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DESIGN AND DEVELOP ENERGY SMART METER WITH AUTOMATIC RECHARGE

By

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DECALARATION

I declare that this research contains my own work except where specifically acknowledged, and it has been passed through the anti-plagiarism system and found to be compliant and this is the approved final version of the research.

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ABSTRACT

The energy meter had been invented in the 19th century, where the meter measured the amount of time electricity was supplied to a load. From time to time, the energy meter has been improved from the early energy meter, induction meters, electro-mechanical meters, digital meters, multifunctional meters, and now smart energy meters are being developed based on the purpose. Despite the development of Energy meters to digital, there are still challenges with the current Meters used by many utilities in Africa, specifically here in Rwanda, where Customers struggle with entering the token by the meter keypad, sometimes requiring addition equipment as ladder mechanism to reach the keypad installed in reasonable distance from the ground. This leads to ineffective and inefficient time management in energy use, which results in dissatisfaction for customers. Now the Smart Energy Meter with auto recharge is an answer for those challenges. This research presents the design and implementation of a smart energy metering system with automated recharge functionality, addressing the limitations of conventional energy meters for optimizing efficiency and preventing unexpected power outages in residential environments. By using IoT and ICT tools, an Energy smart meter with automatic recharge was designed and developed, and the energy is loaded in the energy meter without keypad. Both hardware and software parts were designed and developed as a prototype for this research. The key electrical parameters measured include voltage, current, power, and frequency. These measurements are processed in real-time and stored in a MySQL database, allowing users to monitor their energy consumption via an LCD display. Additionally, the system incorporates SMS notifications to alert users when their energy balance is low, facilitating timely recharges and preventing service interruptions. The methodology involves IoT-based energy monitoring, where real-time data acquisition, processing, and visualization are implemented through a microcontroller-based architecture. The system's performance is evaluated in a real-world setting to assess its effectiveness in enhancing energy reliability and reducing unexpected power disruptions. Experimental results indicate that the system significantly improves energy management by providing real-time consumption data, automated recharge alerts, and enhanced billing accuracy, thereby minimizing energy wastage. The findings demonstrate the feasibility of deploying smart metering solutions to improve energy efficiency and consumer satisfaction.

Keywords: Smart Energy Meter, IoT, PZEM-004T Sensor, ESP32, MySQL Database, SMS Alerts, Real-time Monitoring, Automated Recharge, Energy Efficiency, Blynk.

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LIST OF ABBREVIATIONS AND TERMS

API: Application Programming Interface

ESP: Espressif Systems Protocol

HTML: Hyper Text Markup Language

PHP: Hypertext Preprocessor

CSS: Cascading Style Sheet

WiFi: Wireless Fidelity

ICT: Information and Communication Technology

XML: Extensible Markup Language

IoT: Internet of Things

KWh: Kilowatt-Hour

LCD: Liquid Crystal Display

MySQL: My Structured Query Language

MQTT: Message Queuing Telemetry Transport

PZEM: Power Zero Energy Meter

PZEM-004T: Energy Metering Sensor

REG: Rwanda Energy Group

QoS: Quality of Service

SMS: Short Message Service

Token: A unique identifier used to recharge prepaid meters

Transaction: The process of buying and entering energy credits into a prepaid meter

Balance: The amount of energy credits remaining in the prepaid meter

Flowchart: A diagram representing a process, showing steps and decisions

Funds: Money or credits added to the system to recharge the prepaid meter

ESP32: A low-cost, low-power system on a chip (SoC) with Wi-Fi and Bluetooth capabilities

CHAPTER ONE: GENERAL INTRODUCTION

1.0 Introduction

This chapter presents the design and development of a smart energy meter with automated recharge functionality. The study highlights the challenges associated with energy management, particularly in Rwanda, where traditional energy meters lack real-time monitoring and automated billing capabilities. The primary objective of this research is to develop a system that enables automatic recharging, real-time energy parameter tracking, and seamless data transmission to a database.

This chapter outlines the research problem, objectives, key research questions, and expected outcomes. Additionally, it discusses the scope and significance of the study in enhancing energy efficiency and improving user experience within Rwanda's energy sector.

1.1 Background of the study

The global energy sector is undergoing rapid transformation due to climate change concerns, increasing energy demand, and technological advancements. The International Energy Agency (IEA) projects a 70% rise in global electricity consumption by 2040, underscoring the urgent need for modern energy monitoring systems[1], The global smart meter market is expected to reach $27.7 billion by 2027, growing at a compound annual growth rate (CAGR) of 8.5%, as more countries implement smart grid technologies. Additionally, Sustainable Development Goal 7 (SDG 7) emphasizes the need for universal access to reliable and sustainable energy, driving increased investment in energy management solutions[2]. Africa faces significant energy challenges, with only 48% of the population having access to consistent electricity. This disparity is particularly evident between urban and rural communities. However, countries such as Kenya, Nigeria, and Rwanda have launched ambitious electrification programs to improve access. The African Union's Agenda 2063 recognizes technology as a key enabler of sustainable energy development, with studies indicating that smart metering could reduce energy losses in African cities by up to 30%[3].

In Rwanda, various energy metering solutions have been implemented to enhance electricity access and management. The Rwanda Energy Group (REG) primarily utilizes Cashpower Energy Meters, which operate on a prepaid system requiring users to manually purchase and enter tokens, often leading to delays, unexpected power disconnections, and difficulties in monitoring energy consumption. Despite serving over 1.5 million households, these meters lack real-time tracking and automatic recharge features. Several private companies, particularly in the off-grid solar sector, have introduced smart metering technologies to improve energy accessibility. BBOXX Rwanda, Ignite Power, and Mobisol Rwanda provide solar-based energy solutions integrated with IoT-enabled smart meters, allowing remote monitoring, mobile-based payments, and automated recharge options, benefiting thousands of households in rural and peri-urban areas. Similarly, MeshPower offers a prepaid IoT metering system for solar mini-grids, ensuring efficient energy distribution to small communities. However, most grid-connected households in Rwanda still rely on traditional prepaid meters, lacking automation and real-time monitoring capabilities.

Table1: Energy Metering Solutions in Rwanda

No.	Company/Project	Energy Resource	Capacity (kW)	Number of Connected Households	Technology Used
1	Cashpower Energy Meters (REG)	Grid Electricity	N/A	1,500,000+	Prepaid Smart Metering
2	Energy Smart Meter (Proposed Project)	Grid Electricity	N/A	Pilot Study (Selected Households)	IoT-Based Smart Meter with Auto Recharge
3	BBOXX Rwanda	Solar Power	Varies per unit	50,000+	Pay-as-you-go Smart Metering
4	Ignite Power	Solar Power	Varies per unit	40,000+	IoT Smart Meter with Mobile Payments
5	Mobisol Rwanda	Solar Power	80 - 200 per unit	15,000+	Smart Meter with Remote Monitoring
6	Mesh Power	Solar Mini-Grid	250 - 500	10,000+	IoT Prepaid Metering System

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) has revolutionized energy management, facilitating the development of intelligent energy ecosystems. By 2025, more than 75% of enterprise-generated data is expected to be processed outside traditional centralized data centers, highlighting the transformative potential of IoT-based energy solutions[4]. Despite ongoing developments, inefficient energy monitoring and billing issues remain prevalent in Rwanda, particularly in urban areas. A 2022 Kigali City Authority report revealed that 65% of residents experience billing inaccuracies due to outdated manual meter reading systems, leading to late payments, unexpected power outages, and disputes between consumers and energy providers [5]. Additionally, many households and small businesses lack real-time visibility into their electricity consumption, making it difficult to manage energy costs and minimize waste.

To overcome these challenges, this research proposes the development of an intelligent energy monitoring system that integrates real-time tracking and automated recharge notifications. By leveraging IoT technology and smart meters, the system will provide accurate, real-time electricity usage data, ensuring that users can monitor their consumption efficiently. Additionally, it will alert users when their energy balance is low, preventing unexpected power disconnections and enhancing user convenience. The system will also offer detailed insights into energy consumption patterns, allowing consumers to make informed decisions and optimize their electricity usage. By improving billing accuracy and reducing energy wastage, this solution aims to enhance overall energy management. Furthermore, it aligns with Rwanda's Vision 2050, which prioritizes technological advancements in energy management to ensure a more reliable and efficient power supply.

1.2 The statement of the problem

Rwanda's energy management faces significant challenges due to outdated traditional electrical meters that require addition measures to load energy, manual readings, inefficient billing systems, and the absence of real-time monitoring. According to a 2022 report from the Rwanda Utilities Regulatory Authority (RURA), more than 60% of energy consumers reported billing irregularities, often leading to disputes, financial losses, and abrupt power disconnections. Additionally, the Rwanda Energy Group (REG) estimates that manual meter reading contributes to annual revenue losses of up to 10% due to errors, fraud, and operational inefficiencies [6].

The economic impact of these inefficiencies is substantial. REG reports that billing errors and delays cost the utility sector millions of Rwandan Francs annually, negatively affecting both consumers and service providers. Households and businesses frequently receive unexpectedly high electricity bills because they lack real-time consumption data, making it difficult to control

and optimize energy usage. The reliance on manual meter readings further increases operational costs, as energy companies must deploy field agents, whose errors exacerbate financial losses
A 2021 REG energy sector report revealed that 40% of power disconnections occur because users are unaware of their remaining credit, resulting in unexpected inconveniences. The majority of prepaid meters in Rwanda lack remote monitoring features, automated low-balance alerts, and real-time consumption tracking, requiring users to manually check their balance [7].

Previous solutions, such as conventional prepaid meters, aimed to improve billing efficiency but still required user intervention for balance tracking and recharges. Additionally, past smart metering pilot programs in certain Kigali neighborhoods faced infrastructure challenges, including poor connectivity, high installation costs, and a shortage of skilled technicians for maintenance [7]. While smart metering technology has been successfully implemented in developed countries, Rwanda has been slow to adopt it due to economic constraints and the need for locally adaptable solutions [8].

To address these limitations, this project proposes the Energy Smart Meter system, an IoT-based real-time monitoring and automatic recharge solution that provides comprehensive energy consumption analytics. The proposed system will enable users to monitor electricity usage in real time, receive automated balance notifications, and remotely recharge their accounts. By minimizing billing discrepancies, enhancing energy efficiency, and improving user convenience, this initiative aligns with Rwanda's Vision 2050, which prioritizes technological innovation for sustainable energy management.

1.3 Objectives

1.3.1 General objective

The main objective is to Design and Develop Energy Smart Meter with Automatic Recharge to improve energy management in rural and urban areas.

1.3.2. Specific objective

1. To Design a system capable of measuring energy parameters such as voltage, current, power, and frequency and displaying the data in real-time on an LCD screen.
2. To Develop a prototype for the system that transmits sensor-measured data to a database via an interface made between the devices over a network connection

3. To develop a user interface that presents users with their energy consumption data and automates the energy recharge process, including SMS notifications when the energy balance is nearing depletion.

1.4 Research Questions / Hypothesis

i. Is an Energy Smart meter needed by customers? Why?

Energy Smart meter with automatic recharge is very needed based on the problem stated in the above paragraphs. Utility's customers are aware of their satisfaction for their time management as well as their wellbeing in terms of energy use and monitoring.

ii. Is there any existing system related to the one I want to develop?

Yes, there are systems relating to the one I want to develop. Energy metering systems exist in many forms, but many of them often lack features like real-time energy tracking, automatic recharge. Research into current systems will help determine whether existing models can be adapted or improved to meet modern technological needs.

iii. How can it be upgraded to the current technology?

A new energy metering system can be developed that addresses the key customer needs, such as real-time energy tracking, automatic recharge, and cost-effectiveness. This could be achieved by integrating advanced IoT technologies and real-time data processing capabilities, allowing for automatic recharge alerts and tracking. Additionally, cloud storage and mobile apps can be implemented to provide users with more interactive and remote access to their energy usage and balance.

iv. Can a proposed system be a cost-effective solution for many users?

The proposed system can be developed to be affordable and cost-effective for a wide range of users through optimized design and selection of affordable materials. By choosing cost-effective sensors, microcontrollers, and communication protocols, the overall system cost can be kept within reasonable limits while still providing all the necessary features. Bulk purchasing and local availability of components will also help reduce the final production cost, making it accessible for a wider audience.

v. How can it be developed with cost-effectiveness with maximum efficiency?

The energy smart meter can be developed to balance maximum efficiency and cost-effectiveness through careful material selection and optimized system design. For instance, using low-cost, efficient sensors such as the PZEM-004T, and power-efficient microcontrollers like the ESP32, can ensure that the meter performs its task without excessive energy consumption. Additionally, designing the system with minimal components (e.g., minimizing the number of relays, connectors, and additional sensors) while ensuring the system remains scalable will help improve both efficiency and cost-effectiveness.

vi. Are materials needed for the proposed system available on the Rwandan markets?

Yes, the necessary materials can be found on the Current market, either locally or the international market, and even online market, can be procured through local suppliers. Local electronics stores or suppliers can also be sourced from regional markets if needed. The increasing availability of affordable electronics in Rwanda's growing technology sector is a positive factor in implementing this project locally.

vii. What software may be needed to develop the system that fulfills the purpose of the project?

Some software needed to develop the system should support both the hardware control and user interactions (via an Android app). The system can be programmed using the IDE, Python or MATLAB, which is compatible with the selected sensors, for real-time data processing and communication. For the web interface and data storage, technologies like PHP and MySQL can be used to store and retrieve energy consumption data. Additionally, using platforms like Blynk for the Android app development can allow users to interact with the system through an intuitive interface, providing real-time information and recharge capabilities.

1.5 The Study's Scope

The goal of this project is to develop an energy smart meter that integrates automated recharge capabilities with real-time energy monitoring. The system consists of key hardware components, including the microcontrollers, energy sensor, relay, and an LCD screen for data visualization. Additionally, a PHP-based web interface will be developed to provide users with easy access to their energy consumption data and to automate the recharge process via SMS notifications. A MySQL database will store energy usage information, enabling efficient tracking and management. The project covers hardware and software integration, system testing, and an assessment of its impact on residential energy management.

The project will be carried out over a two-month period, encompassing hardware procurement, system design, prototyping, software development, and testing. The timeline includes:

1. **Phase 1:** Procurement of components, system design, and prototyping.
2. **Phase 2:** Software integration, database setup, and user interface development.

3. **Phase 3:** Field deployment, user feedback collection, and system performance monitoring.
4. **Phase 4:** Data analysis, evaluation of results, formulation of recommendations, and documentation for future improvements and scalability.

This structured approach ensures that the system is thoroughly tested, optimized for real-world applications, and ready for potential future expansion in Rwanda's energy sector.

1.6 Expected Outcomes and Significance of the Study

This study is expected to develop a functional prototype of a smart energy meter system that effectively addresses modern energy management challenges. The study will assess how automated recharge processes and real-time energy monitoring can enhance user satisfaction, energy efficiency, and billing accuracy. Additionally, it will contribute significantly to Rwanda's energy sector by offering an innovative approach to reducing energy waste and improving billing transparency.

1.6.1 Expected Outcome of the Study

- A working prototype of an energy smart meter capable of real-time energy monitoring.
- A database system to store, track, and analyze energy consumption data.
- An automated recharge system with SMS alerts for user convenience.
- Insights into the system's compatibility with Rwanda's existing energy infrastructure.

1.6.2 Significant of the Study

This study is significant as it presents a practical solution to enhance household energy management. By integrating automated recharge, real-time monitoring, and user-friendly interfaces, the system aims to reduce energy waste and promote efficiency. Moreover, it aligns with Rwanda's national goals for sustainability and energy accessibility, providing a scalable solution for other regions facing similar energy challenges. Furthermore, the project serves as a foundation for future innovations in energy technology, contributing to the growing field of IoT-based energy management systems.

1.7 Research outline/ Organization of the study

The Design and Development of an Energy Smart Meter with Automatic Recharge is organized into five chapters, as follows:

- **Chapter One: General Introduction**

This chapter provides an overview of the study, including the problem statement, objectives, research questions, scope, and significance of the project.

- **Chapter Two: Literature Review**

This chapter explores previous research, related studies, and theoretical frameworks relevant to the project. It discusses existing energy metering technologies and their impact on energy management.

- **Chapter Three: Research Methodology**

This chapter details the methodology, data collection techniques, and research design used in the study. It explains the approach for developing and testing the smart energy meter system.

- **Chapter Four: System Design and Implementation**

This chapter presents the hardware and software design of the energy smart meter, including the integration of IoT components, database management, and user interface development. It also explains the implementation process and system testing.

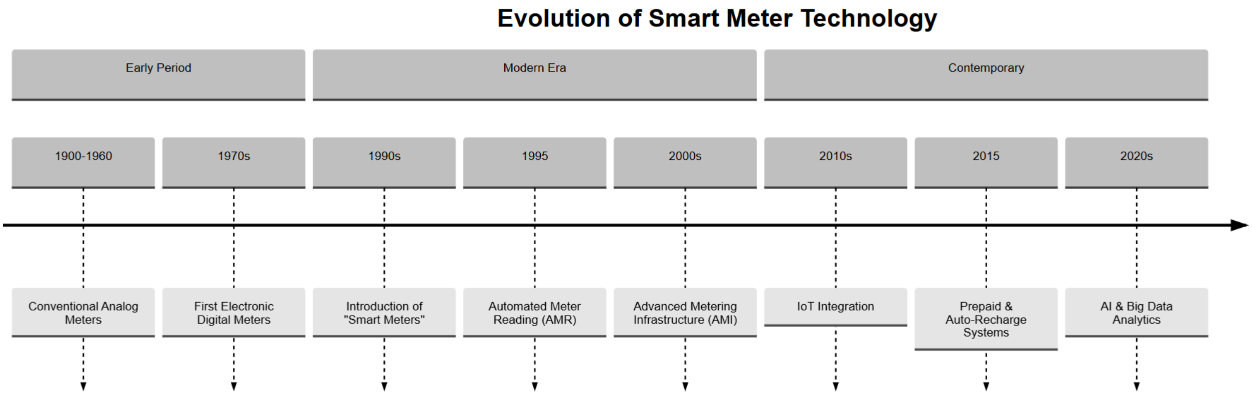
- **Chapter Five: Conclusion and Recommendations**

This chapter summarizes the findings, evaluates the effectiveness of the system, and provides recommendations

CHAPTER 2. HISTORY OF ENERGY SMART METER WITH AUTOMATIC RECHARGE

2.1 Introduction to History

When conventional analogue meters were first used to assess energy use in the early 20th century, the idea for smart meters was born. Manual readings were necessary for these early meters, which were time-consuming and prone to mistakes. The first generation of electronic meters, which offered increased accuracy and decreased need on human readings, were launched in the 1970s with the introduction of digital technology. More advanced gadgets that could transmit data and monitor in real time were made possible by these digital meters [8].



When metering systems began incorporating communication technologies in the 1990s, the term "smart meter" became widely used. Utility companies may receive consumption data from these meters, allowing for remote monitoring and doing away with the necessity for manual meter reading [9]. The introduction of Automated Meter Reading (AMR) systems marked a significant milestone, as it allowed for efficient data collection and billing processes, especially in urban areas. Advanced Metering Infrastructure (AMI), a crucial part of contemporary smart meters, had a sharp increase in usage in the early 2000s. AMI systems allowed for two-way communication between the utility company and the customer in addition to improving data accuracy [10]. Significant developments in metering technology during this time included dynamic pricing, load profiling, and outage detection, all of which highlighted the value of smart meters in energy management.

Integrating smart meters with IoT and renewable energy systems has become more important in recent years. The energy industry has undergone a transformation because to innovations including automatic recharge systems, prepaid meters, and real-time energy analytics [10] . These advancements have had a significant impact on developing nations' energy access issues, allowing for more effective and fair energy distribution. The project makes use of this historical development to create a smart meter system that is specifically suited to the requirements of Rwanda's urban and rural areas.

2.2 Commercial and Industrial aspects

The commercial and industrial sectors have significantly benefited from the adoption of smart meters. Real-time energy usage monitoring enables businesses to identify areas of energy wastage, facilitating informed decision-making that reduces costs, enhances efficiency, and minimizes energy consumption. For energy-intensive industries such as manufacturing, access to real-time data leads to substantial cost savings and operational improvements.

Smart meters also allow businesses to better manage their energy expenditures. By tracking energy consumption during peak and off-peak hours, commercial entities such as retail stores, offices, and other organizations can optimize their operations to capitalize on lower energy costs. This adaptability has made energy usage more flexible and affordable, particularly for small and medium-sized enterprises (SMEs) that are highly sensitive to fluctuating energy prices.

Furthermore, smart meters have enhanced billing accuracy and reduced revenue losses for utility providers by mitigating energy theft and human error. Automatic readings and real-time monitoring eliminate the need for frequent manual meter readings, thereby saving time and reducing operational costs. Additionally, utility companies can leverage smart meter data to predict demand trends, optimize energy distribution, and maintain grid stability.

Smart meters also support advanced energy management features such as demand response programs and load profiling. These tools enable businesses to identify energy-intensive machinery or processes, allowing them to adjust energy usage patterns and participate in demand response programs. By shifting consumption away from peak periods, businesses can benefit from financial incentives while also contributing to grid stability. Such capabilities not only reduce costs but also align with broader sustainability initiatives.

The integration of prepaid systems with smart meters has further expanded their commercial potential. Prepaid energy programs provide businesses with a steady and predictable revenue stream, reducing the risk of unpaid bills and improving cash flow management. This financial stability simplifies the management of operational expenses and enhances overall business sustainability.

Overall, smart meters have revolutionized energy management in the commercial and industrial sectors. By enabling improved grid reliability, cost control, and energy efficiency, they have become an essential component of modern energy systems. As technology continues to evolve, their impact is expected to grow, further driving economic development and promoting environmental sustainability.

2.3 Overview

In order to provide real-time energy monitoring, automated billing, and remote control features, smart meters with automatic recharge functionality combine sophisticated sensing technologies, data analytics, and communication networks. These systems also help to bridge the gap between utility providers and consumers by allowing users to track their energy consumption, receive alerts for low balances, and recharge remotely [12].

These solutions aid in demand management, energy theft prevention, and energy efficiency promotion, making them particularly advantageous in areas with unstable energy supplies. Implementing these systems is in line with international efforts to meet sustainable energy targets under programs such as the Sustainable Development Goal 7 of the UN [13].

2.4 Economic Analysis and Challenges

Smart meter deployment has major financial advantages, especially when it comes to cost savings and energy efficiency. Smart meters like the Cash Power system have been essential in revolutionizing energy distribution and payment procedures in Rwanda, where the Rwanda Energy Group (REG) oversees the energy sector. By enabling customers to buy electricity in advance, these prepaid meters encourage budgeting and do away with the problem of past-due payments. Effective energy budgeting for homes and companies has been made possible in large part by this technique [14].

The capacity of smart meters to reduce energy losses is one of their primary economic benefits. Due to billing errors, energy theft, and system inefficiencies, traditional metering systems frequently cause losses. Smart meters assist REG in quickly identifying and resolving technical losses and energy theft by supplying real-time data on energy consumption. The utility firm has seen an increase in revenue collection as a result, guaranteeing a more sustainable energy supply chain.

Notwithstanding these advantages, there are still obstacles to overcome before smart meters can be widely used, most notably the high upfront and ongoing costs. Many rural communities in

Rwanda still lack access to sophisticated metering infrastructure because of the high cost of implementing such technology.

Even though the Cash Power system has proven effective in urban and peri-urban areas, REG still faces a big obstacle in getting it to distant areas. Disparities in energy access result from low-income households' inability to afford prepaid energy due to financial restrictions.

Adapting to technology improvements presents another economic hurdle. As smart meters develop to incorporate capabilities like mobile app connectivity and IoT integration, REG and other stakeholders will need to make investments in staff training and infrastructure upgrades. Significant capital investment and continuous assistance are needed for this, which can put a burden on financial resources, particularly in developing nations like Rwanda.

Furthermore, strong consumer education initiatives are necessary for the switch to smart meters. Despite the Cash Power system's widespread acceptance, some users still have trouble comprehending how to properly recharge and control their energy consumption. This may result in smart meters' potential being underutilized, which would lessen their overall economic benefit.

even though smart meters like the Cash Power system have greatly increased Rwanda's energy efficiency and revenue collection, there are still issues with guaranteeing fair access and cost. A cooperative strategy including government assistance, public-private partnerships, and ongoing investments in infrastructure and consumer education will be needed to overcome these challenges. By creating an energy meter with automated recharging capabilities, this project seeks to address some of these issues and improve user convenience and economic efficiency.

2.5 Types available

There are several varieties of smart meters, each intended to meet certain requirements in commercial, industrial, and residential settings. Depending on their setup and intended use, these meters offer a variety of features, including data transfer, energy management, and real-time monitoring. The primary categories of smart meters are listed below, along with more information and examples.

2.5.1 Prepaid Smart Meters

Users of prepaid smart meters must buy electricity credits in advance of using them. By automatically subtracting the energy used from the balance, these meters enable customers to monitor their energy expenditures and consumption. Customers can now recharge their accounts using mobile money, kiosks, or online platforms to the Cash Power prepaid system, which has revolutionized energy payments in Rwanda and is widely used by the Rwanda Energy Group

(REG). Utility companies no longer face the fear of delinquent bills to this technology, which guarantees on-time payments [15].

Prepaid smart meters provide the benefit of encouraging energy conservation. Users are more inclined to adopt energy-saving behaviors since they can see their balance in real-time. Affordability for low-income households and accessibility in isolated locations with maybe few recharging stations remain obstacles, nevertheless.

2.5.2 Postpaid Smart Meters

In situations when energy use is billed at the conclusion of a billing cycle, postpaid smart meters are utilized. Manual meter readings are no longer necessary to these meters, which track energy consumption and send the information to utility companies. Postpaid meters are frequently used in commercial and industrial settings where intricate patterns of energy use necessitate close observation. The capacity of postpaid smart meters to accommodate variable pricing schemes, including time-of-use tariffs, which encourage consumers to use energy during off-peak hours, is one of its primary features. Postpaid systems, however, could result in late payments, which would make it difficult for energy firms to keep cash flow stable [11].

2.5.3 Advanced Metering Infrastructure (AMI) Meters

AMI meters are extremely sophisticated gadgets that allow the energy company and the customer to communicate in both directions. These meters provide further information including voltage, frequency, and power quality in addition to recording energy use. They are a crucial component of contemporary energy management systems because they enable utility firms to remotely monitor and control the electrical grid. Adoption of AMI meters is still in its infancy in Rwanda because of the high deployment costs. Nonetheless, they are a wise investment for the future due to their capacity to improve consumer happiness and grid performance [16].

2.5.4 Net Metering Smart Meters

Customers that produce their own electricity, usually using solar panels, are the target market for net metering meters. Both the amount of electricity used from the grid and the extra energy returned to it are measured by these meters. By receiving credits for the excess energy they supply, consumers can use this method to offset their energy expenses. Net metering systems may be essential in promoting the use of renewable energy sources as Rwanda grows its solar energy projects. Integrating these technologies with the current energy infrastructure and making sure that all users have fair policies are challenges [17].

2.5.5 Hybrid Smart Meters

Hybrid smart meters give users flexibility by combining the benefits of postpaid and prepaid systems. Customers can use these meters to switch between payment methods according to their needs or preferences. Because hybrid systems meet a variety of user needs, they are especially helpful in places where access to energy is growing. As Rwandan families and companies adjust to smart metering technologies, hybrid solutions may offer a temporary fix. But because of their complexity, more money might need to be spent on technical assistance and customer education.

The variety of smart meter types available demonstrates how well they can be tailored to meet the needs of different utilities and consumers. Although the Cash Power prepaid system in Rwanda has established a solid basis for smart metering, increasing the use of other varieties, such as AMI and net metering systems, could improve energy efficiency and management even further [18].

2.6 Algorithm and flow chart of existing

Existing smart meter systems typically follow a structured algorithm to ensure seamless functionality

2.6.1 Overview of REG meters

The REG (Cash Power) prepaid energy metering system operates through several key components that work together to ensure efficient energy management. The process begins with the input stage, where the user purchases electricity credits through mobile money, kiosks, or online platforms. Once the purchase is completed, a unique token is generated and sent to the user via SMS or printed on a receipt. The next stage is the metering stage, where the user enters the token into the Cash Power meter. The meter verifies the validity of the token, and if valid, the meter balance is updated accordingly. Following this, the system enters the consumption monitoring stage, where energy usage is monitored in real-time. The meter deducts the consumed energy from the balance and displays the remaining balance along with consumption statistics on its LCD screen in the recharge stage, the user can purchase a new token and repeat the process to continue accessing electricity. These components collectively ensure a seamless and automated energy management system for users.

2.6.2 Flow chart

The flowchart illustrates the operational process of a prepaid energy metering system, such as REG (Cash Power). It starts with the user purchasing a token, which is then input into the meter. The system checks if the token is valid; if invalid, an error is displayed, prompting the user to correct it. If valid, the system verifies if the balance is greater than zero. If the balance is insufficient, the user is prompted to add funds and input a new token, looping back to validation. Once the token is valid and the balance sufficient, the system allows electricity consumption, completing the transaction efficiently and securely.

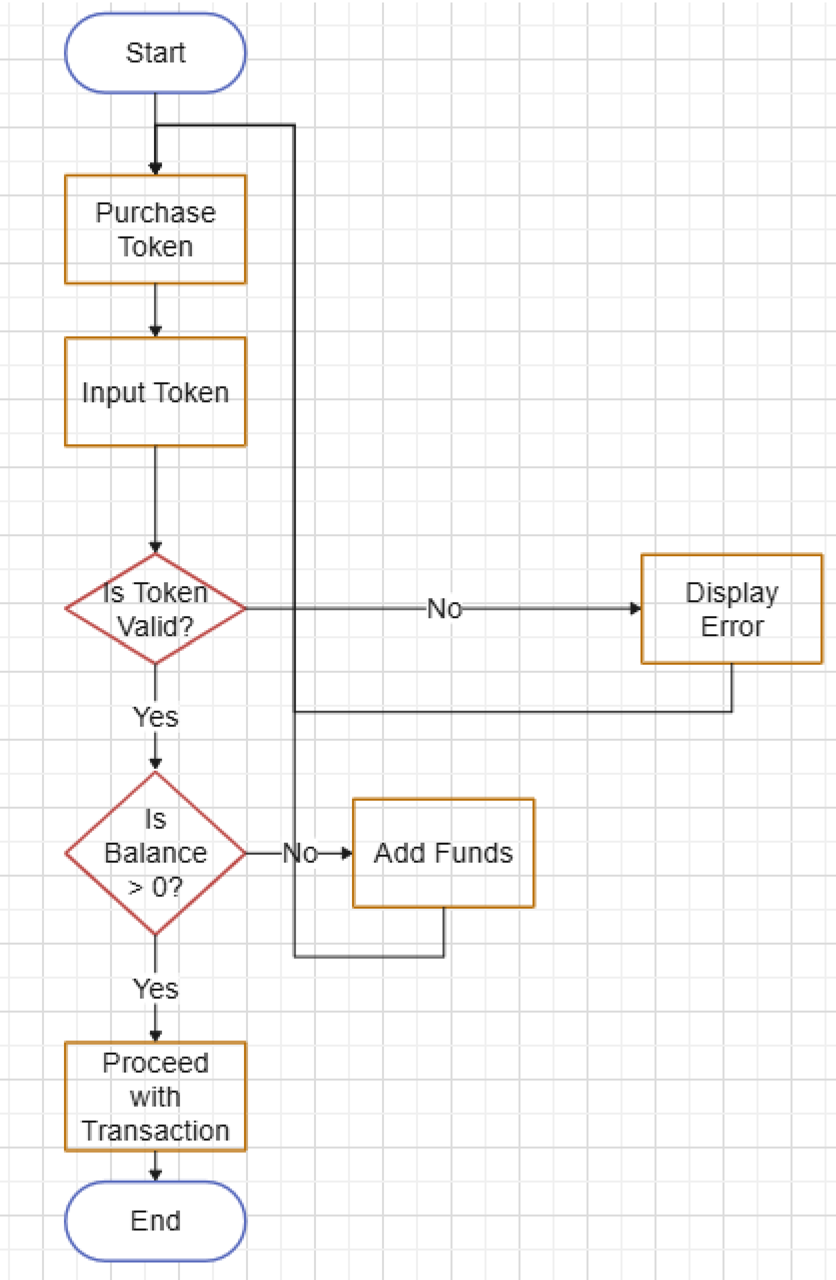


Figure 2. 1: Flowchart

2.6.3 Algorithm of the System

- Start.
- User purchases an energy token.
- Token is entered into the Cash Power meter.
- Meter validates the token:
- If valid, update the meter balance.
- If invalid, display an error message.
- Monitor energy usage and deduct from balance in real-time.
- Check the balance periodically:
- If low, send a low-balance alert.
- If zero, disconnect the power supply.
- Allow the user to recharge by repeating the process.
- End.

2.7 Role of Smart meter

By resolving inefficiencies in conventional metering systems, smart meters form the basis of contemporary energy management. They allow utility companies to improve consumer happiness, minimize losses, and distribute power as efficiently as possible. Smart meters give customers information on how much energy they use, encouraging cost savings and energy conservation. The administrative load of manual recharges is lessened and an uninterrupted power supply is guaranteed by the incorporation of automatic recharge systems [19]. By increasing access, cutting waste, and encouraging the use of renewable energy sources, smart meters can be extremely helpful in Rwanda in reaching its energy objectives. Smart meters help create a more efficient and sustainable energy ecology by giving customers data and control.

CHAPTER 3. METHODOLOGY

3.1 Overall approach of the research

This study uses a multidisciplinary approach that combines user-center approaches, technical design, and economic analysis. By utilizing hardware elements such the ESP32, PZEM-004T sensor, and LCD screen in conjunction with software tools for data transfer and visualization, the project seeks to develop and deploy an energy smart meter with automated recharge capabilities. To guarantee thorough data gathering and analysis, both qualitative and quantitative approaches are used.

3.1.1 Overview of Energy Smart Metering Systems

Energy smart meters are becoming a key piece of equipment for controlling electricity use [20] . research indicates that smart metering technologies assist utility companies and consumers in optimizing energy use and cutting expenses. In order to give customers precise and immediate information on their energy usage, these systems usually measure characteristics like voltage, current, power factor, and energy consumption in real-time. Additionally, they let utility companies to remotely monitor usage and identify problems such as malfunctioning meters or energy theft [21]. When smart meters are integrated with communication technologies like Wi-Fi and GSM, data is transmitted to central systems seamlessly, making it easier to monitor, bill, and manage energy use. The shift to smart grids has been aided by this progression, which has improved energy metering's accuracy, transparency, and usability.

3.1.2 Smart Metering Systems in Rwanda

Smart meter deployment in Rwanda is a component of a larger effort to improve the nation's electrical grid management and expand coverage to rural areas. The implementation of smart metering has revolutionized the distribution and invoicing of power, according to REG [14]In particular, the Cash Power system, which makes use of prepaid smart meters, has improved transparency and drastically decreased revenue loss brought on by incorrect billing. Cash Power has enhanced customer happiness and operational efficiency by enabling consumers to buy electricity credits via mobile platforms and offering real-time consumption tracking. Additionally, the system makes sure that payments are made in accordance with electricity use, which has helped to lower energy losses and encourage financial sustainability in the energy industry.

3.1.3 Challenges in Energy Smart Metering Systems

Energy smart metering systems provide many benefits, however there are also a number of issues. One of the key obstacles is the high upfront cost of deployment and maintenance, which may prevent adoption in developing nations, according to research by [22]. Furthermore, in some places, the full-scale deployment of these systems has been hampered by problems including network dependability and interoperability with current infrastructure. Despite Cash Power's notable advancements, rural electrification in Rwanda is still difficult, with many regions still using antiquated, ineffective metering systems [23]. Furthermore, handling the massive volumes of data produced by smart meters presents technical challenges that need for reliable data processing and storage systems. Therefore, even though smart meters offer a promising way to control energy, these technological and financial obstacles must be overcome before they can be successfully used.

3.1.4 The Role of Automatic Recharge Systems in Prepaid Meters

Prepaid energy meters along with automatic recharge devices have completely changed how electricity is managed. According to research [24] users may continuously monitor their energy consumption and replace their balance without manual intervention when smart meters are integrated with automatic recharge capabilities. By providing convenient recharging choices via mobile money or other digital platforms and sending notifications when energy levels are low, this system improves the user experience regarding Rwanda,

This capability has been added to the Cash Power system, enabling users to automatically replenish their meters via SMS or mobile apps. Service interruptions have significantly decreased as a result of the system, which also makes sure that consumers don't lose power because of a lack of credits. Additionally, it encourages a proactive approach to energy management, which enhances the overall effectiveness of power distribution while enabling consumers to maintain a steady energy supply.

3.2 Literature review with related study

Studies already conducted on smart energy meters show how they can increase user satisfaction, save operating costs, and improve energy efficiency. To enable real-time data transfer, researchers have investigated a number of designs including IoT technology, including ESP32 and MQTT protocols. Studies on the combination of SMS notifications and automatic recharge functions are scarce, nevertheless. Related research includes:

3.2.1 IoT based energy monitoring and management system for smart home using renewable energy resources

Joseph Murk, 2019 wrote on the Energy Management system which continuously monitors the energy consumption. In the second part of the project consists of a set of relays controlled by commands which are provided by making suitable changes in the web page. The system follows a separate operation for each of the components that are attached to the relay. The core of the project is an Arduino Uno board. Power is supplied to the Arduino board and the computer. The electric meter, signal conditioning unit, rectifier, driver circuit, LCD display are attached to the corresponding pins of the controller. A computer or smart phone can be used as a user interface to control the components of home automation system [19].

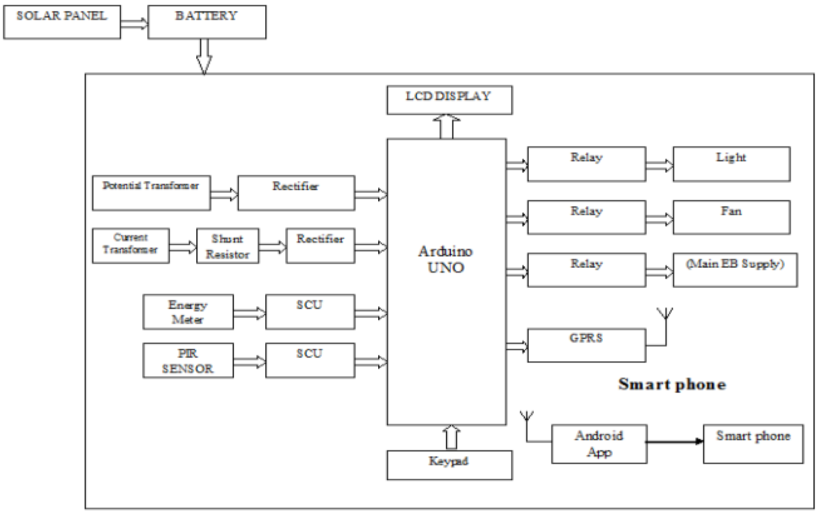


Figure 3. 2 IoT based energy monitoring and management system for smart home using renewable energy resources

3.2.2 A prepaid meter using mobile communication

The study introduces the utility supply to feed the energy meter, which has a prepaid card embedded. The prepaid card feeds a low/high signal, i.e. open/close signal, to the local contactor depending on the balance left in it. The contactor thus controls the supply to the consumer load, disconnecting it when the prepaid card runs out of balance. When the prepaid card is short of sufficient balance, the consumer makes a recharge request to the utility by prepayment through the internet. The utility having received the recharge amount recharges the prepaid card using mobile communication. The utility also receives information about the balance details from the card for the record purposes [12].

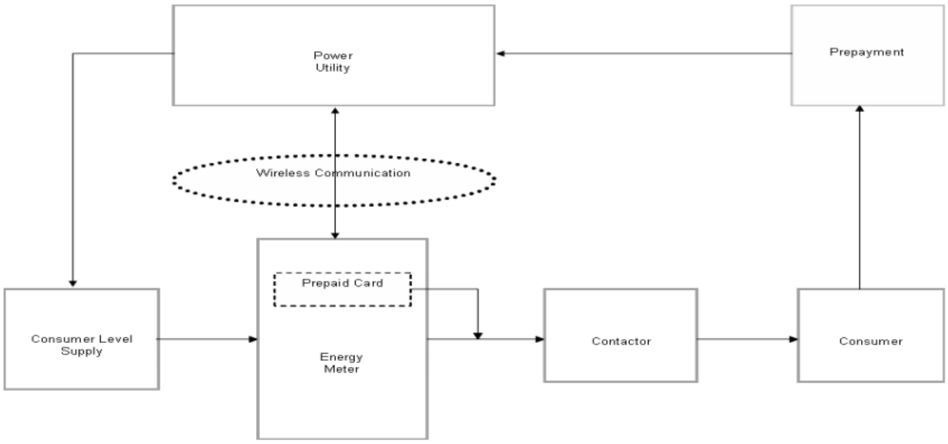


Figure 3. 3 A prepaid meter using mobile communication

3.2.3 The Technology Development of Automatic Metering and Monitoring Systems

Terry Chandler in 2020 wrote: In recent years, AMR and power monitoring have been greatly impacted by the quick advancement of ICT technology, power metering technologies, and power monitoring knowledge bases. Traditionally, power monitoring systems have been either Power Quality and Power Usage (PQ) monitoring systems or automated meter reading (AMR) systems. Costs have come down and we are seeing a merging of system capabilities as network, communication, and computing power technologies have advanced. PQ monitoring systems incorporate AMR functions, and new AMR systems incorporate some PQ capabilities. These are achieved by networked systems or automatic dialup that have automatic power usage, power flow, Kvar, and PF in addition to automatic event alarming, trending, long-term data management, and automatic report generating.

The author comes to the conclusion that intelligent monitoring systems and multilevel AMR with PQ monitoring with a WiFi connection will be features of the next generation of power monitoring systems. The power usage data for AMR parameters like PF, KVAR, and usage duration will be provided by these intelligent monitoring systems, which also feature automatic event classification, immediate event analysis, automatic distance to fault computation, and automatic power trending for all parameters.

3.3 Gap in related literature and make objectives

The technological developments, uses, and implementation issues of energy smart metering systems have been the subject of much research, especially in industrialized countries. Few studies, nonetheless, concentrate on the practical use of these systems in emerging nations, where socioeconomic circumstances, infrastructure, and energy distribution networks pose particular difficulties. The advantages of smart meters, such as increased energy consumption data accuracy, billing efficiency, and real-time monitoring, are frequently highlighted in the literature now in publication. Studies like those conducted by [22] have shown how smart metering can help maximize energy distribution, minimize losses, and give customers more control over how much electricity they use. However, these studies usually concentrate on more developed economies with established infrastructure, where smart meter implementation is more practical.

On the other hand, there are a number of obstacles to the use of energy smart meters that are frequently disregarded in international research, especially in nations like Rwanda. The energy situation in Rwanda, for example, is still developing, with a sizable section of the populace without access to dependable electricity. Furthermore, there are particular difficulties in implementing prepaid systems, like Cash Power in Rwanda, with regard to scalability, integrating with mobile payment platforms, and guaranteeing the seamless transfer of real-time data. The advantages of Cash Power are covered in REG (2020) studies, however there is a lack of research on how smart meters may be effectively utilized in rural areas where electrical infrastructure is still being built.

By concentrating on how an energy smart meter with automatic recharging can be built and developed for real-time energy monitoring and consumption, the study's goals seek to close these gaps in the literature. In particular, the study will look at Rwanda's difficulties implementing these systems and contrast them with more advanced examples found in the literature. Important goals consist of:

Energy Parameter Measurement: The initial goal is to use the PZEM-004T sensor to create a system that measures energy parameters (voltage, current, power, frequency, etc.) precisely. In order to provide consumers in places like Rwanda with more accurate, real-time data, this section of the study will examine the existing energy monitoring techniques and how they could be improved.

Data Transmission to MySQL Database: The second goal is to use an ESP32 to send data about energy usage from the smart meter to a MySQL database via a network. Although similar techniques have been used in previous research, few have examined the practical difficulties of data transmission in places with inadequate network infrastructure, particularly in rural Rwanda.

User Interface for Energy Recharge and use: The third goal is to create a user interface that enables the automation of the energy recharge procedure and shows real-time energy use. This study will close the knowledge gap on how Rwandan consumers may easily recharge their accounts through SMS notifications, particularly when prepaid systems like Cash Power and energy consumption monitoring are more prevalent in metropolitan areas.

By concentrating on low income nations, the difficulties associated with smart metering infrastructure, and the incorporation of renewable energy sources into these systems, these goals offer a novel viewpoint in contrast to previous research.

This research will offer significant insights into the adoption and scalability of energy smart meters in comparable developing contexts by tackling these particular regional issues and offering solutions customized for Rwanda's energy industry. The lack of attention paid to energy smart meters in the context of Rwanda and other developing nations, where the energy landscape is still evolving, is the gap in related research. This study will add to the continuing research on smart energy metering and its role in enhancing energy management internationally by identifying the particular difficulties and creating solutions suited to these areas.

3.4 Data collection (qualitative or quantitative method)

A mixed-methods approach is used for data collection:

3.4.1 Quantitative Data

The technical performance of the energy smart meter system is the main focus of the quantitative data collecting. This covers sensor readings for power, voltage, current, and energy usage. These real-time characteristics are recorded by the PZEM-004T sensor, which gives precise, unbiased information on the energy consumption that the system is tracking. In order to assess how well the smart meter tracks and displays energy use, certain measurements are necessary. An ESP32 microcontroller ensures continuous data logging for analysis by automatically recording and sending the data from these sensors to a MySQL database. The quantitative data forms the basis for assessing whether the technology and design of the system satisfy the necessary accuracy standards for energy monitoring and whether it conforms to industry standards.

3.4.2 Qualitative Data

User input regarding the system's functionality and usefulness is used to gather qualitative data in addition to technical data. Understanding how end users engage with the energy smart meter and its related interface depends on this data. Questionnaires and interviews are used to collect customer feedback. These methods evaluate things like the smart meter's general user satisfaction with its automated recharging procedure, responsiveness, LCD display clarity, and ease of use. The study can assess if the system satisfies the requirements and expectations of its users by obtaining qualitative insights, especially in poorer nations where access to cutting-edge technologies may be restricted. This input is essential for pinpointing areas that want development. such as simplifying the interface, enhancing the user experience, or troubleshooting common issues.

3.4.3 Tools and Techniques

Questionnaires are among the instruments used to collect data, with an emphasis on topics such as system dependability, usability, and general satisfaction. These surveys are intended to record both subjective viewpoints and objective evaluations, offering important insights into how effectively the system performs in practical situations. Additionally, the smart meter system's performance is technically validated using simulation data from multiple software tools. These simulations make it possible to test how the system reacts to various scenarios involving energy consumption and spot possible problems with data transfer, sensor calibration, or energy calculation algorithms. Both the technical and human components of the energy smart meter system are carefully assessed to the combination of simulated technical data and real-world user input.

3.4.4 Integration of Both Data Types

A more comprehensive examination of the system's performance is made possible by the combination of quantitative and qualitative data. While qualitative data provides insights into the user's experience, which is crucial for improving the system to better suit their needs, quantitative data provides the technical measurements that determine the accuracy of the system. By ensuring that both technological dependability and user happiness are carefully investigated, this mixed-methods approach produces a comprehensive understanding of the energy smart meter's efficacy and potential areas for future development.

Through the combination of hard technical data and user-center input, the mixed-methods approach offers a comprehensive and balanced perspective of the smart meter system. This method makes it possible to make better-informed choices about user interface design and system optimization, guaranteeing that the finished result is both practical and easy to use.

3.6 Design

The system is designed to combine technical efficiency, economic feasibility, and user-centric features.

3.6.1 Technical analysis

ESP32

This system uses the ESP32, a strong and adaptable microcontroller, for a number of essential tasks. It is in charge of managing all aspects of the energy smart meter's operation, including gathering, processing, and sending data to the database from the sensors. With its dual Wi-Fi and Bluetooth capabilities, the ESP32 can communicate data to a MySQL database across a network with ease. Other parts of the autonomous energy recharge system, such as the relay, are also controlled by it. The smart meter's logic is managed by the ESP32, which guarantees accurate energy readings and system responsiveness to user inputs.

PZEM-004T Energy Meter Sensor

The main part of this system for measuring energy is the PZEM-004T sensor. Important electrical metrics including voltage, current, power, and energy consumption (kWh) are measured using it. This sensor gives real-time information on the system's energy consumption and links to the ESP32. It assists in monitoring the energy consumption of the load by continuously sampling these parameters, guaranteeing that the energy usage is precisely monitored and represented on the database and display. since of its established dependability in energy metering, the sensor is selected since its precision is essential to guaranteeing that users can trust the data.

Relay

The automatic recharge mechanism of the system depends on the relay. It is employed to regulate the load according to the energy balance that remains. The relay is triggered to switch off the load and stop additional consumption when the system determines that the energy level is low. Another important component of the recharge process is the relay, which, after the recharge is finished, will turn the load back on. This feature helps monitor energy use automatically, removing the need for manual intervention, and guarantees that users are informed before their balance runs out.

LCD Screen (Display)

Users can view the system's data, such as voltage, current, power, and energy consumption, using the LCD screen's visual interface. It acts as the principal user interface for presenting information in real time, allowing users to rapidly comprehend their energy usage and balance. Additionally, the screen displays system status information, such as error warnings and recharge alerts. An key component of the hardware, a clear and succinct display is necessary to guarantee that the user can interact with the system with ease.

Power Supply (5V Battery)
The entire system is powered by a 5V battery, which guarantees that every part has the energy it needs to function. It supplies steady and dependable power to the LCD screen, relay, PZEM-004T sensor, and ESP32. This is especially crucial for making sure the system keeps running even in places where there may be power shortages. Additionally, the battery helps make the system portable if necessary, which is advantageous in places with poor grid power availability.

Load
The appliance or appliances that use the power being monitored are referred to as the load in this system. The PZEM-004T sensor is used to monitor the load, which is connected to the energy metering system. Lights, fans, and any other electrical equipment that the user wishes to monitor for energy use can be included. The relay regulates the load by turning the power on or off in response to the energy balance that the system detects. This feature guarantees effective energy use and helps avoid excessive energy consumption.

MySQL Database
All of the information produced by the system, including the energy readings (voltage, current, power, energy spent, etc.), is kept in the MySQL database. Through network communication, the ESP32 sends data to the database on a regular basis for analysis and storage. This enables customers to see their past energy usage and examine patterns over time. In order to keep customers' energy balances updated in real-time, the database is also essential for tracking the recharge process and managing user accounts.

PHP (Server-side scripting)
PHP is utilized in server-side programming to communicate with the MySQL database and provide users with relevant data displays. The database's energy data is retrieved by the PHP scripts, which then prepare it for the user interface. PHP is also utilized to manage logic for activities like figuring out how much energy is consumed and how much money each user has left. Additionally, it may automatically give users SMS alerts when their energy is running low, reminding them to top off their accounts.

Blynk App (for mobile control)
The Blynk app is a smartphone app that offers an intuitive user interface for managing and keeping an eye on the energy smart meter system. Through internet communication, the app shows real-

time data including power, voltage, current, and energy consumption from the ESP32. Additionally, it lets users communicate with the system from a distance by sending commands to switch on or off the load or checking their balance. By providing a graphical user interface for smartphones, Blynk streamlines the user experience and makes energy management simple.

Arduino IDE (Development Platform)

The ESP32 microcontroller is programmed using the Arduino IDE. The ESP32's code manages the data flow between the hardware parts, including reading, processing, and transmitting data to the MySQL database from the PZEM-004T sensor. The Arduino IDE offers a versatile development environment for modifying and refining the code, as well as the libraries required to connect with the hardware.

An effective and dependable energy monitoring and recharging system is created by the seamless integration of the hardware and software components. As the primary controller, the ESP32 gathers data in real time from the PZEM-004T sensor and sends it to the MySQL database. While the relay regulates the power to the load depending on the energy balance, the LCD display gives the user real-time information. The Blynk app offers a remote interface for users to monitor and manage their energy consumption, while PHP manages server-side logic and database interactions. An effective energy management solution is produced by this integration, which guarantees that the system can automatically monitor, control, and recharge energy use.

3.6.2 Economic analysis

By weighing the system's benefits against its implementation and operating costs, the economic analysis aims to determine how cost-effective the system is. By automating meter readings, doing away with the need for manual inspections, and lowering human error, energy smart meters can drastically lower operating expenses for utility companies. This results in reduced labor expenses, fewer billing errors, and speedier identification of energy theft or failures. By encouraging users to utilize energy more efficiently, the system allows for more precise monitoring of energy consumption, which eventually saves money.

The user experience is also improved by the capability to monitor usage in real time, remotely limit energy consumption, and set warnings for low balances. By preventing usage and being able to recharge only when necessary, users are therefore likely to save money. The smart meter system is a worthwhile investment for better energy management and encouraging sustainable energy usage because of the financial advantages, which include increased efficiency for both utility companies and consumers.

3.6.3 Financial analysis

A thorough understanding of the expenses and income related to the energy smart meter system is given by the financial analysis. Calculating the system's overall cost entails taking into account the costs of hardware (such as buying smart meters, sensors, and microcontrollers like the ESP32), installation (such as the costs associated with configuring the devices and connecting them to the network), and maintenance (continuous costs associated with system maintenance, updates, and technical support). These costs must be weighed against the potential financial benefits generated by the system. One of the key revenue streams is the implementation of prepaid energy plans. Users pay in advance for energy, and the system ensures that they cannot exceed their balance, which eliminates the risk of unpaid bills.

For utility companies, this model may result in steady cash flow, improved cash management, and financial stability. The study also looks at the system's long-term financial viability, evaluating how the money made from prepaid energy sales and lower operating and administrative costs balance the original and continuing investments. From both the utility provider's and the user's point of view, this financial model illustrates the smart meter system's feasibility and the potential for long-term financial gains.

3.7 Simulation and analysis

Before the energy smart meter system is put into use in real-world settings, this step involves testing and validating its functionality using simulation tools like Proteus. All hardware elements, such as the ESP32, PZEM-004T sensor, relays, LCD, and SMS notification system, can be replicated and observed in a virtual environment made possible by Proteus. This makes sure the hardware and software components work together properly and helps validate the system's performance under different operating situations.

Speed of Data Transmission: The simulation evaluates how quickly and efficiently data is transferred from the sensor to the ESP32 microcontroller and then to the MySQL database. To guarantee real-time data processing, it verifies that the connection protocol is tuned for low latency and high throughput.

Measurement of Energy Accuracy: A simulation of the PZEM-004T sensor's voltage, current, power, and energy measurements is made. For correct billing and monitoring, it is essential that the energy readings are dependable and fall within reasonable tolerances.

SMS Notification Reliability in order to make sure that users are informed in a timely manner about low energy balances or other important events, the SMS notification system is also simulated. The simulation tests the connection between the ESP32 and the SMS gateway, confirming that notifications are sent out under a variety of scenarios, including low energy levels or system malfunctions.

3.8 Theoretical Framework of study

The Internet of Things (IoT) and energy management theories, which examine the use of smart technologies to monitor, control, and optimize energy use, serve as the foundation for this study's theoretical framework. The PZEM-004T sensor, ESP32 microcontroller, and communication tools are just a few examples of the devices that can be integrated using the Internet of Things (IoT) to gather, send, and analyses energy data in real time. IoT enables customers to remotely monitor and control their energy usage, increasing energy efficiency and cutting waste.

The philosophy of sustainable development, which emphasizes reducing environmental impact through resource efficiency and energy conservation, is also in line with this study. By encouraging consumers to keep an eye on their energy consumption and make wise decisions to cut back, the energy smart meter system helps to create a more sustainable energy ecosystem. The concept of demand-side management, in which users actively control their energy consumption through the use of smart technologies, is also supported by the theory.

The user-center design concept, which emphasizes developing systems that are user-friendly, accessible, and advantageous, is also the foundation of the study. The objective is to guarantee that the energy management system is both practical and easy to use, providing a comfortable platform for energy recharge and clear insights into energy use by integrating user feedback into the system's design. This strategy encourages broader use of smart energy solutions while also improving the user experience.

In the end, combining IoT with user-centered design and sustainable energy management offers a thorough framework for creating a smart energy meter system that satisfies utility provider and consumer demands while promoting economical, sustainable energy use.

3.9 Results discussion

The study's findings show how well the energy smart meter system works to accomplish its stated goals of data transfer, automated recharge notifications, and real-time energy monitoring. Simulation tests demonstrate dependable data transfer from the sensor to the ESP32 microcontroller and then to the MySQL database, confirming the system's ability to precisely measure important energy parameters like voltage, current, power, and energy consumption using the PZEM-004T sensor. In order to ensure that customers are alerted promptly and have time to recharge their energy credits before they run out, the system's integration with SMS notifications has shown to be useful in warning users about low energy balances.

Furthermore, the design of the system, which consists of both software and hardware components, was validated using simulations and has proven to be resilient in managing data effectively while preserving system stability in a variety of scenarios. These results show that by offering an intuitive interface for monitoring energy use and managing recharges, the energy smart meter system not only satisfies technical specifications but also user needs. The system is a sustainable option for both consumers and energy providers, as evidenced by the economic and financial evaluations that show it has the potential to lower operating costs for utility providers while simultaneously providing cost-saving advantages for users.

CHAPTER 4 DESIGN AND DEVELOPMENT OF PROTOTYPE

4.0 Introduction

The design and implementation of the energy smart meter system are described in this chapter. It describes how the system's algorithm was developed, how the hardware and software components were chosen, and how the system architecture and workflow were depicted using diagrams. To guarantee smooth operation, effectiveness, and user pleasure, the emphasis is on integrating all the parts.

4.1 Component selection

The energy smart meter system's functional requirements determined the component selection process, guaranteeing efficiency, compatibility, and reliability.

4.1.1 ESP32

With built-in Bluetooth and Wi-Fi, the ESP32 is a potent microcontroller. It is made for Internet of Things applications, has a lot of processing power, and several GPIO pins.

Its high-speed processor guarantees effective handling of sensor data, and its integrated Wi-Fi module makes it perfect for sending data to a MySQL database. Sustainable energy systems also benefit from its low power usage.

By gathering data from the PZEM-004T sensor, processing it, sending it to the database, and managing the relay module for load management, the ESP32 acts as the central processing unit.

4.1.2 Energy Meter Sensor PZEM-004T

Voltage, current, power, and energy consumption are among the electrical metrics that the PZEM-004T sensor is specifically made to measure. It uses a serial interface for communication. It is appropriate for this project because to its high precision and real-time measurement capabilities. Seamless integration is further supported by compatibility with the ESP32.

The ESP32 receives the data from the sensor, which measures energy characteristics, then processes and displays it. It guarantees precise energy consumption monitoring.

4.1.3 16x2 LCD screen

One part of the user interface that is utilized to display data is the LCD screen. Clear and instantaneous visual feedback is made possible by its I2C or parallel communication connection to the ESP32. It gives consumers an easy and efficient way to view energy parameters in real time. The connection requires less GPIO pins thanks to the I2C interface.

Users may keep an eye on their energy consumption without the need for extra equipment to the LCD screen's display of voltage, current, power, and energy consumption data.

4.1.4 Relay Module

The system can regulate how the load (appliances) is connected to the power source thanks to the relay module's switch-like function. High-current loads can be securely handled by it. It is the perfect option for automating load disconnection in the event of critical conditions because it can give isolated control and is compatible with the ESP32's GPIO ports.

In order to avoid overuse and guarantee adherence to prepaid energy rules, the relay module cuts off the load when the system detects a low energy balance.

4.1.5 5V battery

The 5V battery serves as a power source that keeps the system running continuously by supplying backup power during blackouts. It is a sensible option for preserving system dependability due to its portability and compatibility with the ESP32's power requirements.

The battery keeps the system running during blackouts, enabling data transfer and monitoring procedures.

4.1.6 Appliance Load

The load is a representation of the energy-using equipment that the system keeps an eye on. It could consist of industrial machinery or household appliances. The load is required to validate the system's capacity to efficiently monitor and control energy use and to simulate real-world energy usage.

The load gives the system a useful application by showing how energy usage is calculated, tracked, and managed in actual situations.

4.2 Algorithm design

The flowchart is represented by the sequence of actions in the project, including:

1. System initialization.
2. Energy parameter measurement.
3. Data processing and analysis.
4. Data transmission to the database.
5. Energy balance check.
6. Load control based on energy balance.
7. SMS notification for low energy balance.
8. End process or repeat monitoring.

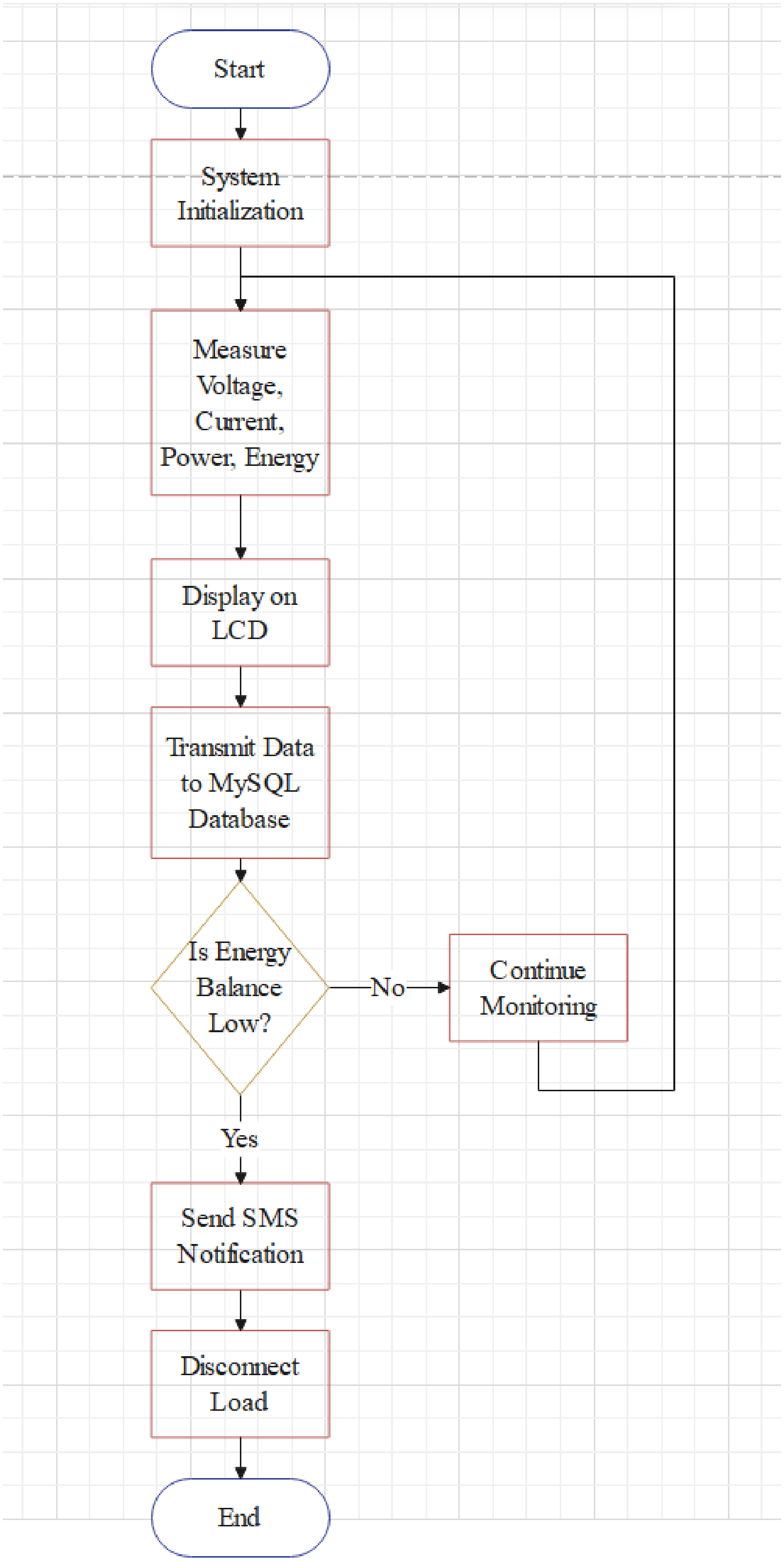


Figure 4. 1: Algorithm design

The smart energy meter system's operational procedure is depicted in the flowchart. After the system has been initialized, energy parameters like voltage, current, power, and energy consumption are measured. These parameters are sent to a MySQL database for storage and tracking, and they are shown in real time on an LCD panel. After then, the system determines if the energy balance is low. Otherwise, it keeps track of energy use. In order to stop additional energy use, the system disconnects the load and notifies the user via SMS if the balance is low. This automated procedure guards against unplanned interruptions and guarantees effective energy management.

4.3 Diagrams

By giving the system a visual representation, these diagrams improve comprehension and guarantee correctness in application.

4.3.1 Block diagram

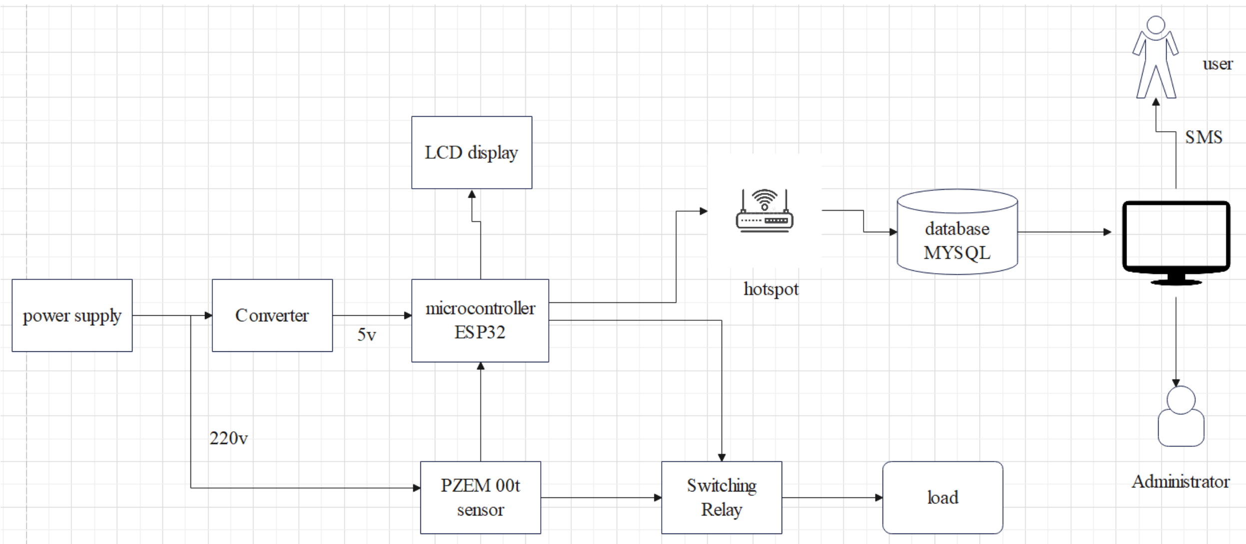


Figure 4. 2: Block diagram

The block diagram shows a smart energy meter system for monitoring and controlling energy use. The ESP32 microcontroller and other components are powered by a power supply that provides 220V AC, which is converted to 5V DC using a converter. The PZEM-004T sensor measures energy parameters (voltage, current, power, and frequency) from the 220V AC supply, and the ESP32 processes and shows this data on an LCD screen in real time. The system has a switching relay to control the electrical load based on predetermined conditions. Data is sent via a Wi-Fi hotspot to a MySQL database, where it is accessible by administrators and users via a user interface. In order to ensure prompt recharges and avoid outages, the system also notifies customers via SMS when energy levels are low. IoT and automation are used in an integrated system to improve user ease and energy management.

4.3.2 Architecture diagram

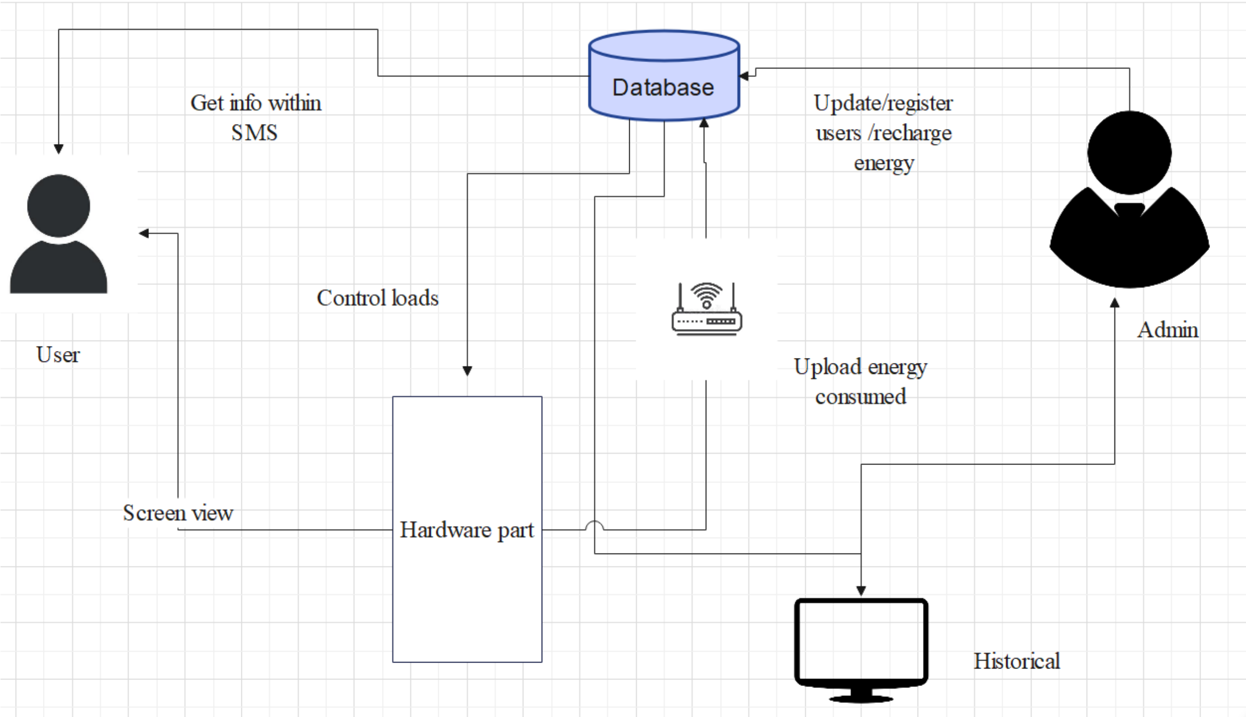


Figure 4. 3: Architecture diagram

The architecture diagram illustrates how a smart energy meter system's user, hardware, database, and administrator interact. Based on user inputs or pre-established criteria, the hardware component gathers data on energy use and regulates electrical loads. Through a Wi-Fi connection, this data is sent to a centralized database for processing and storage. Users can control loads for effective energy management, see their energy usage on a screen view, and get real-time information through SMS notifications. By updating or enrolling users and replenishing energy balances as necessary, the administrator plays a crucial part in system management. Users and administrators can monitor and analyze the past energy consumption records stored in the database. With the use of IoT technologies, this design guarantees smooth hardware, database, and user interface integration, enabling effective energy tracking and management.

4.3.3 Circuit diagram

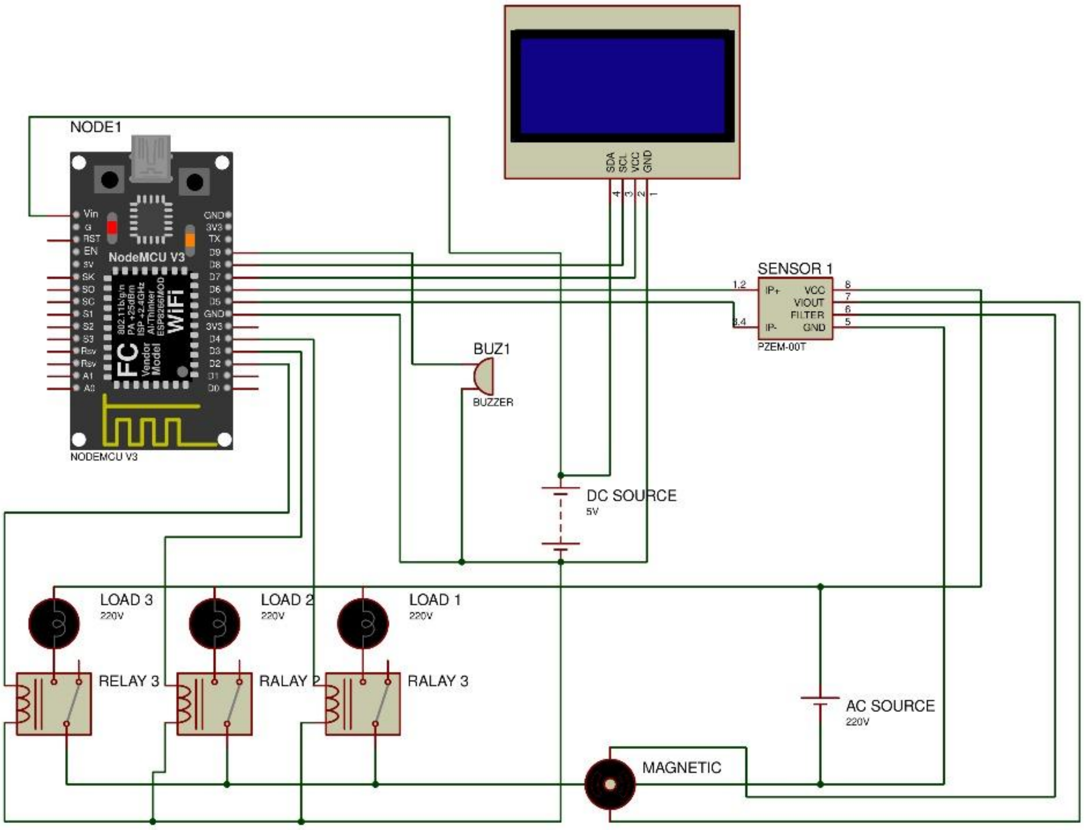


Figure 4. 4: Circuit diagram

A NodeMCU, PZEM-004T energy sensor, relays, and an LCD display are used in this circuit design to demonstrate a smart energy monitoring and control system. As the microcontroller, the NodeMCU interfaces with the PZEM-004T to measure AC source parameters like power, voltage, and current. The LCD shows these measurements in real time. Three loads (Load 1, Load 2, and Load 3) are connected to the relays, enabling the system to control each load independently using logic that has been designed. Power flow is detected using a magnetic sensor, and certain occurrences, such low energy levels, are signaled audibly by a buzzer. The NodeMCU and other low-voltage parts of the system are powered by a 5V DC supply, and the linked loads are powered by an AC source. IoT technology is included into this design for effective load control and energy management.

4.3.4 Website construction

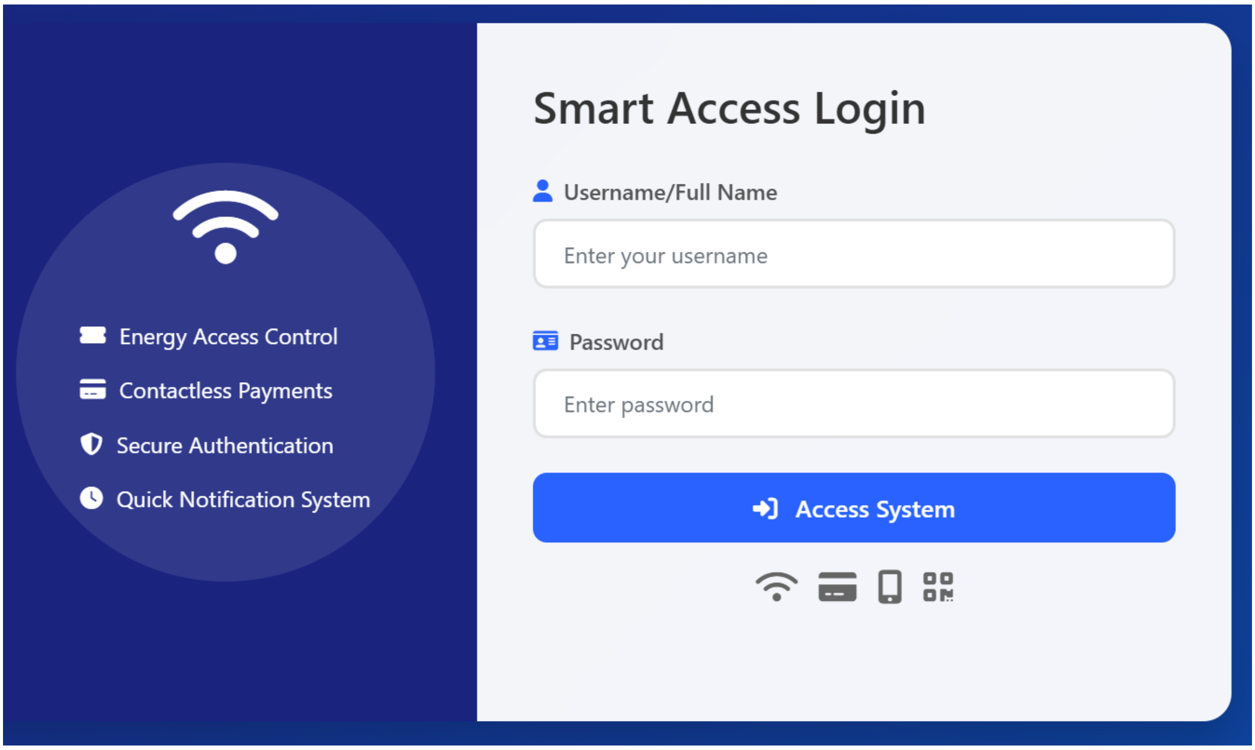


Figure 4. 5: Login Page

A thorough overview of the energy management system is given by the dashboard interface. Important information is shown, including the total number of users, the unit pricing, the meter connection status, the cost estimate for the energy used, and the total energy consumption in kWh. The sidebar, which has multiple buttons with distinct functions, allows users to engage with a variety of elements.

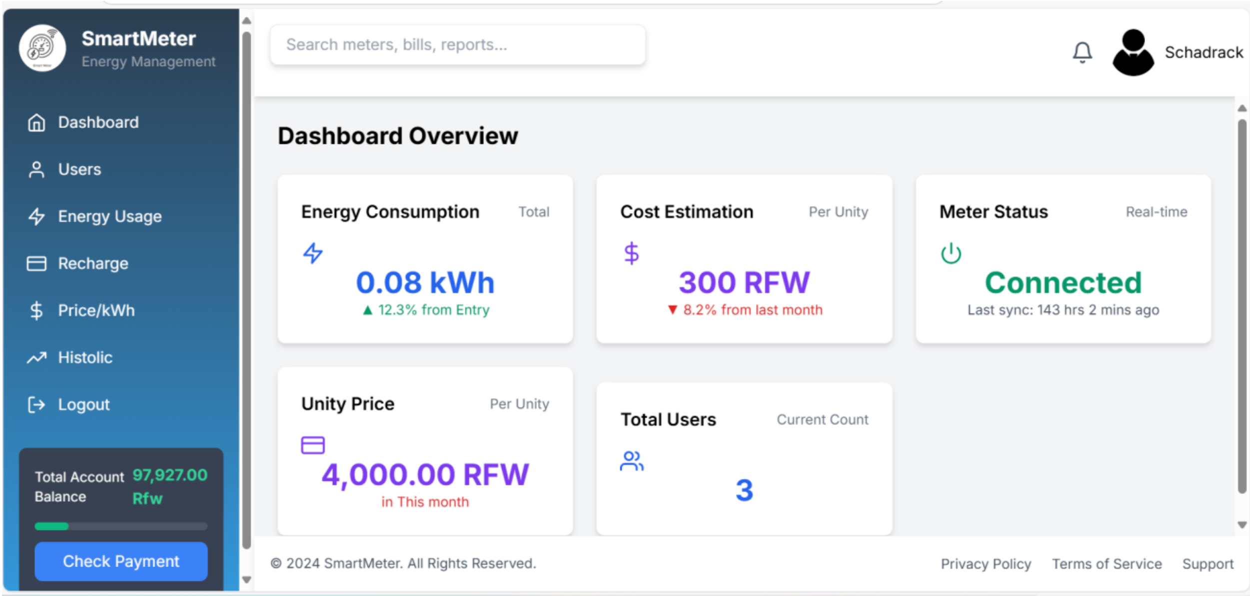


Figure 4. 6: Dashboard

Dashboard: Pressing this button returns the user to the primary overview page, where they can view up-to-date information on expenses, energy usage, and meter status. For speedy decision-making, it offers a brief overview of the most crucial parameters.

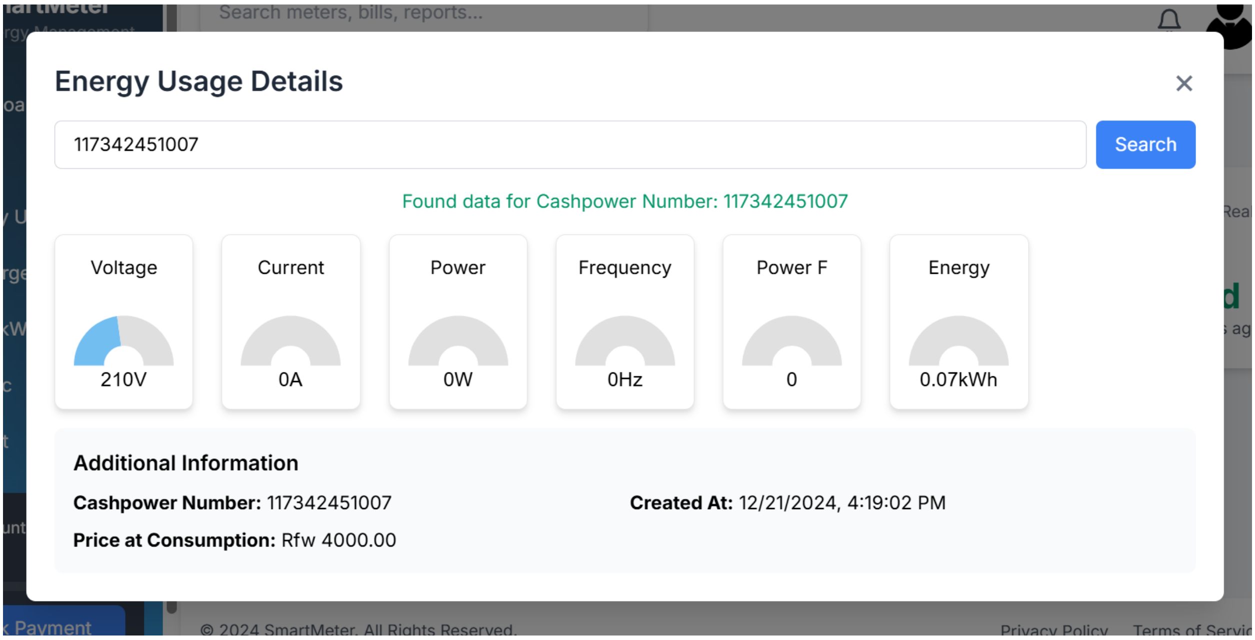


Figure 4. 7: Energy Usage

This tool provides a thorough analysis of trends in energy use over time. Users may optimize their energy consumption by analyzing patterns and identifying times when energy use is highest.

117342451007 Search

Full Name	Sex	Age	Address	Phone	Cashpower Number	Amount	Unity	Date
Schadrack	male	26	Kigali	0788225125	117342451007	10000.00	45.45	2024-12-06 17:44:39
Schadrack	male	26	Kigali	0788225125	117342451007	30000.00	136.36	2024-12-06 17:47:26
Schadrack	male	26	Kigali	0788225125	117342451007	7.00	0.03	2024-12-06 18:01:12
Schadrack	male	26	Kigali	0788225125	117342451007	20000.00	90.91	2024-12-06 22:16:58
Schadrack	male	26	Kigali	0788225125	117342451007	50000.00	227.27	2024-12-20 14:21:17
Schadrack	male	26	Kigali	0788225125	117342451007	66.00	0.30	2024-12-20 14:33:15
Schadrack	male	26	Kigali	0788225125	117342451007	77.00	0.15	2024-12-20 14:47:08
Schadrack	male	26	Kigali	0788225125	117342451007	1000.00	1.00	2024-12-20 15:15:03
Schadrack	male	26	Kigali	0788225125	117342451007	5000.00	5.00	2024-12-20 18:41:56
Schadrack	male	26	Kigali	0788225125	117342451007	4000.00	1000.00	2024-12-21 13:33:05
Schadrack	male	26	Kigali	0788225125	117342451007	4000.00	20.00	2024-12-21 15:35:46
Schadrack	male	26	Kigali	0788225125	117342451007	60000.00	15.00	2024-12-27 15:25:14

Figure 4.8: Historical

Historical information on energy use, expenses, and payments is available to users. Long-term analysis and the creation of reports for accountability benefit from this.

4.3.5 Running With Real Time Monitoring

An effective and user-friendly platform for monitoring energy usage parameters in real time is offered by the Blynk app. A PZEM-004T sensor is utilized in this configuration to measure important parameters like voltage, current, power, and energy usage. An ESP32 microcontroller, which is connected to the Blynk platform via Wi-Fi, processes these measurements. The system can send data to the Blynk server via this connection, where it is updated in real time and shown on the user's mobile dashboard.

A number of widgets on the dashboard in the screenshot graphically depict the data that has been gathered. The Energy widget monitors the total consumption in kilowatt-hours, while the Power gauge shows the power use in real time. The current widget indicates the current draw in real time, and the voltage gauge shows the current voltage level. There is also another number displayed, which is probably the power factor or another performance measure. Users may conveniently access and monitor their energy usage from their mobile devices thanks to this user-friendly interface.

Figure 4. 9: Blynk widget monitoring of energy usage on smart phone

A number of widgets on the dashboard in the screenshot graphically depict the data that has been gathered. The Energy widget monitors the total consumption in kilowatt-hours, while the Power gauge shows the power use in real time. The current widget indicates the current draw in real time, and the voltage gauge shows the current voltage level. There is also another number displayed, which is probably the power factor or another performance measure. Users may conveniently access and monitor their energy usage from their mobile devices thanks to this user-friendly interface. A complete Internet of Things-based energy management solution is provided by the combination of the PZEM-004T sensor, ESP32 microcontroller, and Blynk platform. It shows how the Internet of Things may be used to modernize conventional energy systems by improving user control, guaranteeing dependability, and offering useful insights into energy consumption.

The device has an LCD panel to show energy parameters locally in addition to real-time monitoring via the Blynk app. Instantaneous visual feedback on important parameters including voltage, current, power, and energy usage is provided via the LCD. This feature guarantees that customers can get vital energy statistics even in the absence of a mobile device or internet connectivity. To guarantee that the information shown is always correct and current, the ESP32 microcontroller processes the data from the PZEM-004T sensor and updates the LCD panel in real time.

Quick checks benefit greatly from the usage of an LCD panel since users can quickly access the data without having to navigate through an app. For instance, the screen can clearly show power consumption and current voltage, enabling users to keep an eye on important metrics while modifying equipment or controlling energy loads. The Blynk app's remote monitoring features are enhanced by this local display, which offers a reliable and adaptable way to effectively manage energy use in both online and offline situations.

The system uses an SMS API gateway to send automated notifications to users about their energy status. When the energy level falls below a predetermined threshold, reaches zero, or is successfully recharged, the ESP32 microcontroller sends an API request to the SMS gateway, which includes the user's phone number, a predefined message (such as "Low energy alert," "Energy depleted," or "Recharge successful"), and the API authentication token for secure communication. The gateway processes the request and sends the SMS straight to the user's mobile device. This guarantees that users are informed about their energy status in a timely manner, allowing them to take immediate action to recharge and prevent power outages; additionally, the gateway confirms successful recharges.

CHAPTER 5. RESULTS AND DISCUSSION

5.0 Introduction

The project's results are presented in this chapter, with a focus on system performance, cost analysis, and economic considerations. It comprises an assessment of the system's viability, effectiveness, and financial implications. Additionally, system losses are examined to guarantee that the design and implementation are effective.

5..1 Economic aspect

Through lower operating costs and more efficiency for utility providers and users alike, the project seeks to optimize energy management. Better resource allocation and less energy waste are ensured by the system's integration of smart technologies such the ESP32 and PZEM-004T sensor, which provide real-time energy usage monitoring.

Prepaid energy plans give consumers a handy option to control their energy usage and guard against unplanned disconnections. Utility companies gain from better revenue collection through automated procedures and lower expenses related to manual meter readings.

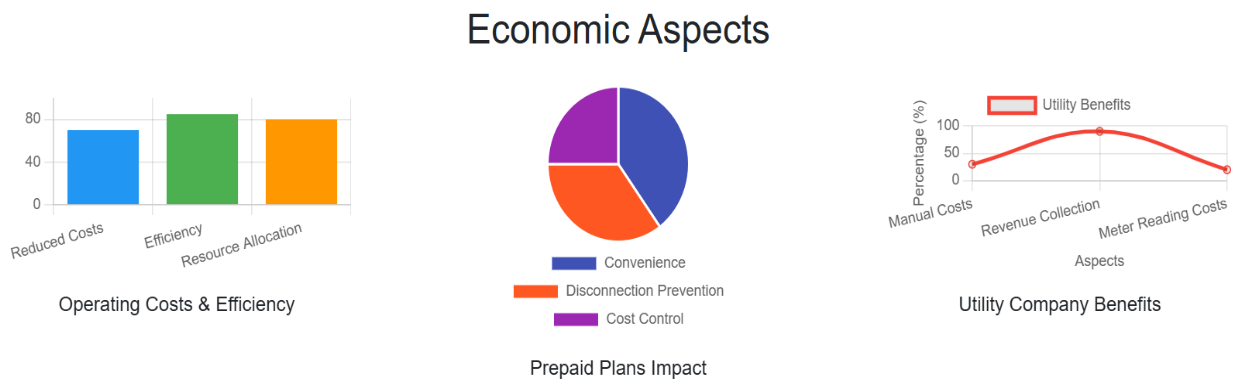


Figure 5. 1: Economic aspect

5.2 Details on economic evaluation

By examining its effects on consumers, utility companies, and Rwanda's economy as a whole, the smart energy meter with automatic recharge system is evaluated economically. Each issue is covered in detail below.

5.2.1 Effect on Users

When compared to the current cash power system, the smart energy meter provides users with significant cost savings. Manual recharges are frequently required by traditional systems, which may result in extra transportation or service costs, particularly for rural individuals who must travel to physical payment facilities.

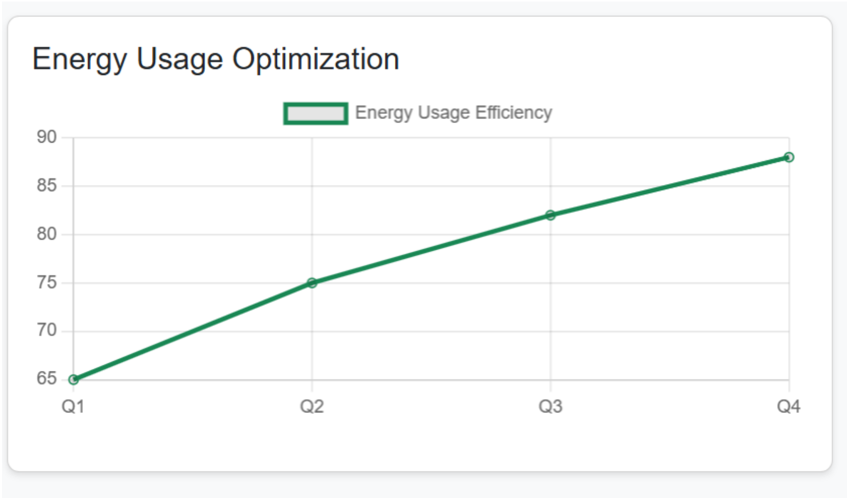


Figure 5. 2: Energy Usage

By removing these costs and guaranteeing continuous service, the automatic recharge feature lowers the possible financial losses associated with power interruptions. Additionally, the LCD's real-time data gives consumers the ability to track and improve their energy use, which could result in cheaper monthly expenses.

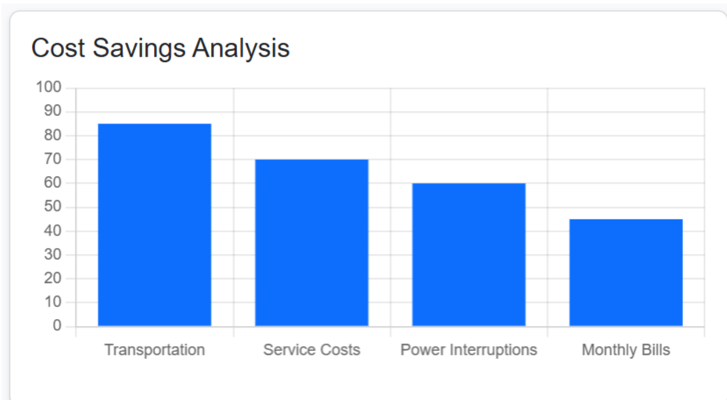


Figure 5. 3: cost Saving for users

5.2.2 Effect on Utility Providers

By eliminating the need for human meter reading and improving billing accuracy, the smart technology lowers operating expenses for utility companies like REG (Rwanda Energy Group). In addition to ensuring timely revenue collection, automated data transmission to a central MySQL database lowers administrative errors that come with manual processes.

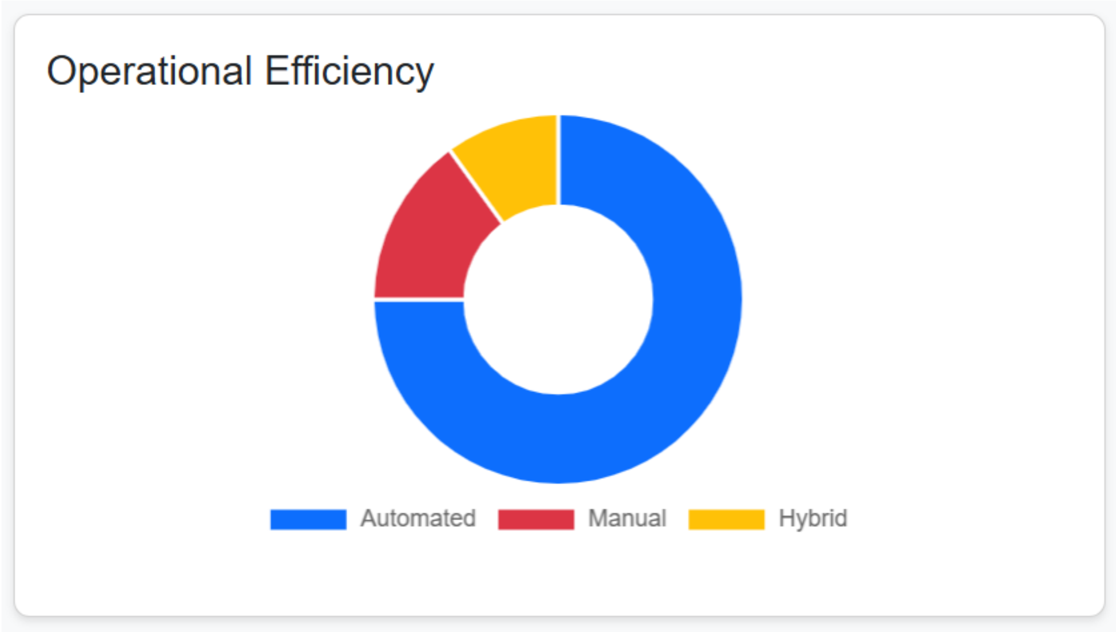


Figure 5. 4: Operation Efficiency

Because it alerts users in advance of low balances, the SMS notification system also reduces customer service expenses by decreasing the number of customer inquiries. Additionally, by promoting prompt payments through prepaid plans, the system can increase the predictability of cash flow for providers.

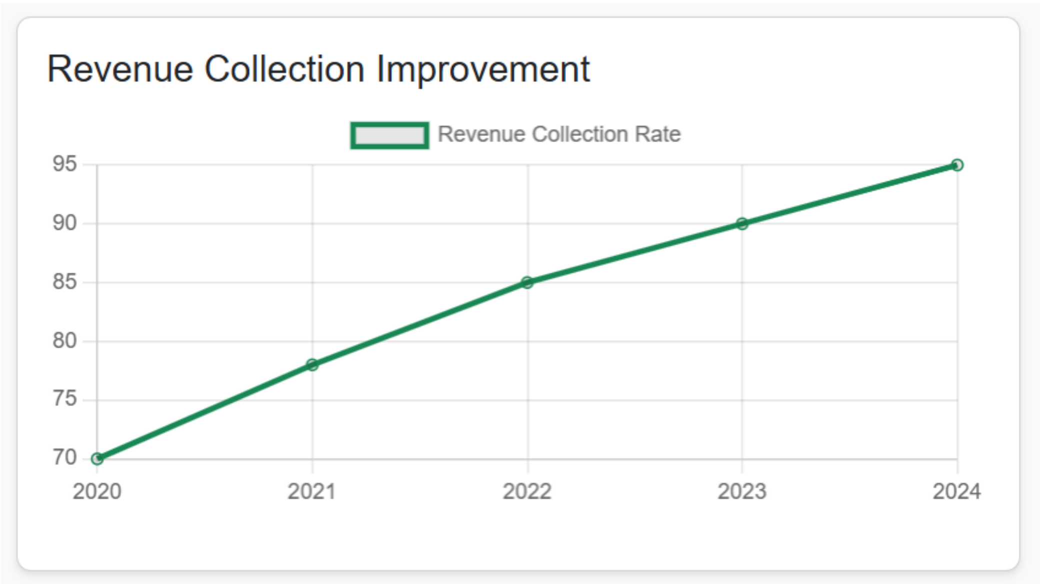


Figure 5.5: Revenue Collection

5.2.3 Effect on the Economy of Rwanda

This innovation supports Rwanda's goal of establishing a digitally connected economy on a national level. It advances the government's overarching objectives of enhancing service delivery and raising electrification rates by modernizing the energy industry.

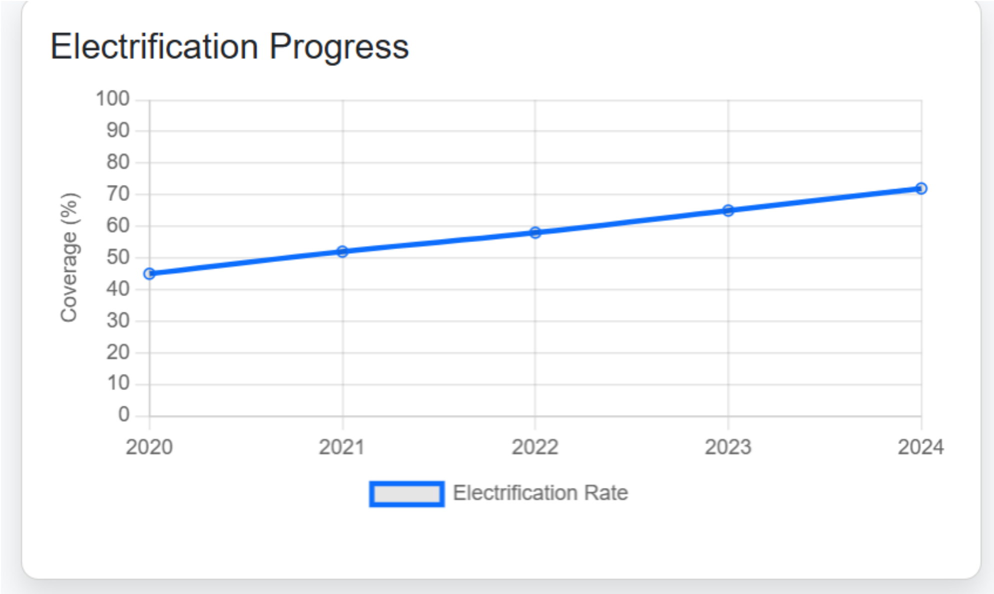


Figure 5.6: electrification progress

By promoting sustainable consumption habits, the system promotes energy efficiency. Furthermore, the nation's economy immediately benefits from the decrease in energy losses brought about by improved monitoring and automated procedures. Through the promotion of local technology innovation, the approach also lessens reliance on pricey imports for conventional prepaid meters.

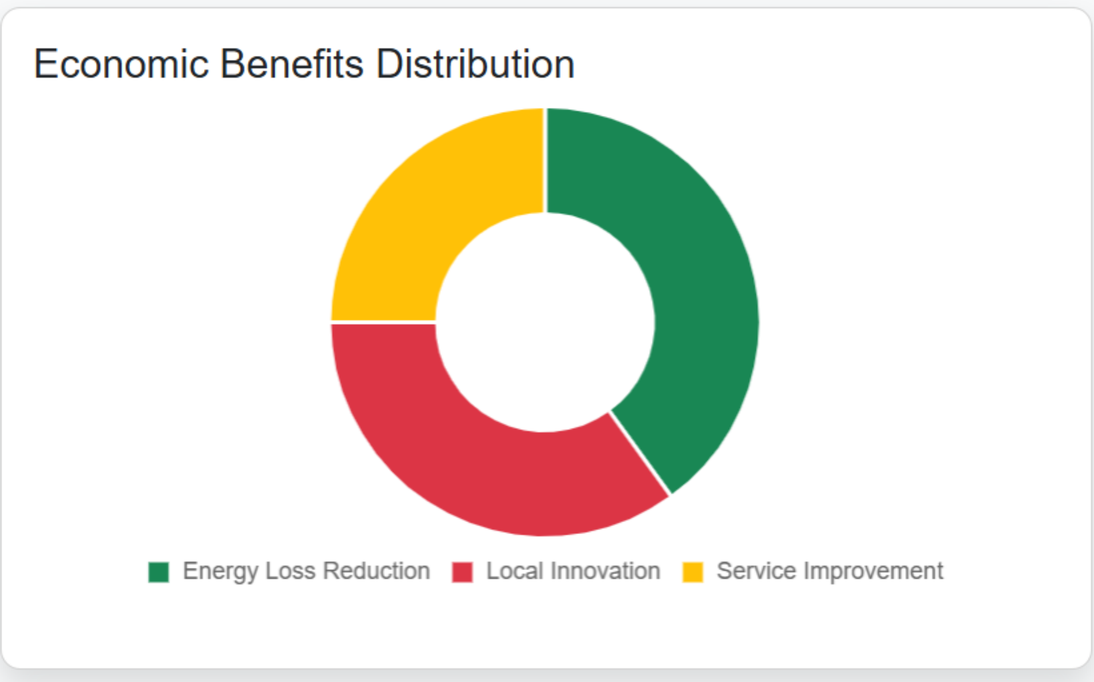


Figure 5. 7: economic benefits distribution

5.3 Cost analysis

The cost analysis focuses on hardware and installation.

Table 2: cost estimation

S/N	Component	Quantity	Unit Price RFW	Total Price RFW
1.	ESP32 Microcontroller	1	15000	15000
2.	PZEM-004T Energy Meter	1	30000	30000
3.	16x2 LCD Screen	1	8000	8000
4.	Relay	1	3000	3000
5.	Miscellaneous jumper wires	1 Set	2000	2000
6.	Power Supply (Adapter)	1	4000	1000
7.	Cables and Connectors	1 meter	500	500
8.	Battery	2	3000	6000
9.	Cover			2500
	Total			75000

5.4 Detailed System Losses

Despite the system's efficient design, several losses could happen when it's in use:

Transmission Losses: Network problems can occasionally cause delays or inaccurate data transmission between the ESP32 and the MySQL database.

Energy Losses: As a result of heat dissipation during operation, components like the relay or LCD display may experience minor energy losses.

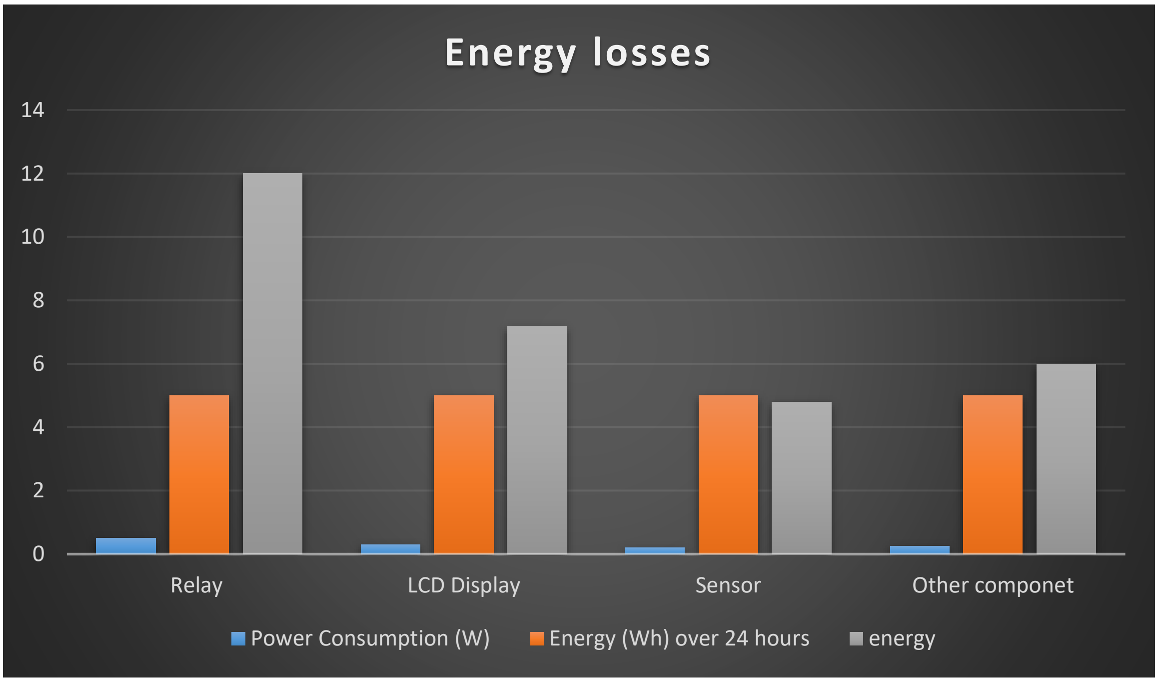


Figure 5. 8: Energy losses graph

User errors can impact overall efficiency by causing users to enter inaccurate recharge amounts or encounter delays in receiving SMS messages.

1. Power Calculation

$P = V \times I$

Where:

- P: Power (in watts, W)
- V: Voltage (in volts, V)
- I: Current (in amperes, A)

Given:

- Voltage (V) = 220V

- Current (I) = 2A

Therefore: P = 220 × 2 = 440 W

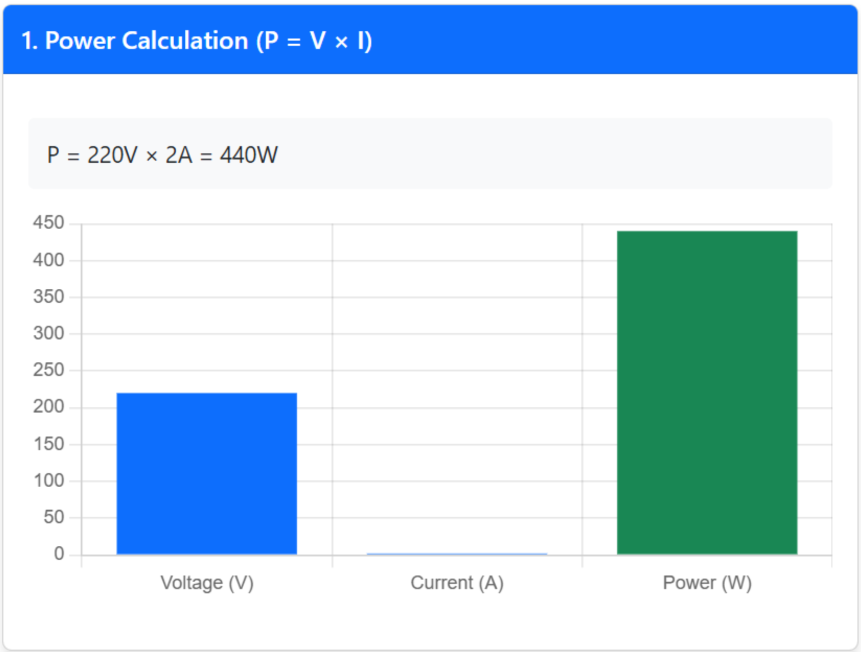


Figure 5.9: power calculations

2. Energy Consumption

E = P × t

Where:

- E: Energy (in watt-hours, Wh)
- P: Power (in watts, W)
- t: Time (in hours, h)

Given:

- Power (P) = 440W
- Time (t) = 3 hours

Therefore: E = 440 × 3 = 1,320 Wh or 1.32 kWh

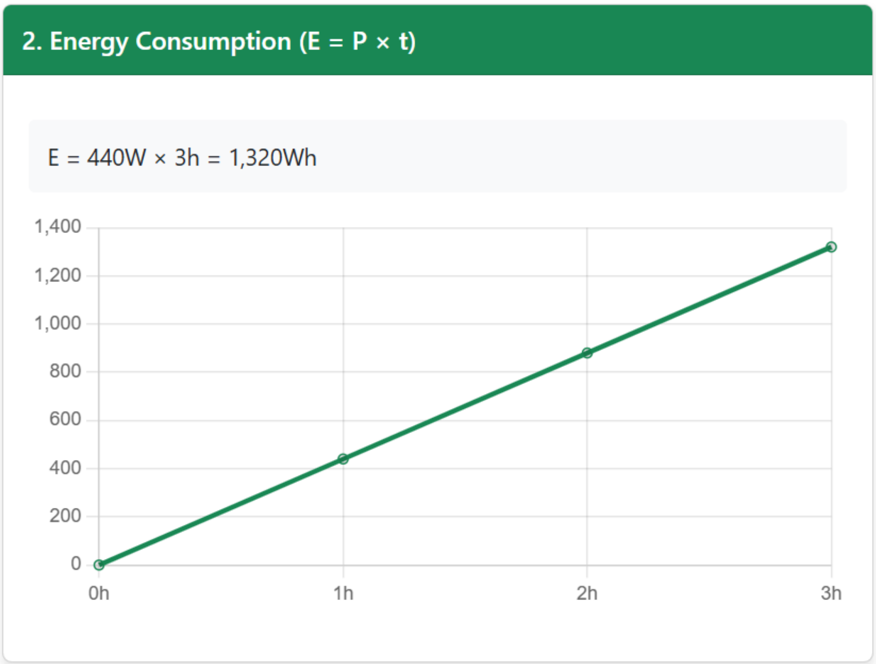


Figure 5.10: Energy consumption

Source: graphs Created independently using CSS, HTML, JavaScript, Bootstrap, and PHP programming languages. Code references (own screenshots)

3. Cost of Energy Consumption

Cost = E × Rate

Where:

- E: Energy (in kWh)
- Rate: Cost per kWh (in RWF or currency unit)

Given:

- Energy (E) = 1.32 kWh
- Rate = 300 RWF per kWh

Therefore: Cost = 1.32 × 300 = 396 RWF

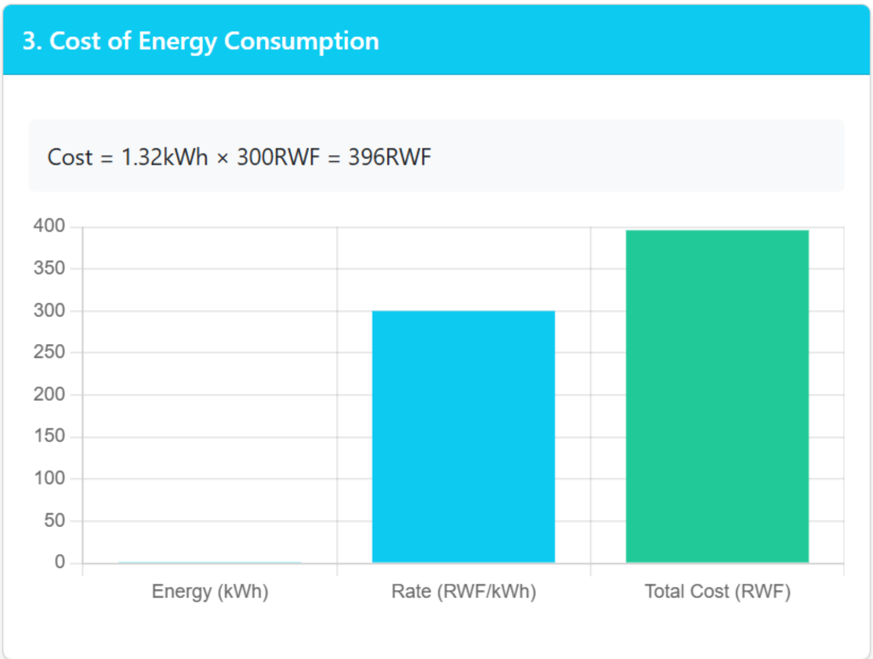


Figure 5. 11: Cost calculation

4. Power Factor (PF)

PF = P / (V × I)

Where:

- P: Real power (in watts, W)
- V × I: Apparent power (in volt-amperes, VA)

Given:

- Power (P) = 440W
- Voltage (V) = 220V
- Current (I) = 2A

Therefore: PF = 440 / (220 × 2) = 440/440 = 1.0

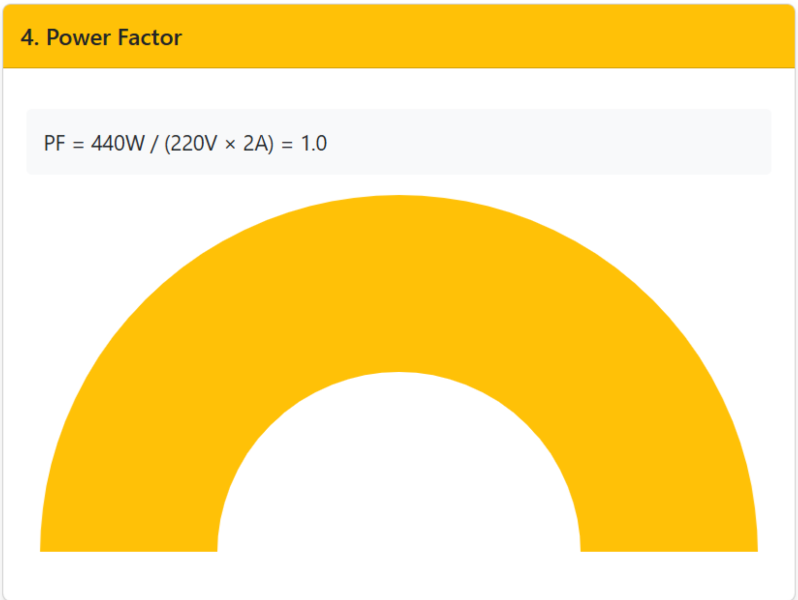


Figure 5.12: power factor

5. Recharge Energy Estimate

Recharge Time = Remaining Balance / Cost per Hour

Where:

- Remaining balance = Amount in RWF
- Cost per hour = Power Consumption (kW) × Rate per kWh

Given:

- Remaining Balance = 2,000 RWF
- Power Consumption = 1.32 kW
- Rate = 300 RWF per kWh

Therefore:

- Cost per Hour = 1.32 × 300 = 396 RWF
- Recharge Time = 2,000/396 ≈ 5.05 hours

6. Energy Efficiency of a Device

Efficiency (%) = (Output Power / Input Power) × 100

Where:

- Output Power = Useful power delivered by the device (in W)
- Input Power = Total power consumed by the device (in W)

Example

Given:

- Output Power = 400W
- Input Power = 500W

Therefore: Efficiency = (400/500) × 100 = 80%

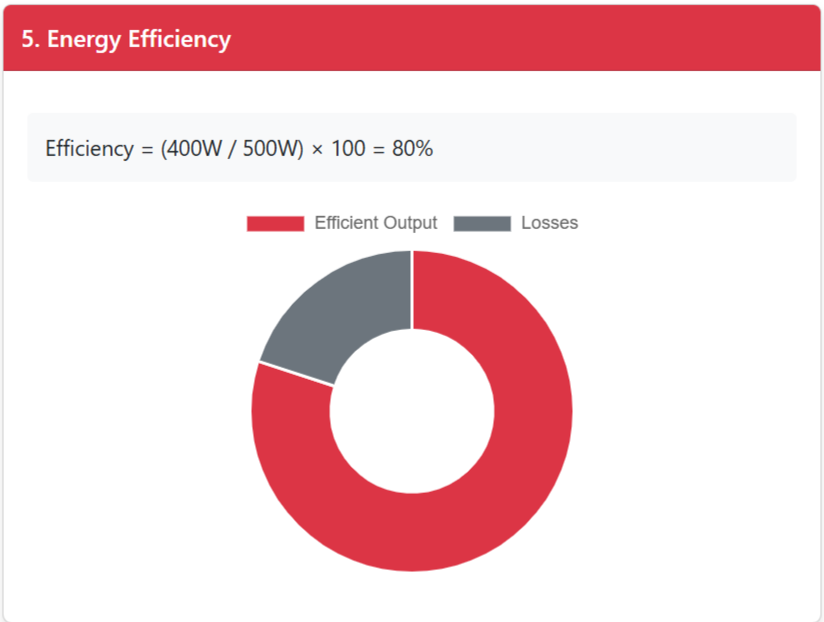


Figure 5.13: Energy Efficiency

7. Energy Losses

Losses = P_{output} - P_{input}

Where:

- P_{input}: Input power (in W)
- P_{output}: Output power (in W)

Given:

- Input Power = 500W
- Output Power = 400W

Therefore: Losses = 500 - 400 = 100 W

8. Battery Recharge Time

Time = Battery Capacity (Ah) / Charging Current (A)

Where:

- Battery Capacity (in ampere-hours, Ah)
- Charging Current (in amperes, A)

Given:

- Battery Capacity = 50Ah
- Charging Current = 5A

Therefore: Time = 50/5 = 10 hours

9. Load Consumption

Load Consumption = Sum of All Devices' Power Consumption

Given:

- Device 1 = 100W
- Device 2 = 200W
- Device 3 = 150W

Therefore: Total Load = 100 + 200 + 150 = 450 W

CHAPTER 6. CONCLUSION AND RECOMMENDATION

6.0 Introduction

The study's findings are presented in this chapter along with suggestions for various stakeholders, such as government agencies, academic institutions, and infrastructure regulators. The purpose of the insights is to help Rwanda adopt and scale smart energy management technologies by providing guidance and information.

6.1 Conclusion

An important step in enhancing Rwanda's energy management is the creation of an energy smart meter system with automated recharge capabilities and real-time monitoring. The solution overcomes significant drawbacks of conventional energy meters, like the inefficiency of manual recharge and the absence of real-time data, by utilizing IoT technology. By integrating a PZEM-004T sensor, ESP32 microcontroller, MySQL database, and SMS notification system, customers may prevent power shortages by having complete visibility into their energy consumption and being able to recharge quickly. These developments encourage a more sustainable approach to energy use by providing customers with ease and improved control.

Additionally, the study illustrates how the system could revolutionize energy management in metropolitan areas. By decreasing energy waste, increasing billing accuracy, and encouraging energy conservation among users, the system supports Rwanda's larger objectives of updating its energy infrastructure. In addition to laying the groundwork for future innovation and deployment in comparable areas around the nation, this research adds to the expanding field of smart energy solutions.

6.2 Recommendation

Key stakeholders should take into account the following suggestions to guarantee the energy smart meter system's effective acceptance and expansion:

Regarding UR-CST, the College of Science and Technology:

Encourage multidisciplinary IoT and energy management research to enhance and expand the system's functionality. To give pupils the tools they need to handle Rwanda's energy problems, integrate smart energy technologies into the curriculum.

Regarding the Rwanda Energy Group (REG):

To assess the scalability and efficacy of the smart energy meter system, pilot it in urban and semi-urban areas. Collaborate with private sector entities to guarantee reasonably priced access to the infrastructure and hardware needed for system deployment.

Regarding the Ministry of Innovation and ICT:

Encourage Rwanda's Smart City projects to incorporate IoT-based energy systems. To promote adoption, support public awareness initiatives that highlight the advantages of smart energy technologies.

Regarding the Infrastructure Ministry:

Make sure rules and regulations are in place to control and facilitate the deployment of smart energy systems Invest in modernizing Rwanda's electrical grid to support data-driven management systems and smart meter technology. Rwanda may make great progress toward realizing its goal of effective and sustainable energy management and advancing the socioeconomic growth of the country by implementing these suggestions.

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APPENDICES

Appendix A: Arduino code

```
#define BLYNK_TEMPLATE_ID "TMPL2XaQ2rujc"
#define BLYNK_TEMPLATE_NAME "POWER CONSUMPTION"
#define BLYNK_AUTH_TOKEN "Q5ljzSsq_tvmXF8J4PdBr_GonNGhBTWE"
#include <ESP8266WiFi.h>
#include <BlynkSimpleEsp8266.h>
#include <SoftwareSerial.h>
#include <PZEM004Tv30.h>
#include <LiquidCrystal_I2C.h>
#include <ESP8266HTTPClient.h>
#include <WiFiClient.h>
#include <WiFiClientSecure.h>
#include <ArduinoJson.h>
// Configuration
const char* smsserver = "https://api.mista.io/sms";
const char* apiToken = "573|q3fyofhnmy7ux39FFrfbseOqufq0nGbQSg2pBxo2";
const char* senderID = "E-Notifier";
const char* ssid = "Xp";
const char* password = "987654321";
const String apiURL = "http://192.168.199.232/energy/save_energy.php";
const String cashpowerNumber = "117342451007";
// Pin Definitions
#define PZEM_RX_PIN D3
#define PZEM_TX_PIN D4
#define LOAD_PIN D6
#define BUZZER_PIN D5
// Thresholds and Timings
const float LOW_ENERGY_THRESHOLD = 0.002;
const unsigned long MEASUREMENT_INTERVAL = 1000;
const unsigned long SERVER_UPDATE_INTERVAL = 3000;
const unsigned long SMS_RETRY_INTERVAL = 3000;
```

```
// Global Variables
LiquidCrystal_I2C lcd(0x27, 16, 2);
SoftwareSerial pzemSWSerial(PZEM_RX_PIN, PZEM_TX_PIN);
PZEM004Tv30 pzem(pzemSWSerial);
bool smsSent = false;
unsigned long lastServerUpdate = 0;
unsigned long lastSMSAttempt = 0;
float lastEnergy = 0;
int smsRetryCount = 0;
const int MAX_SMS_RETRIES = 3;
// New global variables for storing balance and consumed energy
float current_balance = 0;
float current_consumed = 0;
String user_name = "";
String user_phone = "";
struct PowerReadings {
  float voltage;
  float current;
  float power;
  float energy;
  float powerFactor;
  bool isValid;
};
void setup() {
  Serial.begin(115200);
  setupLCD();
  setupPins();
  connectWiFi();
  Blynk.begin(BLYNK_AUTH_TOKEN, ssid, password);
}
void loop() {
  Blynk.run();
  PowerReadings readings = getPowerReadings();
```

```
  if (!readings.isValid) {
    handleSensorError();
    return;
  }
  // Update Blynk with sensor readings
  updateBlynk(readings);
  // Check energy status for alerts
  handleEnergyStatus(readings);
  // Update server and display at regular intervals
  if (millis() - lastServerUpdate >= SERVER_UPDATE_INTERVAL) {
    updateServer(readings);
    lastServerUpdate = millis();
  }
  delay(MEASUREMENT_INTERVAL);
}
void handleSensorError() {
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Sensor Error!");
  lcd.setCursor(0, 1);
  lcd.print("Check Connection");
  delay(2000);
}
void setupLCD() {
  lcd.init();
  lcd.backlight();
  lcd.setCursor(0, 0);
  lcd.print("Energy Meter");
  lcd.setCursor(0, 1);
  lcd.print("Initializing...");
  delay(3000);
  lcd.clear();
}
```

```
void setupPins() {
  pinMode(BUZZER_PIN, OUTPUT);
  pinMode(LOAD_PIN, OUTPUT);
  digitalWrite(LOAD_PIN, HIGH);  // Relay initially ON
  digitalWrite(BUZZER_PIN, LOW); // Ensure buzzer is off
}
void connectWiFi() {
  WiFi.begin(ssid, password);
  lcd.setCursor(0, 0);
  lcd.print("Connecting WiFi");

  int dots = 0;
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    dots = (dots + 1) % 4;
    lcd.setCursor(14, 0);
    lcd.print("    ");
    lcd.setCursor(14, 0);
    for(int i = 0; i < dots; i++) {
      lcd.print(".");
    }
  }
  lcd.clear();
  lcd.print("WiFi Connected");
  lcd.setCursor(0, 1);
  lcd.print(WiFi.localIP());
  delay(2000);
  lcd.clear();
}
PowerReadings getPowerReadings() {
  PowerReadings readings;
  readings.voltage = pzem.voltage();
  readings.current = pzem.current();
```

```
  readings.power = pzem.power();
  readings.energy = pzem.energy();
  readings.powerFactor = pzem.pf();
  readings.isValid = !isnan(readings.voltage) &&
                  !isnan(readings.current) &&
                  !isnan(readings.power) &&
                  !isnan(readings.energy) &&
                  !isnan(readings.powerFactor);

  return readings;
}
void updateBlynk(const PowerReadings& readings) {
  Blynk.virtualWrite(V4, readings.voltage);
  Blynk.virtualWrite(V5, readings.current);
  Blynk.virtualWrite(V6, readings.power);
  Blynk.virtualWrite(V7, readings.energy);
  Blynk.virtualWrite(V3, readings.powerFactor);
}
void updateLCD(const PowerReadings& readings) {
  // This function is no longer used as we'll always show balance and consumed energy
}
void handleEnergyStatus(const PowerReadings& readings) {
    if (current_balance >100) { // Low balance threshold
    handleEnergyRecharge();
   }
  if (current_balance <= 100) { // Low balance threshold
    alertLowEnergy();
   }
  if (current_balance <= 0) {
    handleZeroEnergy();
   }
  lastEnergy = readings.energy;
}
```

```
void alertLowEnergy() {
  // Sound alarm pattern
  for (int i = 0; i < 3; i++) {
    digitalWrite(BUZZER_PIN, HIGH);
    delay(200);
    digitalWrite(BUZZER_PIN, LOW);
    delay(200);
  }
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("LOW ENERGY!");
  lcd.setCursor(0, 1);
  lcd.print("Recharge Soon!");
  delay(3000);

  sendLowEnergyAlert();
}
void handleZeroEnergy() {
  digitalWrite(LOAD_PIN, LOW);  // Cut power
  digitalWrite(BUZZER_PIN, HIGH);
  delay(1000);
  digitalWrite(BUZZER_PIN, LOW);
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("ENERGY DEPLETED!");
  lcd.setCursor(0, 1);
  lcd.print("Power Cut Off");
  sendZeroEnergyAlert();
}
void handleEnergyRecharge() {
  digitalWrite(LOAD_PIN, HIGH);  // Restore power
  smsSent = false;
  smsRetryCount = 0;
```

```
  // Confirmation beep
  digitalWrite(BUZZER_PIN, HIGH);
  delay(100);
  digitalWrite(BUZZER_PIN, LOW);
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Energy Restored");
  lcd.setCursor(0, 1);
  lcd.print("    Power On");
  delay(5000);
}
void sendLowEnergyAlert() {
  if (!smsSent && (millis() - lastSMSAttempt >= SMS_RETRY_INTERVAL)) {
    String message = "Low balance alert for meter " + cashpowerNumber +
                    ". Current balance: " + String(current_balance, 3) +
                    " RWF. User: " + user_name;
    sendDynamicSMS("+25" + user_phone, message);
    lastSMSAttempt = millis();
  }
}
void sendZeroEnergyAlert() {
  if (!smsSent && (millis() - lastSMSAttempt >= SMS_RETRY_INTERVAL)) {
    String message = "Zero balance alert for meter " + cashpowerNumber +
                    ". Power will be cut off. User: " + user_name;
    sendDynamicSMS(user_phone, message);
    lastSMSAttempt = millis();
  }
}
void sendDynamicSMS(const String& userId, const String& alertType) {
  if (smsRetryCount >= MAX_SMS_RETRIES) {
    return;
  }
  WiFiClientSecure client;
```

```
  client.setInsecure();
  HTTPClient https;
    String url = String(smsserver) + "/send";
    if (https.begin(client, url)) {
    https.addHeader("Content-Type", "application/json");
    https.addHeader("Authorization", "Bearer " + String(apiToken));
        StaticJsonDocument<200> doc;
    doc["recipient"] = userId;
    doc["alert_type"] = alertType;
    doc["meter_number"] = cashpowerNumber;
        String payload;
    serializeJson(doc, payload);
        int httpCode = https.POST(payload);
        if (httpCode > 0) {
      String response = https.getString();
      DynamicJsonDocument responseDoc(1024);
      DeserializationError error = deserializeJson(responseDoc, response);
            if (!error && responseDoc["status"] == "success") {
        smsSent = true;
        smsRetryCount = 0;
      } else {
        smsRetryCount++;
      }
    } else {
      smsRetryCount++;
    }
    https.end();
  }
}
void sendDataToServer(float voltage, float current, float power, float energy, float powerFactor)
{
  HTTPClient http;
  http.begin(apiURL + "?cashpower_number=" + cashpowerNumber +
```

```
          "&voltage=" + String(voltage, 2) +
          "&current=" + String(current, 2) +
          "&power=" + String(power, 2) +
          "&energy=" + String(energy, 3) +
          "&power_factor=" + String(powerFactor, 2));
  // Send GET request
  int httpResponseCode = http.GET();
  if (httpResponseCode > 0) {
    String response = http.getString();
    Serial.println("Server response: " + response);
  } else {
    Serial.println("Error sending GET request!");
  }
  http.end();
}
void handleServerResponse(const String& response) {
  DynamicJsonDocument doc(1024);
  DeserializationError error = deserializeJson(doc, response);
  if (!error) {
    if (doc["status"] == "success") {
      current_balance = doc["remaining_balance"].as<float>();
      current_consumed = doc["consumed_energy"].as<float>();
      user_name = doc["user_name"].as<String>();
      user_phone = doc["user_phone"].as<String>();
      // Display updated balance and consumed energy on LCD
      lcd.clear();
      lcd.setCursor(0, 0);
      lcd.print("RFW: ");
      lcd.print(current_balance,3);
      lcd.setCursor(0, 1);
      lcd.print("KWH: ");
      lcd.print(current_consumed,3);
      delay(5000);
```

```
    } else {
      Serial.println("Error in server response: " + response);
    }
  } else {
    Serial.println("JSON Parsing Error: " + String(error.c_str()));
  }
}
void updateServer(const PowerReadings& readings) {
  if (WiFi.status() != WL_CONNECTED) {
    return;
  }
  WiFiClient client;
  HTTPClient http;
  String url = apiURL +
               "?cashpower_number=" + cashpowerNumber +
               "&voltage=" + String(readings.voltage, 2) +
               "&current=" + String(readings.current, 3) +
               "&power=" + String(readings.power, 2) +
               "&energy=" + String(readings.energy, 3) +
               "&power_factor=" + String(readings.powerFactor, 2);
  http.begin(client, url);
  int httpResponseCode = http.GET();
  if (httpResponseCode > 0) {
    String response = http.getString();
    handleServerResponse(response);
    Serial.println("Server response: " + response);
  } else {
    Serial.println("Error sending data to server!");
  }
  http.end();
}
void refreshDisplay() {
  lcd.clear();
```

```
 lcd.setCursor(0, 0);
 lcd.print("Bal:");
 lcd.print(current_balance, 3);
 lcd.print("RWF");
 lcd.setCursor(0, 1);
 lcd.print("Used:");
 lcd.print(current_consumed, 3);
 lcd.print("kWh");
}
```

Appendix A: PHP code

```
<?php
// Database connection
$host = 'localhost';
$user = 'root';
$pass = '';
$db = 'energy';
$conn = new mysqli($host, $user, $pass, $db);
// Check database connection
if ($conn->connect_error) {
    die(json_encode(["status" => "error", "message" => "Connection failed: " . $conn->connect_error]));
}
// Get data from URL parameters
if (isset($_GET['cashpower_number'], $_GET['voltage'], $_GET['current'], $_GET['power'], $_GET['energy'], $_GET['power_factor'])) {
    $cashpower_number = $conn->real_escape_string(trim($_GET['cashpower_number']));
    $voltage = floatval($_GET['voltage']);
    $current = floatval($_GET['current']);
    $power = floatval($_GET['power']);
    $energy = floatval($_GET['energy']);
    $power_factor = floatval($_GET['power_factor']);
    // Fetch the current price per kWh from the `pricing` table
```

```
  $priceQuery = "SELECT price_per_kWh FROM pricing ORDER BY updated_at DESC
LIMIT 1";
  $priceResult = $conn->query($priceQuery);
  if ($priceResult && $priceResult->num_rows > 0) {
    $priceRow = $priceResult->fetch_assoc();
    $price_per_kWh = floatval($priceRow['price_per_kWh']);
  } else {
    $price_per_kWh = 200.00; // Default price
  }
  // Validate cashpower number
  if ($cashpower_number === "117342451007") {
    // Fetch the last energy consumption from `energy_consumed` table
    $lastEnergyQuery = "SELECT energy FROM energy_consumed WHERE
cashpower_number = '$cashpower_number' ORDER BY created_at DESC LIMIT 1";
    $lastEnergyResult = $conn->query($lastEnergyQuery);

    $last_energy = 0; // Default value if no previous record found
    if ($lastEnergyResult && $lastEnergyResult->num_rows > 0) {
      $lastEnergyRow = $lastEnergyResult->fetch_assoc();
      $last_energy = floatval($lastEnergyRow['energy']);
    }
    // Calculate the energy consumed (difference between current energy and last recorded
energy)
    $energy_consumed = $energy - $last_energy;
    if ($energy_consumed >= 0) {
      // Calculate the cost of consumed energy
      $cost_of_consumed_energy = $energy_consumed * $price_per_kWh;
      // Fetch user's current balance
      $balanceQuery = "SELECT paid FROM users_balance WHERE cashpower_number =
'$cashpower_number' ORDER BY created_at DESC LIMIT 1";
      $balanceResult = $conn->query($balanceQuery);
      if ($balanceResult && $balanceResult->num_rows > 0) {
        $balanceRow = $balanceResult->fetch_assoc();
```

```
            $current_balance = floatval($balanceRow['paid']);
            // Deduct the cost of consumed energy from current balance
            $remaining_balance = $current_balance - $cost_of_consumed_energy;
            // Convert remaining balance to kWh
            $remaining_balance_kWh = $remaining_balance / $price_per_kWh;
            // Update the user's balance
            $updateBalanceQuery = "UPDATE users_balance SET paid = '$remaining_balance' WHERE cashpower_number = '$cashpower_number'";
            if ($conn->query($updateBalanceQuery) === TRUE) {
               // Insert data into `energy_consumed` table
               $sql = "INSERT INTO energy_consumed (voltage, current, power, energy, power_factor, cashpower_number, price_at_consumption)
                     VALUES ('$voltage', '$current', '$power', '$energy', '$power_factor', '$cashpower_number', '$price_per_kWh')";

               if ($conn->query($sql) === TRUE) {
                  // Fetch user details
                  $userQuery = "SELECT full_name, phone FROM users WHERE cashpower_number = '$cashpower_number' LIMIT 1";
                  $userResult = $conn->query($userQuery);
                  if ($userResult && $userResult->num_rows > 0) {
                     $userRow = $userResult->fetch_assoc();
                     $full_name = $userRow['full_name'];
                     $phone = $userRow['phone'];
                     // Echo the results to Arduino
                     echo json_encode([
                        "status" => "success",
                        "message" => "Data saved successfully",
                        "remaining_balance" => $current_balance,
                        "consumed_energy"=> $remaining_balance_kWh,
                        "user_name" => $full_name,
                        "user_phone" => $phone
                     ]);
```

```
                } else {
                    echo json_encode(["status" => "error", "message" => "User details not found"]);
                }
            } else {
                echo json_encode(["status" => "error", "message" => "Database error: " . $conn->error]);
            }
        } else {
            echo json_encode(["status" => "error", "message" => "Failed to update balance: " . $conn->error]);
        }
    } else {
        echo json_encode(["status" => "error", "message" => "User balance not found"]);
    }
  } else {
      echo json_encode(["status" => "error", "message" => "Energy consumed cannot be zero or negative"]);
  }
 } else {
     echo json_encode(["status" => "error", "message" => "Invalid cashpower number"]);
 }
} else {
   echo json_encode(["status" => "error", "message" => "Missing or invalid parameters"]);
}
$conn->close();
?>
```