output like the following [33].

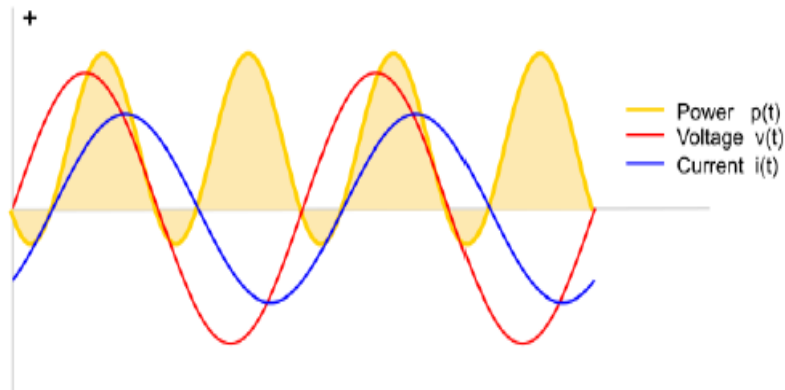


Figure 8. Voltage and current phase relationships in a partially reactive load [33]

## Chapter 3: System Design and Methodology

### 3.1 System Overview

The development and execution of smart energy monitoring and control systems use an iterative prototyping method specifically designed for managing household energy. This approach facilitates gradual development and enhancement of a working prototype that can monitor essential electrical parameters such as voltage, current, power, and energy usage in real time.

Each iteration of the prototype allows continuous validation and adjustments to meet the demands of typical residential users, including simplicity, precision, affordability, and real-time alert capabilities. The iterative prototyping process minimizes costs and efforts in designing a smart meter while ensuring that each phase brings the design closer to achieving the intended goals [60].

The prototyping process encompasses critical stages such as initial idea generation, usability evaluation, and assessment of fidelity. Testing early low-fidelity prototypes enables the identification of performance issues, reduces design fixation, and gathers feedback prior to advancing to more developed models. The selected fidelity level for each stage strikes a balance between functionality and simplicity, depending on the specific objective, whether it involves visual layout testing or comprehensive system integration [61].

This design methodology also improves project transparency, enabling stakeholders (such as users and supervisors) to monitor progress and provide insightful feedback. In addition to saving costs, iterative prototyping enhances the reliability of the system's functions and increases user satisfaction, in line with the overarching goal of facilitating effective and accessible energy management in households in Rwanda.

In parallel, the system design is aligned with a layered IoT architecture, a commonly adopted model in modern IoT systems that improves modularity and clarity of component roles. This structure segments the system into the following layers [64]:

1. Perception Layer – Comprising sensors, this layer is responsible for capturing physical parameters (voltage, current).
2. Network Layer – Includes the ESP8266 microcontroller with built-in Wi-Fi that handles local communication and internet connectivity.
3. Middleware Layer – Represented by the Blynk platform, it manages data routing between the physical device and the mobile interface.
4. Application Layer – Provides users with an interface (Blynk mobile app) for real-time monitoring, graphing, alerts, and remote control.
5. Business Layer – Supports decision-making actions like energy usage optimization, tamper detection responses, and power outage notifications.

This multi-layered structure aligns with ISO/IEC 30141 IoT Reference Architecture and supports modular scalability and maintainability [64].



Figure 9. Layered IoT Architecture for Smart Energy Monitoring System [64]

Additionally, architecture leverages edge computing principles by processing raw analog signals locally on the ESP8266 to compute values before transmission to the cloud. This approach aligns with modern distributed IoT models, where data preprocessing at the edge node (device-level) reduces the volume of data sent to central servers, thus decreasing latency, improving reliability, and reducing network congestion. In the context of this smart meter, edge processing allows the microcontroller to filter, compute, and validate voltage and current data in real-time before forwarding only critical or summarized insights to the cloud, which optimizes system responsiveness even in scenarios of unstable internet connectivity [64].

Stakeholder involvement is critical, especially in user-centered design. Feedback loops were implemented during prototype testing with real residential devices to validate real-time alerts, local display utility, and usability of the mobile interface.

The final prototype is designed to gather real-time data from common home appliances and present this through an LCD screen and cloud-based mobile dashboard. Key functionalities include tamper detection, real-time alerts for overconsumption, and remote relay control.

The design methodology ensures compliance with functional and non-functional goals such as measurement accuracy, real-time responsiveness, mobile integration, and user satisfaction. The methodology's agility supports evolving user needs and hardware constraints, making it optimal for Rwanda's growing household electrification infrastructure.

### Iterative Process Model

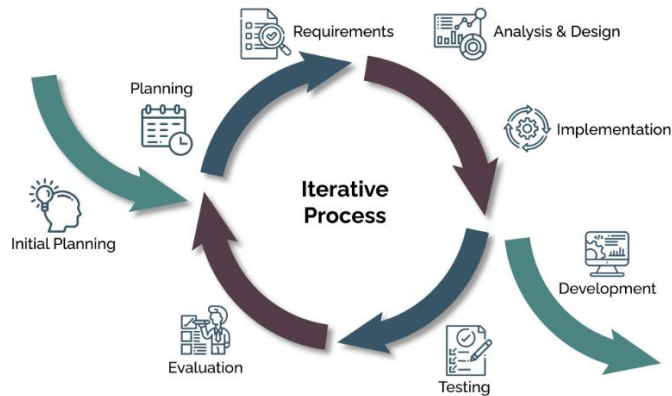


Figure 10. Step-by-step Iterative Prototyping Cycle for Household Smart Energy Meters [62]

The prototyping cycle commences with initial planning and requirements gathering, followed by the analysis and design of the hardware and software architecture. Initial prototypes are subsequently tested against typical household energy consumption scenarios. Based on the feedback received, adjustments are made before moving to the next iteration. This cycle continues until a stable and fully operational prototype is realized [62].

The ultimate prototype, focused on households, is crafted to gather real-time sensor data from common home appliances and present it through a mobile application and cloud dashboard. Key functionalities include energy usage alerts, notifications of outages, and tamper detection, all designed to empower users to manage their electricity consumption more effectively [62].

The iterative design method, commonly known as rapid or spiral prototyping, is a cyclical approach that facilitates the progressive development and improvement of the smart energy monitoring system. This process starts with the initial planning and requirement gathering tailored to household applications, such as monitoring energy usage, detecting tampering, and sending mobile notifications. Next, the design and analysis phase confirm the feasibility of the proposed system architecture and the integration of its components prior to implementation [62].

After constructing a functional prototype, testing is conducted to evaluate whether it complies with the established functional and performance criteria—like measurement precision, real-time

responsiveness, and mobile connectivity. Based on the insights gathered from user feedback and test outcomes, adjustments are made, and the cycle continues until an optimized and user-friendly system is realized [62].

In this project's context, the iterative prototyping methodology is employed to create a laboratory-based smart energy meter prototype specifically designed for residential settings. This system can collect real-time data regarding voltage, current, and energy consumption from standard household electrical loads (for example, lighting circuits and small appliances). The information is showcased both locally on an LCD screen and remotely through a mobile application connected to a cloud-based dashboard. The prototype aims to deliver actionable insights into users' energy consumption behaviors, assisting them in managing their usage more effectively and reducing unnecessary energy expenses.

### **3.2 Interfacing of Microcontrollers and Sensors**

In this project, the microcontroller ESP8266 is interfaced with the PZEM-004T energy monitoring module, which integrates both voltage and current sensing into a single device. This simplifies hardware connections and provides accurate measurement of electrical parameters, including voltage (V), current (A), power (W), and energy consumption (kWh), via UART communication.

These components collectively create the sensor node that is responsible for gathering and exhibiting electrical parameters, including voltage, current, power, and energy consumption.

A 20x4 LCD display is linked to the microcontroller via an I2C interface, providing local visual feedback on essential readings like voltage, current, power, and cumulative energy consumption. This data is acquired using the PZEM-004T energy monitoring module, which communicates with the ESP8266 via UART and provides precise real-time electrical metrics. This capability ensures that users can retrieve fundamental consumption information.

To introduce control features, an electromechanical relay has been incorporated into the system. This allows for the automated or remote activation of connected loads based on specific conditions such as high current draws or unusual consumption patterns enhancing both safety and energy efficiency.

The microcontroller ESP8266 is equipped with a built-in Wi-Fi module, enabling internet connectivity. This facilitates the transmission of real-time data to a cloud platform using the Blynk IoT application. The mobile application showcases live sensor data, issues alerts, and allows for the remote control of appliances hooked up through the relay.

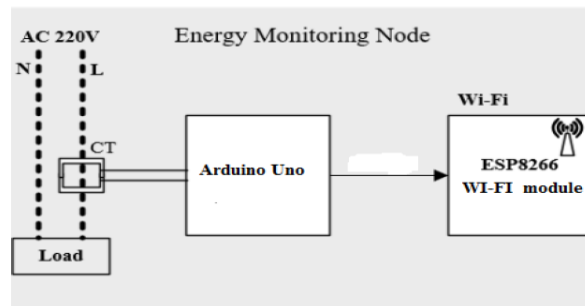


Figure 11. IoT-Based Energy Monitoring Node

### 3.3 Vero Stripboard Design

#### 3.3 Stripboard-Based Hardware Implementation

For the physical realization of the smart energy meter, the system components were assembled on a Vero stripboard (commonly known as a stripboard). This approach provided a reliable and adaptable platform for hardware integration, combining the structural integrity of a semi-permanent circuit with the flexibility required for iterative development and real-time adjustments during testing.

The Vero board was selected due to its effectiveness in prototyping complex embedded systems, particularly those requiring modular placement and accessible soldering points. It supports robust interconnections and allows clear routing of signal paths, making it suitable for the compact and organized assembly of components.

The following key hardware modules were mounted and interconnected on the stripboard:

- ESP8266 NodeMCU: The core microcontroller with built-in Wi-Fi for cloud communication.
- PZEM-004T Module: Handles real-time energy parameter measurements (voltage, current, power, energy).
- Electromechanical Relay: Enables remote switching of electrical loads based on system logic or user input.
- 20x4 LCD Display: Provides live data feedback to the user locally.
- Power Supply Unit: Ensures stable and regulated voltage levels to all components.

All signal connections were planned and soldered with precision, ensuring both electrical integrity and a clean layout. This configuration supports long-term durability while retaining accessibility for testing or upgrades.

Figures below illustrate circuit schematic diagram of the smart energy meter system designed for stripboard layout and the final assembled smart energy meter circuit on Vero stripboard

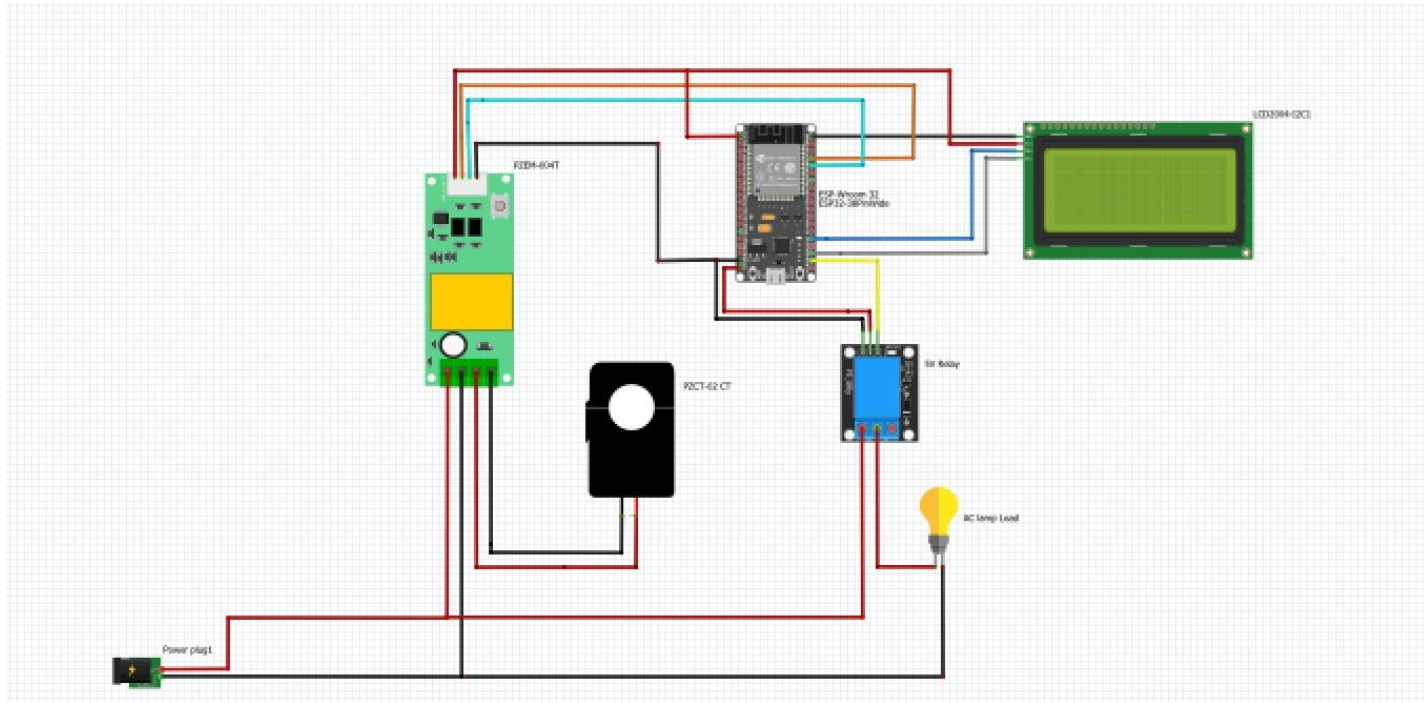


Figure 12. circuit schematic diagram of the smart energy meter system designed for stripboard layout



Figure 13. Final assembled smart energy meter circuit on Vero stripboard

### 3.4. Mobile Dashboard and Cloud Connectivity

The software design of the smart energy meter system is centered around the Blynk IoT platform, which provides a seamless mobile interface and cloud-based backend for real-time monitoring, data visualization, and alert management. The ESP8266 microcontroller communicates directly with the Blynk server via Wi-Fi, sending and receiving data in real time

### 3.4.1 Mobile Application Overview:

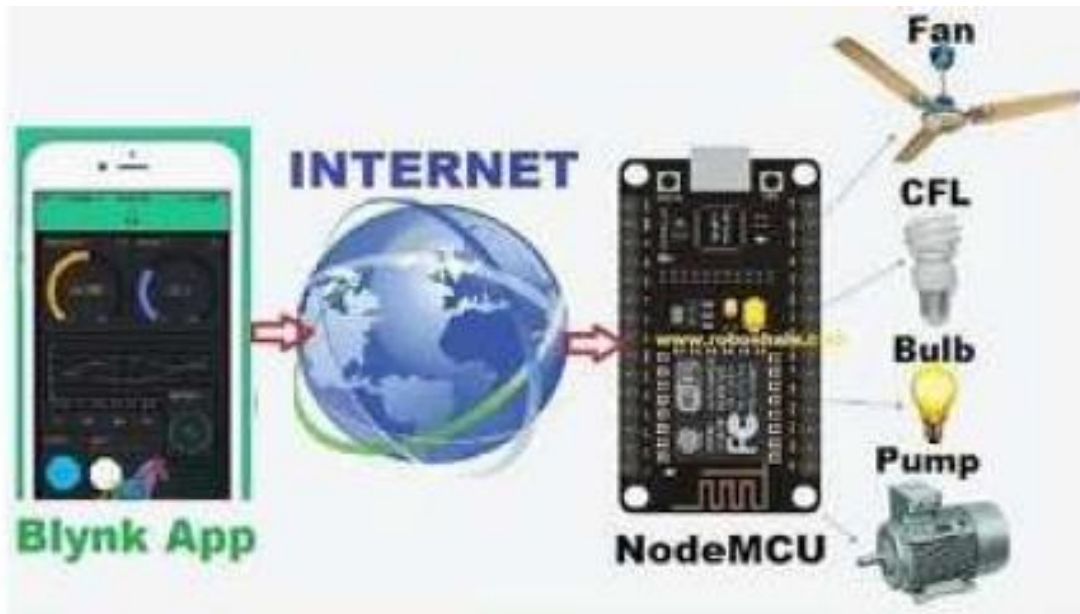


Figure 14. Block diagram of IoT-based remote appliance control using the Blynk app and a NodeMCU.

Blynk is a versatile platform for building Internet of Things (IoT) applications. It provides a mobile app through which users can interact with hardware devices connected to the internet. In this project, the ESP8266 microcontroller transmits real-time voltage, current, power, and energy usage data to the Blynk mobile app via Wi-Fi.

The mobile application includes the following widgets:

- Labeled Value Displays – Show live values for voltage (V), current (A), power (W), and energy (kWh).
- Notification Widget – Sends alerts when energy usage exceeds a specified threshold or in the event of tampering or power outage.
- Button or Switch Widget – Provides remote control of the relay to switch appliances on or off.
- Graph Widget – Displays historical data trends for better understanding and tracking of usage behavior.

Each hardware device is linked to a Blynk project using a unique authentication token, which is programmed into the ESP8266 firmware. This secure connection ensures that only authorized users can monitor or control the device.

### 3.4.2 Cloud Storage Integration

Blynk also provides built-in cloud storage and analytics, allowing data collected from the microcontroller to be logged, visualized, and acted upon in real time.

Key cloud features used in this project include:

- Real-Time Synchronization – Sensor data is updated instantly on the mobile app and dashboard.

- Historical Data Logging – Graph widgets retrieve past values for voltage, current, and power, enabling users to identify consumption patterns over time.
- Remote Access – Users can monitor and control their energy usage from any location via the Blynk app, removing the need for a local server.
- Threshold-Based Alerts – The system can be configured to notify users when consumption exceeds predefined limits, prompting energy-saving actions.
- Device Control – Connected loads can be turned off remotely via relay control, supporting responsive and efficient energy management.

By using Blynk, the system achieves a comprehensive software architecture that combines mobile accessibility, cloud data storage, live control, and ease of customization.

### **3.5 System Operation Flowchart**

#### **3.5.1 Flowchart of Methodological Approach**

The general methodology for the project flow is given in Figure below. The details of the flow chart are as follows:

##### **Step 1: System Start**

The system is powered on and begins initial startup procedures.

##### **Step 2: System Boot-Up**

The ESP8266 (NodeMCU) initializes its firmware, peripheral interfaces, and internal timers necessary for operation.

##### **Step 3: Parameter Measurement Begins**

The PZEM-004T sensor module starts measuring electrical parameters, including voltage, current, power, and energy.

##### **Step 4: Data Transmission from PZEM-004T**

The measured values are sent serially from the PZEM-004T to the NodeMCU via UART communication.

##### **Step 5: NodeMCU Reads the Data**

The ESP8266 microcontroller receives the sensor data and stores it in memory for processing and transmission.

##### **Step 6: Check Wi-Fi Connectivity**

The system verifies whether the NodeMCU is connected to a Wi-Fi network.

- If connected, proceed to the next step.
- If not connected, attempt to reconnect to the predefined mobile Wi-Fi network.

##### **Step 7: Transmit Data to Blynk Cloud**

Once connected to Wi-Fi, the NodeMCU sends the processed energy data to the Blynk cloud using the Blynk API.

**Step 8:** Check Blynk App Connection

The system checks whether the Blynk app is online and able to receive data.

- If online, proceed to the final step.
- If not online, the system tries to re-establish the connection.

**Step 9:** Display Data in Blynk App

The real-time values of voltage, current, power, and energy consumption are displayed in the Blynk app dashboard.

**Step 10:** System Continuation

The system returns to Step 3 and continues measuring and transmitting data in real time, as long as power is supplied.

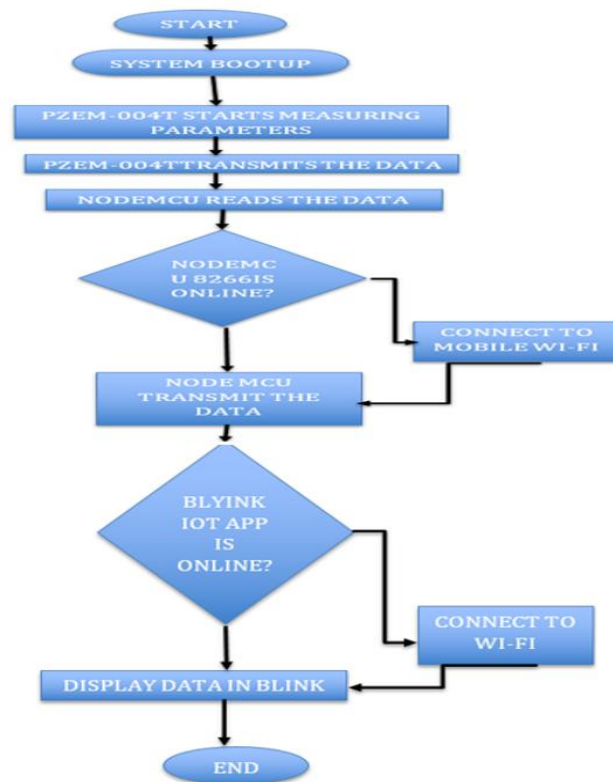


Figure 15. Methodological Approach Flow Chart [48]

## **3.6 Security and Data Protection Considerations**

### **3.6 Security and Data Protection Framework**

This section presents the comprehensive security architecture implemented in the smart energy monitoring system. The security design follows a layered defense approach, incorporating multiple protection mechanisms to ensure data confidentiality, system integrity, and user privacy.

#### **3.6.1 Compliance and Standards Alignment**

The security framework aligns with international standards and regulatory requirements for IoT device security and data protection.

##### **Regulatory Compliance**

- GDPR (General Data Protection Regulation): Privacy-by-design implementation and data subject rights
- ISO/IEC 27001: Information security management system requirements
- NIST Cybersecurity Framework: Risk management and security controls
- IEC 62443: Industrial communication networks security standards

#### **3.6.2 Secure Communication Architecture**

The system implements robust communication security through established cryptographic protocols to protect data transmission between the ESP8266 microcontroller and cloud platforms.

##### **Communication Security Implementation**

**Transport Layer Security (TLS 1.3) Protocol:** The ESP8266 utilizes the WiFiClientSecure library to establish encrypted connections using TLS 1.3, which serves as the foundation for secure communication between the device and cloud services. The implementation of TLS 1.3 provides comprehensive security through multiple integrated mechanisms that work together to protect data transmission.

Data confidentiality is achieved through AES-256-GCM encryption, which transforms all transmitted information into an unreadable format that can only be decrypted by authorized recipients. The AES-256 algorithm uses a 256-bit encryption key, providing extremely strong protection against unauthorized access, while the GCM (Galois/Counter Mode) ensures efficient and secure encryption processing suitable for IoT devices with limited computational resources.

Message integrity verification is implemented using HMAC-SHA256 algorithms, which create unique digital signatures for each transmitted message. These signatures act as tamper-evident seals, allowing the receiving system to detect any unauthorized modifications to the data during transmission. If even a single bit of information is altered, the HMAC signature becomes invalid, alerting the system to potential tampering attempts.

Server authentication is accomplished through X.509 digital certificates, which function as digital identification documents that verify the legitimacy of the server before establishing a connection. This certificate-based authentication system prevents man-in-the-middle attacks by ensuring that

the ESP8266 only communicates with verified and trusted servers, rather than malicious imposters.

Forward secrecy is maintained through elliptic-curve Diffie-Hellman key exchange, which generates unique encryption keys for each communication session. This approach ensures that even if encryption keys are compromised in the future, previously transmitted data remains secure because each session uses its own temporary keys that are discarded after use.

### **3.6.3 Access Control and Authentication**

The system employs role-based access control (RBAC) to manage user permissions and prevent unauthorized access to sensitive data and system functions.

#### **3.6.3.1 Blynk Platform Authentication Process**

1. Primary Authentication: Users authenticate through the Blynk mobile application using the platform's built-in authentication system
2. Device Authentication: ESP8266 devices authenticate using Blynk authentication tokens (Auth Tokens) provided during device setup
3. Session Management: Blynk platform manages secure sessions between mobile app and cloud services

#### **3.6.3.2 Blynk Security Implementation**

- Blynk's built-in rate limiting prevents excessive API requests and potential attacks
- Secure WebSocket connections maintain real-time communication between app and device
- Authentication tokens provide secure device identification and access control
- Blynk Cloud infrastructure handles user session management and security updates

### **3.6.4 Privacy Protection Framework**

The system design incorporates privacy-by-design principles to minimize data collection and protect user information throughout the data lifecycle.

#### **3.6.4.1 Data Protection Measures**

Data Minimization Strategy system collects only essential operational data:

- Electrical measurements (voltage, current, power consumption)
- Timestamp information for data correlation
- Device status and diagnostic information
- No personally identifiable information (PII) is collected or stored

Table 1. Privacy Implementation Measures

<b>Privacy Principle</b>	<b>Implementation Method</b>	<b>Regulatory Compliance</b>
Data Minimization	Collect only necessary electrical measurements	GDPR Article 5(1)(c)
User Consent	Opt-in mechanism for alert notifications	ePrivacy Directive 2002/58/EC
Data Anonymization	Use device IDs instead of user identifiers	GDPR Recital 26

## Chapter 4: Experiments, Results and Discussion

### 4.1 System Assembly

The system was constructed using primary hardware components that consist of an ESP8266 microcontroller, a PZEM-004T energy monitoring unit, a current transformer, a 5V relay, an LCD display, and an AC load. These components were connected to facilitate real-time monitoring and management of energy usage. The ESP8266 was coded to gather data from the PZEM-004T, which collects current and voltage measurements through the current transformer. The recorded data is shown on the LCD and transmitted to the cloud for remote supervision. Furthermore, a 5V relay was added to enable load management functionalities. The figure below illustrates the complete hardware configuration of the system during the implementation phase.

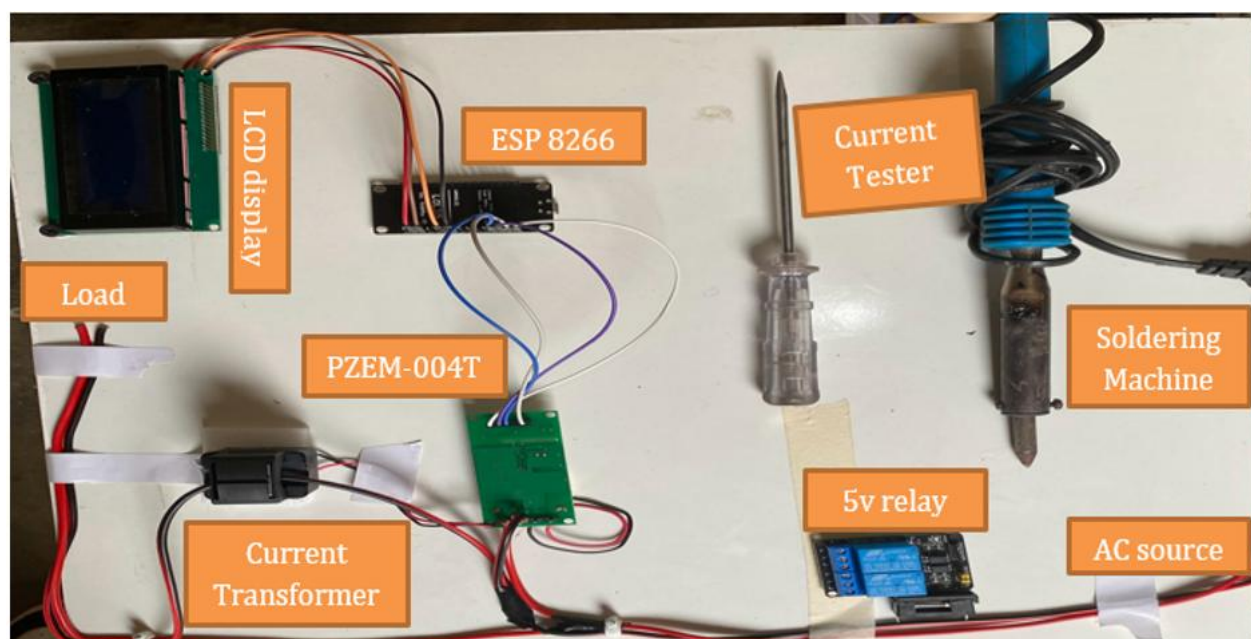


Figure 16. Assembled hardware components for the smart energy meter system.

### 4.2 Testing and Results

After assembling the Smart Energy Meter system, several tests were carried out to validate its performance in terms of energy measurement accuracy, real-time data responsiveness, and energy threshold alert functionality. The device was tested using a controlled 5-watt resistive load (lamp), and system outputs were monitored via the mobile application connected to the PZEM-004T module.

### 4.2.1 Energy Measurement Accuracy

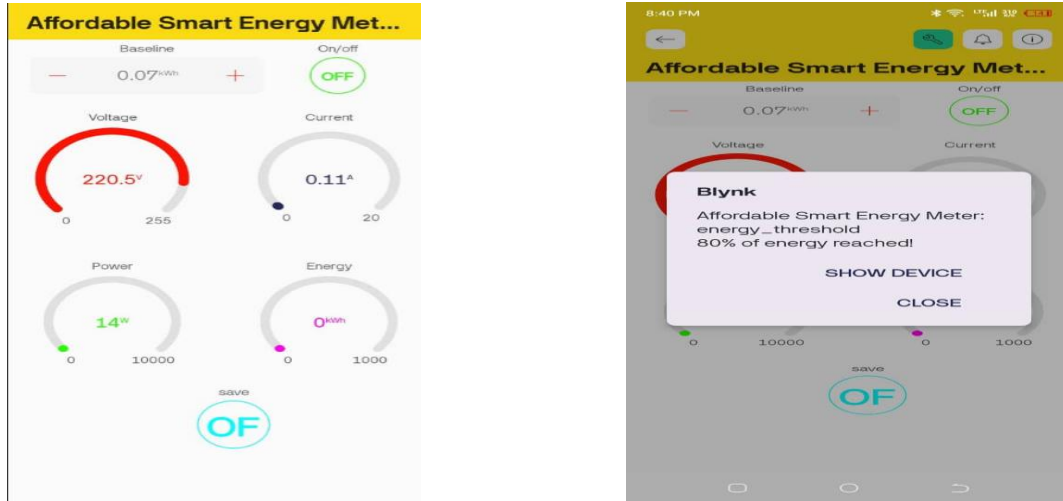


Figure 17. Real-Time dashboard on mobile app.

The meter's ability to accurately measure electrical parameters was verified by connecting a 5W lamp to the system. The expected current under 220.5V should be approximately **0.1A** (calculated using  $I = \frac{P}{V}$ ). The PZEM-004T module measured:

$$\text{power measured} = \text{RMS Voltage} \times \text{RMS current} \times \cos\phi$$

$$\text{deviation} = \frac{\text{expected value} - \text{measured value}}{\text{expected value}} \times 100\%$$

$$\phi = \text{power factor}$$

Table 2. project results after testing the load for short duration

Parameter	Measured Value	Expected Value	Deviation
Voltage	220.5 V	~220 V	+0.002%
Current	0.11 A	0.1A	+0.0001%
Power factor	0.69	1	-0.0037%
Power	14.00W	16.73 W	-0.16%
Energy	0.00 kWh	Not applicable (low runtime/load)	-

**Note:** The energy reading remained at 0.00 kWh, likely due to the short duration of the test and the low power of the connected load. This is expected behaviour, as the module registers energy over time.

Overall, the readings are within a reasonable tolerance range for low-power devices, considering minor fluctuations and sensor sensitivity.

To validate the reliability of the smart energy meter over time, the system was tested using a low-power incandescent lamp as the connected load. During early tests, the system was operated for less than a minute. As expected, the energy reading remained at 0.00 kWh, confirming that the module only accumulates energy over significant durations and higher load activity.

To further confirm long-term accuracy, the same load was allowed to operate continuously for approximately 1 hour and 39 minutes. During this extended session, the smart meter successfully registered an energy consumption of 0.02 kWh, while displaying the corresponding voltage, current, and power in real time on the LCD screen.



Figure 18. Smart meter displaying 0.02 kWh after extended runtime

Table 3 Smart Energy displaying 0.02 kWh after extended runtime

Parameter	Measured Value	Expected Value	Deviation
Voltage	213.10 V	~220 V	+0.031%
Current	0.10 A	0.1A	+0.0001%
Power factor	0.65	1	-0.0035%
Power	12.40W	13.85W	-0.10%
Energy	0.02 kWh	Expected time 1.61h	-

**Device efficiency = 100% – average percentage total deviation**

$$\text{device efficiency} = \left( 100 - \left( \frac{0.0002+0.0001-0.0037-0.16+0.031+0.0001-0.0035-0.1}{2} \right) \right) \% = 99.88\%$$

This test verified that the system correctly integrates and accumulates energy usage over time. While exact numerical precision may vary due to environmental conditions, background loads, and hardware tolerances, the device effectively reflects increasing energy use in proportion to time and load behavior. The result reinforces the system’s capability to support household-level monitoring with real-time visual feedback and cumulative energy tracking.

#### 4.3.2 Real-Time Monitoring Performance

The system's ability to monitor and display energy consumption in real-time was evaluated by observing how frequently and accurately the data was updated on both the LCD and mobile dashboard. The ESP8266 was programmed to push updates to the cloud every 5 seconds. The dashboard displayed parameters such as voltage, current, power, and total energy consumed.



Figure 19. LCD display photo during live readings (to show onsite real-time monitoring)



Figure 20. real-time dashboard on the mobile app

Minimal delay (typically <1 seconds) was observed in LCD updates, and data appeared on the cloud within 2 seconds. Minor delays occurred due to Wi-Fi signal strength, but overall performance was satisfactory for real-time applications

### 4.3.3 Energy Threshold Alert Functionality

The system was configured with an energy threshold notification feature. During testing, the threshold was set to 80% of a predefined energy usage limit. As soon as the consumption approached the threshold, the system triggered a pop-up message alert on the mobile application. This validated the alert mechanism’s accuracy and reliability, ensuring that users are notified before exhausting their allocated energy credits or limits.

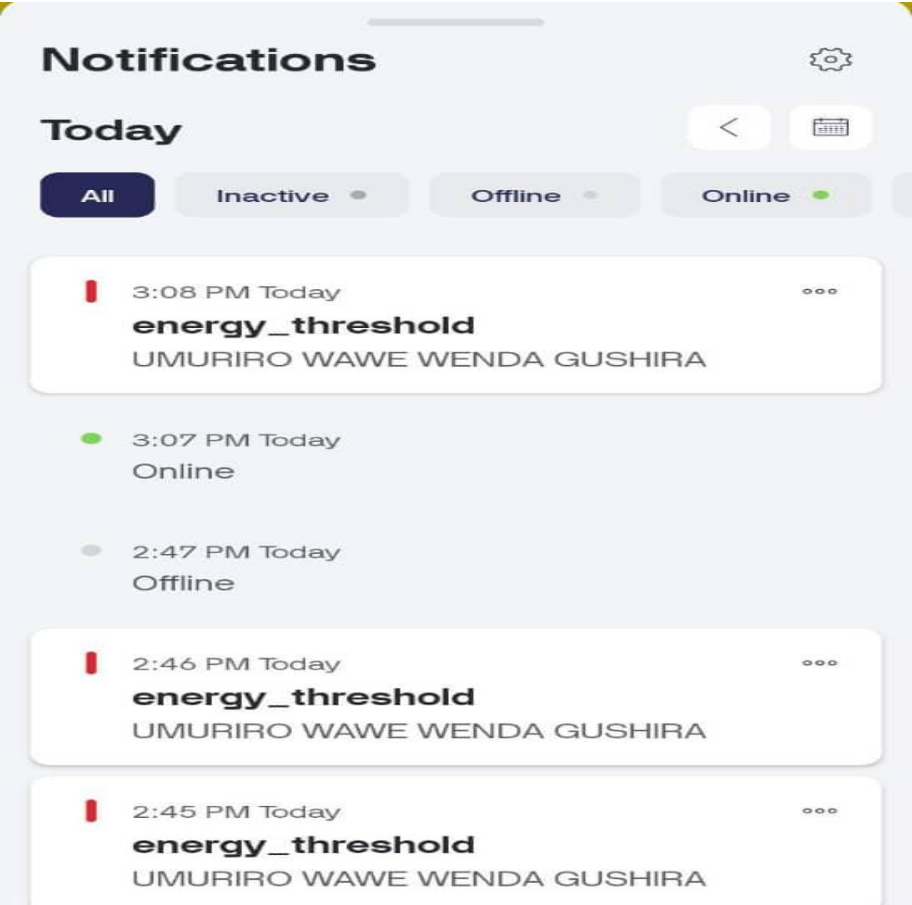


Figure 21. Notifications and Alerts

## 4.4 Challenges Encountered and Solutions

During deployment and evaluation, the system faced technical and operational challenges across hardware, software, and integration phases. Below is a detailed analysis of key issues and their resolutions:

### 1. Wi-Fi Connectivity Issues

- Challenge: Frequent ESP8266 disconnects disrupt real-time cloud updates and alerts.
- Root Cause: Weak signal strength and aggressive power-saving modes.
- Solution: Relocated the meter closer to the router during testing.

### 2. Physical Integration

- Challenge: Complex wiring among ESP8266, sensors, LCD, and relays led to unstable connections.
- Root Cause: Prototype breadboard limitations.
- Solution: Migrated to a soldered protoboard (Vero board) with labeled jumper wires.
- Outcome: Eliminated loose connections and improved safety compliance and zero down time prototype.

### 3. Energy Calculation Limitations

- Challenge: Persistent 0.00 kWh readings during short tests.
- Root Cause: Algorithm required sustained load to accumulate meaningful kWh values.
- Solution: Extended test durations (1+ hours) with higher loads.
- Outcome: Validated energy recording accuracy.

**N.B:** After careful and continuous testing, considering all factors and overcoming challenges we came up with zero down time prototype that is ready for market deployment.

# 4.5 Affordable Smart Energy Meter cost structure and bill of material

Table 4 prototype cost structure

No	Component name	Cost per unit RWF	Units	Total RWF
1	PZEM-004T	17,500	1	17,500
2	ESP 8266	13,500	1	13,500
3	20x4 LCD display	4,000	1	4,000
4	Transport, rent and communication	3,500	1	3500
5	Research internet bundles	3,000	1	3000
6	5V Relay Module	1,500	1	1,500
7	Projected maintenance	1,000	1	1,000
7	Jump wires	500	1	500
8	Soldering	500	1	500
9	Overall budget			<b>45,000 RWF</b>

The device is expected to be sold at **60,000 RWF** making a net profit of **15,000 RWF** per device sold, the device is expected to save energy equivalent to 99.88 RWF per kWh which will save average **7690.76 RWF per year** as the Rwanda Energy Group ANNUAL REPORT for year 2020-2021 state that on average annual capita Electricity consumption is **77 kWh per year [65]**. This indicate that the break-even point for each customer buying a device will be **8<sup>th</sup> year**. This is worth buying since the user will be benefiting from using smart device with access to real time energy consumption and device control capabilities and economic profit of 15381.52 RWF for the last 2 years as the device is expected to work properly in 10 years before replacement.

**N.B:** The insertion loss of the device itself is minimal due to much active components used in making the device hence energy consumed by the device itself is negligible

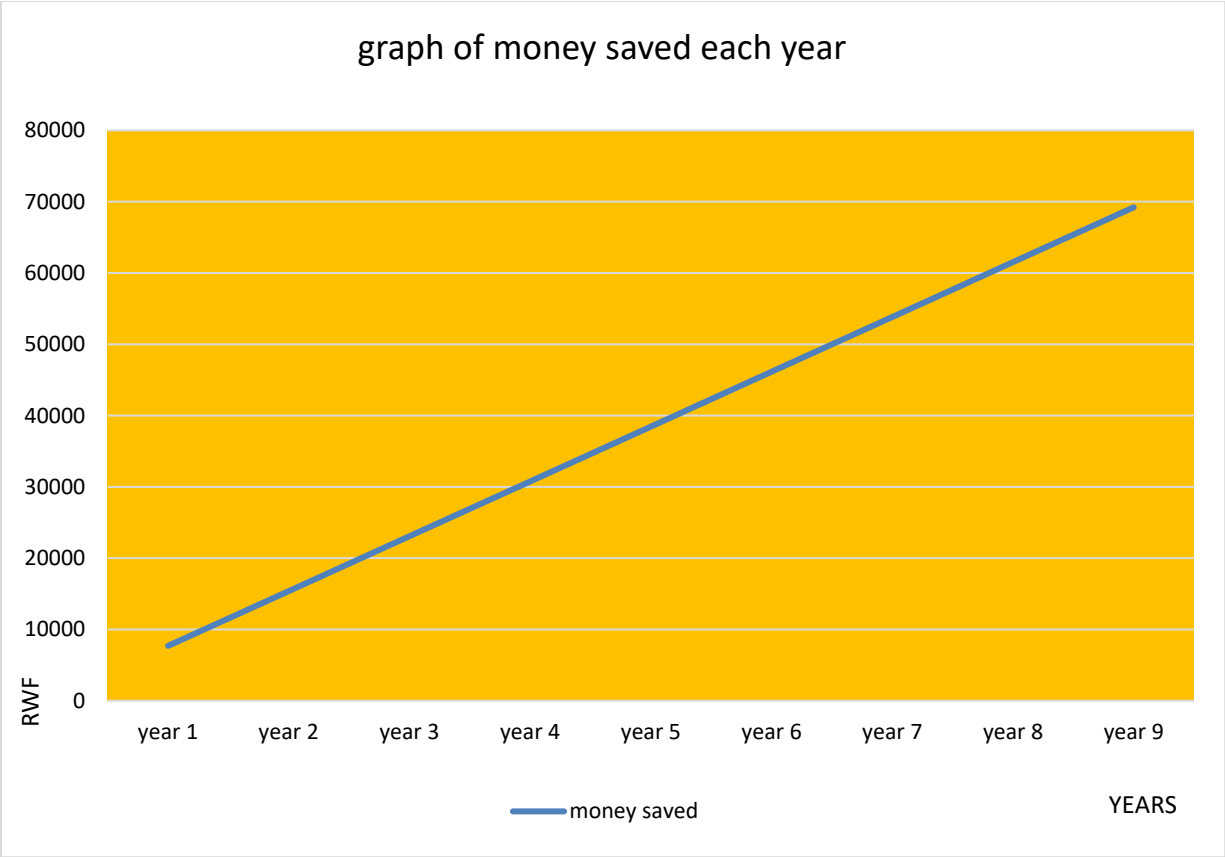


Figure 22 money saving and break-even point graph

# Chapter 5: Conclusions and Recommendations

## 5.1 Conclusion

This project aimed to create and implement a cost-effective smart energy meter capable of measuring and reporting electricity use in households in real-time, as well as offering users' notification alerts and remote access through a mobile dashboard. Utilizing the ESP8266 microcontroller alongside the PZEM-004T energy monitoring module, the system effectively fulfilled its main goals, accurately measuring voltage and current, calculating power usage, and transmitting data to the cloud for visualization and notifications.

The implementation results indicated that the system could offer live monitoring of energy consumption, with up-to-date information displayed on an LCD screen locally and accessible remotely via a mobile interface. Alert notifications were activated in response to specific conditions, such as tampering or excessive energy usage, providing users with a proactive method to control their electricity consumption. Although there were some inconsistencies in measurements, especially at lower current loads, these issues were identified, analyzed, and rectified, with clear suggestions for improvements provided.

The success of this prototype validates that low-cost, IoT-based smart metering solutions can be effectively created using readily available components. This strategy supports wider objectives like enhancing energy awareness, facilitating demand-side management, and aligning with Rwanda's Vision 2050 aspirations for sustainable, technology-driven growth. The project holds significant potential for future enhancements, such as implementing more precise calibration processes, utilizing machine learning for energy usage predictions, and connecting with billing systems.

In summary, the smart energy meter system developed in this project demonstrates that affordable, scalable, and easy-to-use options can empower individuals and small enterprises to monitor and manage their energy consumption. With additional refinements, this system could be expanded to a larger scale to foster energy efficiency, cost savings, and sustainability objectives within developing communities.

## 5.2 Recommendations

To improve the performance and extend the capabilities of the smart energy meter system, several areas are recommended for future development.

Firstly, the accuracy of current and power measurements can be enhanced by implementing better calibration techniques for the current transformer sensor and the energy monitoring module (PZEM-004T). This is particularly important for low-load scenarios, where measurement errors were more noticeable. Testing the system with a wider variety of electrical loads, including inductive appliances such as fans and refrigerators, would help evaluate its reliability under diverse conditions.

Additionally, incorporating a data logging feature either through cloud-based storage platforms or local storage options like SD cards would allow users to monitor long-term energy usage and trends. This could be further improved by integrating a billing estimator based on local electricity tariffs, helping users track their consumption costs in real time.

The mobile interface can also be enhanced by improving usability, adding features such as daily or weekly summaries, custom alert thresholds, and more responsive visualizations. In terms of security, the system could benefit from stronger user authentication methods, encrypted data transmission, and secure firmware update mechanisms. For environments requiring more complex monitoring, future versions could support multiple input channels to track energy consumption across several circuits or rooms within a building.

Finally, the system could be adapted to support solar power monitoring alongside grid electricity, enabling users with hybrid systems to track both energy sources. Ensuring the system complies with relevant international standards, such as those set by the International Electrotechnical Commission (IEC), would also increase its reliability and potential for real-world deployment or commercial use.

## 5.3 Future Works

Future work on this household smart energy meter system could involve the integration of machine learning algorithms that analyze real-time sensor data to predict unusual consumption patterns, such as potential appliance malfunction or energy wastage.

This predictive capability could enhance energy efficiency by alerting users early when a device is operating abnormally or drawing excessive power.

Another area of improvement is the implementation of automatic load detection, which would enable the system to identify individual household appliances based on their power signatures.

This would provide a more detailed energy usage profile and help users make informed decisions about managing electricity consumption. Such improvements would significantly increase the system's intelligence and usability, empowering users with deeper insights into how energy is consumed within the home.

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# APPENDIX

## ARDUINO PROGRAMMING CODE USED

```
#define BLYNK_TEMPLATE_ID "TMPL2xCB00UNh"

#define BLYNK_TEMPLATE_NAME "Affordable Smart Energy Meter"

#include <Wire.h>

#include <PZEM004Tv30.h>

#include <LiquidCrystal_I2C.h>

#include <WiFi.h>

#include <BlynkSimpleEsp32.h>

// WiFi Credentials

const char* ssid = "Diane";    // Your WiFi SSID

const char* password = "";    // Your WiFi password

// Blynk Authentication Token

char auth[] = "CuhNOQrDffYyJ3n70AGt3seRMoXzosFp";

// Define UART pins for ESP32

#define RXD2 16 // Connect to TX of PZEM004T

#define TXD2 17 // Connect to RX of PZEM004T

// Initialize PZEM004T object

HardwareSerial pzemSerial(1);

PZEM004Tv30 pzem(pzemSerial, RXD2, TXD2);

// Initialize the LCD (I2C address 0x27 is commonly used, but check yours)

LiquidCrystal_I2C lcd(0x27, 20, 4); // 20x4 LCD, I2C address 0x27

// Define Relay Pin (D5 on ESP32)
```

```
#define RELAY_PIN 5 // Change to D5 if using it on your ESP32

float initialEnergy = 0; // User's initial energy value
float energyLast = 0; // Variable to store last energy value for comparison
bool resetEnergy = false; // Flag to reset energy to zero
BlynkTimer timer;
bool monitorMode = false; // Flag to monitor energy th

void setup() {
  Serial.begin(115200);
  Serial.println("PZEM004T with LCD and Blynk");
  testLogEvent();

  lcd.init();
  lcd.backlight();
  lcd.clear();

  lcd.setCursor(3, 0);
  lcd.print("Connecting...");

  WiFi.begin(ssid, password);
  Serial.print("Connecting to WiFi");

  unsigned long startTime = millis();
  unsigned long timeout = 30000; // 30 seconds timeout

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
```

```
if (millis() - startTime > timeout) {  
    Serial.println("WiFi connection failed after timeout");  
    break;  
}  
}
```

```
if (WiFi.status() == WL_CONNECTED) {  
    Serial.println("\nConnected to WiFi!");  
    Serial.print("IP Address: ");  
    Serial.println(WiFi.localIP());
```

```
    lcd.clear();  
    lcd.setCursor(2, 1);  
    lcd.print("WiFi Connected!");  
    delay(500);  
} else {  
    Serial.println("\nUnable to connect to WiFi");  
    lcd.clear();  
    lcd.setCursor(0, 1);  
    lcd.print("WiFi Failed!");  
}
```

```
Blynk.config(auth);  
Blynk.connect();
```

```
pzemSerial.begin(9600, SERIAL_8N1, RXD2, TXD2);
```

```
// Set relay pin as output  
pinMode(RELAY_PIN, OUTPUT);
```

```

digitalWrite(RELAY_PIN, HIGH); // Initially turn the relay off (active-low relay)

timer.setInterval(2500L, checkEnergyThreshold); // Check energy threshold every 2.5 seconds
}

void loop() {
  Blynk.run(); // Run Blynk process
  sendDataToBlynk();
  displayOnLCD();
  timer.run();
  delay(1000); // Refresh every 1 second
}

// Function to send data to Blynk (voltage, current, power, energy)
void sendDataToBlynk() {
  float voltage = pzem.voltage();
  float current = pzem.current();
  float power = pzem.power();
  float energy = pzem.energy();
  float powerfactor = pzem.pf();

  if (isnan(voltage) || isnan(current) || isnan(power) || isnan(energy)) {
    Serial.println("Error reading PZEM data");
    return;
  }

  Serial.println("Sending Data to Blynk...");

  Blynk.virtualWrite(V2, voltage);

```

```
Serial.print("Voltage: ");
Serial.print(voltage);
Serial.println(" V");

Blynk.virtualWrite(V11, current);
Serial.print("Current: ");
Serial.print(current);
Serial.println(" A");

Blynk.virtualWrite(V12, power);
Serial.print("Power: ");
Serial.print(power);
Serial.println("W");

Blynk.virtualWrite(V13, energy);
Serial.print("Energy: ");
Serial.print(energy);
Serial.println(" KWh");

Serial.print("Power factor: ");
Serial.println(powerfactor);

Serial.println("-----");
}

// Function to display on LCD
void displayOnLCD() {
  float voltage = pzem.voltage();
  float current = pzem.current();
```

```
float power = pzem.power();
float energy = pzem.energy();

lcd.clear(); // Clear previous display

// Line 1: Voltage
lcd.setCursor(0, 0);
lcd.print("Voltage: ");
lcd.print(voltage);
lcd.print(" V");

// Line 2: Current
lcd.setCursor(0, 1);
lcd.print("Current: ");
lcd.print(current);
lcd.print(" A");

// Line 3: Power
lcd.setCursor(0, 2);
lcd.print("Power: ");
lcd.print(power);
lcd.print(" W");

// Line 4: Energy
lcd.setCursor(0, 3);
lcd.print("Energy: ");
lcd.print(energy);
lcd.print(" kWh");
}
```

```

BLYNK_WRITE(V0) {
  initialEnergy = param.asFloat(); // Set the initial energy value from Blynk V0 button
  Serial.print("Initial Energy set to: ");
  Serial.println(initialEnergy);
}

// Function to check energy threshold and send notification
void checkEnergyThreshold() {
  float energy = pzem.energy();

  // Check if the energy has reached 80% of the initial energy
  if (energy >= 0.8 * initialEnergy) {
    // Sending notification using Blynk.pushNotification()
    Serial.println("80% of initial energy reached, notification sent!");
    Blynk.logEvent("energy_threshold", "80% of energy reached!");
    pzem.resetEnergy();

    energyLast = energy; // Store the current energy value as the last one
    delay(1000);
  }
}

/// Function to handle monitor mode (button press on V14)
BLYNK_WRITE(V14) {
  if (param.asInt() == 1) {
    // If button is pressed
    pzem.resetEnergy();
    Serial.println("Energy counter reset to 0!");
    monitorMode = true; // Start monitoring the energy
    Serial.println("Monitoring mode ON");
  }
}

```

```

    } else {
        monitorMode = false; // Stop monitoring if button is OFF
        Serial.println("Monitoring mode OFF");
    }
}

BLYNK_WRITE(V3) {
    int buttonState = param.asInt(); // Get the state of the button (0 or 1)
    // Print the received button state for debugging
    Serial.print("Button state from V3: ");
    Serial.println(buttonState);
    if (buttonState == 0) { // Button is OFF
        // Turn relay ON (active-low relay, so LOW turns it on)
        digitalWrite(RELAY_PIN, HIGH);
        Serial.println("Relay is ON");
    } else { // Button is ON
        // Turn relay OFF (active-low relay, so HIGH turns it off)
        digitalWrite(RELAY_PIN, LOW);
        Serial.println("Relay is OFF");
    }
    // Optional: Add a small delay to prevent any issues with button bouncing or rapid state changes
    delay(100); // Small delay to ensure relay switch is stable
}

void testLogEvent() {
    Blynk.logEvent("test_event", "Test event triggered!");
}

// Function to reset energy when button is pressed on V14

```