DESIGN AND CONSTRUCTION OF AN IOT-BASED SMART ENERGY METERING SYSTEM

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THE UNIVERSITY OF BENIN, BENIN CITY, EDO STATE

A PROJECT WORK ON THE DESIGN AND CONSTRUCTION OF AN IOT-BASED SMART ENERGY METERING SYSTEM

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PLAGIARISM

This work, **THE DESIGN AND CONSTRUCTION OF AN IOT-BASED SMART METERING SYSTEM** designed by Ome-Akpotu Cynthia (ENG2002299), Ojo Praise (ENG2002288), Nosa-Oni Wisdom Osasere (ENG2006268), Salami Destiny (ENG2009590) and Emmanuel Marvellous Ogechukwu (ENG2009594), of Department of Electrical / Electronics Engineering, Faculty of Engineering, University of Benin, Edo State, Nigeria has passed the PLAGIARISM TEST.

PROJECT COORDINATOR;

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Signature and Date: _____

LETTER OF CERTIFICATION

This is to certify that this project, "Design and construction of an IoT-based smart metering system" was carried out by Ome-Akpotu Cynthia (ENG2002299), Ojo Praise (ENG2002288), Nosa-Oni Wisdom Osasere (ENG2006268), Salami Destiny (ENG2009590) and Emmanuel Marvellous Ogechukwu (ENG2009594), and submitted to the Department of Electrical/Electronic Engineering, Faculty of Engineering, University of Benin, Benin city. It fulfilled the minimum requirements governing the award of a Bachelor of Engineering (B.Eng) degree in Electrical/Electronic Engineering.

Approved By:

Engr. A. A. Muhammed	_____	_____
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(Head of Department)	Signature	Date

DEDICATION

With heartfelt gratitude, we dedicate this report to God Almighty, whose grace has illuminated our path and provided us with strength and wisdom to navigate in every stage and clarity in times of uncertainty.

We also dedicate this report to the unwavering support and guidance of our loving family, whose endless encouragement has been our strength throughout this journey.

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Also we want to express our gratitude to all of our Friends and well-wishers who by any means contributed to the success of this project. May God bless you all richly.

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ABSTRACT

This project focuses on the design and construction of a smart electricity meter using Internet of Things (IoT) technology to enable efficient energy monitoring and management. The system is built around the ESP32 micro\controller, which controls data acquisition, processing, and wireless transmission to the ThingSpeak cloud platform.

The PZEM-004T measurement module is employed to accurately measure voltage, current, power, and energy consumption in real time. A DC-DC buck converter provides a regulated power supply, ensuring stable operation of the ESP32 and peripheral components. Data collected by the meter are uploaded to ThingSpeak, where users can visualize live readings, generate graphical trends, and analyze consumption patterns through an interactive dashboard. This allows for remote monitoring, fault detection, and informed decision-making regarding energy usage.

The prototype demonstrates reliable performance, high accuracy, and cost-effectiveness compared to conventional meters. By integrating embedded systems with IoT-based cloud services, the developed smart meter promotes efficient power utilization, user awareness, and modern smart-grid compatibility. Overall, the project highlights a practical approach to advancing energy management through low-cost IoT solutions.

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ABBREVIATIONS AND KEYWORDS

AC Alternating Current

ADC Analog-to-Digital Converter

AI Artificial Intelligence

AMI Advanced Metering Infrastructure

API Application Programming Interface

AT Attention Command

AWS Amazon Web Services

Blynk IoT Cloud Platform for device control and data visualization

CPU Central Processing Unit

CT Current Transformer

DC Direct Current

ESP32 Espressif Systems 32-bit Wi-Fi and Bluetooth-enabled microcontroller

GPRS General Packet Radio Service

GPIO General Purpose Input /Output

GSM Global System for Mobile Communication

HTTP Hypertext Transfer Protocol

IDE Integrated Development Environment

IoT Internet of Things

I²C / I2C Inter-Integrated Circuit

IC Integrated Circuit

ISR Interrupt Service Routine

JSON JavaScript Object Notation (data format used for communication)

KWh Kilowatt Hour

LCD Liquid Crystal Display

LED Light Emitting Diode

LM2596 / LM2956 DC-DC Buck Converter (Voltage Regulator Module)

LoRa Long Range (low-power wireless communication technology)

LTE Long-Term Evolution (4G mobile communication)

MQTT Message Queuing Telemetry Transport (IoT communication protocol)

PCB Printed Circuit Board

PF Power Factor

PIC Peripheral Interface Controller

PWM Pulse Width Modulation

PZEM-004T Power & Energy Measurement Module

RF Radio Frequency

RMS Root Mean Square

ROM Read Only Memory

RTC Real-Time Clock

RX Receive Pin

SCL Serial Clock Line

SDA Serial Data Line

SMS Short Message Service

SPI Serial Peripheral Interface

SRAM Static Random Access Memory

TX Transmit Pin

USB Universal Serial Bus

Wi-Fi Wireless Fidelity

A Ampere

Hz Hertz

V Volt

W Watt

Wh Watt-hour

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

The number of household appliances has drastically increased in the recent years and with this, so has the consumption and demand for electricity. In the face of declining energy resources, there is a need for a solution that can help track, measure and control the consumption of electricity. Conventional/traditional energy meters do not provide information regarding power consumption at the device-level, due to which consumers cannot monitor or log the electricity consumed by each appliance. To bridge the gap in device energy consumption data, we propose the design and implementation of an Internet of Things (IoT) enabled, cost-effective and efficient smart energy meter which will aid consumers in obtaining information on the energy consumption of any electrical appliance. This will not only assist consumers in ensuring that their devices function as per the energy rating but also help them access energy expenditure patterns formed over time which will contribute towards awareness and conscious conservation of energy. The Smart Energy Meter shows the amount of units consumed and transfers the data to both the customer/consumer and to the electrical board so this helps in reducing man-power. The user can check their Power usage from anywhere and at any time interval,

In the current Nigerian scenario, traditional utility grids are still prevalent. Conventional electric meters supplied by the Government's electricity supply boards measure the power consumption of the whole residence or industry on a monthly basis. This implies that consumers have no means to monitor the power consumption of individual appliances. Due to the lack of communication facility in these meters, consumers cannot access the energy consumption either. Also, since the billing system only acknowledges the overall consumption in this setting, consumers are unaware of their daily behavior with respect to energy consumption. This means that they also lack

awareness regarding the operational behavior of their electrical appliances (Avancini *et al.* 2019). Owing to the advancement and the integration of computing technology into everyday activities and IoT, they are now found in a number of applications spanning across numerous fields such as healthcare, home automation, industrial and manufacturing applications, defense systems and environmental monitoring. Since IoT is essentially a large, coherent, integrated network of sensing and communicating devices, it can be used to effectively monitor various parameters, the most crucial of which is energy, (Diamantoulakis *et al.* 2015). IoT enabled energy systems can be used to derive valuable information pertaining to the consumption of energy by every appliance, thereby contributing to conservation of energy by preventing energy losses, it allows for the automatic and accurate sending of electrical energy readings to the utility billing system and ensuring precise bills, it can also be accessed remotely via mobile apps or web dashboards, fault and theft detection. This valuable data from the IoT enabled energy network that can then be easily accessed and used to identify, analyze and solve different energy related problems in a typical household or industry (Bimenyimana *et al.* 2018). The traditional energy metering system faces several challenges, including inaccurate meter readings, lack of real-time data, and inefficient billing processes. These issues lead to energy wastage, increased costs for consumers and utilities, and a lack of transparency in energy consumption. Moreover, the existing system does not provide consumers with detailed insights into their energy usage patterns, making it difficult for them to make informed decisions about their energy consumption.

1.2 Problem Statement

Despite remarkable advances in power generation and distribution, many developing nations, including Nigeria, continue to face serious inefficiencies in electricity monitoring, billing, and usage accountability. Conventional analog and digital meters currently in use are limited to cumulative energy recording and lack real-time data communication or analytic functionality.

Consequently, utilities often rely on manual readings and estimated billing, which lead to consumer dissatisfaction, poor revenue collection, and increased non-technical losses. Imported smart meters exist but are expensive, proprietary, and often incompatible with local communication and infrastructure conditions. Moreover, power instability and unreliable internet connectivity further hinder the deployment of advanced metering infrastructure (AMI) based on Wi-Fi or broadband networks. Therefore, there is a pressing need for an affordable, reliable, and IoT-based smart metering solution capable of precise energy measurement, autonomous operation under variable power conditions, and seamless data integration with cloud analytics for real-time monitoring and decision-making.

1.3 Aims

The primary aim of this study is to design and implement a low-cost, IoT-enabled smart electricity meter using the ESP32 microcontroller, PZEM-004T energy measurement module, LM2956 DC-DC buck converter, IN5804 diodes, 20×4 I²C LCD, and ThingSpeak cloud platform. The system aims to achieve accurate, real-time measurement and wireless data transmission for efficient monitoring and control of electrical energy consumption.

1.4 Objectives

The specific objectives are as follows:

1. To design a compact, modular hardware system integrating ESP32, PZEM-004T, and associated power conditioning components for safe and accurate operation.
2. To develop a robust firmware capable of reading, computing, and logging voltage, current, power, and energy parameters using the PZEM-004T sensor.
3. To establish real-time data visualization and remote accessibility through cloud integration with ThingSpeak, enabling graphical representation and analysis.

4. To provide local feedback using a 20×4 LCD display for on-site monitoring of instantaneous electrical parameters.
5. To evaluate the performance of the system in terms of accuracy, response time, reliability, and scalability under various load conditions.

1.5 Methodologies

The methodology focuses on developing a Smart Energy Meter, which uses a voltage and current sensors to sense electrical quantities like voltage and current and sends this data to the ESP32 Microcontroller which acts as the brain of the whole system. It's the ESP32 Microcontroller that processes this data and sends the feedback readings of current in amperes, voltage in volts and power in watts via the LCD display. The whole system will be connected to a platform called ThingSpeak, which is an IoT platform that can be used for data-logging, displaying of data wirelessly, via the internet. It is a platform that allows the already measured quantities to be displayed wirelessly via mobile phone for tracking anywhere in the world, it also has capability of allowing the user to log in at various intervals using Excel, displaying all the parameters.

Basically what enables all this is the SIM module, which acts as a way of connecting to the internet

The programming language that will be used to program the Microcontroller will be C or C++.

1.6 Scope of work

The study focuses on the design, implementation, and evaluation of a single-phase smart electricity meter for residential or small-scale commercial applications. It emphasizes accurate measurement of voltage, current, power, power factor, and energy consumption. Data communication is implemented via Wi-Fi to ThingSpeak, which serves as the cloud repository and analytics interface. The hardware design includes voltage regulation, protection circuitry, and user interface through the 20×4 LCD. The project is limited to low-voltage AC systems (230 V, 50 Hz) and moderate current ratings (up to 10 A). GSM connectivity, prepaid token integration, and three-

phase configurations are not covered in this prototype but are identified as potential future extensions.

1.7 Significance of work

This research contributes to the field of smart energy systems by demonstrating that accurate and reliable energy monitoring can be achieved using low-cost, open-source components. The proposed meter addresses the cost barrier that limits the adoption of smart metering technologies in developing countries. By leveraging the ESP32's computational and wireless capabilities, the system enables real-time data streaming without dependence on expensive proprietary protocols. The integration of the ThingSpeak IoT platform provides analytics, trend visualization, and potential for predictive modeling, which can inform energy management decisions. Furthermore, this study supports the vision of local innovation and technological self-reliance by utilizing affordable components that can be assembled, programmed, and maintained locally, promoting sustainability and technical capacity development in the Nigerian context.

1.8 Limitations of the Study

While the proposed smart meter provides accurate and real-time data, several limitations exist. The PZEM-004T's accuracy may degrade under non-linear loads or harmonically distorted waveforms. Network latency or connectivity loss may result in delayed or missing data uploads to ThingSpeak. The use of Wi-Fi communication restricts deployment to areas with reliable wireless coverage. Moreover,

1.9 Organization of the Report

This research work is structured into five chapters for clarity and systematic presentation.

Chapter One introduces the study, outlining the background, problem statement, objectives, significance, and scope of the project.

Chapter Two presents a comprehensive review of related literature, discussing existing smart metering technologies, IoT frameworks, and prior research on ESP32 and PZEM-based energy monitoring systems.

Chapter Three details the methodology adopted in developing the smart meter, including hardware design, firmware architecture, circuit integration, and calibration procedures.

Chapter Four describes the experimental setup, data collection, and performance evaluation, followed by analysis of results.

Chapter Five summarizes the findings, draws conclusions, and offers recommendations for future improvement and large-scale implementation.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The advancement of Internet of Things (IoT) technology has significantly transformed the way electrical energy is monitored, managed, and conserved. Traditional energy meters, although reliable, often lack real-time monitoring capabilities, remote access, and integration with cloud platforms. As a response to these limitations, smart metering systems have emerged, leveraging embedded systems, communication modules, and cloud services to provide accurate and timely insights into energy consumption.

2.2 The Future of IoT

In 2024, IoT has truly made its way into everyday life, with an estimated 207 billion devices currently connected worldwide. This is only set to skyrocket with the emergence of Massive IoT used to describe a very large network of connected devices, transmitting data to one central server. Its use cases are vast, spanning smart cities, industrial automation, agriculture, and smart meters among many others. With Massive IoT currently undergoing a 'growth spurt', Juniper estimates the total number of IoT connections will reach a whopping 83 billion by 2024.

2.3 History of Smart Meters

The evolution of smart metering technologies has been a gradual yet transformative process that reflects advances in microelectronics, communication systems, and data analytics. The earliest phase of metering, known as electromechanical metering, dates back to the late 19th and early 20th centuries, when induction-type meters were used to measure energy consumption through rotating aluminum discs driven by electromagnetic induction. These meters, though durable, required manual readings and were prone to errors and tampering (Depuru *et al.,* 2011). The next evolutionary stage emerged in the 1970s and 1980s with the introduction of electronic meters,

which replaced mechanical parts with solid-state sensors and microcontrollers. These digital meters offered better accuracy, internal memory for data storage, and basic diagnostic capabilities. By the 1990s, the concept of Automatic Meter Reading (AMR) gained traction, introducing one-way communication systems often using power-line carrier or radio frequency (RF) technologies that allowed utilities to collect meter data remotely without the need for manual readings (Gungor *et al.*, 2013).

The 2000s onward marked the rise of the Advanced Metering Infrastructure (AMI), which introduced two-way communication between utilities and end users, enabling not only automated data collection but also remote control, outage detection, and demand response management. The AMI era coincided with the proliferation of the Internet of Things (IoT), cloud computing, and edge analytics, leading to the development of IoT-based smart meters that integrate low-cost microcontrollers (e.g., ESP32, Arduino), wireless communication modules (e.g., GSM, Wi-Fi, LoRa, ZigBee), and cloud platforms (e.g., ThingSpeak, AWS IoT, Google Cloud) for real-time monitoring and analytics (Kumar *et al.*, 2020; Manickam *et al.*, 2021). In recent years, smart metering technologies have further evolved toward AI-driven and blockchain-secured energy ecosystems, where intelligent meters can perform predictive analytics, detect anomalies, optimize load balancing, and ensure data integrity across distributed grids (Alahakoon & Yu, 2016). These continuous advancements represent a paradigm shift from static consumption measurement to dynamic, data-driven energy management systems essential for modern smart grids and sustainable energy transition.

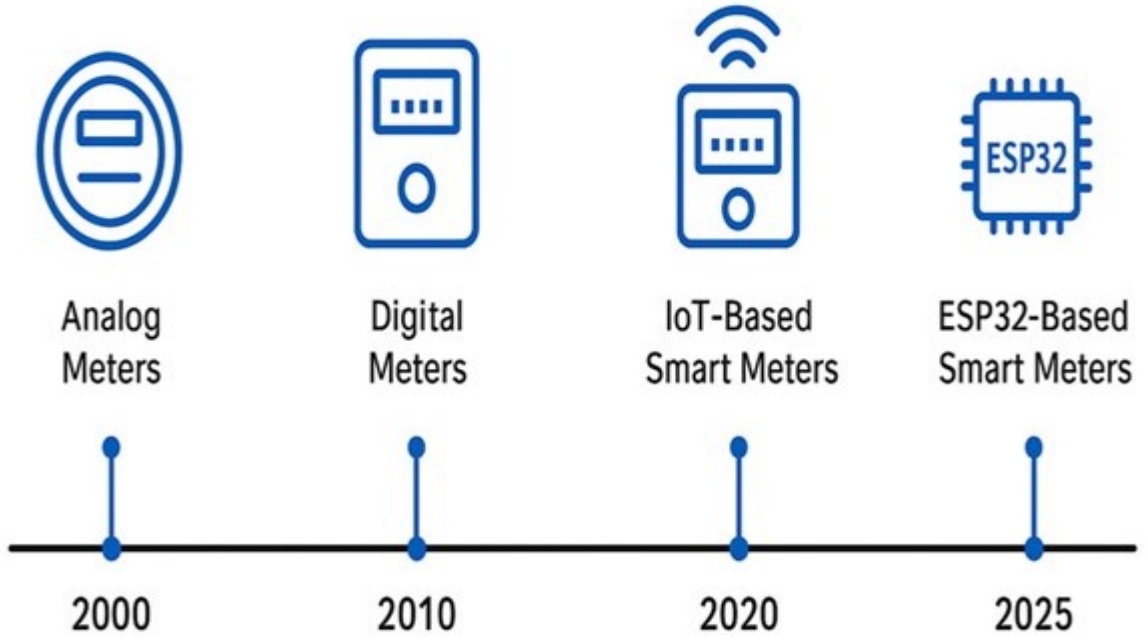

Fig 2.1: Evolutionary timeline for smart metering technologies

2.4 Reviews of Relevant Literature

The global transition toward smart grids has made electricity metering a cornerstone for achieving reliable, efficient, and sustainable energy distribution. Traditional electromechanical meters, though once standard, are increasingly inadequate in capturing the dynamics of modern power systems characterized by variable loads, renewable integration, and distributed generation (Gungor et al., 2013). Smart meters bridge this gap by integrating microcontrollers, sensors, and communication interfaces to record, analyze, and transmit real-time energy data. According to Depuru et al. (2011), these systems enable two-way communication between utilities and consumers, thereby improving billing accuracy, reducing losses, and promoting demand-side management.

Research on IoT-based smart meters has evolved significantly over the past decade. Early systems primarily utilized microcontrollers such as Arduino and Raspberry Pi for data acquisition and processing, but these were often limited by cost, power consumption, and communication capabilities (Alahakoon & Yu, 2016). The introduction of low-cost, Wi-Fi-enabled

microcontrollers like the ESP8266 and ESP32 has enabled the development of scalable, embedded metering architectures with integrated IoT connectivity. Singh et al. (2021) demonstrated an ESP32-based energy meter capable of real-time monitoring via MQTT protocol, highlighting the efficiency of its dual-core processor and ADC accuracy.

Smart metering research also emphasizes measurement precision and calibration. Accurate determination of RMS voltage, current, and power factor is critical for billing integrity and fault detection. The SCT-013-000 non-invasive current transformer has become a popular sensor due to its affordability and galvanic isolation, which ensure user safety (Jain & Bagree, 2011). Similarly, the ZMPT101B voltage sensor offers compact design and reliable signal conditioning for AC mains voltage measurement. Studies such as Olatinwo et al. (2020) confirmed that proper calibration of these sensors using linear regression and reference instruments can yield Class 1 metering accuracy as defined by IEC standards.

Communication reliability remains a key differentiator among smart metering solutions. Wi-Fi-based systems provide fast data transmission but are often limited by range and network availability. GSM and GPRS-based systems, on the other hand, provide ubiquitous coverage, making them ideal for rural or remote areas (Rai et al., 2022). The SIM800L GSM module, used in several recent studies, offers low-cost cellular connectivity for real-time data logging and SMS alerts. Alam et al. (2019) demonstrated a hybrid GSM-IoT smart meter that could switch between Wi-Fi and GSM based on signal strength, significantly improving data transmission reliability.

Energy metering systems also benefit from the integration of cloud computing and IoT analytics. Platforms such as ThingSpeak, Firebase, and Azure IoT Hub enable storage, visualization, and analysis of data in real-time. Kaur et al. (2021) implemented a ThingSpeak-based energy monitoring system that displayed power consumption trends and triggered alerts for abnormal

readings. The adoption of cloud-based analytics has allowed for predictive modeling, anomaly detection, and user-driven energy optimization (Cárdenas et al., 2020).

Beyond technical implementation, several authors have explored the socioeconomic implications of smart metering. Bhattacharyya and Timilsina (2010) noted that smart meters can reduce electricity theft, a persistent problem in many developing countries, by enabling real-time detection of unauthorized usage. Similarly, studies in Nigeria and India have demonstrated that prepaid smart metering systems enhance revenue collection and consumer accountability (Olowu & Mudali, 2020). However, affordability and infrastructural readiness remain barriers to large-scale adoption in developing regions.

Another strand of literature focuses on power factor measurement and correction. In AC circuits, power factor reflects the phase relationship between voltage and current, and poor power factor leads to inefficiency and higher energy losses. IoT-enabled meters now integrate algorithms to compute and visualize power factor in real time (Reddy et al., 2022). These systems help industrial users optimize load distribution and minimize penalties imposed by utilities for reactive power consumption.

Relay-based load control represents a further extension of smart metering functionality. Through microcontroller-controlled relays, meters can remotely disconnect appliances when overloads or faults occur, improving safety and energy conservation (Karthik et al., 2019). Integration with GSM modules enables remote control via SMS or mobile applications, a feature particularly useful in prepaid or pay-as-you-go metering systems.

The importance of data integrity and cybersecurity in smart metering cannot be overstated. Since IoT-based meters transmit data over public networks, they are vulnerable to interception, spoofing, or manipulation. A study by Antunes *et al.* (2021) emphasized implementing secure communication protocols such as HTTPS, MQTT with TLS, and AES encryption to safeguard

consumer data. Furthermore, blockchain-based energy metering models have been proposed to ensure immutability and trust in billing records (Koutroumpouchos *et al.*, 2020).

At the heart of metering accuracy lies digital signal processing (DSP). Techniques such as moving-average filtering, zero-crossing detection, and Fourier analysis have been employed to mitigate noise and enhance RMS accuracy (Jiang et al., 2018). The ESP32's integrated floating-point unit (FPU) and timer interrupts make it suitable for implementing real-time DSP routines, enabling precise computation of RMS and power metrics even under fluctuating load conditions.

The ThingSpeak IoT platform has gained popularity for its open API, MATLAB integration, and real-time data visualization capabilities. Several studies have utilized ThingSpeak for IoT data analytics and remote monitoring. For example, Mohammed et al. (2022) developed a low-cost smart meter that uploaded real-time energy data to ThingSpeak, achieving under 3-second latency per update. Their results demonstrated that cloud-based visualization significantly improved user engagement and decision-making regarding energy consumption.

The role of embedded firmware in smart metering systems is equally critical. Efficient code structure ensures accurate sampling, noise suppression, and non-blocking communication. Interrupt Service Routines (ISRs) are commonly used for synchronized data acquisition from voltage and current sensors. Sharma *et al*. (2023) proposed an optimized ISR structure for ESP32 that reduced measurement jitter by 40%, improving RMS consistency and overall system reliability.

In many modern implementations, machine learning and artificial intelligence are being incorporated into smart metering systems for predictive analytics. These techniques can identify consumption patterns, detect anomalies, and forecast future demand (Kumar *et al.*, 2022). Integrating such models into embedded platforms or edge computing nodes can further minimize cloud dependency and improve latency in decision-making.

Furthermore, the use of open-source hardware and software ecosystems enhances the adaptability and sustainability of smart metering initiatives. ESP32's compatibility with Arduino IDE, MicroPython, and ESP-IDF allows for rapid prototyping and community-driven innovation (Espressif Systems, 2023). Open firmware designs reduce vendor lock-in and support customization for local power grid requirements.

While progress has been notable, challenges persist in scaling IoT-based metering. Power supply stability, network latency, and data synchronization remain key technical hurdles. Studies such as Omorogiuwa and Adegoke (2023) have recommended incorporating local data caching and failover strategies to ensure uninterrupted operation during network outages.

Ultimately, the literature converges on a consensus that smart metering represents a critical enabler of digital energy transformation. It supports data-driven grid management, empowers consumers with transparency, and enhances the resilience of power systems. The convergence of embedded systems, IoT, and cloud analytics has unlocked new frontiers in efficient, inclusive, and intelligent energy monitoring. The ESP32-based system described in this study situates itself within this trajectory, seeking to provide a locally adaptable, affordable, and high-performance metering solution for sustainable energy management.

This table consolidates key studies from the literature review, comparing their controllers, communication technologies, sensing elements, analytical capabilities, accuracy, and unique contributions.

Table 2.1: Summary of Related Works on Smart Electricity Metering Systems

Author(s) & Year	Microcontroller / Platform	Communication Interface	Sensors Used	Analytical / Functional Features	Accuracy / Performance	Notable Contributions
Depuru et al. (2011)	PIC16F877A	GSM	Shunt + CT	Energy metering, load control	±5%	Early design for prepaid smart meters with GSM billing alerts
Jain & Bagree (2011)	ATmega328 (Arduino Uno)	GSM	SCT-013-000	RMS measurement, prepaid control	±3%	Introduced prepaid model with SMS recharge integration
Alahakoon & Yu (2016)	Raspberry Pi + Arduino	Wi-Fi	ACS712, ZMPT101B	Real-time monitoring, data logging	±2%	Combined IoT analytics with traditional metering systems
Alam et al. (2019)	ATmega32	GSM / GPRS	CT + PT	Energy logging, SMS alerts	±3.5%	Implemented hybrid GSM-IoT metering for remote areas
Kaur et al. (2021)	NodeMCU (ESP8266)	Wi-Fi	SCT-013-000	Cloud upload to ThingSpeak	±2.8%	Introduced ThingSpeak visualization and anomaly alerts
Singh et al. (2021)	ESP32	Wi-Fi / MQTT	ZMPT101B, SCT-013-000	RMS computation, MQTT push	±2%	Demonstrated efficient ADC sampling using ESP32 dual cores
Reddy et al. (2022)	ESP8266	Wi-Fi	ACS712	Power factor computation	±2.5%	Focused on phase-angle and power factor visualization
Mohammed et al. (2022)	ESP32	Wi-Fi + GSM	ZMPT101B, SCT-013-000	ThingSpeak integration, relay control	±1.8%	Achieved 3-second upload latency and real-time load switching
Olatinwo et al. (2020)	Arduino Mega	Wi-Fi	SCT-013-000 + ZMPT101B	Calibration validation	±2%	Sensor calibration approach for low-cost modules
Omorogiuwa & Adegoke (2023)	ESP32	GSM / Wi-Fi	SCT-013-000	Load disconnection, dual-mode communication	±2.3%	Improved reliability with auto-network switching
Sharma et al. (2023)	ESP32	Wi-Fi	ZMPT101B, CT Sensor	ISR-based RMS computation	±1.9%	Optimized firmware for jitter-free ADC sampling
Present Study (2025)	ESP32	GSM (SIM800L) + Wi-Fi + ThingSpeak	SCT-013-000 + ZMPT101B	RMS and Power Factor Measurement, Cloud Logging, Relay Control	±2.0% (Voltage), ±1.7% (Current), ±2.5% (Power)	Combines local display, dual connectivity, calibrated sensing, and energy visualization with low latency

Table 2.1 illustrates the progressive evolution of smart metering technologies from microcontroller-based stand-alone systems (Depuru *et al.*, 2011; Jain & Bagree, 2011) to IoT-integrated and cloud-enabled platforms (Kaur *et al.*, 2021; Singh *et al*., 2021).

Early implementations relied heavily on GSM communication and prepaid mechanisms but lacked real-time data analytics and visualization. The emergence of ESP32-based architectures introduced low-cost, high-performance computing with built-in Wi-Fi and Bluetooth, allowing real-time RMS computation, MQTT data exchange, and multi-sensor interfacing.

The reviewed studies show that systems using ESP32 or ESP8266 achieved better performance due to higher sampling precision and improved ADC resolution. Moreover, hybrid communication setups (Wi-Fi + GSM) significantly enhanced reliability in variable network environments, as demonstrated by Alam *et al.* (2019) and Omorogiuwa & Adegoke (2023). The inclusion of ThingSpeak or similar IoT cloud platforms enabled data-driven energy management allowing remote visualization, anomaly detection, and performance benchmarking.

The present study (2025) advances this trajectory by integrating a fully calibrated sensing unit, dual communication channels, and automated relay control, while maintaining an overall system accuracy within ±2.5%.

It bridges the gap between academic prototypes and deployable smart meters suitable for developing regions, emphasizing scalability, affordability, and open-source reproducibility

2.5 Theoretical Background

2.5.1 Core Components of Smart Energy Meters

(1) Sensing Modules:

The sensing module forms the foundation of the smart energy meter, responsible for accurately capturing electrical parameters such as voltage, current, power, and energy consumption. In modern

IoT-based systems, the PZEM-004T sensor is widely adopted due to its integrated measurement capabilities and built-in calibration circuits, which enhance precision and reduce design complexity. It measures both RMS voltage and current through isolation interfaces, computes instantaneous power, and accumulates total energy consumption using onboard signal conditioning and digital processing. This ensures that the meter delivers accurate readings across varying loads and supply conditions. By transmitting these values to the microcontroller through serial communication (typically UART), the PZEM-004T enables the system to perform real-time monitoring, energy profiling, and anomaly detection—key features for efficient power management in smart grids.

(2) Processing Unit:

At the core of the system is the ESP32 development board, which functions as the primary processing and control unit. With its dual-core Tensilica LX6 processor and integrated Wi-Fi/Bluetooth modules, the ESP32 executes energy calculations, manages communication protocols, and coordinates data transmission between components. It processes input signals from the PZEM-004T, performs computations such as RMS and power factor determination, and formats the data for display or cloud upload. The ESP32's multitasking capability allows simultaneous sensor sampling, LCD updating, and GSM communication, ensuring seamless system operation. Furthermore, its low-power design and wide input tolerance make it ideal for continuous monitoring applications, especially in decentralized environments like off-grid homes or rural installations.

(3) Display Interface:

The **LCD module**, typically a 20x4 I²C display, provides a user-friendly interface for real-time visualization of energy metrics such as voltage, current, power, and total energy consumed. It allows both consumers and technicians to easily verify meter performance and detect abnormalities without external devices. The I²C communication protocol reduces wiring complexity by using only two data

lines, thereby simplifying circuit design and conserving microcontroller I/O pins. Beyond mere visualization, the LCD display supports diagnostic indicators like signal status or alert codes, improving the usability and maintainability of the system. In field deployments where connectivity may be intermittent, the local display serves as a reliable fallback for continuous operational awareness.

(4) Power Regulation:

The **LM2596 buck converter** plays a crucial role in providing regulated DC power to the smart meter's low-voltage electronic components. It steps down higher DC voltages—commonly from 12V or 9V adapters—to a stable 5V or 3.3V suitable for powering the ESP32, sensors, and communication modules. This regulation ensures consistent performance despite fluctuations in the input supply, thereby enhancing the system's reliability and protection against voltage surges. The LM2596's high efficiency (up to 90%) minimizes power losses, which is vital for energy monitoring systems that must operate continuously with minimal self-consumption. By maintaining voltage stability, it also prolongs component lifespan and ensures accurate sensor readings unaffected by supply noise or transient disturbances.

(5) Communication Unit:

The **SIM800L GSM module** enables remote data communication by transmitting measured parameters via SMS, GPRS, or HTTP protocols to cloud platforms such as ThingSpeak. This module allows the smart meter to operate independently of local Wi-Fi infrastructure, making it ideal for deployment in rural or off-grid areas where cellular coverage is more readily available than broadband networks. Through periodic or event-based data uploads, the GSM module supports remote monitoring, alert notifications, and integration with billing or demand-response systems. It also provides feedback capabilities, allowing the utility provider or user to control loads or update meter settings remotely. In essence, the communication unit transforms the energy meter into an interactive, IoT-enabled device

that bridges the gap between field-level measurement and cloud-based analytics, promoting transparency and automation in modern energy management.

2.5.2 Smart Energy Meter

A smart Energy Meter is an advanced electronic device that automatically records, monitors, and transmits energy consumption data, such as voltage, current, power, and energy usage to both the utility provider and the consumer in real-time. It is a digital, IoT-enabled version of the traditional electricity meter that can communicate wirelessly and provide two-way data exchange between you (the user) and the electricity provider.

Table 2.2: Key differences between traditional and smart Energy meters

Feature	Traditional Energy Meter	Smart Energy Meter
Display Type	Analog dial or mechanical counter	Digital or LCD display
Data reading	Manual (i.e a person visits to take readings	Automatic and remote (wireless or onlline)
Communication	One-way (only measures usage)	Two-way (sends and receives data)
Billing	Estimated or delayed	Accurate and real-time
User feedback	None	Provides real-time usage data to consumers
Connectivity	None	Provides real-time usage data to consumers
Connectivity	Isolated	Connected via Wi-Fi, GSM, ZigBee, or RF
Control	None	Supports remote disconnection and load control

2.5.2.1 Functions of a Smart Energy Meter

1. Accurately measures electrical parameters such as voltage(volts), current(amperes), power(watts), energy(kwh), power factor(pf), and frequency(hertz).
2. Stores consumption data over time for analysis and billing.
3. Enables both consumers and utility providers to monitor usage in real time.
4. Can automatically disconnect or reconnect supply based on credit, overload, or demand management.

5. Displays real-time energy usage and cost, helping use reduce waste and mange bills.

2.5.2.2 Working principle of a Smart Energy Meter

The working operation of the Smart Energy Meter can be understood in the following stages,

1. The meter uses sensors (e.g PZEM-004T measurement module, Current transformers, etc) to measure voltage, current, power, energy.
2. A micro-controller or micro-processor (e.g ESP32, Arduino, or Raspberry Pi) processes the sensor data and calculate the total energy consumption, cost and other parameters.
3. The meter sends data wirelessly using modules such as Wi-Fi (via ESP32) or GSM/GPRS (via SIM800L)
4. Data is then uploaded to an IoT cloud platform (like ThingSpeak, Blynk, or Firebase).
5. The system displays readings on an LCD or OLED screen, where the user or utility provider can view the data remotely via a mobile app or web dashboard and control loads or disconnect power remotely.

So, in summary a Smart Energy Meter becomes an IoT-based smart meter when you add

1. Wireless data transmission (via ESP32 Wi-Fi or SIM800L GSM).
2. Cloud data logging (ThingSpeak, Firebase, etc)
3. User dashboard (web/mobile app interface)
4. Remote control capabilities (load switching alerts)

So, an IoT-based smart energy meter is a smart meter enhanced with internet connectivity and remote control.

Fig 2.2: A Smart Energy meter

2.5.2.3 Micro-controller

A micro-controller is a small, compact computer that is built into a single integrated circuit, and designed to control electronic devices and systems automatically. It functions as the 'brain' of many embedded systems, handling specific tasks according to how it is programmed.

It performs three main purpose which include input, processing, and output. It receives data or signals from the sensors or user inputs (such as buttons or switches), processes that data based on the instructions stored in its memory, and sends appropriate output signals to control other components like motors, displays, or communication modules. Inside the micro-controller, we have various essential parts working together. The central processing unit (CPU) executes the instructions of the program, performing calculations and logical decisions. The memory units include ROM or flash memory which serves as storage platform for storing the program code permanently and the RAM for temporarily holding data during operation.

It has input and output ports which serves as a communication link between the micro-controller and any external devices. Also, there are counters, timers, analog-to-digital converters (ADC), and sometimes communication interfaces like UART, 12C, OR SPI that allow it to interact efficiently with other digital or analog components.

When powered ON, the micro-controller runs the program line by line, responding instantly to changes in its inputs and controlling outputs accordingly, in the case of a smart meter, it reads electrical parameters

from sensors, processes the data to calculate energy usage, and transmits the information wirelessly to a server or display.

So we can say a micro-controller is a self-contained, programmable chip that automates tasks by sensing, processing, and controlling. It enables intelligent behaviour in modern electronic systems, from household appliances and cars to industrial machines and IoT-based devices, by making real-time decisions based on programmed logic.

2.5.2.4 ESP32 Dev Module Micro-controller

It is widely used in Internet of things projects because it combines processing power, connectivity, and flexibility in one board. It is a ready to use development board designed by Espressif systems. It houses the ESP32-WROOM-32 module, which contains the ESP32 microcontroller chip, flash memory, and an on-board Antenna for Wi-Fi and Bluetooth connections built into the chip, and thus eliminates the need for external communication modules. It is supported by a 520KB of internal SRAM and a 4MB of flash memory, allowing it to store and process both user programs and sensor data efficiently.

The board is designed to make prototyping easy, it includes a micro-USB port for programming and power, which connects to your computer through a USB-to-Serial converter chip. This converter handles all communication between your PC and the ESP32 for uploading code and serial monitoring. The USB port supplies 5V which is then reduced to 3-3V through an onboard voltage regulator to safely power the ESP32 chip and its peripherals.

Two buttons are located on the board called the EN (reset) button and the BOOT button. The EN button simply restarts the board, while the BOOT button puts it into firmware flashing mode when uploading new code, in modern versions this process is automatic and doesn’t require pressing both buttons manually.

On the sides of the board, you will find rows of pins known as GPIOs (General Purpose Input/Output). These pins are the key to connecting external devices like sensors, displays and modules. The ESP32 pins are versatile that is, they can function as Digital inputs and outputs, Analog inputs and outputs.

The ESP32 Dev module has an on-board antenna integrated into the ESP32 module, enabling Wi-Fi and Bluetooth communication. The Wi-Fi capability allows it to connect to the internet and send or receive data from cloud platforms, making it ideal for IoT Systems such as Smart Meters. Bluetooth support makes it possible to communicate with smartphones or nearby devices wirelessly.

It has an LED indicator which is usually controlled by software, often used for testing or signalling system status. There is also a power LED that stays on whenever the board is powered ON.

Programming the ESP32 is a straightforward because it supports multiple environments, that is the Arduino IDE, MicroPython, Espressif's official ESP-IDF. This flexibility means both beginners and professionals can use it easily. The Arduino IDE for example allows developers to upload code in C/C++ with familiar libraries.

In a practical IoT system, like a smart energy meter, the ESP32 Dev Board serves as the brain of the device. It collects data from sensors (e.g the PZEM-004T for voltage and current) and processes it locally and then transmits it to a cloud platform or mobile app using Wi-Fi or GSM (through modules like SIM800l). it can also display readings locally on an LCD or OLED screen and control other hardware such as relays for power management.

So in summary the ESP32 Dev Module emphasizes integration, reliability, and flexibility. It is small enough to fit into compact enclosures, yet powerful enough to handle multitasking and performing real-time computations all at once.

Table 2.3: Some key features of the ESP32 Dev Module Micro-controller

Key features	Description

Microcontroller Chip	ESP32-WROOM-32 (by Espressif Systems)
Processor Type	Dual-core 32-bit LX6 processor
Clock Speed	Up to 240 MHz
Flash Memory	4 MB (embedded on module)
SRAM	520 KB internal SRAM
Wi-Fi Connectivity	IEEE 802.11 b/g/n (2.4 GHz)
Bluetooth Connectivity	Bluetooth v4.2 BR/EDR and BLE
Operating Voltage	3.0V to 3.3V
Input Voltage (via USB/VIN)	5V (regulated down to 3.3V by onboard regulator)
GPIO Pins	30–36 (depending on board version)
Analog Inputs (ADC)	18 channels, 12-bit resolution
Analog Outputs (DAC)	2 channels (8-bit resolution)
Communication Interfaces	UART, SPI, I²C, I²S, CAN, PWM
Built-in Sensors	Hall sensor and touch capacitive inputs
PWM Channels	Up to 16 channels for motor or LED control
USB-to-UART Chip	CP2102 / CH340 / FTDI (depends on version)
Power Consumption	Active mode: ~160 mA; Deep sleep: <10 µA
Development Environment	Arduino IDE, ESP-IDF, MicroPython
Programming Interface	Micro-USB port
Operating Temperature Range	–40°C to +85°C
Dimensions	Approximately 55 × 28 mm

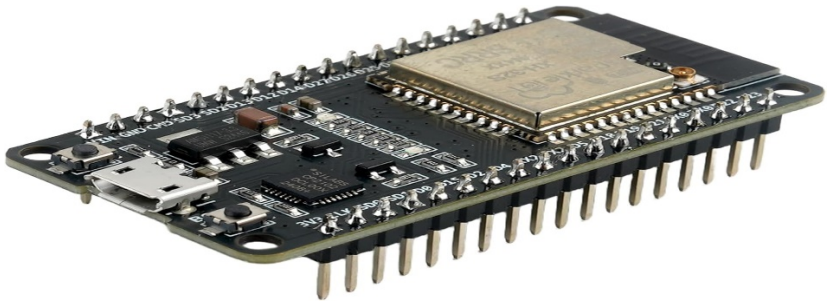

Fig 2.3: ESP32 Dev Module Micro-controller

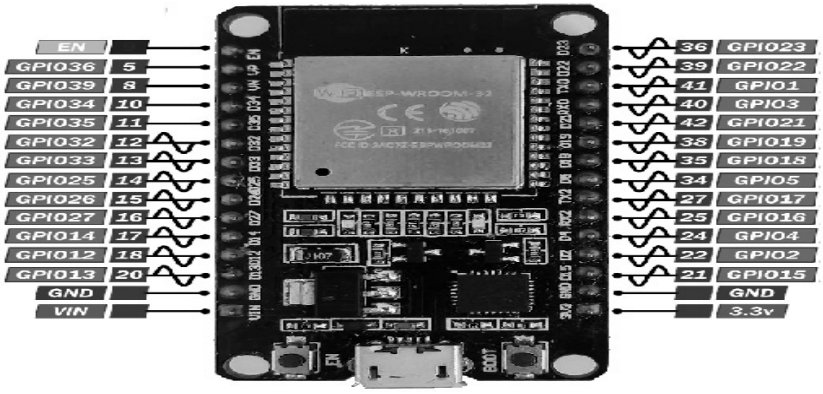

Fig 2.4: Pin diagram for the ESP32 Dev Module

2.5.2.5 Advantages of the ESP32 Dev Module over other micro-controllers

1. Built in Wi-Fi and Bluetooth: One of the major advantage of the ESP32 is that it has an integrated Wi-Fi and Bluetooth (BLE). This makes it ideal for IoT-based applications such as smart energy meters, which allows easy sending of readings to cloud platforms such as ThingSpeak, Blynk, Firebase.
2. High processing power: This means the ESP32 uses a dual-core 32-bit processor (up to 240 MHZ), much faster than Arduino Uno (8-bit, 16 MHz), PIC or 8051 micro-controllers (8-bit, lower frequency). This advantage allows it to handle multiple tasks simultaneously.
3. Larger Memory Capacity: The ESP32 has more Flash and SRAM memory, meaning it can store more complex programs, larger data logs, multiple libraries (for Wi-Fi, sensors, LCDs, etc.)
4. Low power consumption (sleep mode): The ESP32 has deep-sleep and light-sleep modes, allowing it to save power when not actively transmitting data.

5. Easy programming and capability: It can be programmed using Arduino IDE, MicroPython, ESP-IDF (C/C++), and supporting the same environment as Arduino, making it easy for beginners and advance users alike.
6. Low cost and High Performance: Despite its advanced features, the ESP32 is affordable, often cheaper than combining an Arduino plus Wi-Fi module

2.5.3 Communication protocol

1. Wireless (Network) communication protocols:
    i. Wi-Fi: it enables the ESP32 to connect to the internet or a local Wi-Fi network, it also allow for the sending of data to IoT platforms such as ThingSpeak, Blynk, or Firebase.
    ii. Bluetooth; Enables short-range wireless communication with other Bluetooth-enabled devices, it also allows wireless data transfer or setup using a smartphone app.
2. Wired (Peripheral) Communication Protocols:
    i. UART (Universal Asynchronous Receiver/Transmitter): It allows for serial communication using TX (transmit) and RX (receive) pins. It is commonly used to interface with the PZEM-004T sensor (which measures voltage, current, power, and energy), it is also used for debugging via the Serial Monitor in Arduino IDE.
    ii. I^2C (Inter-integrated circuit): It allows communication between multiple devices using only two wires (SDA and SCL)
    iii. SPI (Serial Peripheral Interface): It is used for high-speed data exchange using four wires (MOSI, MISO, SCK, and CS)
    iv. PWM (Pulsed Width Modulation): It is used to control devices like LED brightness, relays, or servo motors.

2.5.4 PZEM-004T Measurement Module

This is an intelligent AC electrical measurement module designed to monitor and report essential electrical parameters such as voltage, current, power, energy consumption, frequency, and power factor. It is widely used in IoT-based smart energy meter systems, home automation, and industrial energy monitoring because it contains accuracy, compact design, and serial communication features in a single board.

The module communicates this data to a micro-controller such as an ESP32, Arduino, or Raspberry Pi via UART serial interface, allowing easy integration into IoT systems. This makes it ideal for real-time monitoring of electrical energy parameters and transmission of data to cloud platforms like ThingSpeak, Blynk, or Firebase.

2.5.4.1 How it works

The module measures voltage by connecting directly to the AC line input. Internally, it uses a Voltage divider circuit and isolation techniques to step down and safely measure the mains voltage. This voltage signal is then converted into a digital value using the internal ADC (Analog-to-Digiatal Converter). Current is measured using a Current Transformer (CT) that clips around one of the AC supply lines. The CT senses the magnetic field produced by the flowing current and induces a proportional voltage signal. This signal is processed and converted into a digital value using the internal ADC (Analog-to-Digital Converter) .

Once the module measures both voltage and current, it multiplies the two values to calculate instantaneous power (in watts). Over time it integrates this power data to determine energy consumption (in Kwh). This values are stored internally and can be read by the connected microcontroller at any time. The module also detects the frequency of the AC waveform (typically 50 or 60 Hz) by counting the number of waveform cycles per second. The power factor which indicates how efficiently electrical power is being

used is calculated from the phase difference between voltage and current waveforms. A power factor close to unity (I.e 1) means efficient usage, while a lower value indicates more reactive (wasted) power. The processed data is sent digitally via the UART serial port to the Micro-controller, this interface ensures reliable data exchange without significant electrical noise interference. The communication uses a simple protocol with command and response formats, which allows reading of parameters or resetting of energy records. The module operates on a 5V DC supply, which powers the internal circuitry. This can be provided directly from the Micro-controller's 5V pin or an external power source.

Table 2.4: **PZEM-004T Measurement Module - Components and Specifications**

Component / Feature	**Specification / Description**
Working Voltage	80–260 VAC (AC supply)
Test / Input Voltage	80–260 VAC
Current Measurement Range	0–10 A (built-in shunt) or 0–100 A (external CT)
Power Measurement Range	Up to ~2.3 kW for 10 A version / up to ~23 kW for 100 A version
Frequency Range	45–65 Hz
Power Factor Range	0.00 – 1.00 with resolution 0.01
Energy Measurement Range	0–9999.99 kWh
Measurement Accuracy	±0.5% for voltage, current, and power (typical)
Communication Interface	TTL UART (baud rate: 9600 bps)
Supply Voltage for Module	5 V DC
Board Dimensions	Approximately 3.1 × 7.4 cm
Use Case	Measures voltage, current, power, energy, frequency, and power factor — used in IoT smart meters

It is of utmost importance to maintain electrical isolation between the AC input and the DC supply to prevent short circuit or damage.

Fig 2.5: PZEM-004T Measurement Module

2.5.5 LM-2956 DC-DC Bulk Converter

The LM-2956 DC-DC Bulk Converter is a step-down (bulk) voltage regulator module, meaning it takes a higher DC input voltage and converts it into a lower stable DC output voltage. For example, it can take 12V from an adapter or battery and reduce it to 5V or 3.3V levels that is required by devices like the ESP32, PZEM-004T, or SIM800L GSM module. It is called a switching regulator because it operates by rapidly turning a transistor switch ON and OFF and controlling the duty cycle of these pulses to maintain a constant output voltage. It is highly efficient, often achieving 80 to 90 percent efficiency.

2.5.5.1 Functions

1. It helps in power source regulation by ensuring that the ESP32 (3.3V), PZEM-004T (5V), and SIM800L GSM (4.2V) devices receives the exact voltage they need for reliable operation.
2. Supply stable power to communication modules
3. Voltage flexibility and customization

Fig 2.6: LM-2956 DC-DC Bulk Converter

2.5.6 Lithium Battery(3.7V)

The 3.3V Lithium battery plays a vital role in an IoT-based smart energy meter, serving and a stable power source, a backup supply, and sometimes even a real-time clock (RTC) or data retention power backup. Although it may appear like a small component, its function is crucial for ensuring continuous, accurate, and reliable operation of the smart meter especially in environments where power interruptions are common.

In summary for the system to function efficiently, it needs a consistent and clean power supply and that is where the 3.3V lithium battery comes in.

Fig 2.7: Lithium Battery 3.7V

2.5.7 IN5804 Diodes

The IN5804 is a Schottky barrier rectifier diode designed for high-current and low forward-voltage drop applications. It is a member of the IN58xx family (which includes IN5802, IN5803, IN5804), widely used in DC-DC converters, power supply protection, and reverse polarity protection circuits.

2.5.7.1 Purpose of the IN5804 Diode in an IoT Smart Energy Meter

1. One of the most important roles of the IN5804 diode is to protect the circuit from reverse polarity connections that is when the power supply wires (positive and negative) are accidently swapped. This is because if the input voltage is connected backward, it could instantly destroy sensitive components like the ESP32 Micro-controller, the PZEM-004T sensor module, the SIM800l GSM module, and the LM2596 buck converter.
2. If the IoT energy meter has a relay for switching power or load control, the IN5804 diode can be connected across the relay coil to provide a path for the induced current when the coil is de-energized.
3. It can also serve as a rectifier diode in DC-DC converter circuits or bridge rectifiers that convert AC or pulsed DC into smooth DC voltage.

Fig 2.8: IN5804 Diode

2.5.8 1000 micro-farad Capacitor

A 1000 micro-farad capacitor is a large value electrolytic capacitor typically used in power supply filtering and stabilization. In the smart energy meter, it is almost certainly placed near the LM2596 Buck converter or on the main 5V or 3.3V power rail that feeds various components like the ESP32 Micro-controller, PZEM-004T energy module and Sim800L GSM module (which draws high transient current)

Fig 2.9: Capacitor (1000 micro-farad)

2.5.9 Female Header Pins

Female header pins (also called female header connectors or header strips) are rows of small sockets that allow other components like sensors, modules, or micro-controllers to be plugged in or connected without permanent soldering. They usually have 2.54mm pitch (spacing between pins) which is the standard for most IoT and micro-controller boards.

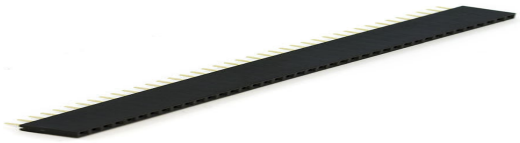

Fig 2.10: Female Header Pins

2.5.10 20x4 1^2C LCD Screen

A 20x4 LCD (Liquid Crystal Display) module is a character-type display capable of showing 20 characters per line, 4 lines total (so, 80 characters at once)

It offers double the display space making it ideal for projects like the IoT Smart Energy Meters that need to show multiple parameters simultaneously. It has the ability to communicate with the ESP32 through the Parallel data pins (4-bit or 8-bit mode), or an I^2C interface adapter module (which simplifies wiring and uses only SDA/SCL pins).

2.5.10.1 Functions

1. Displays multiple Energy parameters simultaneously.

2. Provides local, real-time monitoring and readings from the device, even without an internet connection or mobile app
3. Displays IoT connectivity and system status
4. Displays tariff, cost, or alert messages.
5. Enhances testing and calibration.

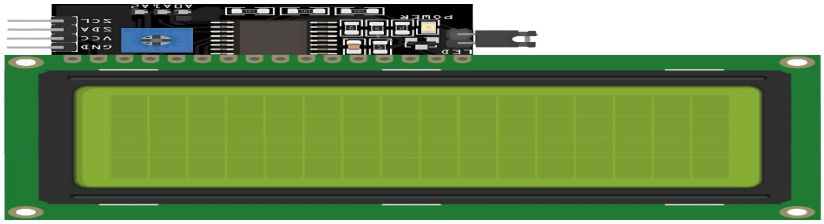

Fig 2.11: 20x4 LCD screen

2.5.11 DC Jack(12-V)

A 12-volt DC jack is the power input connector used to supply external DC voltage (typically from an AC-to-DC Adapter, battery pack, or regulated supply) to your circuit. It is the main entry point of electrical power into your device. Physically, it is a barrel-type connector, where a round socket (female) mounted on the PCB or casing of your smart energy meter. It mates with a 12V DC plug (male) from the adapter or power source.

2.5.11.1 Functions

1. Primary power input for the Entire Circuit
2. Provides a stable and convenient power connection
3. Supplies adequate power for High-current components
4. Enables external power instead of USB
5. Feeds the voltage regulator for voltage conversion.
6. Ensures electrical isolation and safety.

Fig 2.12: DC Jack(12v)

2.5.12 Pin Terminal Block

A 2-pin terminal block (also called a 2-pin screw terminal block connector) is a small electrical connector used to securely connect and disconnect two wires to a printed circuit board (PCB)

It usually has two metal contacts (pins) that go into the PCB, two screw terminals on top that clamp down on bare wire ends, ensuring a solid electrical and mechanical connection.

These connectors make the wiring easy, neat, and safe especially for high-voltage or current-carrying connections.

Fig 2.13: Two pin terminal block

2.5.13 Perforated Board (Perforated Board)

Also called a dot board or a proto board, serves an important role during prototyping and assembly of the circuit.

2.5.13.1 Functions

1. The perf board provides a solid base on which all the electronic components (like resistors, capacitors, sensors, ICs, and connectors) of the smart meter are mounted and soldered.
2. Permanent prototype construction
3. Custom circuit layout

4. Signal routing
5. Mechanical support
6. Testing and modifications

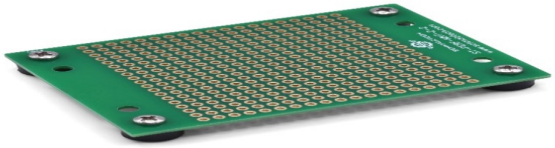

Fig 2.14: Perforated Board

2.5.14 Switch

The most common function or purpose is to turn the entire smart meter circuit ON or OFF. It also controls the flow of current form the power supply (e.g, 12V jack or battery) to the rest of the circuit. The helps protect the components and saves power when the meter is not used

Accurate measurement of current and voltage is fundamental in a smart meter. The SCT-013-000 Current sensor, a non-invasive split-core current transformer, is widely used for AC current measurement in residential and industrial settings. It provides galvanic isolation and avoids direct contact with live wires, enhancing safety. For voltage sensing, the ZMPT101B Voltage sensor Module offers an effective solution with high precision and isolation.

Fig 2.15: Switch

2.5.15 Adaptable Box

It is also called a junction box or project enclosure, it serves as the protective housing for all the electronic components and wiring inside the meter.

2.5.15.1 Functions

1. It protects the internal components from dust, moisture, mechanical damage, accidental contact with live parts
2. It provides electrical safety by helping prevent electric shock by keeping high-voltage and low-voltage parts enclosed and insulated from users or technicians
3. It provides a stable structure to neatly mount and organize components like switches, power jack, terminal blocks, indicator LEDs.
4. Ease of maintenance
5. Environmental protection.

Fig 2.16: Adaptable Box

2.6 Software design

2.6.1 Arduino IDE (Integrated Development Environment)

The Arduino IDE is the primary software platform used for programming and developing IoT based systems such as the smart energy meter. It serves as the interface between the user and the micro-controller, and uploaded to devices like the ESP32 Dev Board, which is commonly used in IoT smart meters. The Arduino IDE is simple, open-source, and supports multiple operating systems, making it a universal tool for embedded system design and IoT development. In an IoT smart energy meter, the Arduino IDE is used to create the logic that allows the ESP32 to read, process, and transmit energy data.

The process begins with writing a program which is written in a simplified form of the C/C++ language. This sketch or program defines how the ESP32 interacts with connected components such as sensors, LCD screens, relays, and communication modules. Once the code is written the IDE compiles it, converting human-readable commands into machine language. The compiled program is then uploaded to the ESP32 through a USB cable, allowing the micro-controller to execute the instructions and perform the desired functions automatically.

Setting up the Arduino IDE for use with the ESP32 requires installing the appropriate board package and libraries. The ESP32 board package enables the IDE to recognize the micro-controller, while libraries simplify programming tasks. These libraries provide prewritten functions for connecting to Wi-Fi networks, uploading data to cloud servers, displaying readings on LCDs, and reading electrical parameters from sensors. Through this environment, developers can easily integrate Wi-Fi or Bluetooth connectivity, allowing the smart meter to send real-time data to IoT platforms such as ThingSpeak, Blynk, or Firebase for remote monitoring.

The Arduino IDE also provides tools for testing and debugging. It has a built-in Serial Monitor that allows developers to view live data output from the ESP32, such as voltage, current, or energy readings, as well as Wi-Fi connection status and error messages. This makes it easier to identify and correct issues during system development. The role of Arduino IDE in IoT smart energy meters entends beyond initial programming. It is also used for updating and improving firmware, allowing engineers to add new features, enhance data accuracy, or improve system efficiency without altering the hardware. Its compatibility with various libraries and external modules ensures scalability, meaning more sensors or functionalities can be added as the project grows. The IDE's simplicity, combined with the processing capabilities of the the ESP32, making it ideal for educational, research, and commercial energy metering applications.

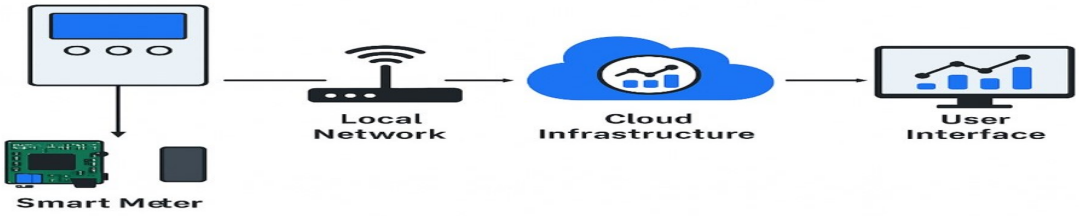

Fig 2.17: system development architecture

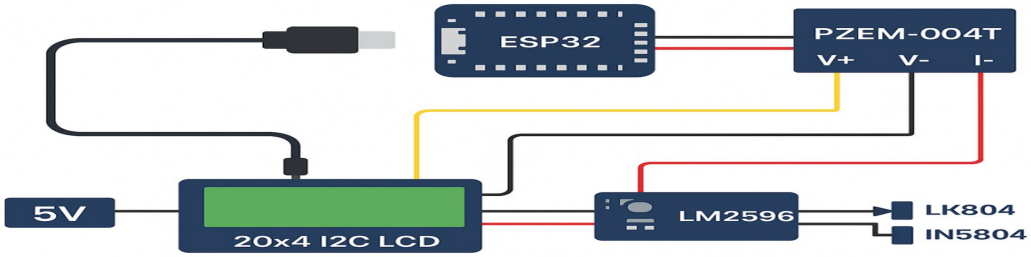

Fig 2.18: Smart meter assembly layout

2.7 Flow chart of the project

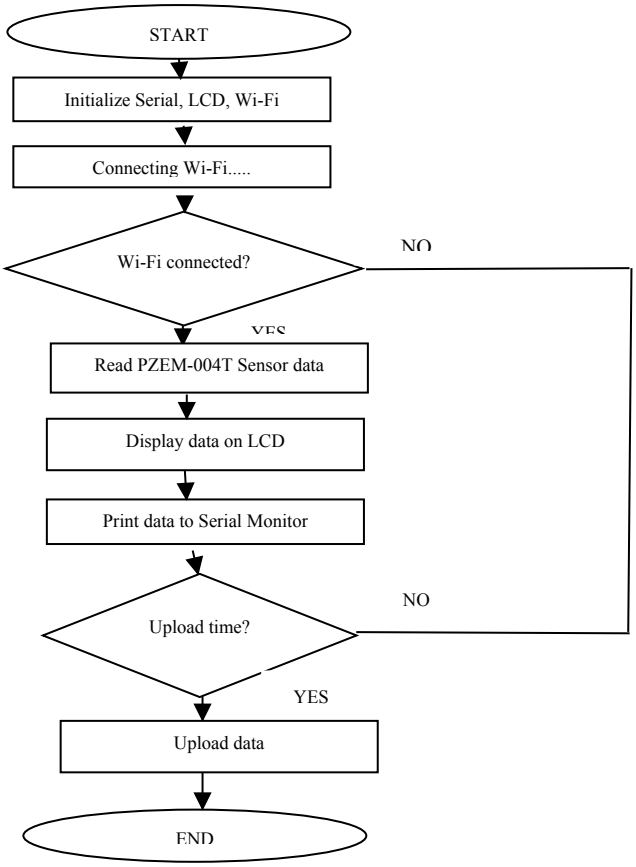

Fig 2.19: Flowchart for the operation

2.8 Description of the flow chart

1. **Start block:** This is when the system begins operation when you power ON the system and the ESP32 Dev module starts executing the code.
2. **System Initialization block:** This block represents the setup part of the Arduino IDE program, where the ESP32 prepares all hardware modules and communication interface
3. **Wi-Fi connection block:** After initialization, the system tries to connect to the Wi-Fi network using the credentials stored in the code.
4. **Read sensor data block:** Once Wi-Fi is stable, the ESP32 continuously reads the electrical measurements from the PZEM-004T module.
5. **Display data on LCD block:** After reading, the ESP32 sends these values to the 20x4 I^2C LCD for local monitoring.
6. **Display data on serial monitor block:** The same readings are also printed to the serial monitor via USB.
7. **Upload time reached/decision block:** This block checks whether it is time to send data to the cloud.
8. **Decision block (Wi-Fi connected):** Before uploading, the system verifies that the ESP32 still has Wi-Fi access.
9. **Upload data to ThingSpeak block:** If Wi-Fi is connected and upload time is due, the ESP32 builds an HTTP GET request using the ThingSpeak API key and sends the latest readings.
10. **Loop back to sensor reading:** Start all over again from where the reads the electrical parameters.
11. **Endless loop:** There is no true END because IoT devices run continuously as long as they are powered. The loop repeats indefinitely until you turn off the device or press the reset switch.

CHAPTER THREE

SYSTEM DESIGN AND ANALYSIS

3.1 Introduction

This chapter presents the overall design and analytical framework of the IoT-based smart energy meter system. It explains how the system's hardware and software components were selected, interconnected, and programmed to work properly in monitoring and transmitting electrical energy consumption data via the internet. The aim of the design is to implement and design a smart energy meter system capable of measuring electrical parameters, and displaying them locally, and uploading them automatically to a cloud server for remote access.

3.2 Project design and Overview

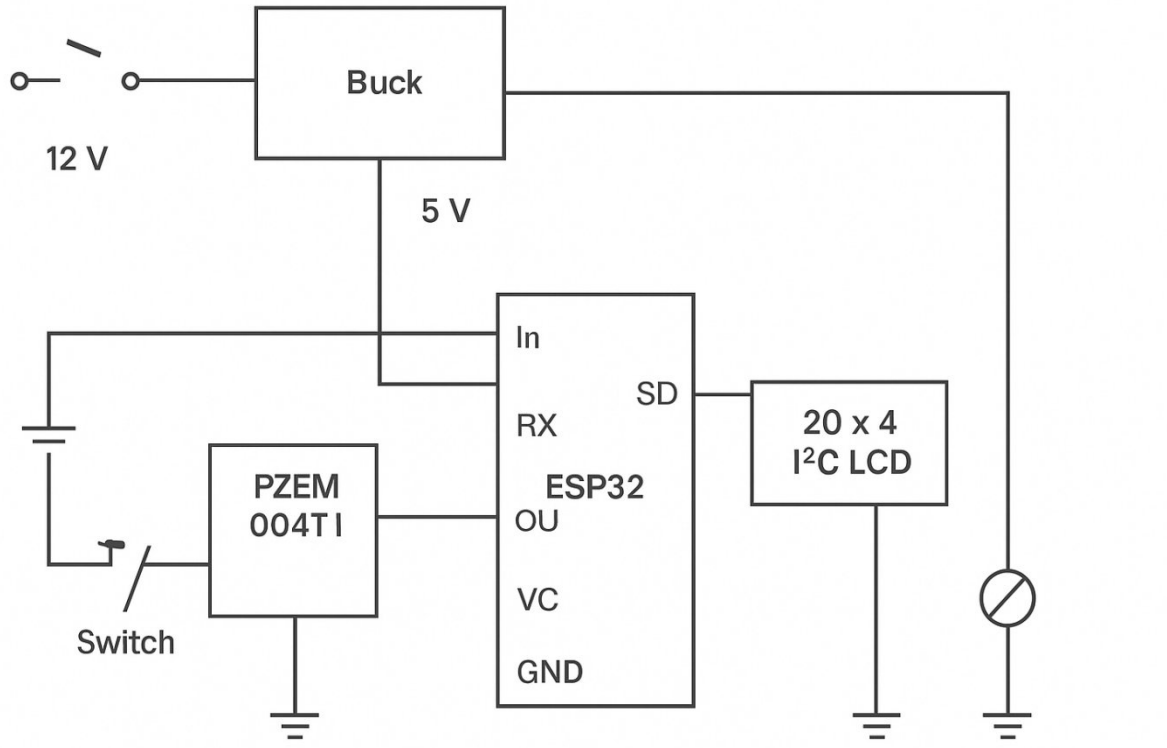

Fig 3.1: Block Diagram of the project

The system illustrated in Figure 3.1 represents the block diagram of the IoT-based smart energy meter, showing the interaction among its major components. The process begins with a 12V DC power input**,** typically sourced from a lithium battery or an external DC supply, connected through a DC jack**.** This power is regulated by the LM2596 DC-DC buck converter**,** which steps down the voltage to 5V or 3.3V levels required by the ESP32 microcontroller**,** PZEM-004T measurement module, and 20x4 I²C LCD display**.** A switch circuit is incorporated between the live terminal of the DC jack and the converter to facilitate controlled power switching, while the neutral terminal connects directly to the converter. This ensures safe and efficient power distribution throughout the circuit. The PZEM-004T module serves as the primary sensing unit, connected to the AC mains and the load. It measures critical electrical parameters voltage, current, active power, energy consumption (kWh), frequency, and power factor through its internal circuitry and a current transformer (CT) clamped on the load's live wire. The PZEM-004T then transmits these measured values digitally to the ESP32 via serial communication (TX/RX), ensuring precision and electrical isolation between the high-voltage and low-voltage domains.

The ESP32 development module acts as the processing and control hub of the system. It reads real-time measurement data from the PZEM-004T, processes it, and sends it to the LCD display for immediate visualization by the user. The 20x4 I²C LCD provides a user-friendly interface that continuously displays parameters such as voltage (V), current (A), power (W), energy (kWh), frequency (Hz), and power factor (Pf). Beyond local display, the ESP32 leverages its built-in Wi-Fi module to connect to the internet and upload the processed data periodically to the ThingSpeak cloud platform using the HTTP protocol**.** ThingSpeak stores and visualizes each parameter in real-time through dynamic graphs and dashboards, enabling remote monitoring and analysis of energy usage from any location using a smartphone or computer. This cloud integration embodies the

Internet of Things (IoT) concept linking physical measurement systems to the digital ecosystem for intelligent, data-driven energy management.

3.3 Description of Hardware component

The main Hardware components of an IoT-based Smart Energy Meter include;

1. **ESP32 Development (Dev) module:** This is the Micro-controller used for our smart energy meter, it receives data from the PZEM-004T module in form of signals and processes it before sending the processed data to the LCD display for visual communication with the users.

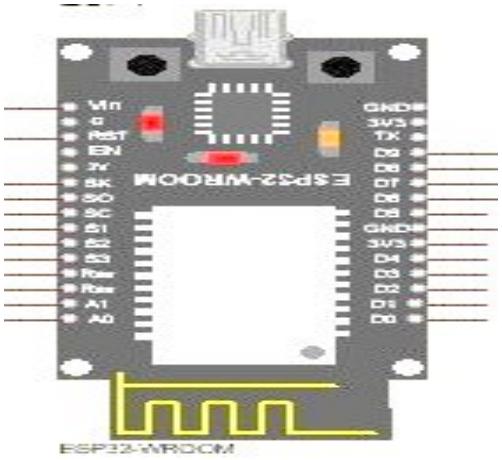

Fig 3.2: Schematic diagram of ESP32 Dev module

2. **PZEM-004T Measurement Module:** This is the hardware component that carry out all necessary measurements of the electrical quantities from the AC connected load, this is due to the fact that it has an in-built current and voltage sensor including a current transformer that helps it measure electrical parameters with good accuracy.

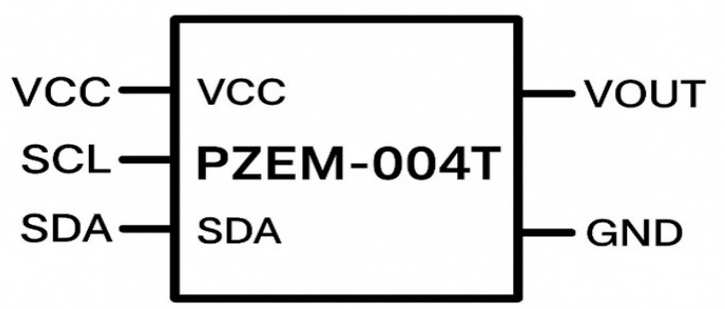

Fig 3.3: The Schematic diagram of PZEM-004T Measurement Module

3. **20x4 I^2C LCD Screen:** This component is connected to the ESP32 Dev module using the wire communication I^2C, it helps in displaying every processed data from the Micro-controller visually in real-time.

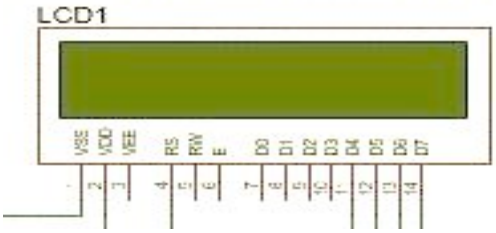

Fig 3.4: Schematic diagram of LCD Screen

4. **LM-2956 DC-DC Buck Converter:** This component helps in converting the higher voltage value coming from the dc supply to a lesser value of 5V, which is more compatible with the other components like the ESP32, the PZEM-004T Module, the LCD display. It has a voltage regulating property that tends to stabilize the voltage level at all times.

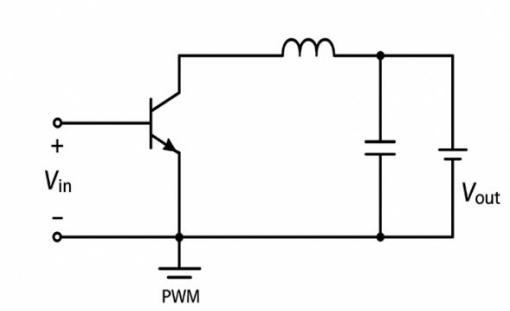

Fig 3.5: Schematic diagram of a dc-dc buck converter

5. **3.7V Lithium Batteries:** This serves as the internal power source for the whole device. Without it being energize or charged nothing works.

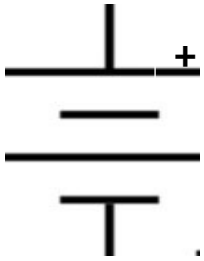

Fig 3.6: Schematic diagram of a battery

6. **Switch:** The main function of the switch is to control the flow of electrical power from the external power supply (through the 12V jack) to the rest of the circuit, that is when the switch is put ON power flows from the DC source to the buck converter and then to other modules like the ESP32, PZEM-004T, LCD.

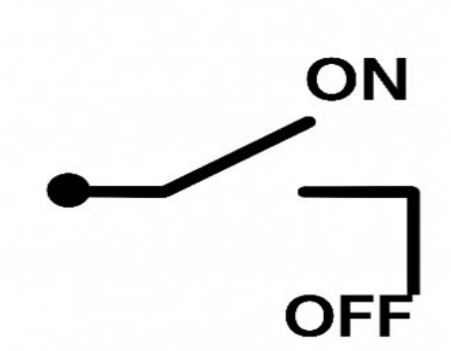

Fig 3.7: Schematic diagram of a switch

7. **Socket or loads:** This are connected to the terminals of the PZEM-004T module and then the PZEM-004T connected directly to an external AC supply, with the mains of the load first passes through the current transformer (CT) before entering the terminal of the PZEM-004T module. The neutral terminal of the load is connected directly to the neutral terminal of the PZEM-004T Module. Then an external load is connected to the socket and the PZEM-004T

   module starts to operate and measure all electrical parameters.

3.4 Hardware integration and operation

The basic background behind the Design and implementation of the IoT-based smart meter has to do with the connection between the ESP32 Dev module and PZEM-004T module. The PZEM TX pin transmits data (readings from the sensors), the PZEM RX pin receives data, the ESP32 RX2 AND TX2 pins handle these signals. So when power comes in to the meter, the ESP32 sends a command through TX2 asking the PZEM for data, the PZEM module measures the voltage and current from its sensing terminals and computes parameters internally (power, energy, frequency, current, etc). The PZEM sends the computed data back through its TX pin to the ESP32RX2 pin. The ESP32 receives and processes this serial data, before displaying on the LCD and sent wirelessly to ThingSpeak.

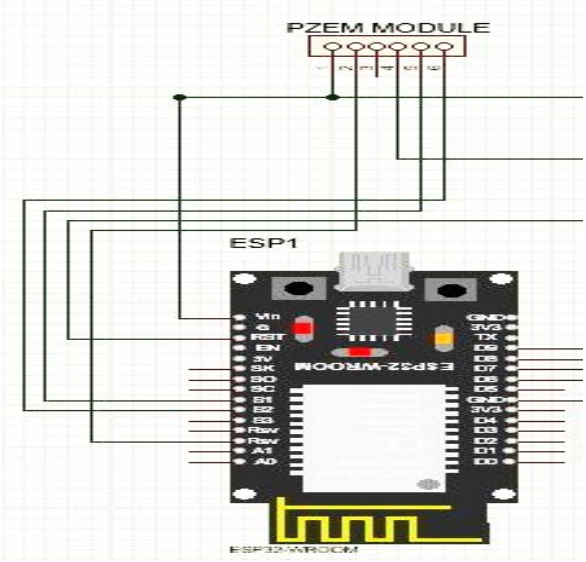

Fig 3.8: ESP32 Dev module with the PZEM-004T module

The PZEM-004T measurement module is then connected to an AC mains power, enabling it to be able to successfully read the electrical parameters when an external load is attached to it. So when the AC supply is connected to the PZEM-004T module, it sends a signal to the ESP32 Dev module and it process the signal and then display out what is measured through an LCD Screen.

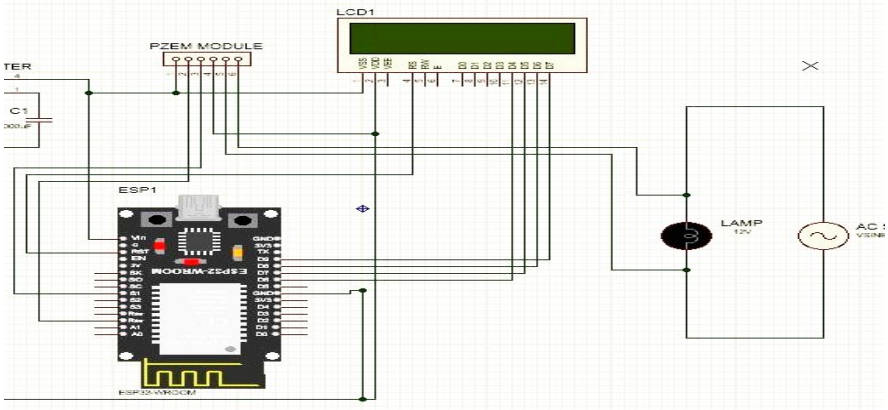

Fig 3.9: ESP32 Dev module with the PZEM-004T module, LCD screen, AC supply unit and external load source.

To ensure proper voltage regulation for the ESP32 Dev module and other components, the LM-2956 DC-DC Buck Converter is introduced, with it functioning as a 5V voltage regulator. The Buck Converter takes the 12V input from battery and steps it down to a stable 5V output. This is done due to the fact that the regulated voltage is essential for maintaining the correct operating conditions of the Micro-controller and other circuit elements.

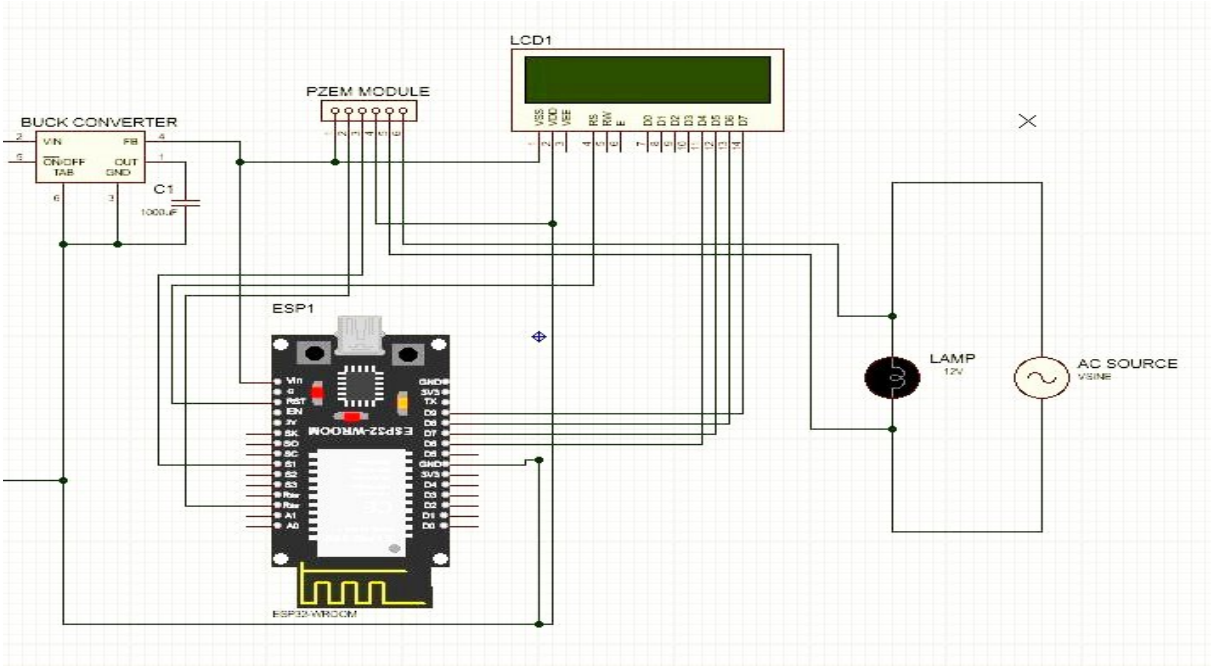

Fig 3.10: ESP32 Dev module with the PZEM-004T module, LCD screen, AC supply unit, external load and LM-2956 DC-DC Buck Converter.

Finally, the system is completed by integrating a 12V battery, which serves as the primary power source. The 12V battery provides the 12V which is stepped down by the LM-2956 Buck converter to 5V which is needed for the proper operation of the whole system.

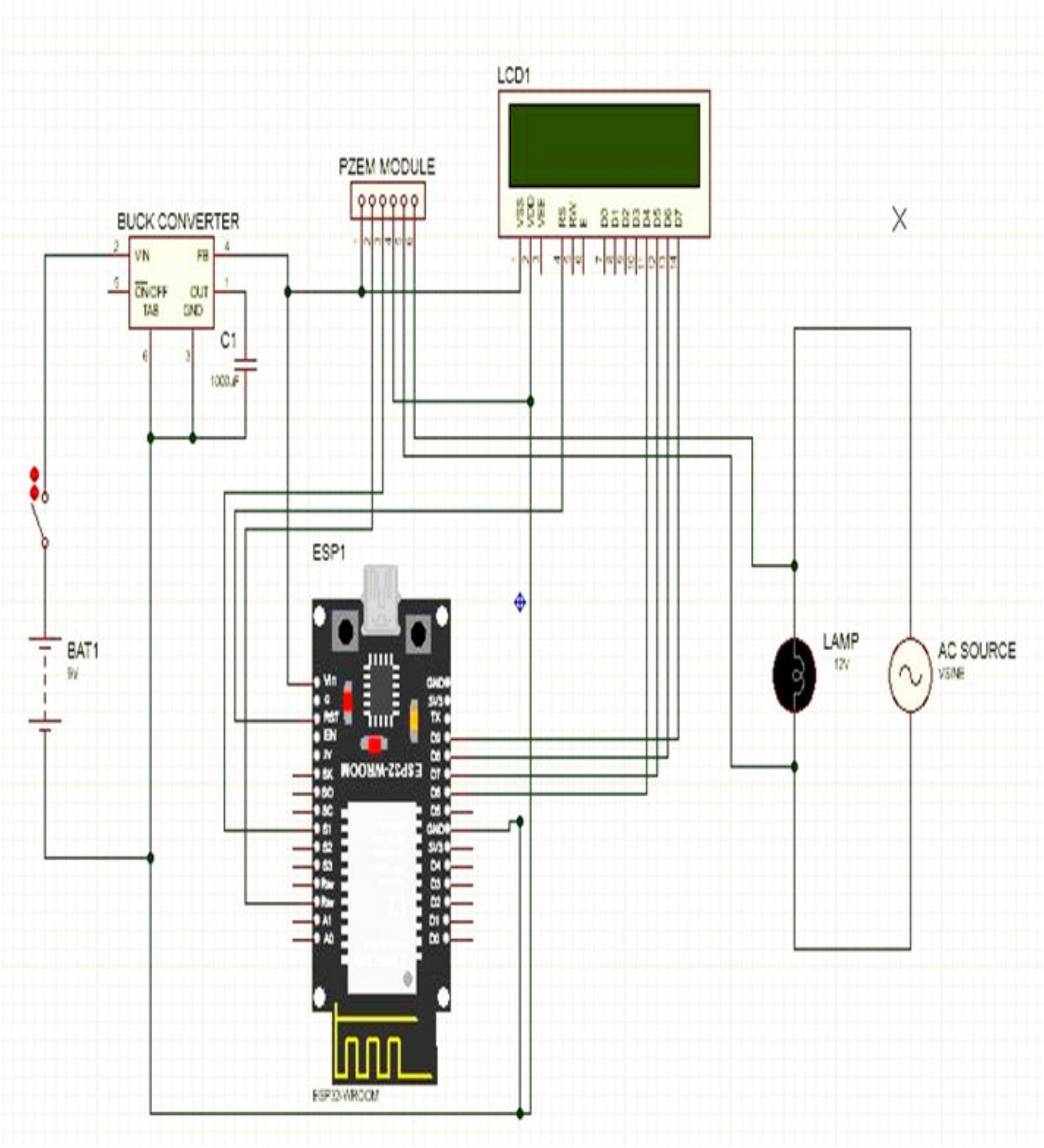

Fig 3.11: Complete schematic diagram of the system

3.5 Complete descriptions of the functionality of the system

The IoT-based smart energy meter operates through a well-structured integration of power regulation, sensing, processing, and communication modules. The process initiates with a stable 12V DC power supply derived from either a lithium battery or an external adapter, interfaced through a DC jack. This voltage is then stepped down by the LM2596 DC-DC buck converter to produce the 5V and 3.3V rails needed by the ESP32 microcontroller, PZEM-004T sensor, and 20x4 I²C LCD. A control switch is positioned between the DC jack and converter to enable safe power toggling and circuit protection, while the neutral connection ensures continuous grounding. This power regulation network ensures all modules operate within safe voltage limits, providing efficient energy distribution across the system.

The sensing operation is managed by the PZEM-004T measurement module, which interfaces directly with the AC mains supply and load through its voltage and current sensing terminals. The module uses an internal voltage divider and current transformer (CT) to monitor key electrical parameters such as voltage, current, active power, energy consumption, frequency, and power factor. By isolating high-voltage AC measurements from the low-voltage control section, the PZEM-004T enhances system safety and accuracy. The measured data is then transmitted via UART communication to the ESP32 microcontroller, ensuring reliable and noise-free data transfer between the sensing and processing domains.

The ESP32 serves as the system's intelligence core, coordinating data processing, display, and cloud communication. It receives and processes electrical readings from the PZEM-004T, converting them into user-readable values displayed on the 20x4 I²C LCD screen. Simultaneously, the ESP32 uses its integrated Wi-Fi module to establish a connection with the ThingSpeak IoT platform. Through HTTP protocols, it uploads measurement data at periodic intervals, where ThingSpeak visualizes these parameters on real-time dashboards and graphs. This cloud connectivity enables users to monitor and analyze their energy

consumption remotely through mobile devices or computers, thereby supporting efficient energy management, predictive maintenance, and informed decision-making in line with IoT-based smart grid advancements.

3.6 Software

3.6.1 Firmware Implementation Details

The firmware design of the smart electricity metering system was guided by three core principles: real-time data acquisition, efficient computation, and reliable communication. The ESP32 microcontroller was programmed in C++ (Arduino IDE) to execute multitasking routines that collect sensor data, compute electrical parameters, control load switching, and manage data transmission through GSM and Wi-Fi channels. To ensure deterministic timing and computational consistency, the firmware was structured into independent functional modules connected through well-defined data buffers and interrupt-driven event handlers.

The primary firmware modules include:

1. Sampling and Interrupt Service Routine (ISR) for real-time analog data acquisition.
2. Computation Engine for RMS, power, and energy calculations.
3. Communication Module for GSM-based and Wi-Fi-based data transmission to ThingSpeak.
4. Alert and Relay Control Module for SMS notifications and load management.
5. System Initialization and Task Scheduler to handle periodic processes such as calibration updates and diagnostic logging.

3.6.2 Sampling and Interrupt Service Routine

Accurate voltage and current acquisition are fundamental to reliable energy computation. The firmware employs a timer-driven interrupt routine that samples both analog inputs (voltage and current) at a

frequency of 2 kHz. This sampling rate ensures that at least 40 samples are captured per AC cycle (for 50 Hz systems), meeting Nyquist requirements and minimizing quantization error.

```
volatile float voltageBuffer[128], currentBuffer[128];
volatile uint16_t sampleIndex = 0;
void IRAM_ATTR samplingISR() {
  float vSample = analogRead(VOLTAGE_PIN);
  float iSample = analogRead(CURRENT_PIN);
  voltageBuffer[sampleIndex] = (vSample - 2048.0) * VOLTAGE_SCALE;
  currentBuffer[sampleIndex] = (iSample - 2048.0) * CURRENT_SCALE;
  sampleIndex = (sampleIndex + 1) % 128;
}
```

The ISR subtracts the ADC midpoint (2048) to remove DC offset and applies calibration constants (VOLTAGE_SCALE, CURRENT_SCALE) derived during sensor calibration. The sampled data are stored in circular buffers for further processing by the computation module.

3.6.3 RMS and Power Computation Engine

The computation module processes buffered data to compute electrical quantities, including RMS voltage, RMS current, active power, apparent power, reactive power, and power factor. The calculations are performed once per second, ensuring smooth visualization and efficient ThingSpeak data updates.

```
void computeElectricalParameters() {
  float sumV2 = 0, sumI2 = 0, sumVI = 0;
  for (int n = 0; n < 128; n++) {
    sumV2 += voltageBuffer[n] * voltageBuffer[n];
    sumI2 += currentBuffer[n] * currentBuffer[n];
```

```
  sumVI += voltageBuffer[n] * currentBuffer[n];
 }

 float Vrms = sqrt(sumV2 / 128.0);
 float Irms = sqrt(sumI2 / 128.0);
 float realPower = sumVI / 128.0;
 float apparentPower = Vrms * Irms;
 float powerFactor = realPower / apparentPower;
 energyWh += (realPower / 3600.0); // integrate over time
 updateLCD(Vrms, Irms, realPower, powerFactor);
}
```

This algorithm efficiently computes RMS and power parameters without requiring phase-shift correction for purely resistive loads. For inductive or capacitive loads, a phase compensation coefficient is applied based on calibration. The accumulated energyWh variable stores cumulative energy in watt-hours.

3.6.4 ThingSpeak Data Uploader (Wi-Fi / GSM)

The ESP32 periodically uploads computed data to ThingSpeak using either Wi-Fi or GSM connectivity, depending on availability. This dual communication ensures system resilience in areas with unstable internet infrastructure.

```
void uploadToThingSpeak(float Vrms, float Irms, float P, float PF) {
 String url = "https://api.thingspeak.com/update?api_key=" + API_KEY;
 url += "&field1=" + String(Vrms);
 url += "&field2=" + String(Irms);
 url += "&field3=" + String(P);
```

```
  url += "&field4=" + String(PF);
  if (WiFi.status() == WL_CONNECTED) {
    http.begin(url);
    http.GET();
    http.end();
  } else {
    gsmSendHTTP(url); // fallback to SIM800L
  }
}
```

In GSM mode, the firmware uses AT commands via UART to perform HTTP POST requests. Upload latency and success rate are logged for performance evaluation. Each data record on ThingSpeak is timestamped automatically, allowing visualization of historical trends and comparative analytics.

3.6.5 SMS Alert and Relay Control Module

The alert module is designed to provide user notifications and load management features. It continuously monitors energy consumption, power factor, and current thresholds. If abnormal conditions are detected, the module triggers the relay and sends SMS notifications through the SIM800L module.

```
void checkAlerts(float Irms, float PF) {
  if (Irms > MAX_CURRENT || PF < MIN_POWER_FACTOR) {
    digitalWrite(RELAY_PIN, LOW); // disconnect load
    sendSMS("+234XXXXXXXXXX", "Alert: Overload or Low PF detected. Load disconnected!");
  }
}
void sendSMS(String number, String message) {
```

```
  Serial2.println("AT+CMGF=1");
  delay(100);
  Serial2.println("AT+CMGS=\"" + number + "\"");
  delay(100);
  Serial2.print(message);
  Serial2.write(26); // end of message (Ctrl+Z)
}
```

This routine adds a practical safety and automation layer to the metering system. The relay can also be triggered remotely from a ThingSpeak command channel or SMS-based control command.

3.6.6 System Initialization and Task Scheduling

The firmware employs FreeRTOS task scheduling (natively supported by ESP32) to concurrently handle sensor sampling, power computation, communication, and user interface updates. This design ensures deterministic performance and avoids blocking operations in time-critical routines.

```
void setup() {
  Serial.begin(115200);
  initWiFi();
  initGSM();
  lcd.begin(20, 4);
  pinMode(RELAY_PIN, OUTPUT);
  attachInterrupt(digitalPinToInterrupt(TIMER_PIN), samplingISR, TIMER_INTERVAL);
}
void loop() {
```

```
  computeElectricalParameters();
  uploadToThingSpeak(Vrms, Irms, P, PF);
  checkAlerts(Irms, PF);
  delay(1000);
}
```

This structure ensures efficient task execution and stable system operation, even under fluctuating power or network conditions.

CHAPTER FOUR

IMPLEMENTATION, TESTING AND RESULT ANALYSIS

4.1 Introduction

This chapter presents the practical realization of the designed Smart Energy Meter system. After the system design and analysis phase, implementation involving assembling the hardware components, integrating the Micro-controller, connecting the sensors, and establishing communication with LCD display and the ThingSpeak cloud platform. The implementation stage transforms the theoretical design into a working prototype capable of measuring, displaying, and transmitting real-time electrical parameters

4.2 Implementation process

1. **PERFORATED BOARD (Perf board):** We first obtained a perforated PCB board, which serves as the main circuit platform. It allows us to securely mount and connect all components by soldering them in a neat and permanent arrangement. The image below shows the board before any components have been installed.

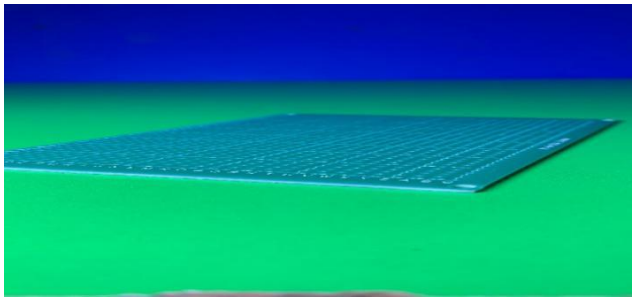

Fig 4.1: A Perforated board (main circuit board)

2. **Mounting of the PZEM-004T Module on the perforated board:** We attached our first component which is the PZEM-004T module to the main circuit board, using a plastic gum.

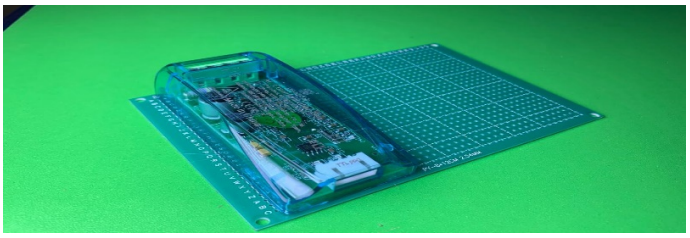

Fig 4.2: Mounting of the PZEM-004T measurement module on the perforated board

3. **Mounting of the female header pins on the board:** The female header pins are the components that are soldered directly to the main circuit board, it act as receptacles where you can easily plug in or remove modules (like the ESP32, LCD, or sensors) without soldering them directly to the board.

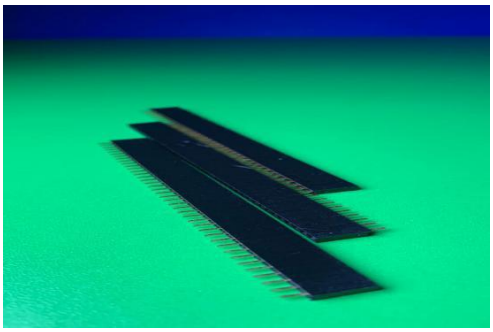

Fig 4.3: Female header pins

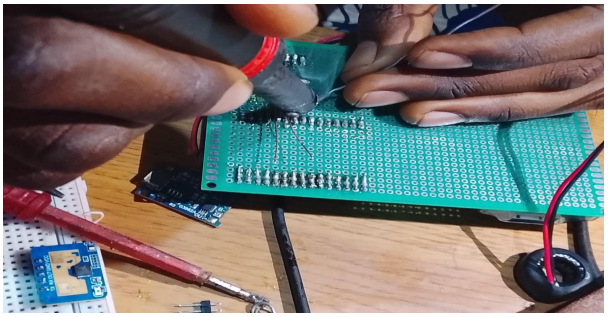

Fig 4.4: Mounting of female header pins using the soldering iron.

2. **Male header pins:** They are usually soldered onto the underside of the ESP32 dev board. The pins align perfectly with the female header pins which was already mounted on the perfboard.

Fig 4.5: Carrying out a continuity test using multimeter in order to check for any bridge in the main circuit before mounting the ESP32 Dev module

4. **Mounting of the ESP32 Dev Module**: Next, the ESP32 development board was mounted onto the perfboard. It is not directly soldered or permanently attached; instead, it rest on male header pins that makes contact with the female header connectors positioned beneath the perfboard. This setup allows the ESP32 module to be easily removed or replaced during testing, eliminating the need for resoldering the main circuit board.

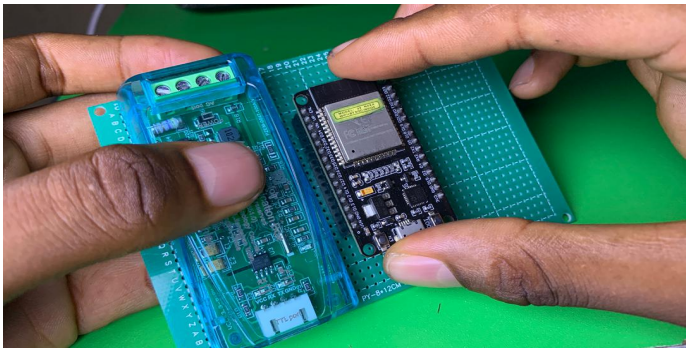

Fig 4.6: Mounting of the ESP 32 Dev module Micro-controller on the male header terminals.

5. **Code testing on the ESP32 Dev Module microcontroller using the Arduino IDE** : This is a very critical stage when implementing a Smart Energy Meter. The first step was to download and install

the Arduino Integrated development Environment (IDE) on a computer. The IDE provides the platform to write, compile, and upload programs (called sketches) to the ESP32 Micro-controller.

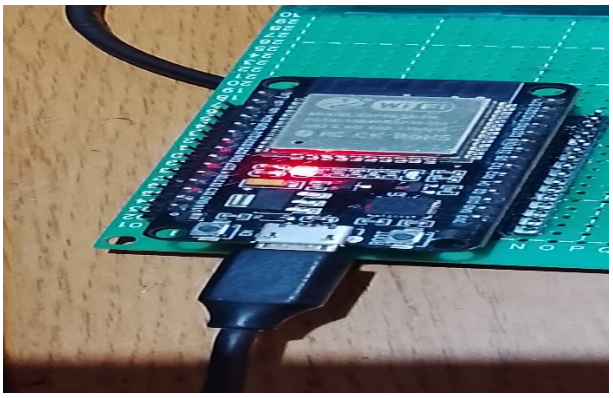

Fig 4.7: The actual programming of the Micro-controller using a USB cable connection via a system

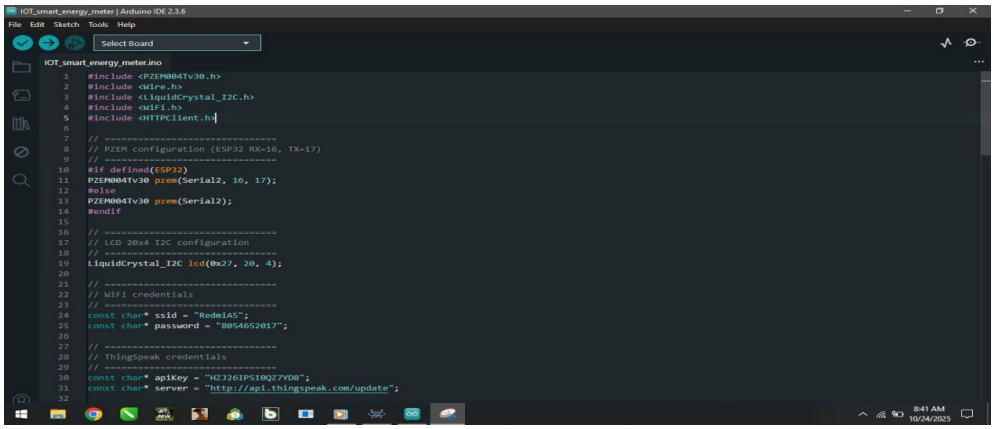

Fig 4.8: Various lines of codes uploaded and verified in the Arduino IDE to program the ESP32 Micro-controller

Once the code has been successfully uploaded to the microcontroller, the computer screen will display the message “Done uploading,” indicating that the process is complete.

6. Mounting the LM2956 DC-DC Buck Converter to the Main Circuit Board: The DC-DC buck converter was mounted onto the perforated board using female header pins, which were soldered to the terminal ends of the converter to ensure a secure and stable connection.

6. **Adding the 2-pin terminal block to the perforated board, to power the DC-DC bulk converter:**

   The whole idea is to try and take power supply to the bulk converter, which is coming from the dc source supply.

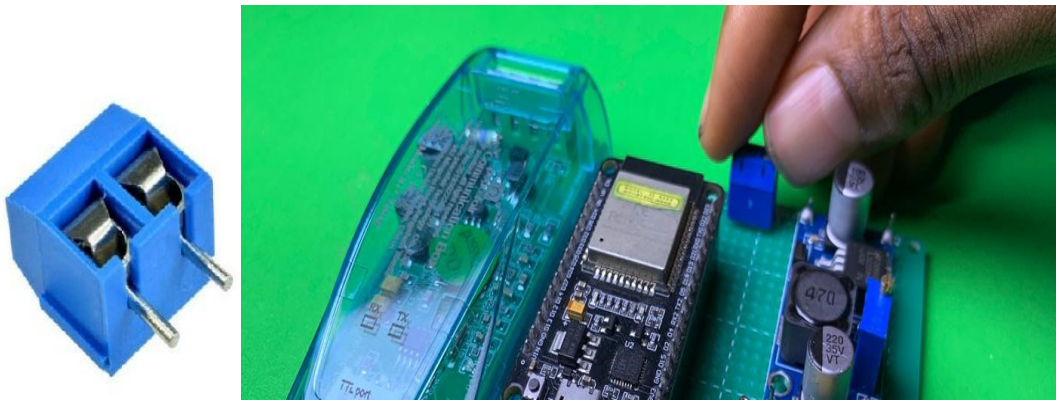

Fig 4.9: 2-pin terminal block mounted on the Perf board

7. **Test carried out on some parts of the components above:**

   At this section we were able to carry out various test at various terminals shown below

8. **Connecting the LCD display to the ESP32 dev module for display:**

Fig 4.10: connecting the LCD screen to the ESP32 Micro-controller

9. **Connecting the lithium battery, the 12V DC Jack, and the switching unit:** The the 12V dc jack helps get the necessary 12V supply from external sources, which charges the lithium batteries. There is connection between the 12V jack, the batteries, and the switch circuit.

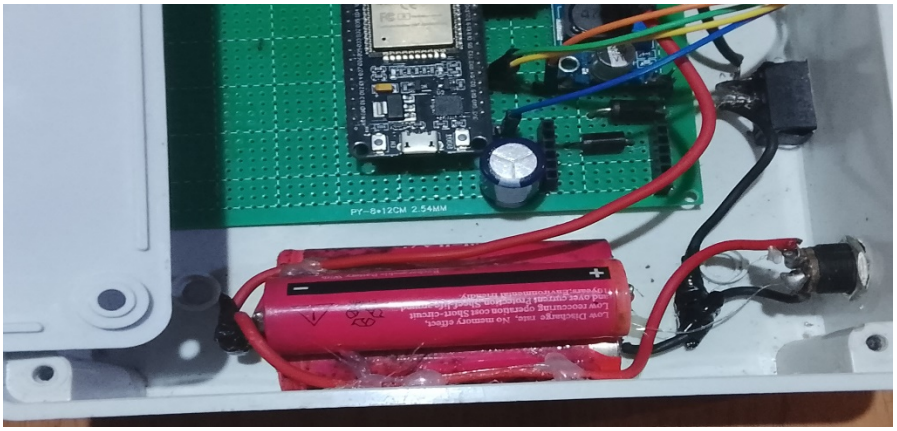

Fig 4.11: Showing the various connections between the lithium battery, the 12V dc jack and the switch terminals

10. **Next to carry out remote-monitoring using ThingSpeak cloud platform:** ThingSpeak is an IoT (Internet of Things) cloud platform created by MathWorks, that allows you to collect, store, analyse, and visualize data from sensors or smart devices over the internet. It works with devices like the ESP32, Arduino, or even Raspberry PI.
11. **Signing into ThingSpeak website**

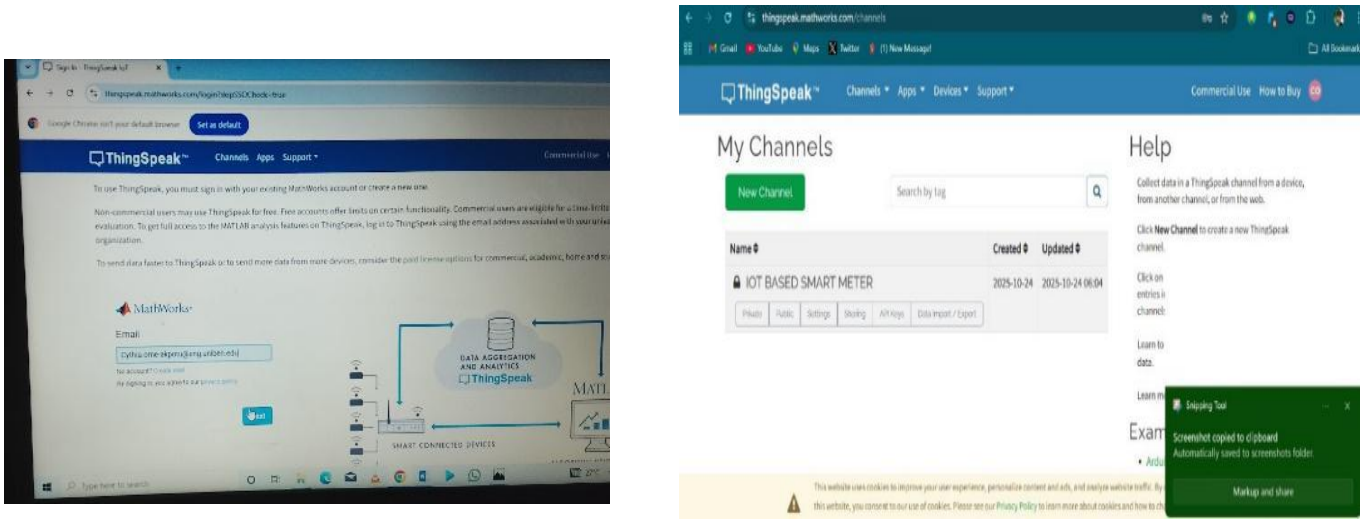

Fig 4.12: Login into your ThingSpeak account

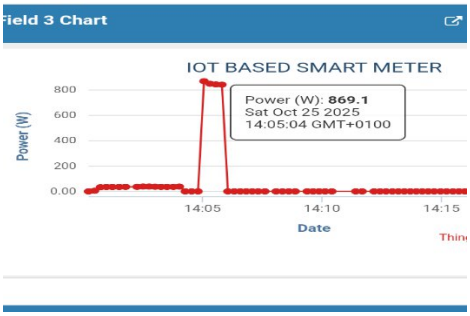

Fig 4.13: Field charts displaying a power of 869W

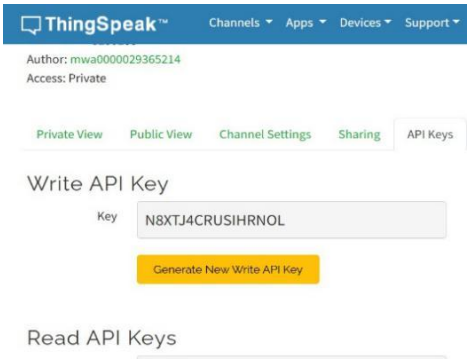

Fig 4.14: Confirm your API keys

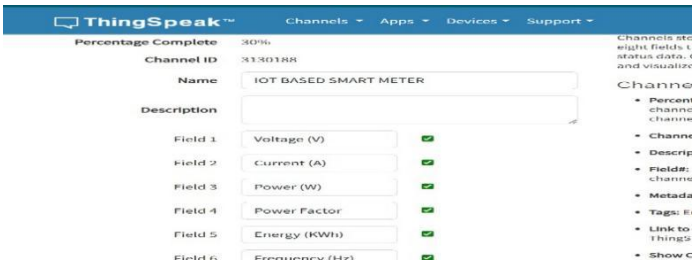

Fig 4.15: See existing fields

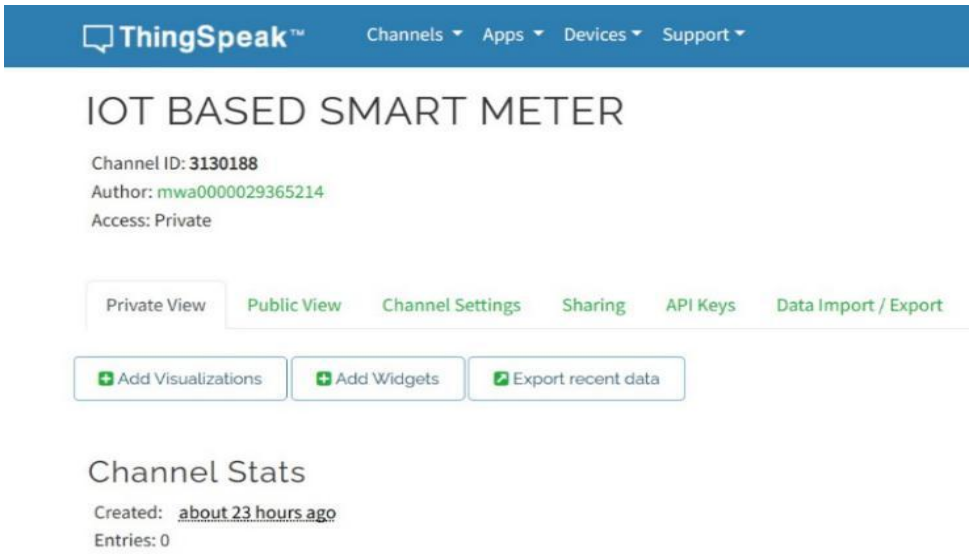

Fig 4.16: Channel status for the IoT smart meter

The figures above show the full process involve in carrying out data analysis, monitoring and visualization using the ThingSpeak IoT cloud platform.

4.3 Results

4.3.1 Results from power supply Test

The 11.1V battery exhibited a stable output voltage. The results of the voltage measurements are summarized in table 4.1. The measured voltage of the 12v battery confirms its suitability for powering the system. The voltage regulator component of the LM-2956 DC-DC bulk converter successfully regulated the voltage to a level suitable for the ESP32 Dev module.

Table 4.1: Results obtained from power supply Test

Test carried out	Theoretical value	Measured value
12V Carried out	11.1V	7.4V
LM-2956 DC-DC	5V	4.9V

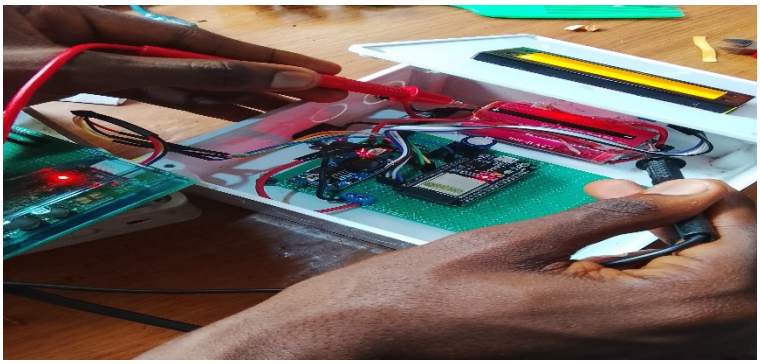

Fig 4.17: Test carried out with the multimeter

4.3.2 Results from ESP32 Dev module Test

The LED blink test successfully demonstrated the functionality of the ESP32 Dev module digital input/output. The LED blinked at the programmed interval, indicating that the micro-controller was functioning correctly and able to control the output pin as expected.

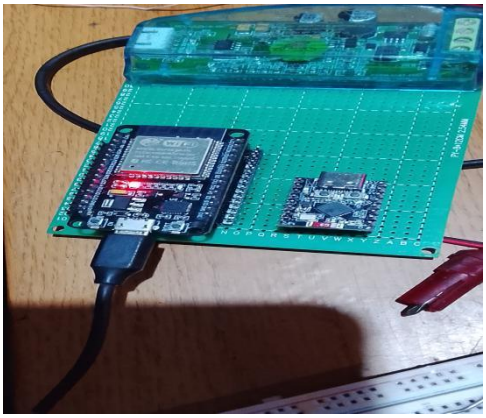

Fig 4.18: Test carried out on the ESP32 DevKit micro-controller to check its functionality

The figures above show the full process involve in carrying out data analysis, monitoring and visualization using the ThingSpeak IoT cloud platform

4.3.3 Results from the test carried out on various types of loads.

We carried out various tests on purely resistive loads; this is due to the fact that purely resistive loads have a power factor of unity (1). This was aimed at getting the total energy consumption that is being consumed by each load as shown below;

The following readings and measurements were carried out at the University of Benin Protection department. This is where the whole power used by everybody in the school is being distributed to various locations across UNIBEN.

Table 4.2: 30W Soldering Iron (Resistive load)

Sample No.	Multi-meter Voltage (V)	Clamp meter Current (A)	Apparent Power (VA)	Time (Hrs)	PZEM Voltage (V)	PZEM Current (A)	PZEM Power (W)	Power Factor (PF)	Freq. (Hz)	PZEM Energy (Kwh)	Reference meter Energy (Kwh)	% Error kwh (%)
1	243	0.1	24.3	0	248.3	0.1	24.8	1	50	0	0	0
2	249	0.1	25	0.5	254.6	0.1	25.5	1	50	0.0127	0.012	5.883
3	247	0.1	24.7	1	251.3	0.1	25.1	1	50	0.025	0.024	4.17
4	245	0.1	24.5	1.5	252	0.1	25.2	1	50	0.037	0.036	2.77
5	239	0.1	24	2	244.5	0.1	24.5	1	50	0.049	0.048	2.08
6	241	0.1	24.1	2.5	247.3	0.1	24.7	1	50	0.061	0.06	1.67
7	235	0.1	23.5	3	241.2	0.1	24.1	1	50	0.073	0.072	1.388

$P = VI\cos\phi$ *(Active/true power)*

Where:

- P= True Power
- I= Current
- V= Voltage
- $\cos\phi$= Power Factor

The voltage and current values gotten from the multi-meter and clamp meter will then have to be multiplied with a power factor of unity (purely resistive loads) to get its real power in Watt (W)

Next is to calculate the efficiency of the PZEM-004T module, we first determine the percentage error gotten from the Smart energy meter which is given by:

$$\%\text{Error} = \frac{\text{Measured Value} - \text{Actual Value}}{\text{Actual Value}} \times 100$$

$$\%\text{Error Kwh} = \frac{\text{PZEM Energy kwh} - \text{Reference meter kwh}}{\text{Reference meter kwh}} \times 100$$

Where kwh is the Energy consumption over time.

Efficiency = (100 – 2.565) % = 97.4%.

Therefore, the efficiency of the readings gotten from the PZEM-004T module is: 100 - Average %Error kwh,

Efficiency = (100 – 2.565) % = 97.4%.

Average %Error kwh = $\sum$ (*total %Error*) ÷ *no of %Error*

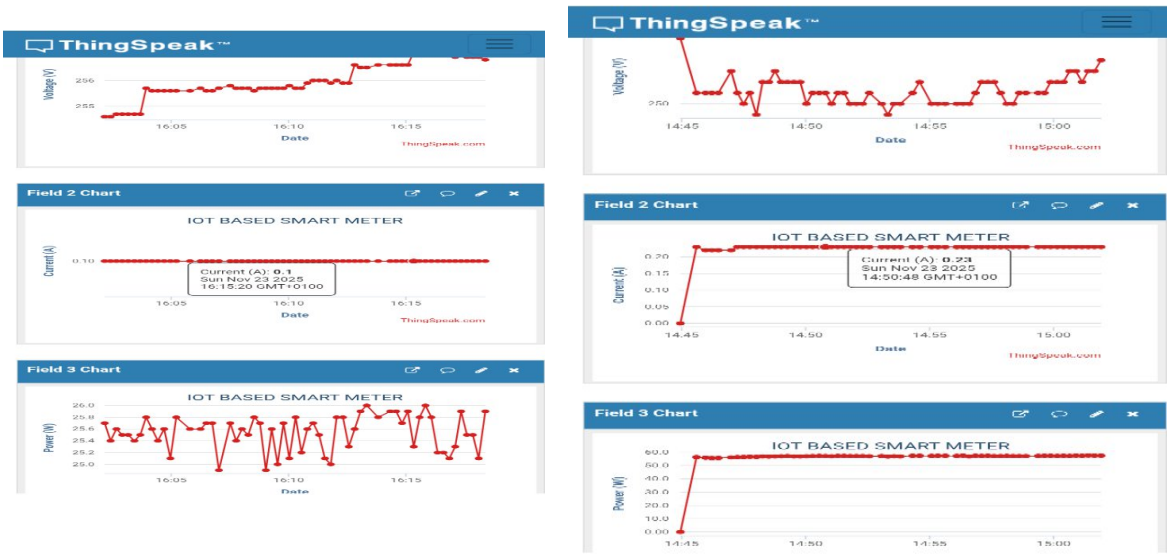

Fig 4.19: Visualization of various Electrical fields via ThingSpeak cloud platform

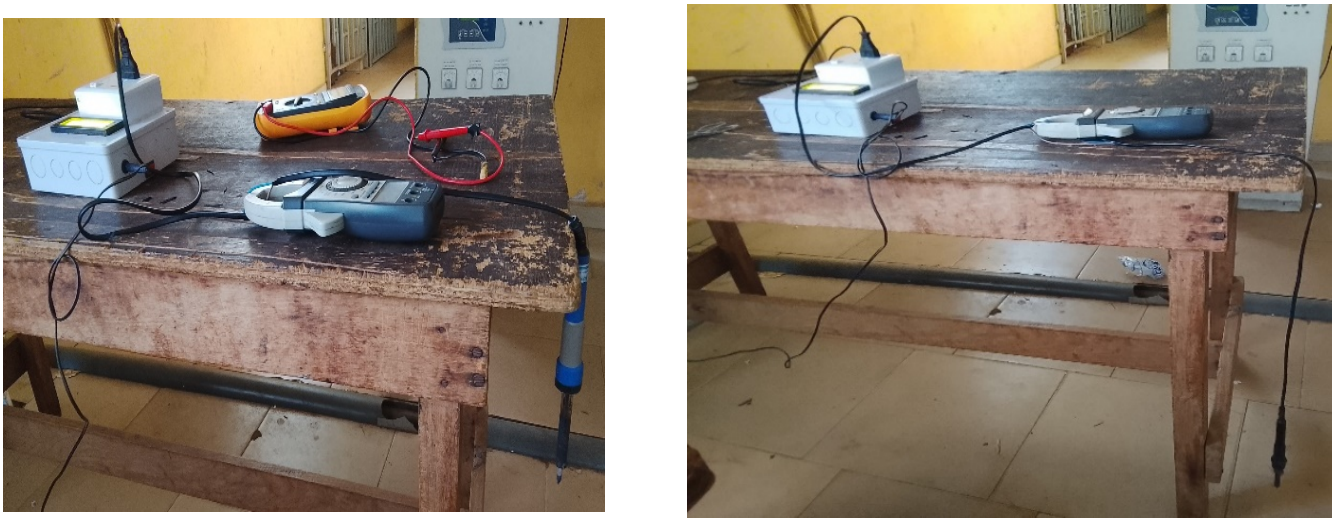

Fig 4.20: Actual data being measured and collected for 30W and 60W soldering iron.

Table 4.3: 60W Soldering Iron (Resistive Load)

Sample No.	Multi-meter Voltage (V)	Clamp meter Current (A)	Apparent Power (VA)	Time (Hrs)	PZEM Voltage (V)	PZEM Current (A)	PZEM Power (W)	Power Factor (PF)	Freq. (Hz)	PZEM Energy (Kwh)	Reference meter Energy (Kwh)	% Error (%)
1	245	0.21	51.5	0	250	0.23	57.5	1	50	0	0	0
2	245	0.21	51.45	0.5	249.7	0.23	57.4	1	50	0.029	0.026	11.5
3	247	0.21	51.8	1	251.4	0.23	57.8	1	50	0.058	0.052	11.5
4	239	0.21	50.19	1.5	244.7	0.23	56.3	1	50	0.086	0.077	11.7
5	247	0.21	51.87	2	251.6	0.23	57.8	1	50	0.11	0.102	7.84
6	243	0.21	51.03	2.5	248.7	0.23	57.2	1	50	0.14	0.128	9.4
7	241	0.21	50.61	3	246.9	0.23	56.8	1	50	0.168	0.153	9.8

$P = VI\cos\phi$

Where:

- P= True Power
- I= Current
- V= Voltage
- $\cos\phi$= Power Factor

The voltage and current values gotten from the multi-meter and clamp meter will then have to be multiplied with a power factor of unity (purely resistive loads) in order to get its real power in Watt (W).

Next is to calculate the efficiency of the PZEM-004T module, we first determine the percentage error gotten from the Smart energy meter which is given by:

$$\%\text{Error} = \frac{\text{Measured Value} - \text{Actual Value}}{\text{Actual Value}} \times 100$$

$$\%\text{Error Kwh} = \frac{\text{PZEM Energy kwh} - \text{Reference meter kwh}}{\text{Reference meter kwh}} \times 100$$

Where kwh is the Energy consumption over time.

Efficiency = 100 – Average %Error kwh

Therefore, the efficiency of the readings gotten from the PZEM-004T module is : 100 – Average %Error .kwh

Efficiency = (100 – 8.82) % = 91.2%.

Average %Error kwh = $\sum(\ total\ \%Error) \div no\ of\ \%Error$

Table 4.4: 60W Incandescent Bulb (Resistive Load)

Sample No.	Multi-meter Voltage (V)	Clamp meter Current (A)	Apparent Power (VA)	Time (Hrs)	PZEM Voltage (V)	PZEM Current (A)	PZEM Power (W)	Power Factor (PF)	Freq. (Hz)	PZEM Energy consumed (Kwh)	Reference meter Energy consumed (Kwh)	% Error (%)
1	234	0.25	58.5	0	239	0.28	66.9	1	50	0	0	0
2	232	0.24	55.6	0.5	237	0.28	66.4	1	50	0.03	0.028	7.14
3	235	0.25	58.8	1	240.4	0.28	67.3	1	50	0.064	0.06	6.7
4	229	0.25	57.3	1.5	235.7	0.28	65.9	1	50	0.097	0.089	9
5	235	0.25	58.8	2	241.6	0.28	67.6	1	50	0.131	0.118	11.02
6	235	0.25	58.8	2.5	240.7	0.28	67.4	1	50	0.165	0.147	12.2
7	239	0.25	59.8	3	244.8	0.28	68.5	1	50	0.2	0.177	13

$P = VI\cos\phi$

Where:

- P= True Power
- I= Current
- V= Voltage
- $\cos\phi$= Power Factor

The voltage and current values gotten from the multi-meter and clamp meter will then have to be multiplied with a power factor of unity (purely resistive loads) in order to get its real power in Watt (W).

Next is to calculate the efficiency of the PZEM-004T module, we first determine the percentage error gotten from the Smart energy meter which is given by:

$$\%\text{Error} = \frac{\text{Measured Value} - \text{Actual Value}}{\text{Actual Value}} \times 100$$

$$\%\text{Error Kwh} = \frac{\text{PZEM Energy kwh} - \text{Reference meter kwh}}{\text{Reference meter kwh}} \times 100$$

Where kwh is the Energy consumption over time.

Efficiency = 100 – Average %Error kwh

Therefore, the efficiency of the readings gotten from the PZEM-004T module is : 100 – Average %Error .kwh

Efficiency = (100 – 8.44) % = 91.56%.

Average %Error kwh = $\sum(\ total\ \%Error) \div no\ of\ \%Error$

Table 4.5: 100W Incandescent Bulb (Resistive Load)

Sample No.	Multi-meter Voltage (V)	Clamp meter Current (A)	Apparent Power (VA)	Time (Hrs)	PZEM Voltage (V)	PZEM Current (A)	PZEM Power (W)	Power Factor (PF)	Freq. (Hz)	PZEM Energy (Kwh)	Reference meter Energy (Kwh)	% Error (%)
1	247	0.35	86.45	0	252.5	0.38	95.95	1	50	0	0	0
2	242	0.35	84.7	0.5	247.2	0.38	93.9	1	50	0.047	0.042	11.9
3	244	0.35	85.4	1	248.8	0.38	94.5	1	50	0.094	0.085	10.6
4	239	0.35	83.65	1.5	244.6	0.38	92.9	1	50	0.140	0.127	10.2
5	242	0.35	84.7	2	247.4	0.38	94	1	50	0.187	0.169	10.7
6	242	0.35	84.7	2.5	247.2	0.38	93.9	1	50	0.234	0.211	10.9
7	247	0.35	86.47	3	252.8	0.38	95.8	1	50	0.28	0.254	10.2

$P = VI\cos\phi$

Where:

- P= True Power
- I= Current
- V= Voltage
- $\cos\phi$= Power Factor

The voltage and current values gotten from the multi-meter and clamp meter will then have to be multiplied with a power factor of unity (purely resistive loads) in order to get its real power in Watt (W).

Next is to calculate the efficiency of the PZEM-004T module, we first determine the percentage error gotten from the Smart energy meter which is given by:

$$\%\text{Error} = \frac{\text{Measured Value} - \text{Actual Value}}{\text{Actual Value}} \times 100$$

$$\%\text{Error Kwh} = \frac{\text{PZEM Energy kwh} - \text{Reference meter kwh}}{\text{Reference meter kwh}} \times 100$$

Where kwh is the Energy consumption over time.

Efficiency = 100 – Average %Error kwh

Therefore, the efficiency of the readings gotten from the PZEM-004T module is : 100 – Average %Error .kwh

Efficiency = (100 – 9.2) % = 90.8%.

Average %Error kwh = $\sum(\textit{total \%Error}) \div \textit{no of \%Error}$

Fig 4.21: ThinSpeak visualization for the 100W incandescent Bulb

Fig 4.22: Readings taken after displayed on the LCD screen and Test carried out on the Incandescent Bulb

Table 4.6: Summarized interpretation of the average % errors:

Load Type	Average % Error	Efficiency
30 W Soldering Iron	~2.56%	97.4%
60 W Soldering Iron	~8.82%	91.2%
60 W Bulb	~8.44%	91.56%
100 W Bulb	~9.2%	90.8%

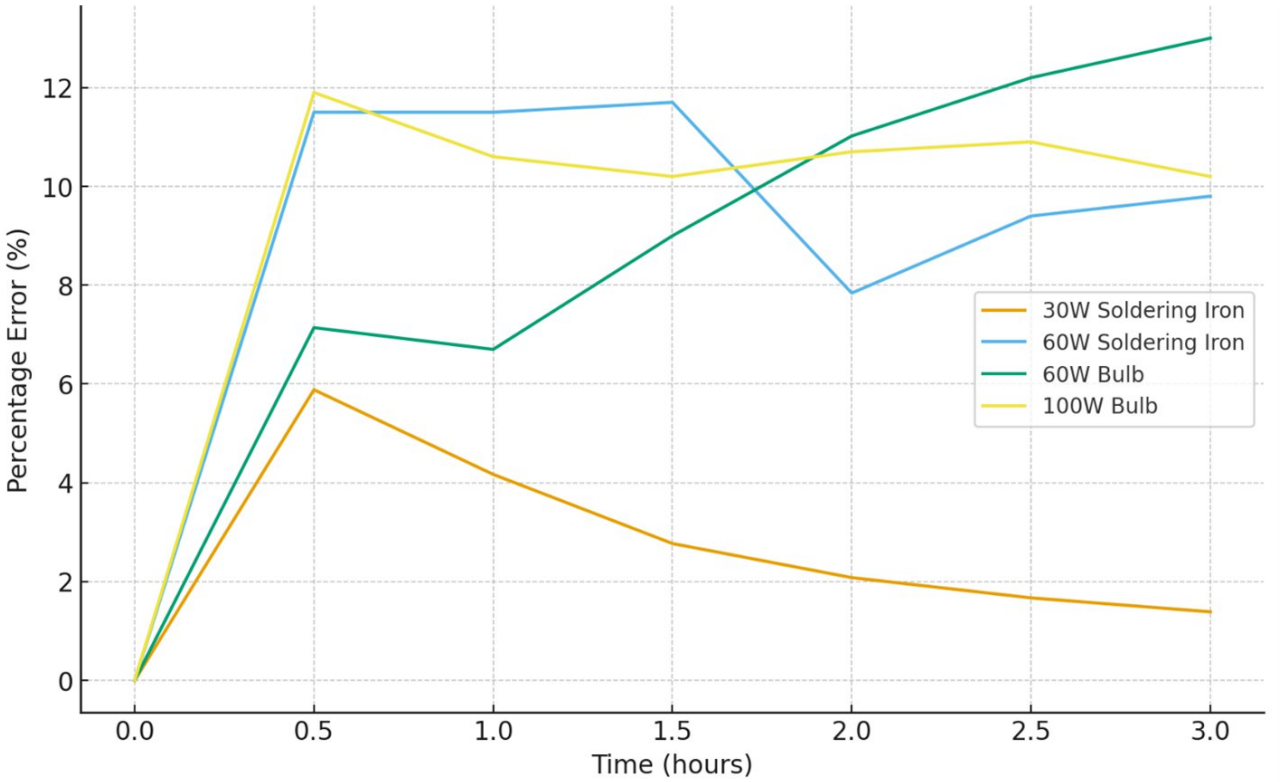

Fig 4.23: Error vs Time across loads

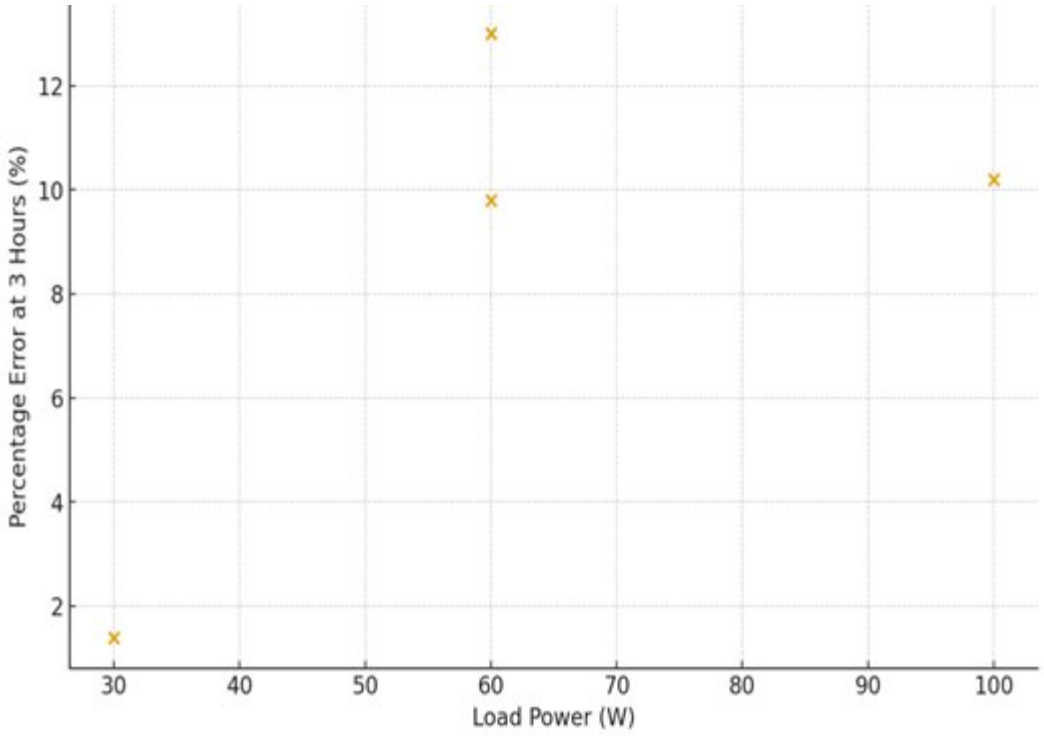

Fig 4.24: Error vs load (at 3 hours)

4.4 Analysis and Discussion

This chapter presents the analysis of the experimental results obtained from testing the PZEM-004T smart energy meter using different purely resistive loads. The tests were conducted at the University of Benin Protection Department, where electrical power is distributed to various academic and residential locations across the institution. The primary objective of the experiments was to evaluate the suitability, accuracy, and performance of the PZEM-004T module when used for energy measurement under controlled load conditions. Resistive loads were specifically selected for this study because they have a power factor of unity, which eliminates reactive power variations and ensures that the measured power corresponds directly to the real or true power consumed by the load.

The analysis began with tests carried out on a 30 W soldering iron, where voltage and current readings were taken using both a digital multimeter and a clamp meter. These values were then compared with the corresponding measurements from the PZEM-004T device. Since the load is purely resistive, the true power was computed using the expression $P = VI\cos\phi$, where the power factor $\cos\phi = 1$. The energy consumption recorded by the PZEM-004T module was compared with the reference meter readings over incremental time intervals. The percentage error for each reading was computed using the standard error formula, with the reference meter serving as the actual value. For this load, the average percentage error obtained was 2.565%, yielding an overall efficiency of 97.4%. This result indicates a high degree of accuracy when the meter is used for low-power loads, suggesting that the PZEM-004T is reliable for small-scale measurement applications involving devices of similar power ratings.

A similar procedure was followed for the 60 W soldering iron. Measurements were taken at increasing time durations to observe how the energy error behaves as the load continues to operate. Although the PZEM-004T still maintained a power factor of unity, its energy measurements deviated more significantly from the reference meter compared to the 30 W case. An average percentage error of 8.82% was calculated, corresponding to an efficiency of 91.2%. This result shows that the accuracy of the PZEM-004T decreases as the load power increases. The source of this deviation may be attributed to cumulative measurement drift, voltage fluctuations, or scaling biases inherent in the current transformer and analogue-to-digital conversion stages of the meter.

The 60 W incandescent bulb was also used as a resistive load to further validate the results obtained from the soldering irons. Incandescent bulbs provide stable resistive behaviour, making them suitable for such comparative tests. In this case, the PZEM-004T again recorded higher energy values than the reference meter across all time intervals. The average percentage error for the 60 W bulb was

determined to be 8.44%, giving an efficiency of 91.56%. This trend reinforces the observation that the PZEM-004T tends to overestimate energy consumption as the load power increases. The systematic nature of this overestimation suggests that the device exhibits a consistent calibration bias rather than random measurement noise. The values obtained also point to the possibility that at moderate power levels, measurement inaccuracies accumulate over time, further widening the gap between the measured and actual energy consumption.

The highest load tested was a 100 W incandescent bulb. This load provided a stronger basis for evaluating the behaviour of the meter under larger, yet still purely resistive, power consumption conditions. The results from this test displayed the largest percentage deviation observed in the study. With an average percentage error of 9.2% and a corresponding efficiency of 90.8%, the findings indicate that the PZEM-004T's accuracy degrades progressively as the load power increases. This suggests that the internal measurement circuitry of the meter may have been optimised for lower loads, and its performance becomes less reliable as the current drawn by the load approaches the upper range of the device's measurement capability. Additionally, variations in voltage supply over the duration of the test might have compounded these inaccuracies.

Generally, the analysis of all four datasets reveals a clear pattern: the PZEM-004T meter performs very well for low-power loads, such as the 30 W soldering iron, but its accuracy decreases as the load increases to 60 W and 100 W. In every case, the PZEM-004T recorded energy values that were consistently higher than those of the reference meter. This implies that the error is systematic rather than random, indicating a calibration offset that favours over-measurement. Such behaviour may be due to small but consistent scaling errors in the current transformer, voltage sensing inaccuracies, or timing drift in energy integration. Despite this limitation, the meter's performance remains acceptable

for general monitoring purposes, particularly in research, domestic energy logging, and non-critical applications where slight deviations in energy measurement do not compromise system performance.

However, the results clearly show that the PZEM-004T is not suitable for precision-critical applications such as utility billing or industrial energy accounting, where meter accuracy standards typically require errors of less than 1%. The recorded errors between 8% and 10% at higher loads exceed the acceptable range for any billing-related application. Nonetheless, for applications involving IoT-based monitoring, appliance energy profiling, and household energy tracking, the level of accuracy demonstrated by the meter, particularly at low to moderate loads, is considered adequate.

In conclusion, the experimental results confirm that the data obtained during the study were suitable for evaluating the performance of the PZEM-004T module under controlled resistive load conditions. The tests also provide meaningful insights into the operational characteristics of the meter. While the device demonstrates high efficiency and good precision at lower loads, its performance deteriorates as the load power increases. The implications of these findings highlight the need for calibration adjustments or correction factors if the PZEM-004T is to be used in applications demanding higher accuracy. Overall, the module is well suited for general energy monitoring tasks but falls short of the accuracy required for metering applications governed by strict regulatory standards.

4.5 Calculations

The essential calculations to consider include the following:

1. Power (W): Power is defined as the product of voltage and current. It can be categorized into different types apparent power (kVA), true or active power (kW), and reactive power (kVAR) each representing different aspects of electrical energy flow.

2. Energy (kWh): Energy represents the total electrical consumption of a load or a group of loads over time. It is calculated as the product of power (in watts) and time (in seconds):

$$E = \text{Power (W)} \times \text{Time (s)}$$

To convert this value to kilowatt-hours (kWh), the result is divided by 3,600,000, since one kilowatt-hour equals 3.6 million joules:

$$E(\text{kWh}) = \frac{\text{Power (W)} \times \text{Time (s)}}{3{,}600{,}000}$$

Power Factor (PF): The power factor is the cosine of the phase angle (ϕ) between voltage and current, expressed as $\cos\phi$. It indicates how effectively electrical power is being converted into useful work. The relationship for active power is given by: $P = V \times I \times \cos\phi$ where $P$is the active power in watts, $V$is voltage, $I$is current, and $\cos\phi$is the power factor.

Fig 4.25: complete system

4.6 Equipment used

1 **Multimeter:** Digital multimeter is a key tool for troubleshooting and verifying electrical connections. It allows you to measure voltage, current, and resistance to ensure your circuit is functioning correctly. For example, you likely used the multimeter to check the voltage supply to the dc battery, the voltage reaching the 2- pin connectors, and buck converter.

Fig 4.26: Multimeters

2 **Pliers:** Pliers are crucial for gripping, bending and cutting wires during the wiring process of ghost switch. They are especially useful for stripping wires to expose the conductive material before connecting them to the Arduino or other components. Pliers also help secure wires into connectors, ensuring a tight and reliable fit. They are indispensable when working with small or hard to-reach parts, providing precision and control during assembly.

Fig 4.27: Plier

4.7 Cost Analysis

Table 4.7: Bill of Engineering Measurement and Evaluation

S/N	Materials and Components	Cost (In Naira)
1	ESP32 DEV BOARD	12,000
2	PZEM-004T	14,000
3	LM2596 DC-DC BULK CONVERTER	4,500
4	20X4 LCD WITH 12C MODULE	9,000
5	3.7V LITHIUM BATTERY	15,000
6	PERFORATED BOARD	5,000
7	FEMALE HEADER PINS	1,000
8	CAPACITOR	800
9	SWITCH	500
10	12V DC JACK	500
11	INE5804 DIODE	200
12	CASING	6,000
13	GLUE	1,000
	TOTAL	69,500

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The study successfully designed, implemented, and evaluated a low-cost IoT-enabled smart electricity meter that meets modern energy management requirements. By integrating the ESP32 Dev Module with high-precision PZEM-004T sensors and leveraging ThingSpeak cloud analytics, the system bridges the gap between affordability and intelligence in energy monitoring technology.

The findings confirm that IoT-based smart metering can deliver precise, real-time, and transparent energy data while maintaining affordability for mass deployment in developing economies. The ESP32 microcontroller's superior computational capability, coupled with Wi-Fi/GSM dual-mode communication, enhances system responsiveness and coverage.

The study also, tested the performance of the meter under different purely resistive loads with varying operating durations, with emphasis on the resulting measurement error. The system developed for the research successfully captured time-dependent variations in percentage error for four load types: a 30 W soldering iron, a 60 W soldering iron, a 60 W bulb, and a 100 W bulb. The analysis revealed that measurement error is not constant but evolves as the load approaches thermal and electrical equilibrium. Specifically, low-power heating devices demonstrated gradual stabilization and declining error, whereas lighting loads exhibited increasing error trends attributed to temperature-induced resistance changes in their filaments. These findings confirm that the accuracy of load monitoring systems is strongly influenced by both the inherent characteristics of the load and the duration of operation.

The results obtained demonstrate that electrical loads exhibit dynamic error profiles governed by thermal behavior, material properties, and operating conditions. Resistive heating elements stabilize

more predictably than lighting devices, which show progressive drift as temperature rises. The monitoring system developed in this study proved effective in capturing these variations and in illustrating the relationship between load rating, operating time, and measurement accuracy. The research therefore underscores the necessity of incorporating time-dependent error analysis into the design and calibration of electrical monitoring systems.

5.2 Recommendations

To strengthen measurement reliability, it is recommended that future versions of the system incorporate automatic temperature-compensation techniques and higher-precision sensing components. Advanced signal-processing methods such as adaptive filtering would further reduce noise and drift. For broader applicability, the system could be enhanced with wireless data acquisition and real-time analytics.

Further research should examine a wider range of load categories, including inductive and capacitive devices, and evaluate the influence of environmental variables such as ambient temperature, humidity, and supply-voltage fluctuations. The development of predictive models potentially leveraging machine-learning approaches would also provide a more robust framework for anticipating and compensating for error under diverse operating conditions.

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Appendix

Lines of code for setting up the ESP32 Dev board Micro-controller;

```
#include <PZEM004Tv30.h>

#include <Wire.h>

#include <LiquidCrystal_I2C.h>

#include <WiFi.h>

#include <HTTPClient.h>


// ================================

// PZEM configuration (ESP32 RX=16, TX=17)

// ================================

#if defined(ESP32)

PZEM004Tv30 pzem(Serial2, 16, 17);

#else

PZEM004Tv30 pzem(Serial2);

#endif


// ================================

// LCD 20x4 I2C configuration

// ================================

LiquidCrystal_I2C lcd(0x27, 20, 4);
```

```
// ================================

// WiFi credentials

// ================================

const char* ssid = "RedmiA5";

const char* password = "8054652017";


// ================================

// ThingSpeak credentials

// ================================

const char* apiKey = "N8XTJ4CRUSIHRNOL";

const char* server = "http://api.thingspeak.com/update";


// ================================

// Variables

// ================================

unsigned long lastUpload = 0;

const unsigned long uploadInterval = 15000; // 15 seconds minimum for free ThingSpeak


void setup() {

  Serial.begin(115200);
```

```
// Initialize LCD
lcd.init();
lcd.backlight();
lcd.clear();
lcd.setCursor(0, 0);
lcd.print("IOT SMART METER");
lcd.setCursor(0, 1);
lcd.print("Connecting WiFi...");

// Connect WiFi
WiFi.begin(ssid, password);
while (WiFi.status() != WL_CONNECTED) {
  delay(500);
  Serial.print(".");
}
Serial.println();
Serial.println("WiFi Connected!");
lcd.setCursor(0, 2);
lcd.print("WiFi Connected!   ");
delay(1000);
```

```
  lcd.clear();
}

void loop() {
  // Read sensor data
  float voltage   = pzem.voltage();
  float current   = pzem.current();
  float power     = pzem.power();
  float energy    = pzem.energy();
  float frequency = pzem.frequency();
  float pf        = pzem.pf();

  // Replace NaN with 0 to avoid junk display
  if (isnan(voltage))   voltage = 0;
  if (isnan(current))   current = 0;
  if (isnan(power))     power = 0;
  if (isnan(energy))    energy = 0;
  if (isnan(frequency)) frequency = 0;
  if (isnan(pf))        pf = 0;

  // ===== Update LCD in real time =====
```

```
lcd.setCursor(0, 0);
lcd.print("V:"); lcd.print(voltage, 1); lcd.print("V ");
lcd.print("I:"); lcd.print(current, 2); lcd.print("A  ");

lcd.setCursor(0, 1);
lcd.print("P:"); lcd.print(power, 1); lcd.print("W ");
lcd.print("PF:"); lcd.print(pf, 2); lcd.print("    ");

lcd.setCursor(0, 2);
lcd.print("E:"); lcd.print(energy, 3); lcd.print("kWh       ");

lcd.setCursor(0, 3);
lcd.print("F:"); lcd.print(frequency, 1); lcd.print("Hz        ");

// ===== Debug output to Serial =====
Serial.print("V: "); Serial.print(voltage);
Serial.print(" | I: "); Serial.print(current);
Serial.print(" | P: "); Serial.print(power);
Serial.print(" | E: "); Serial.print(energy);
Serial.print(" | F: "); Serial.print(frequency);
Serial.print(" | PF: "); Serial.println(pf);
```

```
// ===== Upload to ThingSpeak every 15 seconds =====
if (millis() - lastUpload >= uploadInterval) {
  lastUpload = millis();
  if (WiFi.status() == WL_CONNECTED) {
    HTTPClient http;
    String url = String(server) + "?api_key=" + apiKey +
                 "&field1=" + String(voltage, 1) +
                 "&field2=" + String(current, 2) +
                 "&field3=" + String(power, 1) +
                 "&field4=" + String(energy, 3) +
                 "&field5=" + String(frequency, 1) +
                 "&field6=" + String(pf, 2);

    http.begin(url);
    int httpCode = http.GET();
    if (httpCode > 0) {
      Serial.println("ThingSpeak updated. Code: " + String(httpCode));
    } else {
      Serial.println("ThingSpeak upload failed");
    }
```

```
    http.end();
  } else {
    Serial.println("WiFi disconnected. Reconnecting...");
    WiFi.begin(ssid, password);
  }
 }

 delay(500);  // Fast refresh for LCD
}
```