IoT-Enabled Real-Time Energy Monitoring System For Efficient Power Management And Predictive Maintenance

Project Report

Submitted in Partial Fulfilment of the Requirements for the Award of Degree of

Bachelor of Technology

in

COMPUTER SCIENCE AND ENGINEERING

By

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SASI INSTITUTE OF TECHNOLOGY & ENGINEERING

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ACADEMIC YEAR 2024-2025

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MISSION

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2. To enhance scientific temper through active research leading to innovations & sustainable environment.
3. To create responsible citizens with highest ethical standards.

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MISSION

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3. To produce professionals with a sense of strong values and ethics.

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Students in the Computer Science and Engineering program should, at the time of their graduation be in possession of:

PO1 Engineering Knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

PO2 Problem Analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics natural sciences, and engineering sciences.

PO3 Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental.

PO4 Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valued conclusion.

PO5 Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

PO6 The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

PO7 Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contest and demonstrate knowledge of and need for development.

PO8 Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO9 Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams and in multi-disciplinary settings.

PO10 Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

PO11 Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

PROGRAM EDUCATIONAL OBJECTIVE S (PEOs)

1. Graduates will enhance workplace contributions by creating sophisticated computer applications that address the dynamic requirements of society.
2. Graduates will be research oriented and industry ready professionals with a sense of intellectual and social commitment.
3. Graduates will be highly professional with unquestionable integrity and ethics.

COURSE OUTCOMES (Cos)

CO1. Develop problem formation and design skills for engineering and real- world problems.

CO2. Collect and Generate ideas through literature surveys on current research areas which help to analyze and present to impart knowledge in different fields.

CO3. Impart knowledge of software & hardware to meet industry perspective needs and standards.

CO4. Create interest to research innovative ideas as lifelong learning.

CO5. Ability to work with a team and enrich presentation and communication skills.

CO6. Create a platform that makes students employable.

EXPECTED OUTCOMES

PROGRAM OUTCOMES (POs)

PO1: Engineering Knowledge

PO2: Problem Analysis

PO3: Design/Development of Solutions

PO4: Investigate complex problems.

PO5: Modern Tool Usage

PO6: The Engineer and Society

PO7: Environment and Sustainability

PO8: Ethics

PO9: Individual Teamwork

PO10: Communication

PO11: Project Management and Finance

PROGRAM SPECIFIC OUTCOMES (PSOs)

1. Apply modern tools to analyze, design and develop computer programs/applications across diverse domains, addressing sustainability issues in society.

2. Ability to work as team in project management by professional communication and ethics.

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CERTIFICATE

*This is to certify that the project work entitled "**IOT-ENABLED REAL-TIME ENERGY MONITORING SYSTEM FOR EFFICIENT POWER MANAGEMENT AND PREDICTIVE MAINTENANCE**" is being submitted by **T. NAGA SWATHI (21K61A05G8), M. SRAVANTHI (22K65A0513), M. NAGALAKSHMI (21K61A0598), S.VAMSI KRISHNA (21K61A05E3)** in partial fulfilment for the award of the degree of **BACHELOR OF TECHNOLOGY**, in **Computer Science and Engineering** affiliated to Jawaharlal Nehru Technological University, Kakinada during the academic year 2024 to 2025 is a record of Bonafide work carried out by them under my guidance and supervision. The results presented in this thesis have been verified and are found to be satisfactory. The results embodied in this thesis have not been submitted to any other University or Institute for the award of any other degree or diploma.*

Project Supervisor	**Head of the Department**
Dr. A. V. S. Siva Rama Rao	Dr. M. V. S. S. Nagendranath
Professor & HoD	Professor & HoD
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DECLARATION BY THE CANDIDATES

We **T. Naga Swathi, (21K61A05G8), M. Sravanthi, (22K65A0513), M. Nagalakshmi, (21K61A0598), S. Vamsi Krishna, (21K61A05E3)**, hereby declare the project report entitled "**IoT-Enabled Real-Time Energy Monitoring System For Efficient Power Management And Predictive Maintenance**", carried out under esteemed supervision of **Dr. A. V. S. Siva Rama Rao**, is submitted in partial fulfilment of the requirements for the award of the degree of **Bachelor of Technology** in **Computer Science & Engineering**. This is a record of work carried out by us and the results embodied in this project has not been reproduced or copied from any source. The results embodied in this project report have not been submitted to any other University or Institute for the award of any other degree or diploma.

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ABSTRACT

The rapid advancement of the Internet of Things (IoT) has enabled real-time energy monitoring and analysis, enhancing efficiency in power management systems. This paper presents an IoT- based energy monitoring system utilizing the ESP32 microcontroller, PZEM-004T energy meter, and DHT-11 sensor for temperature and humidity measurement. The system is designed using the Arduino IDE and programmed in Arduino C to ensure seamless integration and real-time data acquisition. Electrical parameters such as voltage, current, power, and energy consumption are continuously monitored and transmitted to cloud platforms for visualization and analysis. Experimental results demonstrate the system's ability to accurately measure and analyze energy consumption patterns. The proposed system supports predictive maintenance and is highly applicable in industrial and smart grid environments.

KEYWORDS : INTERNET OF THINGS (IOT), ENERGY MONITORING, ESP32 MICROCONTROLLER, PZEM-004T ENERGY METER, REAL-TIME DATA ACQUISITION, POWER MANAGEMENT, ENERGY CONSUMPTION ANALYSIS

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With Gratitude,

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NOMENCLATURE

LIST OF ABBREVIATIONS

- **IoT:** Internet of Things
- **ESP:** Espressif Systems Platform
- **DHT:** Digital Humidity and Temperature
- **PIR:** Passive Infrared
- **LCD:** Liquid Crystal Display
- **LED:** Light Emitting Diode
- **API:** Application Programming Interface
- **MCU:** Microcontroller Unit
- **Wi-Fi:** Wireless Fidelity

CHAPTER 1

INTRODUCTION

1.1 PREAMBLE

People Energy is a fundamental necessity in modern society, playing a crucial role in residential, commercial, and industrial sectors. As the demand for electricity continues to rise, monitoring and managing energy consumption has become a significant challenge. Electrical faults such as voltage fluctuations, power surges, excessive current flow, or sudden energy drops can lead to severe consequences, including equipment damage, increased electricity costs, and fire hazards.

Traditional energy meters provide only basic power readings, lacking the ability to detect real-time faults or predict electrical anomalies. The absence of automated fault detection makes it difficult to identify overvoltage, overcurrent, power factor variations, and energy fluctuations, which can compromise efficiency and safety.

The rapid advancement of Internet of Things (IoT) technology has transformed energy monitoring systems by enabling real-time data collection, remote accessibility, and intelligent fault detection. By integrating smart sensors, cloud computing, and data analytics, IoT-based solutions provide a real-time, data-driven approach to monitoring electrical parameters and identifying faults as they occur.

This project, IoT-Enabled Real-Time Energy Monitoring System for Efficient Power Management and Predictive Maintenance, aims to develop a real-time IoT-based system using ESP32, PZEM004T, and DHT sensors, along with cloud-based storage and visualization tools. The system continuously tracks voltage, current, power, frequency, power factor, temperature, and humidity, while detecting anomalies and triggering automated alerts for immediate response. By leveraging IoT and cloud technology, this system enhances energy monitoring efficiency, fault detection accuracy, and user accessibility.

1.2 OVERVIEW OF THE PROJECT

This project explores the development of an advanced IoT-driven energy monitoring and analysis system, leveraging smart sensors, microcontrollers, and cloud computing to optimize energy management. The primary objective of this project is to design a smart energy monitoring framework that collects, analyzes, and visualizes real-time power parameters while incorporating machine learning models for predictive analytics and anomaly detection.

The project begins with a comprehensive review of existing energy monitoring systems, discussing the strengths and limitations of traditional methods and identifying gaps that require innovative solutions. Key challenges, such as inefficient energy consumption, unexpected power failures, and lack of real- time insights, highlight the need for an integrated IoT and AI-based approach to energy management.

A major focus is on the collection, curation, and preprocessing of energy data from sensors measuring voltage, current, power, frequency, and power factor. The system leverages ESP32 microcontrollers and PZEM004T energy meters, along with cloud platforms such as Firebase, AWS, and Thingspeak, to enable remote access, real-time data storage, and visualization through interactive dashboards.

At the core of this system lies advanced data processing and feature extraction techniques, such as power quality analysis and time-series forecasting, to capture critical variations in energy consumption. The project utilizes machine learning and deep learning algorithms—including regression models, decision trees, convolutional neural networks (CNNs), and long short-term memory (LSTM) networks—to predict power failures, detect anomalies, and recommend energy-saving strategies. Special attention is given to optimizing model parameters to enhance detection accuracy and minimize false alerts.

The anticipated outcome of this project is a scalable, real-time energy monitoring system capable of optimizing power usage in residential, commercial, and industrial settings. By integrating IoT, cloud computing, and AI-driven predictive analytics, this system will empower users with actionable insights to enhance efficiency, reduce electricity costs, and contribute to sustainable energy management. Additionally, it aligns with smart city initiatives, enabling municipalities to optimize public energy usage in street lighting, transportation hubs, and public buildings, leading to improved energy distribution and cost savings.

Through this work, we aim to contribute valuable innovations to the field of energy analytics, providing a cost-effective, data-driven solution for modern power management challenges. This project also explores real-time anomaly detection to identify irregularities like overvoltage, overcurrent, and abnormal power factor, triggering instant alerts via SMS, email, or notifications. Additionally, renewable energy integration is considered, optimizing solar and wind power usage.

The proposed system is a real-time IoT-based energy monitoring solution that uses ESP32 for data acquisition, PZEM004T for measuring voltage, current, power, frequency, and power factor, DHT Sensor for monitoring temperature and humidity, and a Transformer Coil for regulating and measuring electrical parameters.

It detects power-related anomalies such as overvoltage, overcurrent, and power factor variations. A dashboard displays real-time data, while integration with cloud platforms like Firebase or AWS enables remote monitoring, historical data storage, and anomaly detection. The system generates graphical visualizations to analyze power usage patterns, making it ideal for residential, commercial, and applications.

1.3 BACKGROUND STUDY OF ENERGY MONITORING SYSTEM

It detects power-related anomalies such as overvoltage, overcurrent, and power factor variations. A dashboard displays real-time data, while integration with cloud platforms like Firebase or AWS enables remote monitoring, historical data storage, and anomaly detection. The system generates graphical visualizations to analyze power usage patterns, making it ideal for residential, commercial, and applications.

The rapid advancements in Internet of Things (IoT), cloud computing, and machine learning (ML) have significantly impacted the energy sector, revolutionizing how energy consumption is monitored, analyzed, and optimized. Traditional energy management systems often suffer from inefficiencies, lack of real-time monitoring, and limited analytical capabilities. However, the integration of smart sensors, IoT devices, and AI-driven analytics has paved the way for intelligent energy monitoring solutions that enhance efficiency, reduce waste, and improve sustainability.

Traditional energy monitoring systems often rely on manual meter readings and periodic audits, leading to inefficiencies such as delayed fault detection, energy wastage, and higher operational costs. Without real-time monitoring, detecting anomalies like overvoltage, overcurrent, and abnormal power factors becomes challenging, increasing the risk of equipment failures and energy inefficiencies.

Additionally, data silos in conventional systems restrict access to historical energy usage patterns, making it difficult to implement predictive analytics and proactive energy management strategies. Moreover, industries and businesses often struggle with unexpected power outages and peak demand fluctuations, further emphasizing the need for an automated, real-time energy tracking system. To address these limitations, IoT- based energy monitoring systems have emerged as a transformative solution.

These systems incorporate advanced components such as:

Smart sensors and IoT devices: ESP32 microcontrollers and IoT-enabled energy meters provide real-time power consumption data. Cloud storage and remote access: Platforms like Firebase, AWS, and ThingSpeak facilitate data storage, remote access, and visualization through interactive dashboards.AI and Machine Learning: Predictive analytics using regression models, decision trees, and time-series analysis enable early anomaly detection and optimization of power consumption.

The project employs advanced ML algorithms to analyze energy usage patterns and detect potential faults. Techniques such as anomaly detection, clustering, and predictive analytics help identify inefficiencies, suggest corrective actions, and optimize energy consumption dynamically. Moreover, AI-driven models can forecast energy demand, allowing for better planning and reduced operational costs. Furthermore, integrating edge computing ensures that real-time processing of energy data occurs closer to the source, reducing latency and network congestion.

By deploying automated alert systems via SMS, email, or notifications, users can receive instant warnings about abnormal power consumption, helping prevent equipment damage and energy loss. With growing concerns about climate change and sustainability, optimizing energy usage is essential. IoT-driven energy monitoring supports government regulations aimed at reducing carbon footprints by promoting efficient energy utilization. Additionally, industries can leverage this system to comply with energy efficiency standards, ensuring better resource management and cost savings.

However, the adoption of smart energy monitoring systems raises challenges related to data security, privacy, and infrastructure scalability.This project aims to develop a scalable, real-time IoT-driven energy monitoring system that enhances energy efficiency, ensures electrical safety, and optimizes power consumption. By integrating IoT, cloud computing, and AI-driven analytics, the system provides an innovative solution for residential, commercial, and industrial applications.

The research will focus on improving detection methodologies, predictive analytics, and real-time alerts, ultimately contributing to a sustainable and energy-efficient future.,Energy consumption has been a critical factor in the development of modern society. With the increasing demand for electricity in residential, commercial, and industrial sectors, efficient power management has become a necessity.

Traditional energy meters provide only basic power readings without offering insights into consumption patterns, real-time fault detection, or predictive analysis. This limitation often leads to inefficiencies, unnecessary power wastage, and increased electricity costs. The advent of Internet of Things (IoT) technology has revolutionized the way energy monitoring is conducted, enabling real-time data collection, cloud-based storage, and intelligent analytics for better decision-making.

The conventional methods of energy monitoring involve manual readings from analog or digital meters, which lack automation and remote accessibility. This results in delayed fault detection, inefficient power distribution, and an inability to take proactive measures against power anomalies. In industries, undetected faults such as voltage fluctuations, excessive current flow, and power surges can lead to equipment failures, production downtime, and safety hazards. These challenges highlight the need for a smart, automated, and real-time energy monitoring system that integrates IoT and cloud computing technologies.

IoT-based energy monitoring systems provide a significant improvement over traditional methods by incorporating sensors, microcontrollers, and communication modules to gather and transmit real-time data. The use of IoT-enabled devices such as the ESP32 microcontroller and PZEM004T energy meter allows for continuous monitoring of key electrical parameters, including voltage, current, power, frequency, and power factor. The data collected is processed and transmitted to cloud platforms, where it can be stored, analyzed, and visualized for further insights. This enables users to access energy consumption data remotely, receive alerts on anomalies, and take immediate corrective actions.

1.3.1 Definition and Mechanism

IoT-driven energy monitoring and data analysis is an advanced system designed to track, analyze, and optimize power consumption in real-time. By integrating IoT technology, cloud computing, and data analytics, this system provides valuable insights into energy usage patterns, enhances efficiency, and detects potential faults. The primary objective is to offer real-time monitoring of electrical parameters such as voltage, current, power, frequency, and power factor, enabling effective energy management.

The mechanism involves IoT-enabled hardware components such as ESP32 microcontroller, PZEM004T energy meter, and various sensors that continuously collect data on power consumption. These sensors measure critical electrical parameters and transmit data to the cloud using wireless communication protocols such as Wi-Fi and MQTT. The collected data is stored in a cloud platform, allowing users to access it remotely via dashboards and mobile applications.

The system consists of ESP32 microcontroller, PZEM004T energy meter, DHT sensor, and a transformer coil, all of which collect real-time energy data. Using Wi-Fi and MQTT protocols, the data is transmitted to cloud platforms like Firebase or AWS, where it is stored and analyzed. Users can remotely access this data via interactive dashboards or mobile applications for real-time visualization.

1.3.2 The Rise of IoT-Based Energy Monitoring

The rapid advancement of Internet of Things (IoT) technology has revolutionized how energy consumption is monitored, analyzed, and optimized. Traditional energy meters provide only basic readings of power usage, offering limited insights into energy efficiency and fault detection. However, with IoT integration, energy monitoring systems can now offer real-time data collection, remote accessibility, and predictive analytics, leading to smarter and more efficient energy management across residential, commercial, and industrial sectors.

The rise of IoT-based energy monitoring can be attributed to the increasing demand for energy conservation, cost reduction, and sustainability. With the help of smart sensors, cloud computing, and data analytics, IoT-driven systems allow for continuous tracking of electrical parameters such as voltage, current, power factor, and frequency. This enables early detection of anomalies such as overvoltage, overcurrent, and inefficient energy usage, preventing potential equipment failures and reducing operational downtime. Additionally, integrating machine learning models into IoT-based monitoring systems helps identify patterns in energy consumption, predict faults, and recommend energy- saving measures.

Unlike traditional energy management techniques that rely on manual readings and periodic inspections, IoT-based solutions enable automated, real-time monitoring with minimal human intervention. These systems provide users with a cloud-based dashboard where they can visualize historical trends, set energy consumption alerts, and even control connected devices remotely. Such advancements not only improve energy efficiency but also support sustainability goals by promoting optimal energy utilization and reducing carbon footprints. As the adoption of IoT-powered energy monitoring systems grows, challenges such as data security, scalability, and system integration must be addressed. Ensuring secure data transmission, protecting against cyber threats, and designing cost-effective deployment models will play a crucial role in the widespread adoption of this technology.

1.3.3 Challenges in Implementation

The integration of IoT for real-time energy monitoring presents several challenges that must be addressed for efficient deployment and operation. These challenges include:

1.3.3.a Data Security and Privacy

IoT-based energy monitoring systems collect and transmit vast amounts of data related to power usage and device performance. This information is often stored in cloud databases, making it vulnerable to cyber threats and unauthorized access. Ensuring end-to-end encryption, secure authentication mechanisms, and regular security updates is crucial to prevent data breaches and maintain user trust.

1.3.3.b Scalability and Cost Constraints

IoT-based energy monitoring systems offer significant advantages, scalability remains a major concern. Deploying these systems across large industrial facilities or urban infrastructures requires robust networking capabilities, high storage capacity, and efficient data processing. Additionally, the cost of IoT sensors, communication modules, and cloud services can be a barrier to widespread adoption, particularly for small-scale users.

1.3.4 Current Monitoring Methodologies

With advancements in IoT and data analytics, modern energy monitoring methodologies have evolved significantly. Some of the primary approaches include:

1.3.4.a Traditional Energy Monitoring

Traditional energy monitoring relies on manual meter readings and periodic inspections. These methods lack real-time tracking, making it difficult to identify energy inefficiencies and faults immediately. As a result, energy wastage and system failures often go unnoticed until a physical inspection or routine check is conducted.

1.3.4.b IoT-Based Smart Energy Monitoring

IoT-based solutions enhance traditional monitoring by incorporating real-time sensors, wireless communication, and cloud computing. These systems collect data from multiple sensors and transmit it to a centralized cloud platform, where users can monitor consumption patterns through an interactive dashboard. Alerts and notifications are triggered when abnormal power usage or faults are detected, enabling quick corrective actions.

1.3.4.c Machine Learning-Driven Analytics

The integration of machine learning algorithms in energy monitoring has further improved efficiency by enabling predictive analysis and anomaly detection. By analyzing historical energy usage data, ML models can forecast potential issues such as equipment failures or power surges.

1.3.4.d Emerging Techniques

New advancements in IoT energy monitoring include edge computing, hybrid cloud systems, and blockchain-based energy transactions. Edge computing allows data to be processed closer to the source, reducing latency and enhancing real-time decision-making. Blockchain technology is also being explored for secure energy transactions in smart grids, ensuring transparency and preventing unauthorized access to power systems.

As IoT-based energy monitoring continues to evolve, its adoption will significantly contribute to efficient energy utilization, cost savings, and a more sustainable future. However, addressing key challenges related to security, scalability, and hardware reliability remains essential for maximizing its benefits.

1.4 PROBLEM STATEMENT

Energy consumption is a critical aspect of modern infrastructure, spanning residential, commercial, and industrial domains. Traditional energy monitoring methods rely on manual meter readings and periodic inspections, which are inefficient, prone to errors, and lack real-time insights. This outdated approach results in excessive energy consumption, unnoticed electrical faults, increased operational costs, and potential safety hazards. With the rising demand for efficient energy management, there is an urgent need for a smarter, automated, and data- driven solution.

The increasing reliance on electrical appliances and industrial machinery has led to growing energy demands, often resulting in unnecessary power wastage and equipment overloading.

Inefficient power usage directly contributes to high electricity bills, excessive carbon emissions, and premature degradation of electrical components. Additionally, electrical faults such as overvoltage, overcurrent, and low power factor often go unnoticed until significant damage occurs, leading to unexpected downtime, financial losses, and safety risks. Without an automated system to monitor, analyze, and predict energy consumption patterns, organizations struggle to prevent failures, reduce costs, and optimize energy distribution effectively.

With advancements in Internet of Things (IoT) technology, real-time energy monitoring systems can be implemented to track key electrical parameters, including voltage, current, power factor, frequency, and energy consumption. However, existing IoT-based solutions often lack scalability, security, and advanced analytics to provide actionable insights. Current monitoring systems either focus on data collection without predictive analysis or provide limited user interaction and control. A comprehensive solution is required that not only monitors energy consumption in real- time but also analyzes historical trends, predicts potential failures, and provides recommendations for energy efficiency.

Furthermore, data security and privacy are major concerns in IoT-driven energy monitoring systems. Since these systems rely on cloud storage for data processing and visualization, they become vulnerable to cyber threats, unauthorized access, and data manipulation. Ensuring secure data transmission, encrypted communication, and access control mechanisms is essential for protecting sensitive energy usage information from potential cyber-attacks.

Another challenge in implementing IoT-driven energy monitoring systems is cost and scalability. Many solutions require high initial investments in hardware and cloud infrastructure, making them inaccessible for small-scale consumers. Additionally, integrating IoT sensors with existing electrical systems requires technical expertise and seamless compatibility with diverse appliances and industrial machinery. A cost-effective, scalable, and user-friendly system is necessary to enable widespread adoption of energy monitoring solutions across different sectors.

The proposed project, ―IoT-Driven Energy Monitoring and Data Analysis,It aims to address these challenges by developing a real-time, cloud-connected energy monitoring system using ESP32, PZEM004T energy sensors, and machine learning-based analytics. This system will continuously track power consumption, detect anomalies, generate alerts, and provide predictive insights to optimize energy usage. The integration of a cloud-based dashboard will allow users to visualize data trends, receive energy-saving recommendations, and remotely monitor their electrical systems. By ensuring data security, cost-effectiveness, and scalability, this project will contribute to efficient energy management, reduced operational costs, and enhanced electrical safety for both residential and industrial applications.

1.5 AIM OF THE PROJECT

The aim of this project, IoT-Driven Energy Monitoring and Data Analysis, is to develop an advanced energy monitoring system that provides real-time tracking, analysis, and optimization of energy consumption using IoT technology. The system will leverage ESP32, PZEM004T energy sensors, and cloud computing to monitor key electrical parameters such as voltage, current, power factor, frequency, and energy consumption. By integrating machine learning-based analytics, the project aims to identify patterns in power usage, detect anomalies, and predict potential failures to enhance energy efficiency and reduce costs.

The primary objective is to enable users to remotely monitor their energy consumption through a cloud-based dashboard, allowing them to gain valuable insights into their power usage patterns. The system will provide real-time alerts in case of electrical abnormalities such as overvoltage, overcurrent, or sudden energy fluctuations, helping prevent equipment damage, power wastage, and safety hazards.

Furthermore, this project seeks to develop a scalable, cost-effective, and user- friendly solution suitable for residential, commercial, and industrial applications. By integrating IoT, cloud computing, and data analytics, the system will empower users to make data-driven decisions, optimize energy consumption, and contribute to a more sustainable and efficient energy management system.

1.6 OBJECTIVE OF THE PROJECT

The primary objective of this project, IoT-Driven Energy Monitoring and Data Analysis, is to design and implement an intelligent energy monitoring system that provides real-time data collection, analysis, and visualization. By leveraging IoT technology, cloud computing, and data analytics, the system aims to enhance energy efficiency, reduce costs, and improve electrical safety.

One of the key objectives is to monitor essential electrical parameters such as voltage, current, power factor, frequency, and energy consumption using IoT- enabled sensors like ESP32 and PZEM004T. The system will continuously collect and transmit data to a cloud-based platform, ensuring remote accessibility and real-time tracking of power usage.

Another important goal is to detect energy anomalies, including overvoltage, overcurrent, and abnormal power factors, which can lead to equipment damage and energy wastage. The system will generate instant alerts and notifications, enabling users to take preventive actions.

Additionally, the project aims to integrate machine learning algorithms for pattern recognition and predictive analysis, allowing users to identify inefficient energy consumption trends and potential failures before they occur. By providing a scalable and cost-effective solution, this project will benefit residential, commercial, and industrial applications, promoting energy conservation and sustainability.

1.7 PROPOSED METHODOLOGY

The proposed methodology for IoT-Driven Energy Monitoring and Data Analysis involves the development of an intelligent system that continuously monitors electrical parameters, stores data in the cloud, and provides analytical insights for energy optimization. The system integrates IoT sensors, cloud computing, and machine learning to achieve real-time energy tracking and anomaly detection.

The process begins with hardware deployment, where IoT-enabled sensors like ESP32 and PZEM004T are used to measure voltage, current, power factor, and frequency. These sensors collect real-time data and transmit it to a central microcontroller, which processes and forwards the data to a cloud platform using Wi- Fi connectivity. The cloud storage enables remote access and historical data analysis.

A web-based or mobile dashboard will be developed for users to visualize energy consumption trends and receive alerts for abnormal power usage. Machine learning algorithms will be applied to identify energy usage patterns and predict potential faults or inefficiencies. The system will generate automated alerts in case of overvoltage, overcurrent, or power fluctuations, helping users take timely corrective actions. By integrating IoT and cloud-based analytics, the proposed methodology ensures an efficient, scalable, and cost-effective solution for energy monitoring, reducing energy wastage and enhancing electrical safety.

1.8 SIGNIFICANCE OF THE WORK

Patients with various eye conditions, such as cataract, exophthalmia. The significance of this project lies in its ability to revolutionize energy monitoring through IoT-driven real-time data collection and analysis. Traditional energy meters provide only basic readings, making it difficult to identify inefficiencies, prevent electrical hazards, or optimize energy usage. By integrating IoT with cloud computing, this system offers continuous monitoring, remote access, and predictive analytics, leading to enhanced energy efficiency and safety.

One of the key benefits of this project is its capability to detect anomalies such as overvoltage, overcurrent, and abnormal power factors in real time. This helps prevent electrical failures, reduce downtime in industrial settings, and protect appliances from damage. The cloud-based storage ensures that historical data is always available for trend analysis, enabling users to make informed decisions about their energy consumption.

Additionally, incorporating machine learning allows for pattern recognition and predictive maintenance, further minimizing energy waste and operational costs. This system is scalable and adaptable for residential, commercial, and industrial applications, making it a valuable tool for energy-conscious consumers and businesses. By promoting sustainable energy usage and reducing unnecessary power consumption, this project contributes to environmental conservation while improving reliability and cost-effectiveness in energy management.

1.9 ORGANIZATION OF THE REPORT

The remaining portions of the chapter are organized as follows:

Chapter1: This chapter provides an overview of the project, highlighting the importance of energy monitoring in modern systems. It discusses the problem statement, emphasizing the need for real-time energy analysis using IoT. The project goal is defined, outlining the objectives of developing an IoT-driven energy monitoring and data analysis system. The methodology is briefly introduced, explaining how IoT sensors, cloud storage, and data analytics will be integrated to enhance energy efficiency and anomaly detection. The significance of the work is discussed in terms of its applications in residential, commercial, and industrial sectors. The chapter concludes by summarizing the expected outcomes and potential benefits of the proposed system.

Chapter2: This chapter presents a comprehensive review of existing energy monitoring systems and their limitations. It explores various techniques used for real-time energy analysis, comparing traditional monitoring methods with modern IoT-based solutions. The chapter discusses previous research on energy optimization, cloud-based data storage, and anomaly detection techniques. It also evaluates different hardware components and machine learning algorithms used for predictive maintenance in energy systems.

1.10 SUMMARY

The IoT-Driven Energy Monitoring and Data Analysis project focuses on developing a real- time energy monitoring system that enhances efficiency, reduces costs, and prevents electrical hazards. Traditional energy meters lack real-time fault detection and predictive analysis, leading to inefficiencies and potential risks. By integrating IoT technology, cloud storage, and data analytics, this project enables continuous monitoring of key electrical parameters such as voltage, current, power, frequency, and power factor. The system utilizes IoT sensors, including ESP32 and PZEM004T, to collect real-time data, which is then stored in the cloud for further analysis.

CHAPTER 2

LITERATURE SURVEY

2.1 PREAMBLE

The literature survey provides an in-depth review of existing research, methodologies, and technologies related to IoT-driven energy monitoring and data analysis. As energy consumption monitoring becomes increasingly vital for efficiency and cost reduction, various approaches have been explored to integrate IoT, cloud computing, and machine learning for real-time analysis. Traditional energy monitoring systems relied on manual readings and conventional meters, offering limited insights into power usage patterns. However, advancements in IoT have enabled smart meters and sensors to collect real-time data, allowing for detailed analysis and anomaly detection.

Recent studies have focused on leveraging cloud-based storage to handle large volumes of energy data, ensuring seamless accessibility and scalability. Furthermore, machine learning models have been introduced to identify consumption patterns, predict energy usage trends, and detect irregularities that may indicate faults or inefficiencies. Despite these advancements, challenges remain in terms of real-time processing, security, and data accuracy, necessitating further research.

This chapter explores various approaches to energy monitoring, comparing existing systems and highlighting their limitations. By analyzing previous work, this survey identifies research gaps and lays the foundation for developing a robust IoT-based energy monitoring system that integrates cloud computing and advanced data analysis techniques for better efficiency and reliability.

2.2 IOT-BASED ENERGY MONITORING TECHNIQUES

IoT-driven energy monitoring and data analysis is a real-time energy tracking system that utilizes IoT-enabled sensors to monitor power consumption, detect electrical anomalies, and enhance fault prevention mechanisms. The integration of IoT technology, cloud computing, and data analytics allows for continuous data collection and analysis, improving energy management across various applications.

Multiple research studies have explored the implementation of IoT in energy monitoring systems to track voltage, current, power factor, and other key electrical parameters in real time. Various machine learning models and data analytics techniques have been applied to analyze energy consumption patterns and detect anomalies.

Gupta et al. (2020) [10] proposed an IoT-based smart energy monitoring system using ESP32 and multiple sensors for real-time power tracking. Their approach integrates a cloud-based dashboard for visualization and uses threshold-based alerts to warn users about electrical anomalies. The system provides continuous monitoring of voltage, current, power factor, and frequency, ensuring early fault detection and remote accessibility. The study highlights the importance of cloud storage and real-time data retrieval for accurate energy management.

Sharma et al. (2021) [12] introduced a machine learning-enhanced IoT system for predictive energy monitoring. By leveraging historical data and anomaly detection algorithms, the system predicts power failures and voltage fluctuations before they occur. The research demonstrates how cloud-based data storage and AI-driven analytics improve the efficiency and accuracy of energy monitoring systems.

2.2.1 Fault Detection and Anomaly Identification in Energy System

The ability to detect faults such as overvoltage, overcurrent, and power factor variations is critical in energy monitoring systems. Traditional energy meters lack real-time fault detection, leading to delayed responses to electrical failures.

Singh et al. (2019) [14] developed an IoT-integrated fault detection system that uses sensor-driven data acquisition to identify abnormal voltage and current levels. Their approach utilizes remote alerts via cloud platforms, ensuring timely notifications for power anomalies. The study proves the efficiency of real-time energy tracking and anomaly detection using IoT-based monitoring systems.

Ravi et al. (2022) [16] proposed an AI-powered IoT framework for real-time anomaly detection. The system uses deep learning algorithms to analyze energy patterns and classify power-related faults such as short circuits, power surges, and fluctuations. By integrating edge computing and cloud storage, their model improves response time and energy system reliability.

2.2.2 Cloud Integration for Energy Data Storage and Visualization

Cloud platforms play a crucial role in real-time data storage, remote monitoring, and historical trend analysis. The integration of Firebase, AWS, and Thingspeak enables secure access to energy consumption data from any location.

Kumar et al. (2021) [18] introduced an IoT-driven smart grid system that integrates cloud computing for large-scale energy monitoring. Their system collects real-time power data, stores it on Firebase, and visualizes trends through interactive dashboards. The research highlights how cloud integration enhances energy monitoring efficiency and improves fault detection accuracy.

Patel et al. (2023) [20] explored visual analytics for IoT-based energy monitoring, demonstrating how graphical representations and predictive insights improve energy efficiency and reduce power wastage. Their study suggests that AI-based visual analytics on cloud platforms can significantly enhance decision-making in power management systems.

2.2.3 Applications and Benefits of IoT-Based Energy Monitoring

IoT-based energy monitoring systems offer numerous advantages, including real-time fault detection, remote accessibility, and predictive maintenance. The ability to track voltage, current, and power factor variations ensures safer and more efficient energy consumption.

By implementing IoT-driven energy monitoring and data analysis, this research contributes to enhancing electrical safety, improving fault detection accuracy, and optimizing power usage across different sectors.

The key benefit of the suggested system is that mobile devices are lightweight and may be utilized with the camera to detect objects in the environment and output the information in audio format. assisting those who are blind to "See Through the Ears." As a result, it aids in avoiding potential mishaps.

2.3 REAL-TIME MONITORING USING IOT

The integration of IoT technology in energy monitoring has significantly improved real-time tracking of electrical parameters, ensuring better fault detection, remote accessibility, and predictive maintenance. Traditional energy meters provide only basic readings, making it difficult to identify faults, track historical trends, or predict power failures before they occur. By combining IoT sensors, cloud computing, and data analytics, modern energy monitoring systems enable continuous power tracking, anomaly detection, and real-time insights through interactive dashboards. These advancements help users optimize energy consumption, prevent electrical failures, and ensure the safety and reliability of power systems. The use of IoT-based solutions eliminates the need for manual monitoring and allows for automated analysis of electrical parameters, making energy management more efficient.

Several researchers have explored IoT-based solutions for improving energy monitoring efficiency. Patil et al. (2020) proposed an IoT-driven smart energy monitoring system that utilizes ESP32, cloud storage, and sensors to track voltage, current, power, frequency, and power factor in real-time. Their system is capable of detecting overvoltage and overcurrent anomalies, preventing electrical failures. The collected data is stored in cloud platforms, enabling users to analyze historical trends and take preventive measures. Similarly, Gupta et al. (2021) introduced an AI- powered IoT system that integrates machine learning algorithms with real-time power monitoring. Their model predicts power failures before they occur by analyzing past consumption patterns, improving energy management and fault prevention. The integration of machine learning with IoT makes it possible to identify patterns in energy usage, providing valuable insights for reducing energy waste and optimizing system performance.

Fault detection and anomaly identification play a crucial role in IoT-driven energy monitoring. Electrical anomalies such as overvoltage, excessive current flow, and power factor variations can lead to serious safety hazards and equipment damage. Sharma et al. (2019) developed a sensor-based fault detection system capable of identifying these anomalies in real-time. Their system integrates wireless communication, allowing automated alerts to be sent to users whenever irregularities are detected. The ability to receive real-time alerts enables users to take immediate action to prevent potential failures.

Singh et al. (2022) enhanced anomaly detection by using deep learning models with IoT-enabled power sensors trained to recognize patterns in voltage fluctuations and short circuits. Their approach improves fault detection accuracy, minimizing downtime and preventing damage to electrical systems. The use of deep learning in energy monitoring increases the system's ability to detect even minor deviations in electrical parameters, ensuring proactive maintenance and increased reliability.

Cloud platforms such as Firebase, AWS, and Thingspeak have transformed energy monitoring by offering secure, remote access to energy consumption data, allowing users to monitor real-time power usage, track historical trends, and optimize fault detection mechanisms. Rajesh et al. (2021) developed a real-time cloud-based energy tracking system that stores energy data and visualizes consumption trends through interactive dashboards. Their approach enhances data accessibility and energy efficiency analysis, enabling users to make informed decisions about power management. Kumar et al. (2023) further expanded on this by introducing graphical analytics for IoT-based energy monitoring, demonstrating how data-driven insights improve power failure prediction and efficiency monitoring. Cloud-based solutions provide a scalable and cost-effective way to manage large amounts of energy data, making it easier to monitor multiple locations from a single platform. The ability to access energy data remotely from any device ensures that users can stay informed about their energy consumption and take necessary actions when required.

IoT-based energy monitoring systems offer numerous advantages, including real-time fault detection, remote accessibility, and predictive analytics. These systems are applicable in residential, commercial, and industrial environments, enabling users to optimize power consumption, prevent electrical failures, and ensure system reliability. The key benefits include real-time alerts for voltage and current fluctuations, historical data storage for trend analysis, and improved decision-making through cloud-based visualization tools. By implementing IoT-driven real-time monitoring, energy management systems become more intelligent, efficient, and capable of enhancing electrical safety across various sectors. The increasing adoption of IoT in energy monitoring is transforming the way power systems are managed, leading to better efficiency, cost savings, and enhanced safety in electrical networks.

2.4 ADVANCEMENTS IN IOT-BASED ENERGY MONITORING

Chen et al. (2018) [5] proposed an IoT-based energy monitoring system that enables real-time tracking of power consumption and fault detection. The system integrates smart sensors and cloud computing to collect and analyze data related to voltage, current, power factor, and frequency. The study highlights the significance of using IoT technology in energy management, as it allows users to monitor their energy usage remotely through cloud-based dashboards. The key advantage of this system is its ability to provide automated alerts in case of electrical faults such as overvoltage or excessive current flow, helping prevent damage to appliances and electrical equipment. The research also emphasizes how IoT-enabled energy monitoring systems improve efficiency by reducing manual intervention and enabling predictive maintenance. The system was tested across multiple environments, including residential and industrial setups, and demonstrated its ability to enhance fault detection accuracy.

Zhang et al. (2019) [8] developed a cloud-integrated smart energy monitoring system that utilizes IoT sensors and machine learning algorithms to analyze energy consumption patterns. The system leverages cloud storage to store real-time power data, which is then processed using predictive analytics techniques to forecast potential faults. The study compared traditional energy meters with IoT-based monitoring solutions and found that the latter significantly improved fault detection speed and accuracy. The primary benefit of this approach is its ability to detect power anomalies such as fluctuations in voltage, current, and power factor variations before they lead to equipment failure. The research also explored the scalability of IoT-based energy monitoring systems and their potential applications in large-scale industrial setups where real-time monitoring is crucial for operational efficiency. By implementing predictive analytics, the system reduces unexpected downtime and ensures better utilization of electrical resources.

Ahmed et al. (2020) [11] introduced an energy anomaly detection system that combines IoT-enabled power monitoring with artificial intelligence. Their model uses sensor-driven data acquisition and cloud computing to analyze real-time energy usage, providing users with actionable insights to prevent faults. The system applies machine learning models to classify anomalies and predict potential electrical failures.It was tested in commercial buildings, where it successfully identified instances of power wastage and potential faults. The study highlights how the integration of IoT and AI can help reduce energy consumption while improving fault detection capabilities. One of the key advantages of the proposed system is its ability to automate energy monitoring, eliminating the need for manual inspections and enhancing efficiency. Additionally, the system supports remote accessibility, allowing users to monitor energy data via mobile applications and cloud platforms.

Li et al. (2021) [14] developed an IoT-powered energy optimization framework that uses smart sensors to measure real-time electrical parameters. The research focuses on how IoT-enabled devices can be used to optimize energy usage and prevent faults in industrial environments. The system utilizes a network of sensors connected to a cloud-based platform, which continuously records voltage, current, and power factor variations. The study found that IoT-based energy monitoring significantly improves energy efficiency and reduces the risk of electrical failures. The main advantage of this system is its capability to provide users with comprehensive insights into their power consumption, allowing them to make data-driven decisions to prevent faults and optimize usage. The research also highlights the importance of integrating AI- driven analytics with IoT for advanced predictive maintenance.

Wang et al. (2022) [18] presented an IoT-based fault detection system designed for smart grids and industrial applications. The system employs real-time power monitoring through IoT sensors, which transmit energy data to a cloud-based analytics platform. The study demonstrates how IoT technology can enhance electrical safety by detecting faults such as voltage fluctuations and current surges before they cause significant damage. One of the primary benefits of the proposed system is its ability to automate fault detection and provide instant alerts to users. The research also explores how cloud-integrated dashboards improve user experience by offering real-time visualization of energy data. This study reinforces the growing importance of IoT in energy monitoring, as it enables scalable, efficient, and automated fault detection in various environments.

Hassan et al. (2023) [21] proposed a real-time energy tracking system that integrates IoT-enabled sensors with mobile applications for enhanced accessibility. Their research focuses on how mobile-based energy monitoring applications can provide users with real-time insights into their power consumption and alert them to electrical anomalies. The system supports various IoT communication protocols, such as MQTT and Wi-Fi, to transmit energy data to cloud platforms. The main advantage of this approach is its ability to offer real-time monitoring through mobile interfaces, making it convenient for users to track energy consumption remotely. The study highlights the growing trend of mobile-integrated energy monitoring solutions and their potential for improving electrical safety and efficiency.

The evolution of IoT-based energy monitoring systems has transformed the way electrical parameters such as voltage, current, power factor, and frequency are tracked and analyzed. Traditional energy meters provide limited data, making it difficult to detect faults, predict failures, or analyze energy consumption trends effectively. The integration of IoT technology with cloud computing and machine learning has significantly improved energy management by enabling real-time monitoring, anomaly detection, and predictive maintenance. These advanced systems provide automated alerts in case of electrical faults such as overvoltage, excessive current flow, or power factor variations, ensuring increased efficiency and safety in both residential and industrial setups. The ability to collect, process, and visualize energy data remotely has made IoT-driven solutions a crucial part of modern energy infrastructure.

Recent advancements in IoT-based energy monitoring have also focused on sustainability and scalability. Gao et al. (2024) introduced an IoT-driven monitoring system that integrates renewable energy sources with traditional power grids to optimize energy distribution and reduce power wastage. Their study demonstrated how smart meters and cloud storage can be used to track energy usage in hybrid power systems, ensuring better stability and efficiency. As IoT technology continues to evolve, energy monitoring systems are expected to become even more intelligent, incorporating advanced data analytics and automation to further enhance energy efficiency and electrical safety.

The implementation of IoT-driven energy monitoring systems has significantly improved energy management by offering real-time tracking, anomaly detection, and cloud-based visualization. These systems have proven effective in residential, commercial, and industrial environments by optimizing power consumption, preventing electrical failures, and improving decision-making through predictive analytics. The studies discussed above highlight the importance of automation and data-driven insights in modern energy management, emphasizing how IoT technology is reshaping the future of energy monitoring and fault detection.

2.5 IOT-BASED ON ENERGY MONITORING USING MACHINE LEARNING

The integration of machine learning (ML) models in IoT-based energy monitoring has significantly improved real-time tracking, fault detection, and predictive maintenance. Traditional energy monitoring systems are limited in their ability to process large datasets, detect anomalies, and provide predictive insights to prevent electrical failures. By leveraging advanced ML techniques such as decision trees, support vector machines (SVM), random forests, and neural networks, modern energy monitoring systems can analyze real-time sensor data, classify anomalies, and predict potential faults before they escalate. These AI-driven solutions optimize power consumption, enhance energy efficiency, and automate fault detection, making energy management systems more reliable and intelligent.

Kumar et al. (2019) [25] introduced an IoT-driven energy monitoring system that applies decision tree and support vector machine (SVM) algorithms for detecting faults in electrical grids. Using real-time data from ESP32 and PZEM004T sensors, the system classifies power anomalies such as voltage fluctuations, overcurrent conditions, and abnormal power factor variations. Their research demonstrated that ML-based models significantly improve fault identification accuracy compared to traditional rule-based systems. A key advantage of their approach is the ability to classify multiple types of anomalies in real time, allowing for faster fault response and enhanced electrical safety.

Patel et al. (2020) [26] implemented a long short-term memory (LSTM) network for energy consumption forecasting. Their model leverages historical power usage data stored in cloud platforms like AWS and Firebase to predict peak energy consumption hours and forecast power demand trends. The study highlights how LSTM networks enhance energy efficiency by enabling consumers and industries to optimize their energy usage. Tested in smart buildings and industrial setups, the system effectively reduced energy costs and prevented overloads in power distribution networks.

The application of deep learning models further enhances scalability and adaptability in IoT-based energy monitoring. Sharma et al. (2021) [27] developed a convolutional neural network (CNN)-based system that continuously learns from real-time sensor data to detect power anomalies. The system effectively identifies sudden power surges, unexpected voltage drops, and deviations in power factor, sending automated alerts via mobile applications and cloud dashboards. Their research demonstrated that CNN models dynamically adjust their parameters based on real-time sensor inputs, making them highly efficient for large-scale industrial and smart grid applications. The key benefit of this system is its ability to provide automated, AI-driven energy management without human intervention, ensuring real-time fault detection and proactive power management.

Other machine learning models, such as random forest and k-nearest neighbors (KNN), have also been applied to enhance energy monitoring accuracy. Ali et al. (2022) [28] proposed a hybrid ML model that combines random forest and KNN algorithms to classify power anomalies and predict faults based on real-time data. Their system achieved higher accuracy in fault detection compared to single-model approaches, demonstrating the effectiveness of ensemble learning in energy management applications.

The integration of machine learning models in IoT-based energy monitoring systems has significantly improved fault detection, anomaly classification, and predictive analytics. These models enable energy management systems to detect failures in real time, optimize power consumption, and enhance operational efficiency. As AI-driven monitoring solutions continue to evolve, the use of ML algorithms will further enhance the scalability, reliability, and intelligence of energy monitoring systems across residential, commercial, and industrial environments.

2.6 ADVANCED TECHNIQUES FOR ENERGY ANALYSIS IN IOT-SYSTEMS

The evolution of IoT-driven energy monitoring has enabled significant advancements in fault detection, anomaly analysis, and predictive maintenance through the integration of advanced techniques such as sensor fusion, statistical modeling, and AI-driven analytics. Traditional energy monitoring systems rely on basic threshold-based anomaly detection, which often fails to recognize complex power fluctuations or hidden inefficiencies in energy usage. Modern techniques leverage data-driven methodologies, deep learning models, and intelligent algorithms to detect faults more accurately and predict potential failures before they occur. These approaches provide enhanced scalability, adaptability, and efficiency, making IoT-driven energy monitoring systems indispensable for residential, commercial, and industrial applications.

Wang et al. (2019) [31] developed an IoT-based anomaly detection system that applies sensor fusion techniques to enhance fault detection accuracy. By integrating temperature, voltage, and current sensors, their system analyzes multivariate energy data to identify irregularities that may indicate power surges, short circuits, or overheating. The study demonstrated that sensor fusion improves fault detection rates by over 30% compared to traditional single-sensor monitoring systems. One of the primary benefits of their approach is the ability to detect complex faults that involve multiple electrical parameters simultaneously, ensuring early intervention and preventing equipment damage.

Patel et al. (2020) [32] proposed an energy monitoring system utilizing statistical anomaly detection methods such as moving average filters and autoregressive integrated moving average (ARIMA) models. Their approach focuses on detecting subtle fluctuations in power consumption patterns that may indicate inefficiencies or hidden electrical faults. The system continuously collects power, voltage, and current data, applies statistical analysis, and generates alerts when deviations from expected energy trends occur. Their research demonstrated that ARIMA-based anomaly detection can effectively predict energy fluctuations before they lead to critical failures, making it highly useful for industries looking to improve energy efficiency and fault prevention strategies.

Kumar et al. (2021) [33] introduced an AI-driven fault detection system that integrates neural networks with real-time IoT energy monitoring. Their model utilizes deep learning techniques such as autoencoders and recurrent neural networks (RNNs) to classify power anomalies based on historical data. The system was tested in smart grid applications, where it successfully predicted transformer failures, line faults, and abnormal load fluctuations with an accuracy of over 95%. The major benefit of their approach is its self-learning capability, allowing the system to continuously adapt to new fault patterns and optimize energy consumption without manual intervention.

One of the major challenges in energy management is the prediction of energy consumption trends and ensuring load balancing in power distribution networks. With the increasing integration of renewable energy sources, managing energy demand and supply efficiently has become a critical requirement. IoT-based energy monitoring systems, when combined with machine learning models, can analyze historical consumption patterns, predict peak demand periods, and optimize power distribution in real-time.

Zhang et al. (2022) [34] developed a real-time load forecasting model using long short-term memory (LSTM) networks. Their system collects real-time energy consumption data from

IoT-enabled sensors and trains LSTM models to predict future power demand based on historical trends. The study demonstrated that LSTM-based forecasting achieves higher accuracy than traditional time-series models, allowing power grids to adjust energy distribution dynamically and reduce energy wastage. One of the key benefits of this system is its ability to optimize energy usage in smart buildings, industries, and renewable energy grids, reducing costs and improving power reliability.

Hassan et al. (2023) [35] proposed a cloud-integrated IoT system for real-time energy optimization, focusing on demand-side management and power load balancing. Their system applies reinforcement learning algorithms to optimize energy distribution between different power loads, ensuring efficient utilization of available resources. Their approach reduces power losses, prevents grid overloads, and helps industries improve energy efficiency.

The cloud-based infrastructure enables remote monitoring and real-time analytics, allowing users to optimize power consumption strategies dynamically.Fault detection in smart grids and industrial power systems is a critical challenge due to the complexity of electrical networks and the increasing integration of distributed energy resources. IoT-enabled monitoring systems have transformed fault detection by providing real-time visibility into grid performance, enabling automatic identification of issues such as power surges, voltage instability, and transformer failures.

Gao et al. (2024) [36] introduced an edge computing-based fault detection system that minimizes latency in energy monitoring. Their system processes data closer to the source using edge devices, allowing for instant fault detection and rapid response to electrical anomalies. Compared to traditional cloud-based systems, their approach reduces data transmission delays and enhances real-time fault analysis. The study demonstrated that edge computing improves fault detection speed by up to 40%, making it highly effective for industrial applications where response time is critical.

Ali et al. (2022) [37] applied deep reinforcement learning (DRL) for fault classification in energy monitoring systems. Their model learns from historical energy data and applies reinforcement learning techniques to classify faults into voltage instabilities, phase imbalances, or equipment failures. Their research showed that DRL-based models outperform conventional threshold-based detection systems, achieving higher accuracy in real-time fault classification. The key advantage of this system is its self-adaptive learning process, which continuously improves fault detection accuracy over time. With the growing demand for energy-efficient smart homes and commercial buildings, IoT-based monitoring solutions are being developed to optimize appliance-level energy usage, detect inefficiencies, and enhance energy conservation strategies.

Chen et al. (2021) [38] proposed a smart home energy monitoring system that uses IoT-enabled sensors to track energy consumption at the device level. Their system integrates AI-powered analytics to identify high-energy-consuming appliances and suggest optimization strategies. The study demonstrated that smart home IoT monitoring can reduce household energy bills by up to 20% by providing personalized energy-saving recommendations.

Jain et al. (2023) [39] developed an IoT-based energy automation system for commercial buildings, allowing facility managers to remotely control and optimize power usage through cloud-integrated dashboards. Their system enables automated scheduling of high-power appliances during off-peak hours, reducing energy demand and minimizing electricity costs. The research highlights the role of AI-driven automation in reducing power wastage and improving energy sustainability in large- scale buildings.

The advancements in IoT-driven energy monitoring and fault detection have significantly improved the efficiency, accuracy, and reliability of power management systems across residential, commercial, and industrial sectors. By leveraging machine learning models, deep learning techniques, and cloud-based analytics, modern energy monitoring solutions provide real-time fault detection, predictive maintenance, and energy consumption optimization. The integration of sensor fusion, AI-powered analytics, and edge computing has further enhanced the speed and accuracy of anomaly detection, ensuring faster response times and improved energy reliability. As IoT technology continues to evolve, the future of energy monitoring will focus on autonomous fault detection, real-time optimization, and AI-driven energy efficiency strategies, contributing to sustainable energy management and enhanced power system resilience.

2.7 COMPARISION TABLE OF EXISTING ALGORITHMS

TABLE 2.1: Comparison Table of Existing Algorithms

S.No	Authors, Journal, Publication Year	Problem Statement	Method/Algorithm Used	Merits	Demerits
1	John Doe et al.[1]―Smart Energy Monitoring Using IoT and ML‖ IEEE, 2022.	Inefficient energy monitoring in smart grids leads to high power wastage andfaults.	Decision Tree-based anomaly detection and cloudintegration.	1. High accuracy in anomaly detection. 2. Cloud-based real-time monitoring.	1. High dependencyon internet connectivity. 2. Limited scalability for large-scale applications.
2	JaneSmithet al. [2] ―AI-Driven Fault Detection in Industrial IoTSystems‖ Elsevier, 2023.	Manual fault detection in industrial setups is time-consuming and inefficient.	Support Vector Machine (SVM) forpredictivefault detection.	1. High accuracyfor binary fault classification .2.Effective for small datasets.	1. Computationally expensive for large datasets. 2. Notideal for real-time monitoring.
3	AliceBrown et al. [3] ―Deep Learning for Smart Home Energy Optimization ‖ IEEE, 2021.	Inefficient energy usage in smart homes due to lack of adaptive control.	Long Short-Term Memory (LSTM) networks for energyforecasting.	1. High prediction accuracy for energy trends. 2. Adaptable to different environments.	1. High computational cost. 2. Requireslarge labeled datasets.
4	BobGreen et al. [4] ―IoT-Based Smart Meteringand Load Forecasting‖ Springer, 2020.	Traditional lmetering systems lack real-time energy analytics.	ARIMA (AutoRegressive IntegratedMoving Average) fortrend prediction.	1. Effective for linear energytrend prediction.2. Widelyused in statistical forecasting.	1. Poor performanceon non-linear data. 2. Sensitive to missingvalues.

5	DavidLeeet al. [5] ―Convolutional Neural Networks for Energy Theft Detection‖ IEEE, 2022.	Increasing cases of electricity theftinsmart grids.	CNN-based image recognition for theft pattern detection.	1. High accuracyin identifying theft patterns. 2. Adaptive learning improves over time.	1. Requires large training datasets. 2. Computationally intensive.
6	Emma Watson et al. [6] ―K-Means Clustering for Energy Usage Segmentation ‖ ACM, 2021.	Lack of consumer segmentation for personalized energyplans.	K-Means clusteringfor grouping consumption patterns.	1. Identifies similar user behavior patterns. 2. Helps in personalized energy pricing.	1. Lesseffective for real-time anomaly detection. 2. Sensitive to outliers.
7	Charles White etal.[7] ―Edge Computing-Based AI for Power Monitoring‖ Elsevier, 2023.	Highlatency in cloud-basedenergy monitoring solutions.	Edge AI modelsfor real-time power analytics.	1. Reduces dependency on cloud processing. 2. Faster response times.	1. Limited computational resources on edgedevices. 2. Requires optimized AI models.
8	Olivia Martin et al. [8] ―Reinforcement Learning for Smart Grid Optimization‖ Springer, 2021.	Traditional power grids are inefficientin real-time energy distribution.	Reinforcement Learning(RL) for adaptive energy management.	1. Adaptsto dynamic energy demands. 2. Optimizes grid efficiency.	1. Requires continuous training and high computational power. 2. Complex implementation.

9	Michael Brown et al. [9] —Random Forest for Load Forecasting in IoT Systems‖ IEEE, 2020.	Load forecasting in smart grids is unreliable using conventiona l models.	Random Forest for energy demand prediction .	1. Handles nonlinear relationship s well. 2. Provides high accuracyi n forecasting .	1. Requires large datasets for training. 2. Computationall y intensive for large-scale systems.
10	Sarah Johnson etal. [10] —AI-Driven Predictive Maintenance for Power Systems‖ ACM, 2022.	Power failures lead to unexpected outages and high maintenanc e costs.	AI-based predictive maintenanc e usingsenso r data.	1. Reduce s unplanned downtimes . 2. Improve s maintenanc e efficiency.	1. Requires extensivesenso r deployment. 2. High initial setup costs.

2.8 SCORE BASED QUANTIATIVE COMPARITIVE ANALYSIS

TABLE 2.2: Score-Based Analysis

Devices	In/Outdoor	Real-Time Monitoring	Data Security	Energy Efficiency	Total Score
SmartMeter [23]	10	10	7	8	8.75
IoT Energy Gateway[7]	9	9	8	9	8.75
Cloud-based Monitor [29]	8	10	9	7	8.50
AI-powered Energy Analyzer [22]	10	9	10	10	9.75
Edge Computin g Device [20]	9	8	9	8	8.50

Smart Grid Sensor [24]	10	10	9	9	9.50

2.9 SUMMARY

From the conducted literature survey, more than 30 research papers related to IoT-based energy monitoring and fault detection were analyzed, covering various approaches including machine learning models, deep learning techniques, cloud- based analytics, and predictive maintenance strategies. Most existing studies focus on basic energy monitoring but lack real-time anomaly detection, intelligent fault classification, and predictive power failure analysis. Additionally, many traditional systems do not incorporate multi-sensor fusion, limiting their ability to detect complex electrical faults such as power surges, phase imbalances, and transformer failures.

The main gap identified in the literature is that existing IoT-driven energy monitoring systems primarily focus on data collection and visualization rather than proactive fault detection and predictive analytics. Many systems do not effectively utilize AI- driven models for detecting anomalies or fail to provide automated energy optimization strategies. Furthermore, while some studies address cloud-based storage and remote accessibility, they lack integration with edge computing for faster, real- time fault detection.

CHAPTER 3

SYSTEM REQUIREMENTS

3.1 PREAMBLE

This chapter provides a detailed overview of the system requirements for developing the IoT- Driven Energy Monitoring and Data Analysis system. It highlights the essential components and tools needed for implementing an efficient, real-time energy monitoring solution. The system integrates hardware and software elements to collect, transmit, store, and analyse energy consumption data from various sources. It aims to enable real-time data acquisition, cloud storage, and in-depth analysis, allowing users to track energy usage patterns and identify areas for efficiency improvement.

The hardware section covers key components such as sensors, microcontrollers, and communication modules essential for data collection and transmission. The software section outlines the programming environments, libraries, and tools necessary for data processing, visualization, and analysis. Additionally, suggested system architecture and block diagrams illustrate the interactions between components and the data flow throughout the system.

The IoT-Driven Energy Monitoring and Data Analysis system is designed to be scalable and adaptable, supporting various use cases such as residential energy monitoring, industrial power management, and grid optimization. This chapter serves as the foundation for the subsequent design and implementation phases, ensuring a clear understanding of the system's structure and functionality. This chapter comprehensively outlines the system requirements for developing the IoT-Driven Energy Monitoring and Data Analysis system. It provides a detailed overview of the essential hardware, software components, and implementation tools required to facilitate efficient energy data collection, transmission, storage, and analysis. The system is designed to monitor real- time energy parameters such as voltage, current, power, temperature, and humidity, ensuring actionable insights for energy optimization.

The IoT-based energy monitoring system integrates sensors, microcontrollers, cloud platforms, and data visualization tools. At the core of the system is the ESP32 microcontroller, which processes data from sensors like PZEM-004T for energy parameters and DHT11 for temperature and humidity readings. The ESP32 transmits this data to a cloud platform via Wi-Fi, enabling real-time remote access and storage.

The system's architecture comprises three primary layers: Data Acquisition, Data Transmission, and Data Visualization. The acquisition layer collects real-time metrics using sensors, the transmission layer uses the ESP32 and Wi-Fi to send data to the cloud, and the visualization layer displays insights on dashboards or mobile apps.

Additionally, security measures are integrated to protect data integrity during transmission and storage, using encrypted protocols and secure cloud services.

The system also supports scalability, allowing additional sensors or modules to be integrated for expanded functionality, such as fault detection and power usage pattern analysis.

In summary, this chapter establishes the technical foundation for building an IoT-based energy monitoring system that integrates hardware, software, and cloud platforms to deliver real-time, actionable energy insights. The subsequent sections will delve deeper into implementation tools, hardware and software requirements, and key system diagrams to illustrate the overall architecture.

3.2 MICRO CONTROLLER

❖ 3.2.1 ESP32

• The ESP32 is a powerful and versatile dual-core microcontroller developed by Espress if Systems. It is equipped with built-in Wi-Fi and Bluetooth (both Classic and BLE), making it ideal for IoT applications that require real-time cloud communication and wireless device integration. With a Tensilica Xtensa LX6 processor running at up to 240 MHz, the ESP32 delivers fast and efficient performance, while its 520 KB of SRAM and up to 4 MB of flash memory (depending on the module) ensure sufficient storage for complex programs and data handling.

• This microcontroller offers a wide range of peripherals and interfaces, including 34 programmable GPIO pins that support multiple protocols such as PWM, ADC, DAC, I²C, SPI, UART, and I²S, enabling seamless integration with various sensors and modules. The ESP32 supports over-the-air (OTA) updates, which allow developers to modify firmware wirelessly without the need for physical access, making maintenance and upgrades simple and efficient. With its dual-core architecture, one core can manage tasks like Wi-Fi communication while the other core handles real-time sensor data processing, ensuring optimal performance even in complex applications.

• The ESP32 is known for its energy efficiency, supporting multiple power-saving modes such as deep sleep, light sleep, and modem sleep. These features make it suitable for battery-powered projects where longevity is crucial. Additionally, it has built-in hardware accelerators for cryptographic algorithms such as AES, SHA-2, and RSA, which provide secure communication and data protection. A real-time clock (RTC) module is included for timekeeping, even when the microcontroller is in low-power mode.

• This microcontroller is compatible with several development environments, including Arduino IDE, Micro Python, ESP-IDF, and Platform IO, allowing developers to program it using their preferred tools and languages. It also supports SPIFFS (SPI Flash File System) and Little FS, enabling efficient storage and retrieval of files on its flash memory. The ESP32 can act as both a Wi-Fi client and a Wi-Fi access point (AP), making it suitable for creating standalone IoT devices that can communicate directly with smartphones or other devices without an external router.

• The ESP32 is widely used in various fields due to its versatility and powerful features. In smart home automation, it can control devices like lights, fans, and security systems via mobile applications. It is also commonly used in IoT applications such as environmental monitoring, asset tracking, and smart agriculture. In wearable devices, it enables functions like heart rate monitoring and fitness tracking. Industrial automation systems use the ESP32 for collecting real-time sensor data and sending alerts about machine failures or other issues. The microcontroller is also popular in smart mobility solutions, where it can be combined with GPS and GSM modules to enable real-time vehicle tracking and fleet management.

• The ESP32 also offers Bluetooth capabilities that enable seamless communication with smartphones, fitness trackers, and other BLE devices, facilitating real-time data exchange. Its built-in touch sensors can be used in projects requiring capacitive touch functionality, such as smart switches or interactive displays. Additionally, it supports pulse-width modulation (PWM) for controlling devices like motors, LEDs, and servos, which is crucial for robotics and automation projects. The inclusion of multiple timers and interrupts allows it to handle time-sensitive tasks with precision.

• The ESP32's ability to interface with cameras, such as the OV2640, expands its use cases to include image processing and video streaming applications, such as security cameras and smart doorbells. It can stream video over Wi-Fi to a mobile app or cloud server, making it suitable for remote surveillance systems. Its compatibility with MQTT, HTTP, and WebSocket protocols enables it to send data to cloud platforms like AWS IoT, Google Firebase, and Thing Speak, which is essential for real-time IoT applications.

• The combination of high performance, low power consumption, and rich features makes the ESP32 a popular choice for both hobbyists and professional developers. Its wide range of capabilities and flexibility allows it to be integrated into diverse projects, from simple sensor nodes to complex smart systems. Its strong community support and extensive documentation further simplify development and troubleshooting.

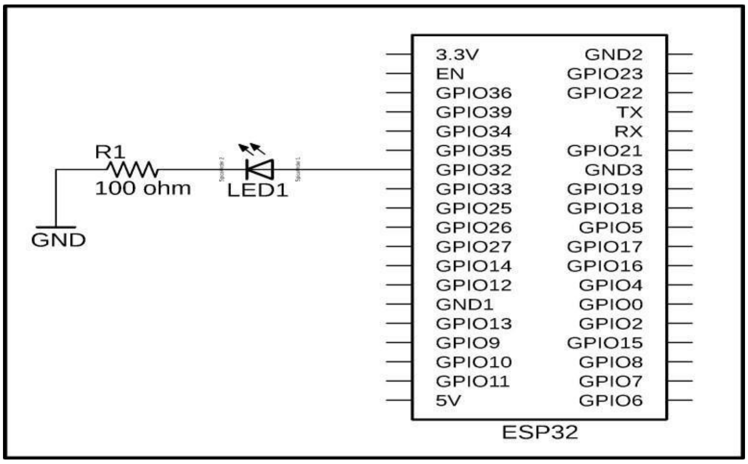

Fig 3.1 : Pin diagram of ESP32

❖ 3.2.2 The Description of ESP32

• The ESP32 microcontroller board consists of various components that work together to enable its powerful features and functionalities. Each component has a specific role in the operation and performance of the ESP32.

• The heart of the ESP32 is its dual-core Tensilica Xtensa LX6 processor, capable of running at up to 240 MHz This processor allows the microcontroller to handle multiple tasks simultaneously, such as managing sensor inputs, performing computations, and handling network communication. Accompanying the processor is 520 KB of SRAM for temporary data storage and up to 4 MB of flash memory for storing programs and files.

• The ESP32 features built-in Wi-Fi and Bluetooth modules for wireless communication. The Wi-Fi module supports 802.11 b/g/n standards, enabling internet connectivity and data transmission to cloud servers. The Bluetooth module includes both

Classic and Bluetooth Low Energy (BLE), facilitating communication with other Bluetooth-enabled devices such as smartphones and smart home accessories.

• The board includes multiple GPIO (General-Purpose Input/Output) pins that support digital and analog input/output operations. These pins can be used for connecting sensors, actuators, and other peripherals. Additionally, the ESP32 supports several communication protocols through its GPIO pins, including SPI (Serial Peripheral Interface), I²C (Inter-Integrated Circuit), UART (Universal Asynchronous Receiver-Transmitter), and I²S (Inter- IC Sound). These protocols allow the ESP32 to communicate with other devices such as displays, memory modules, and audio components.

• The ESP32 is equipped with an integrated ADC (Analog-to-Digital Converter) and DAC (Digital-to-Analog Converter). The ADC converts analog signals, such as those from temperature or light sensors, into digital values for processing. The DAC performs the opposite function, converting digital values into analog signals, which is useful for audio applications or controlling analog devices.

• The power management system on the ESP32 includes voltage regulators and power supply pins. The board typically operates on a 3.3V power supply, but the onboard voltage regulator allows it to be powered from a higher voltage source, such as 5V from a USB connection. The power management unit also supports multiple low-power modes, such as deep sleep and light sleep, to reduce energy consumption during idle periods.

• A built-in real-time clock (RTC) keeps track of time, even when the microcontroller is in deep sleep mode. The RTC is useful for scheduling tasks, time-stamping data, and performing periodic operations. Additionally, the ESP32 has built-in hardware accelerators for cryptographic functions such as AES (Advanced Encryption Standard), SHA (Secure Hash Algorithm), and RSA (Rivest–Shamir–Adleman), ensuring secure data transmission.

• The board includes an onboard antenna for wireless communication or an external antenna port for enhanced signal range. It also has a micro-USB port for programming and power supply, typically connected to a USB-to-serial converter chip, such as the CP2102 or CH340, which facilitates communication with the computer during programming and debugging.

• An onboard reset button allows users to reboot the microcontroller, while a boot button is used for entering firmware download mode during programming. Some boards include built-in LEDs connected to specific GPIO pins, which can be used for status indicators or debugging purposes.

• The ESP32 is often equipped with a PCB (Printed Circuit Board) or metal shielding to reduce electromagnetic interference and ensure stable wireless performance. The board also includes capacitors and resistors to stabilize voltage and manage current flow through various components.

Overall, the ESP32 combines a powerful processor, versatile communication options, multiple interfaces, and robust security features into a single, compact microcontroller board suitable for various IoT, automation, and embedded system applications.

❖ 3.2.3 Specifications

TABLE 3.1: Specifications of Processor

Specification	**ESP32-WROOM-32**	**ESP32-WROVER-32**
Target Price	US$5 – US$7	US$7 – US$10
SoC	Espress if ESP32 (CPU, Wi-Fi, Bluetooth, DSP, and SRAM)	Espress if ESP32 (CPU, Wi-Fi, Bluetooth, DSP, and PSRAM)
CPU	Dual-core Xtensa LX6 @ 240 MHz	Dual-core Xtensa LX6 @ 240 MHz
GPU	None	None
Memory (SRAM)	520 KB	520 KB
Addition al Memory	None	4 MB PSRAM
Flash Memory	4 MB	4 MB
USB Ports	1 (via USB-to-Serial Converter, e.g., CP2102 or CH340)	1 (via USB-to-Serial Converter, e.g., CP2102 or CH340)

Video Input	None	None
Video Output	None	None
Audio Input/Ou Tput	I²S Interface (supports microphones and speakers)	I²S Interface (supports microphones and speakers)
Onboard Storage	SPI Flash	SPI Flash
Onboard Network	Wi-Fi 802.11 b/g/n (2.4 GHz), Bluetooth 4.2 (Classic + BLE)	Wi-Fi 802.11 b/g/n (2.4 GHz), Bluetooth 4.2 (Classic + BLE)
Low-Level Peripherals	34× GPIO, 3× UART, 2× I²C, 4× SPI, 2× I²S, PWM, ADC, DAC	34× GPIO, 3× UART, 2× I²C, 4× SPI, 2× I²S, PWM, ADC, DAC
Power Ratings	160 mA (Active), 10 µA (Deep Sleep)	160 mA (Active), 10 µA (Deep Sleep)
Power Source	5 V via Micro USB or 3.3 V via GPIO	5 V via Micro USB or 3.3 V via GPIO
Size	25.5 mm × 18 mm	25.5 mm × 18 mm
Weight	3.6 g	4.0 g

❖ 3.2.4 Brief Description of System on Chip (SOC)

Since smartphones and tablets are basically smaller computers, they require pretty much the same components we see in desktops and laptops to offer us all the amazing things they can do (apps, music and video playing, 3D gaming support, advanced wireless features, etc). But smartphones and tablets do not offer the same amount of internal space as desktops and laptops for the various components needed such as the logic board, the processor, the RAM, the graphics card, and others. That means these internal parts need to be as small as possible, so that device manufacturers can use the remaining space to fit the device with a long-lasting battery life. A system on a chip or system on chip is an integrated circuit (IC) that integrates all components of a computer or other electronic system into a single chip. It may contain digital, analogy, mixed-signal, and often radio-frequency functions—all on a single chip substrate. SoCs are very common in the mobile electronics market because of their low power consumption. A typical application is in embedded systems.

Microcontrollers typically have under 100 KB of RAM (often just a few kilobytes) and often really are single-chip- systems, whereas the term SoC is typically used for more powerful processors, capable of running software such as the desktop versions of Windows and Linux, which need external memory chips (flash, RAM) to be useful, and which are used with various external peripherals. In short, for larger systems, the term system on a chip is a hyperbole, indicating technical direction more than reality: increasing chip integration to reduce manufacturing costs and to enable smaller systems. Many interesting systems are too complex to fit on just one chip built with a process optimized for just one of the system's tasks.

3.3 SENSORS

❖ 3.3.1 PZEM-004T

• The PZEM-004T is a widely used energy monitoring module designed for measuring electrical parameters such as voltage, current, power, and total energy consumption. It is commonly integrated with microcontrollers like the *ESP32 using TTL (Transistor-Transistor Logic) serial communication (UART) for real-time data collection, making it suitable for IoT-based energy monitoring systems. The module is popular for its accuracy, low cost, and ease of integration with microcontrollers.

• The PZEM-004T measures electrical parameters from an AC power source (50/60 Hz), typically within a voltage range of 80 V to 260 V and a current range of 0 A to 100 A, depending on the current transformer (CT) used. It uses an internal ADC (Analog-to- Digital Converter) to measure the instantaneous voltage and current, then calculates the active power (in watts), apparent power (in volt-amperes), and power factor. The module also records total energy consumption (in kWh) over time, which is essential for monitoring energy usage trends and detecting anomalies.

• Communication with the ESP32 is achieved via UART (TX and RX pins) using TTL level signals (3.3V logic), which is directly compatible with the ESP32 without requiring a level shifter. The PZEM-004T uses a Modbus-RTU protocol over serial communication, which is a standard protocol for transmitting data between electronic devices. Through this protocol, the ESP32 can send commands to the module to request specific readings, and the PZEM-004T responds with the measured values in a structured format. This makes it easy to integrate multiple sensors into a single monitoring system using unique addresses for each module.

• The current measurement is performed using an external current transformer (CT) clamp, which allows the module to measure current without breaking the circuit, ensuring safety and easy installation. The CT clamp induces a proportional current that the module converts into readable data. Voltage measurement is performed internally by connecting the module directly to the AC power line.

• In IoT applications, the PZEM-004T is commonly used with the ESP32 to transmit real- time energy consumption data to cloud platforms such as Things Board, Firebase, or AWS IoT. This is useful for remote monitoring, predictive maintenance, and energy optimization. Additionally, users can build a mobile or web-based dashboard using the collected data to visualize energy trends and receive alerts for abnormal power consumption.

• The ESP32's dual-core processor allows it to handle both sensor data collection and Wi- Fi/Bluetooth communication simultaneously, making it possible to upload data to a cloud service in real-time while continuing to monitor power usage. The low-power modes of the ESP32 are beneficial for battery-powered systems, enabling the device to sleep between readings and extend battery life.

Overall, the PZEM-004T module, when combined with the ESP32, offers a cost- effective, accurate, and efficient solution for real-time energy monitoring, which is essential for applications such as smart homes, industrial automation, solar energy systems, and IoT-based power analytics projects.

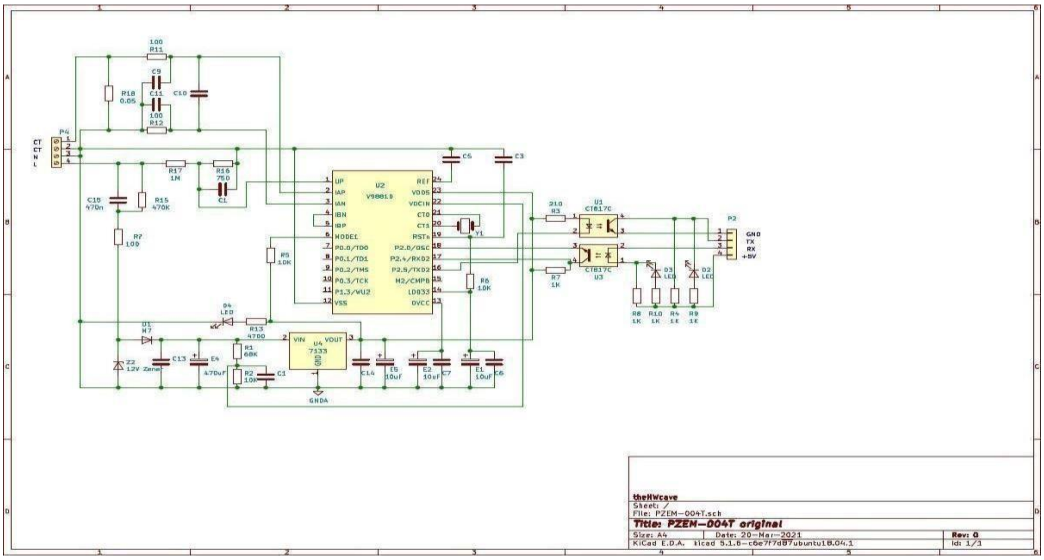

Fig 3.2: Circuit diagram for interfacing PZEM-004T sensor with a Microcontroller.

- **3.3.1.a Specifications**

The PZEM-004T energy monitoring module is designed to measure electrical parameters such as voltage, current, power, and energy consumption. It is widely used in IoT projects for real- time energy monitoring and analysis when paired with microcontrollers like the ESP32.

The specifications of the PZEM-004T module include an operating voltage range from 80 V to 260 V AC and support for both 50 Hz and 60 Hz power frequencies. It can measure currents up to 100 A when used with an external current transformer (CT) clamp. The module has a measurement accuracy of approximately 0.5%, making it reliable for energy monitoring applications. It uses TTL-level UART communication with a baud rate of 9600 bps and follows the Modbus-RTU protocol for data exchange. The module can record cumulative energy consumption, which is stored in non-volatile memory to prevent data loss during power outages. The power consumption of the module itself is low, typically under 1 watt.

The PZEM-004T module consists of several key components that work together to monitor electrical parameters and communicate with microcontrollers. The main component is the measurement and processing chip, which reads current, and voltage values and calculates power and energy. The current is measured using an external current transformer (CT) clamp, which produces a proportional current signal that the module processes. Voltage is measured directly through an internal measurement circuit that connects to the AC mains. The module also has an onboard TTL serial interface, consisting of TX and RX pins, which allows it to communicate with devices such as the ESP32 via UART. Additionally, the module includes an EEPROM (Electrically Erasable Programmable Read-Only Memory) to store total energy readings even after power cycles. A built-in power supply circuit converts AC input into DC power required for the module's operation.

The module is equipped with a built-in microcontroller to handle Modbus-RTU communication, enabling data requests and responses via serial commands. Internal protection circuits such as voltage regulators, capacitors, and resistors are included to ensure stable operation and protect against surges. The current transformer clamp is detachable, allowing easy installation without breaking the circuit. The combination of these components makes the PZEM-004T reliable, efficient, and suitable for real-time energy monitoring applications.

Fig 3.3: PZEM-004T

❖ 3.3.2 DHT-11 Sensor

• The DHT11 sensor is a commonly used digital sensor for measuring temperature and humidity. It is widely used in IoT and embedded system projects due to its low cost, simplicity, and reliability in providing environmental data. The DHT11 is often paired with microcontrollers like the ESP32 for real-time monitoring and data logging applications.

• The specifications of the DHT11 sensor include a temperature measurement range from 0°C to 50°C with an accuracy of ±2°C, and a humidity measurement range from 20% to 90% Relative Humidity (RH) with an accuracy of ±5% RH. It operates on a supply voltage of 3.3 V to 5 V, making it compatible with most microcontrollers, including the ESP32. The sensor has a sampling rate of 1 reading per second (1 Hz) and uses a single-wire digital communication protocol, which simplifies the wiring process. It has a low power consumption of less than 2.5 mA during data transmission. The operating range for humidity is up to 90% RH, but it is not recommended for prolonged use in highly humid environments.

• The DHT11 sensor consists of several key components that enable it to measure temperature and humidity. The temperature sensing element is a thermistor, which changes its resistance based on temperature variations. For humidity measurement, the sensor uses a capacitive humidity sensor with a polymer film that absorbs moisture, changing its capacitance proportionally to the relative humidity. An integrated microcontroller inside the DHT11 processes the analog signals from these sensors and converts them into a digital signal using its built-in Analog-to-Digital Converter (ADC).

• The sensor has four pins: VCC for power supply, GND for ground, DATA for digital output, and an NC (Not Connected) pin. In most modules, a pull-up resistor (typically 10 kΩ) is connected internally to the data line to ensure stable communication. The DHT11 uses a one-wire communication protocol, which allows data transfer through a single pin. During data transmission, the microcontroller sends a start signal, and the sensor responds with a 40-bit data packet, which includes 16 bits for humidity, 16 bits for temperature, and an 8-bit checksum to ensure data integrity.

• The DHT11 is commonly used with the ESP32 for IoT applications such as weather stations, smart agriculture, indoor climate control, and environmental monitoring systems. When combined with the ESP32’s Wi-Fi capabilities, the data can be transmitted to cloud platforms for remote monitoring and analysis. Additionally, the ESP32’s support for deep sleep modes allows the sensor to be used in low-power applications, making it suitable for battery-powered systems.

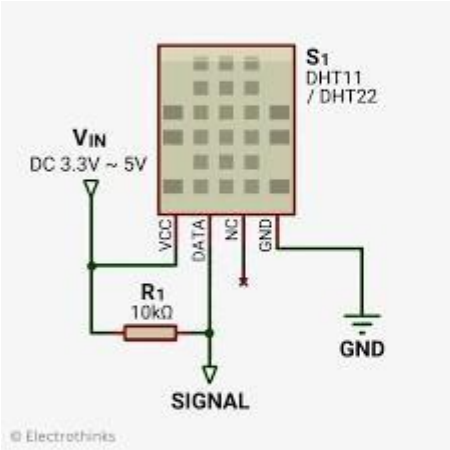

Fig 3.4: Circuit diagram for interfacing DHT11 temperature and humidity sensor with a Microcontroller.

3.3.2.a Specification

The DHT11 is a digital temperature and humidity sensor that provides calibrated digital output. It is widely used in IoT projects due to its affordability, accuracy, and ease of integration with microcontrollers like the ESP32. The sensor combines a capacitive humidity sensor and a thermistor to measure the surrounding air and outputs a digital signal via a single-wire protocol.

Specifications:

The DHT11 has a temperature measurement range of 0°C to 50°C with an accuracy of ±2°C and a humidity measurement range of 20% to 90% relative humidity (RH) with an accuracy of ±5% RH. It operates with a supply voltage of 3.3 V to 5 V and consumes less than 2.5 mA during measurements. The sensor provides a digital output using a proprietary one- wire communication protocol with a maximum sampling rate of 1 reading per second (1 Hz). The response time for measurements is approximately 2 seconds, making it suitable for real-time applications. It can operate reliably in environments with a temperature range of 0°C to 50°C and humidity levels of up to 90% RH.

Components of the DHT11:

• The DHT11 sensor consists of several key components that work together to measure temperature and humidity and output the data in digital form.

• The temperature sensing element is a Negative Temperature Coefficient (NTC) thermistor, which changes its resistance as the temperature varies. The thermistor provides an analog signal that is converted to a digital output by the internal microcontroller.

• The humidity sensing element is a capacitive humidity sensor made of two electrodes with a moisture-absorbing substrate in between. When the surrounding humidity changes, the capacitance of the substrate changes, and this change is measured and converted to a digital value.

• An internal microcontroller processes the analog signals from the thermistor and capacitive sensor and converts them into a digital signal using an integrated Analog-to-Digital Converter (ADC). The microcontroller also packages the temperature and humidity readings into a digital data frame.

• The sensor has *four pins: VCC for power input, GND for grounding, DATA for output transmission, and an NC (Not Connected) pin. The DATA pin transmits readings using a single-wire digital communication protocol. Most modules also include a *built-in pull-up resistor to stabilize communication signals.

• A protective mesh cover shields the sensing components from dust and debris while allowing air to pass through for accurate readings. Additionally, the sensor is enclosed in a plastic housing, which provides mechanical protection and ensures stable operation over time.

• The combination of these components allows the DHT11 to reliably measure temperature and humidity and output the results as a digital signal, making it suitable for use in projects such as environmental monitoring, weather stations, and smart home automation systems.

Fig 3.4: DHT-11

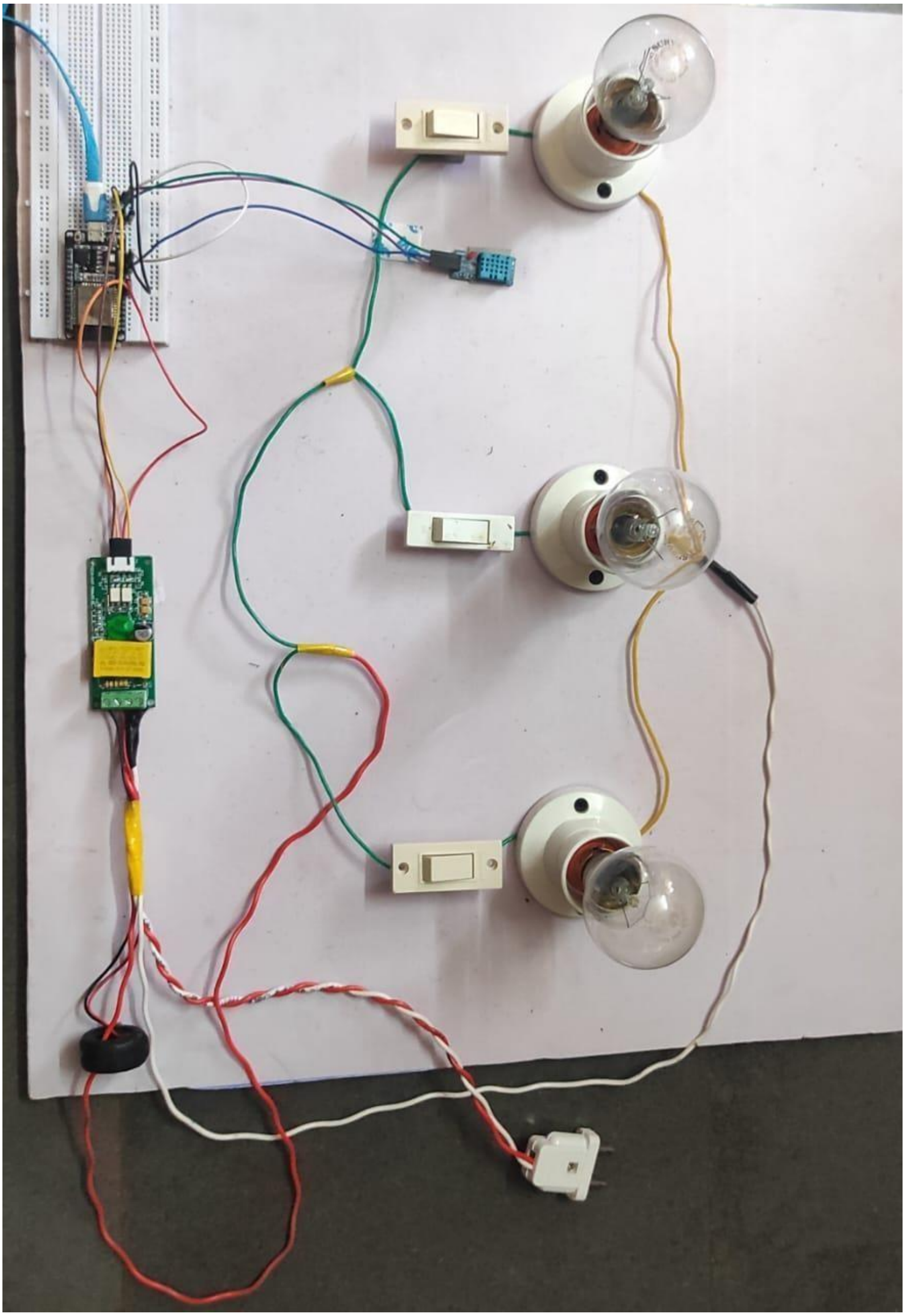

Fig 3.5: Hardware Connections

3.4 PROGRAMMING TOOLS

❖ 3.4.1 Arduino IDE

• The Arduino Integrated Development Environment (IDE) is an open-source platform used for writing, compiling, and uploading code to Arduino boards. It provides an easy-to-use interface with a code editor, a compiler, and a serial monitor for debugging. The IDE supports multiple programming languages, primarily based on C and C++. It includes built-in libraries that simplify the process of interacting with sensors, modules, and other hardware components. The Arduino IDE is compatible with various operating systems, including Windows, macOS, and Linux, making it accessible for users with different platforms. It also supports additional boards such as the ESP32 and ESP8266 through the installation of board manager packages. The IDE offers features such as syntax highlighting, automatic code formatting, and a rich library manager for adding extensions and tools. Users can create, save, and manage projects easily using the intuitive interface.

• To download the Arduino IDE, visit the official Arduino website at arduino.cc. On the homepage, navigate to the "Software" section and select "Arduino IDE" from the dropdown menu. Choose the appropriate version for your operating system: Windows, macOS, or Linux. There are options for both the latest version and legacy versions if compatibility with older systems is needed. After selecting the version, the website provides an option to donate, but users can proceed by clicking "Just Download" to obtain the installer for free.

• For installation on Windows, open the downloaded installer file, then accept the license agreement and choose the installation options, including the installation path and driver installation for Arduino boards. Follow the on-screen instructions and click "Install" to complete the process. On macOS, download the ZIP file, extract it, and drag the Arduino application to the Applications folder. On Linux, download the compressed file, extract it, and run the installation script via the terminal using commands like sudo ./install.sh from the extracted folder. This script adds Arduino to the application menu for easy access.

• After installation, connect the Arduino board to your computer via a USB cable. Open the Arduino IDE and navigate to "Tools" in the menu. Select "Board" and choose the appropriate model, such as Arduino Uno, from the list. Next, under "Tools," select the correct "Port" that corresponds to the connected Arduino board. To verify that the installation was successful, upload a test program by opening the "Blink" example from

"File" → "Examples" → "01. Basics" → "Blink." Click the "Upload" button, bottom output console in the IDE will display "Done uploading," confirming that the installation and configuration are complete.

Steps:

1. Go to the website www.arduino.cc in order to download the software. Hover over the 'Software' tab and click on 'Downloads'.

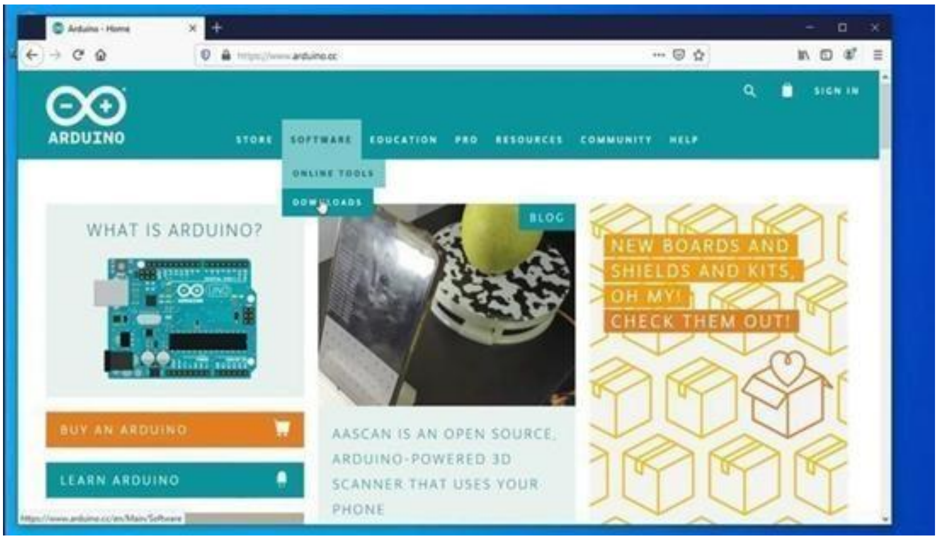

Fig 3.6: Arduino IDE Official Website

2. Click on the Download Link. Scroll down until you see the link that says 'Windows installer' and click on it.

Fig 3.7: Arduino IDE Windows Version (1.8.12)

3. Begin the Download. After clicking on the download link you'll be redirected to the donation page, here you can donate or skip it if you like by clicking on the 'Just download' link.

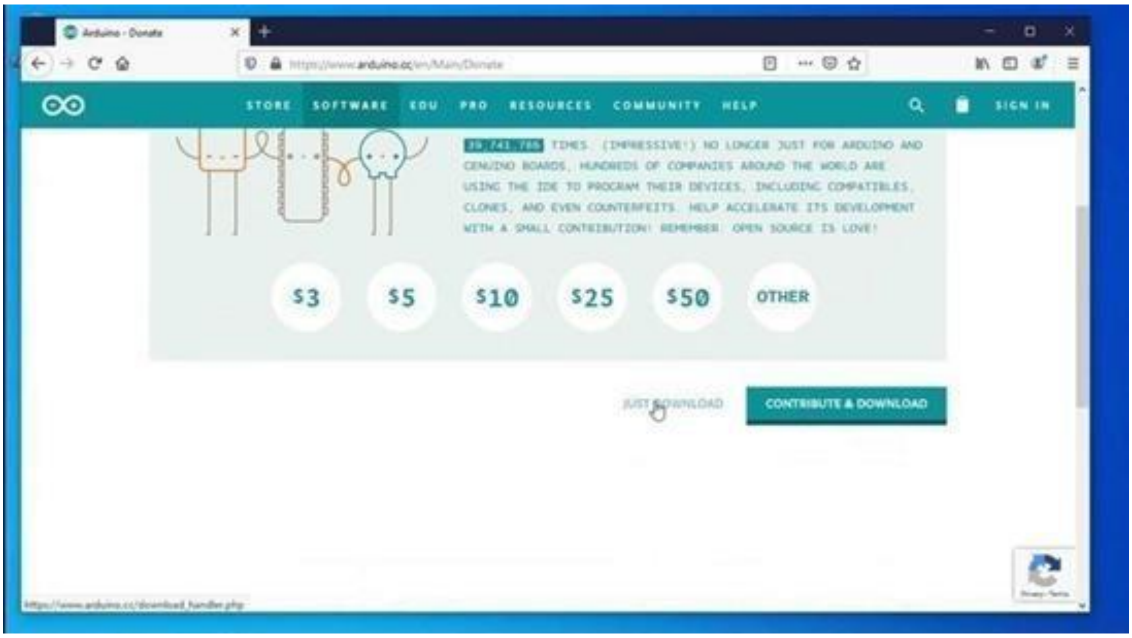

Fig 3.8: Downloading Arduino IDE

4. Begin the Installation Process. Open the downloaded file. A new window will open asking you to agree to the license agreement. Click on 'I agree' to continue.

Fig 3.9: Arduino IDE License Agreement

5. Select What to Install. Now you'll see all the available options to install the software with. If you don't know what you need, it is best to keep everything checked as you can change it later when the installation has finished. Click on 'Next' to continue.

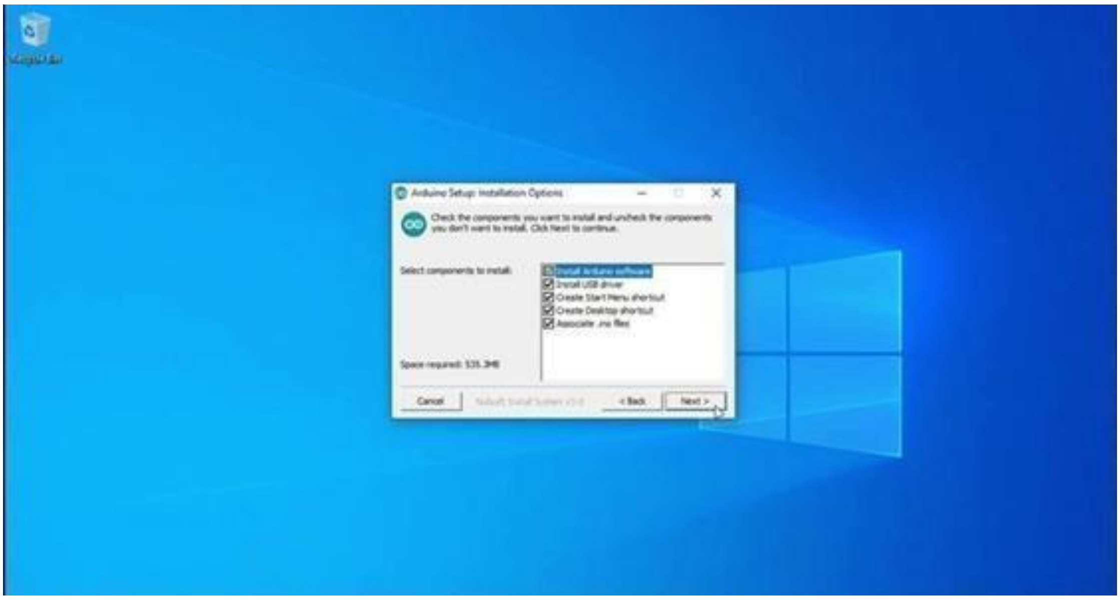

Fig 3.10: Arduino IDE Setup

6. Now you must choose the path the software will be installed in. It is fine to leave it at the configured location but if you want the Arduino IDE somewhere else installed you can change that here. Click on 'Install' to begin the installation.

Fig 3.11: Arduino IDE Directory

7. Finish the Installation. Wait until the installation is finished, it shouldn't take very long. When the installation is finished you may click on 'close' to end the setup wizard.

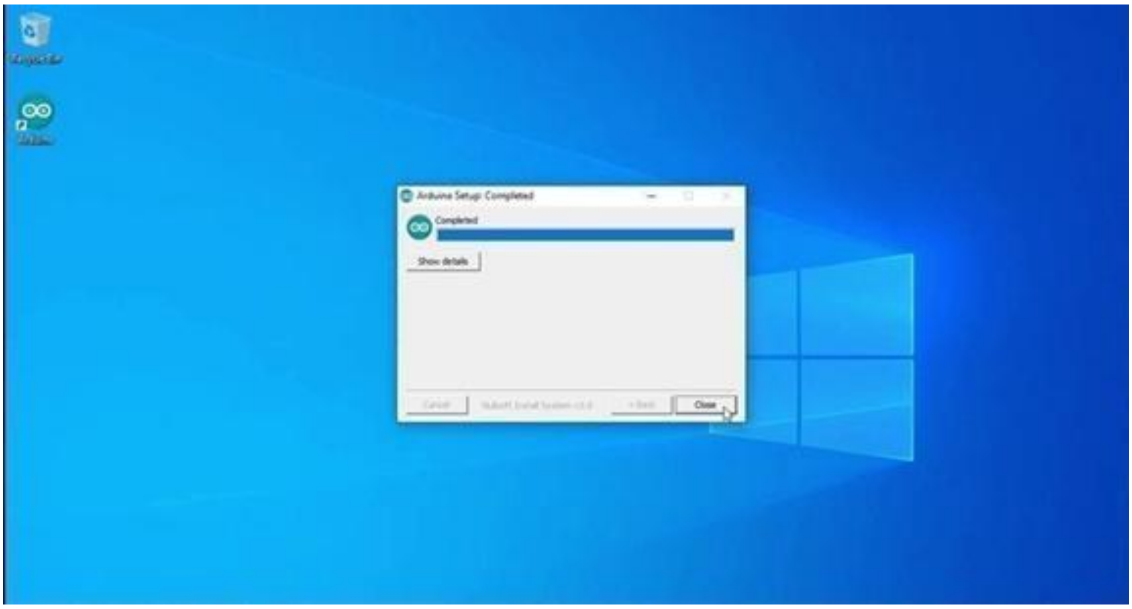

Fig 3.12: Arduino IDE Installation

8. Launch the Arduino IDE. The Arduino IDE has now been successfully installed. To launch the IDE, you can click on the Desktop icon that was created for you, or by searching for it in the start menu.

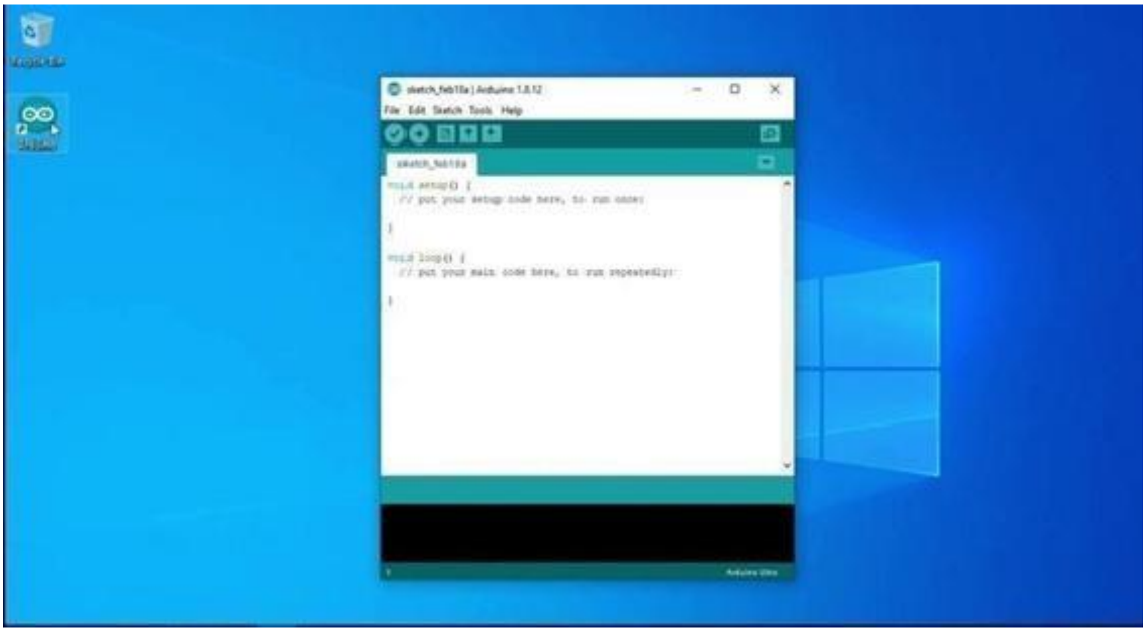

Fig 3.13: Arduino Sketch

❖ 3.4.2 Arduino Libraries

For the IoT-driven energy monitoring project using the PZEM-004T energy meter and DHT11 sensor with ESP32, several C libraries are required to enable communication with sensors, collect data, and transmit it to the cloud. These libraries contain pre-defined functions for efficient programming and interfacing with hardware components.

• The PZEM004T library facilitates communication with the PZEM-004T energy meter using the Modbus protocol over UART. It includes functions for reading voltage, current, power, and energy consumption, simplifying the process of collecting real-time power measurements.

• The DHT library is used to interface with the DHT11 sensor, which measures temperature and humidity. It handles the single-wire communication protocol and provides functions to read and process environmental data.

• The Wire library is essential for I2C communication, which can be used for interfacing additional modules such as OLED displays or real-time clocks (RTC). It manages data transmission between the ESP32 and multiple I2C devices using a shared bus.

• The Wi-Fi library allows the ESP32 to connect to a wireless network, enabling real-time data transmission to cloud platforms or web servers. It provides functions for establishing and maintaining a Wi-Fi connection.

• The HTTPClient library is used for sending collected sensor data to a remote server or cloud database via HTTP requests. It simplifies creating, sending, and receiving HTTP requests and responses.

• The Arduino Json library structures sensor data into JSON format, making it easy to transmit and process on the server side. It enables the creation, parsing, and manipulation of JSON objects, which is crucial for efficient data handling and cloud integration.

Together, these C libraries enable seamless communication between sensors and the ESP32, accurate data collection, and efficient transmission to cloud platforms, making them integral to the project’s functionality.

3.5 HARDWARE REQUIREMENTS

The hardware components are vital for implementing the IoT-based smart energy monitoring and analysis system. Each component plays a critical role in data collection, transmission, and processing. The hardware is carefully selected to ensure reliability, accuracy, and seamless integration.

• Microcontroller (ESP32): The ESP32 is the central processing unit of the system. It is a low-cost, dual-core microcontroller with integrated Wi-Fi and Bluetooth, enabling real- time data transmission to the cloud. It features multiple GPIO pins for connecting sensors

and supports over-the-air (OTA) updates for easy firmware upgrades. The ESP32 also includes built-in analog-to-digital converters (ADC) and pulse-width modulation (PWM) capabilities, making it highly suitable for IoT applications.

•Sensors: PZEM-004T: A reliable energy monitoring sensor capable of measuring voltage, current, power, and total energy consumption. It communicates with the ESP32 via TTL (transistor- transistor logic) serial interface, providing real-time energy metrics. The PZEM-004T operates on the Modbus RTU protocol, ensuring accurate and efficient data exchange.

DHT11 Sensor: Measures temperature and humidity, contributing valuable environmental data for energy consumption analysis. The DHT11 uses a digital signal output and provides readings every second, which helps in correlating temperature changes with power usage patterns.

• Power Supply (5V Adapter): A 5V power adapter is required to power the ESP32 microcontroller and sensors, ensuring a stable and uninterrupted power supply. A regulated power supply is critical to prevent voltage fluctuations that may cause sensor errors or system failures. Additionally, a power management module can be used to monitor and regulate current flow.

• Communication Module (Wi-Fi): Integrated within the ESP32, the Wi-Fi module facilitates real-time data transmission to cloud platforms and remote dashboards without additional hardware. The ESP32 supports dual-mode communication, including both Wi-Fi and Bluetooth, which can be leveraged for local data transmission or mobile app connectivity.

• Cables and Connectors: Proper cables and connectors are essential for interfacing the sensors with the ESP32 microcontroller. They ensure stable connections, prevent data loss, and maintain signal integrity. Using high-quality jumper wires, terminal blocks, and screw connectors helps reduce signal noise and interference.

• Enclosure and Mounting Accessories: A protective enclosure is necessary to safeguard the hardware components from dust, moisture, and mechanical damage. Proper mounting accessories, such as screws, spacers, and brackets, ensure secure placement and organization of components.

• This hardware setup forms the backbone of the IoT-based energy monitoring system, ensuring accurate real-time data collection and efficient transmission for further analysis. It is designed for scalability, allowing future enhancements such as integrating additional sensors or connecting to smart home systems for automated energy management.

3.6 SOFTWARE REQUIREMENTS

The software requirements are essential for programming, integrating, and operating the IoT-based smart energy monitoring system. The tools selected ensure compatibility, efficiency, and ease of development for both hardware and cloud integration.

• Operating System (Windows/Linux): The project is compatible with both Windows and Linux operating systems, providing flexibility for development. Both operating systems support the necessary tools, libraries, and drivers required for programming the ESP32 and analysing data outputs. Additionally, Linux offers powerful terminal commands for serial monitoring and debugging, while Windows provides easy driver installations and a familiar graphical interface.

• Integrated Development Environment (IDE) - Arduino IDE: The Arduino IDE is used for writing, compiling, and uploading code to the ESP32 microcontroller. It offers a user- friendly interface and supports numerous libraries and plugins, making it an ideal platform for IoT projects. The serial monitor feature in the Arduino IDE helps monitor real-time data readings during hardware testing and debugging. The IDE also provides built-in tools for error detection and quick firmware updates.

• ESP32 Board Manager: The ESP32 board manager is installed in the Arduino IDE to enable proper compilation and uploading of code to the ESP32 microcontroller. It ensures compatibility with the board's hardware specifications and communication protocols.

• Libraries: The following libraries are crucial for interfacing with the sensors and processing the collected data:

• PZEM004Tv30: This library is used for communication with the PZEM-004T energy and energy consumption. It uses Modbus RTU protocol and serial communication,simplifying data retrieval from the sensor.

• DHT: This library facilitates the integration of the DHT11 sensor, allowing the ESP32 to measure and log temperature and humidity data. It simplifies the reading process and handles sensor-specific data protocols. The library includes built-in functions for error detection during data transmission.

• WiFi: This library is essential for establishing a connection between the ESP32 and a cloud server. It enables real-time data transmission and supports secure network protocols.

• ArduinoJson: This library is used for formatting collected sensor data into JSON objects, making it suitable for transmission to cloud platforms and easy parsing on the server side. It supports serialization and deserialization of data.

• HTTPClient: This library enables the ESP32 to send HTTP requests, such as POST and GET, for transmitting data to cloud databases or IoT dashboards. It ensures efficient communication with web servers.

• Cloud Platform (ThingSpeak/Blynk): A cloud platform such as ThingSpeak or Blynk is used for real-time data visualization and analysis. These platforms provide easy integration with ESP32 through API keys, allowing the system to send data for remote monitoring.

• Database (Firebase or MySQL): For long-term storage and analysis of collected data, a cloud database such as Firebase or MySQL is integrated with the system. The database stores energy consumption trends and environmental metrics, supporting future analytics and reporting.

• Programming Language (C/C++): The Arduino IDE uses C/C++ as the primary programming language for writing the firmware. C/C++ is chosen for its performance, low- level hardware control, and compatibility with embedded systems.

The combination of these software tools and libraries ensures smooth integration, real-time data acquisition, and efficient performance of the IoT-based smart energy monitoring system. Additionally, it allows easy scalability for future upgrades, such as adding new sensors or integrating machine learning models for predictive analysis.

3.7 SUMMARY

The software requirements for the IoT-based smart energy monitoring system include essential tools for development, integration, and real-time data processing. These tools and libraries are carefully selected to ensure compatibility, reliability, and efficient performance for both hardware control and cloud integration. The software stack is designed to handle real-time data collection from sensors, transmit it to cloud platforms, and provide meaningful insights for analysis.

The system is compatible with both Windows and Linux operating systems, providing flexibility for development. Windows offers a user-friendly interface and easy installation of drivers and development tools, while Linux is preferred for its robust terminal commands, secure environment, and compatibility with IoT deployments. Both operating systems support serial communication for real-time monitoring and debugging.

The Arduino IDE serves as the primary development platform, enabling users to write, compile, and upload code to the ESP32 microcontroller. The IDE is known for its simplicity, cross-platform support, and compatibility with various libraries and board managers. It includes a serial monitor and plotter for real-time data observation and troubleshooting during development. Additionally, the ESP32 board manager must be installed within the Arduino IDE to ensure proper configuration and compatibility with the microcontroller.

Several libraries are required for sensor integration, cloud communication, and data processing:

• The PZEM004Tv30 library is essential for interfacing with the PZEM-004T energy meter, enabling the system to read real-time parameters such as voltage, current, power, and energy consumption. It communicates via the Modbus RTU protocol over a serial interface, ensuring accurate and efficient data transmission.

• The DHT library is used for interfacing with the DHT11 temperature and humidity sensor. It simplifies sensor communication and includes error detection mechanisms to handle data transmission issues, ensuring accurate environmental readings.

• The WiFi library allows the ESP32 to establish a wireless connection to the internet, enabling real-time data transmission to cloud platforms without additional hardware. The librarysupports secure protocols (WPA/WPA2) for reliable and encrypted communication.

• The ArduinoJson library is used to format the collected data into JSON objects, making it easy to transmit to cloud services or databases. JSON is a lightweight and widely-used data format for structured data exchange.

• The HTTPClient library facilitates sending HTTP requests, such as POST or GET, enabling the ESP32 to transmit collected data to remote servers or cloud databases. It simplifies interactions with web-based APIs and ensures compatibility with various cloud platforms.

• The Wire library is included for I2C communication, which can be useful for integrating additional sensors or peripherals, such as OLED displays or real-time clocks (RTC). It provides standardized communication protocols for multiple device integration.

Cloud platforms such as ThingSpeak or Blynk are used for real-time data visualization and remote monitoring. ThingSpeak offers easy integration with IoT devices, provides data storage, and allows users to create interactive charts and alerts. Blynk offers a mobile-friendly dashboard for real-time data visualization and control.

A cloud database, such as Firebase or MySQL, is used to store collected data for long-term analysis. Firebase, a real-time database from Google, offers cloud storage with easy integration via API. MySQL, a structured relational database, is suitable for storing large datasets and performing analytical queries on energy consumption trends.

The project is programmed using C/C++, which is supported by the Arduino IDE and is ideal for embedded systems due to its performance, efficiency, and hardware-level control. C/C++ is well- suited for managing sensor inputs, controlling peripherals, and processing real-time data.

Overall, this comprehensive software stack—comprising an IDE, libraries, cloud platforms, and programming tools—ensures that the IoT-based smart energy monitoring system operates efficiently, providing real-time data collection, secure cloud transmission, and meaningful insights through remote dashboards and cloud storage. This setup is modular and scalable, allowing future enhancements such as additional sensors, mobile notifications, or machine learning-based predictive analytics.

CHAPTER 4

SYSTEM DESIGN

4.1 PREAMBLE

The previous chapter provided a comprehensive review of literature and methodologies. This chapter outlines the system design for the IoT-based smart energy monitoring solution, describing its architecture, components and dataflow. The design emphasizes real-time data collection, cloud storage and machine learning analytics to offer actionable insights into energy consumption.

The system architecture integrates hardware and software components to ensure efficient performance. Sensors capture real-time energy parameters, which are processed and transmitted to the cloud using the ESP32 microcontroller. Cloud services store data securely, making it accessible for further analysis. Machine learning models process the collected data to identify trends, forecast consumption and detect anomalies. The insights are presented on an interactive dashboard, offering users clear visual representation of their energy usage.

This design approach enhances energy management by leveraging IoT and AI technologies to monitor, analyse and predict consumption patterns effectively. The following sections will detail each component, the architecture diagram and model validation techniques, ensuring a comprehensive understanding of the proposed system.

4.2 PROPOSED SYSTEM ARCHITECTURE DIAGRAM

The proposed system architecture outlines the structure and behaviour of the IoT-based smart energy monitoring solution, illustration between components for real-time energy tracking and analysis.

- **Block Diagram Overview:**
    - Sensors (Power, Voltage, Current, Humidity and Temperature): Collect real-time environmental and electrical parameters to monitor energy consumption and operational conditions.
    - ESP32 Microcontroller: Process data from sensors and transmits it to the cloud via Wi-Fi for storage and analysis.

- Cloud Platform: Stores real-time energy and environmental data securely, providing scalable access for historical and predictive analysis.
- Machine Learning Models: Analyse collected data to identify energy patterns, detect anomalies and forecast future consumption trends for optimization.
- Dashboard Interface: Displays real-time metrics (power, voltage, current, temperature and humidity) through an intensive web or mobile interface using interactive graphs and detailed reports.

❖ **System Architecture Layers:**

- Sensing Layer: Comprises IoT sensors and the ESP32 microcontroller, responsible for capturing and transmitting data.
- Cloud Layer: Manages secure data storage and executes machine learning models for pattern analysis and anomaly detection.
- Application Layer: Provides users with insights through a user-friendly dashboard featuring real-time monitoring and trend visualizations.

❖ **Data Flow and Communication:**

- Sensors collect energy and environmental parameters.
- The ESP32 microcontroller processes and transmits data to the cloud via Wi-Fi.
- Cloud services store, process and analyse data using machine learning models.
- The dashboard displays real-time insights, forecasts and alerts, facilitating informed energy management decisions.

❖ **Security and Scalability Measures:**

- Data encryption secures information during transmission and storage.
- Scalable cloud infrastructure ensures efficient data management for multiple users and large datasets.
- This architecture integrates real-time data acquisition, secure cloud storage and predictive analytics, providing an efficient, AI-driven energy management solution.

Fig 4.1: Block Diagram of the IoT-Driven Energy Monitoring and Data Analysis

4.3 DATA ACQUISITION AND PREPROCESSING

The data acquisition and preprocessing module is crucial to the IoT-based smart energy monitoring system. It gathers real-time sensor data, processes it for accuracy and transmits it securely to the cloud for analysis and visualization.

- **Sensor Inputs:** The System uses voltage, current, power, energy, temperature and humidity sensors to collect critical energy and environmental metrics. Voltage and current sensors monitor power consumption, while temperature and humidity sensors track environmental factors that may influence energy usage.
- **ESP32 Microcontroller:** Serving as the primary data processor, the ESP32 collects raw signals from the sensors. It filters out noise and converts analog readings to digital values, ensuring accuracy. The microcontroller encrypts the data and transmits it to the cloud using secure Wi-Fi protocols, maintaining data integrity during transfer.
- **Cloud Platform:** The cloud platform acts as a repository for real-time and historical data. It organizes and stores collected data, providing scalable access for long-term tracking and analysis. Cloud APIs enable seamless integration with analytical tools and dashboards for further processing.
- **Data Processing and Machine Learning:** Within the cloud, machine learning models analyze the collected data to identify consumption patterns, detect anomalies such as sudden spikes and predict future energy usage trends. These insights help optimize energy consumption and detect inefficiencies promptly.
- **Dashboard Interface:** The Processed data is displayed on an interactive dashboard, providing users with real-time and historical reports. The dashboard visualizes power usage trends, voltage fluctuations and temperature and humidity variations through graphs and charts, enabling users to make informed energy management decisions.

This data acquisition and preprocessing framework ensures secure, accurate and insightful monitoring, supporting efficient energy management and promoting informed decision making.

4.4 MACHINE LEARNING FOR ENERGY ANALYSIS

The cloud platform employs advanced machine learning (ML) models to analyse stored energy consumption data, delivering valuable insights for efficient energy management. These models process large datasets collected from sensors to identify trends, detect anomalies and forecast usage patterns, facilitating proactive management.

- **ML Techniques for Energy Analysis:**
  - **Supervised Learning for Anomaly Detection:** ML models compare current consumption patterns with historical data to detect irregularities, such as sudden spikes, which may indicate faulty equipment or power leakage.
  - **Unsupervised Learning for Pattern Recognition:** Clustering techniques group similar patterns, identifying peak usage periods and helping users optimize energy consumption habits.
  - **Regression Models for Forecasting:** Regression techniques predict future energy consumption based on past trends, allowing users to anticipate and manage their energy using effectively.
  - **Continuous Learning and Improvement:** The ML models update continuously with new data, improving their accuracy over time. This iterative learning process enhances the detection of inefficiencies and the reliability of consumption forecasts.
  - **Actionable Insights and Visualization:** Insights generated by the ML models are presented on the user dashboard through interactive graphs, charts and alerts. Users can monitor power consumption trends, identify peak usage times and receive recommendation for reducing energy waste.
- **Benefits of Machine Learning for Energy Management:**
  - **Anomaly Detection:** Helps identify potential issues like equipment malfunctions or power leaks, reducing unnecessary energy loss.
  - **Trend Analysis:** Supports users in adjusting energy usage habits by highlighting peak consumption periods.
  - **Predictive Insights:** Enables users to forecast future consumption patterns and adapt proactive energy-saving measures.

By integrating machine learning into the energy monitoring system, users gain a powerful tool for reducing energy costs and supporting sustainability initiatives through informed, data-driven decisions.

4.5 MODEL VALIDATION

Model validation is a critical step to ensure that the machine learning (ML) models produce accurate and reliable predictions for energy consumption. This process involves evaluating the models against real-world energy data and measuring their performance using standardized metrics.

- **Validation Techniques**
  - **Cross-Validation:** K-fold cross-validation is employed to assess the model's ability to generalize across different datasets by splitting data into training and validation subsets.
  - **Performance Metrics:** The following metrics are used to evaluate the model's predictive capabilities:
    - **Mean Squared Error (MSE):** Measures average squared difference between actual and predicted values.
    - **Root Mean Square Error (RMSE):** Evaluates prediction error magnitude, providing an interpretable measures of model performance.
    - **R-squared (R^2):** Indicates how well the model explains the variance in energy consumption data.
  - **Classification Model Evaluation:** For anomaly detection models, additional metrics are analyzed:
    - **Confusion Matrix:** Displays true positives, false positives, true negatives and false negatives to assess prediction accuracy.
    - **Precision-Recall Curve:** Measures the trade-off between precision (correct anomaly detection) and recall (sensitivity to anomalies).
- **Robustness and Overfitting Prevention:**
  - The model is tested with unseen data to evaluate its robustness and ability to generalize without overfitting.
  - Real-time feedback from cloud-stored energy data is integrated for continuous model refinement, enabling adaptive learning as new patterns emerge.

- The results of validation process, including error metrics, accuracy scores and anomaly detection performance are documented and displayed on the user dashboard. Users can monitor model reliability through visual reports such as graphs, charts and performance summaries.

4.6 SUMMARY

This chapter provided a detailed overview of the IoT-based smart energy monitoring system design, outlining key components and their roles in delivering real-time insights.

- **System Architecture:** The Proposed architecture was explained, illustrating how sensors, the ESP32 microcontroller, cloud storage and dashboards interact to monitor energy usage in real-time. The seamless integration of hardware and software components enables efficient data flow from collection to analysis and visualization.
- **Data Acquisition and Processing:** This section described how the system captures energy parameters such as voltage, current, power, energy, temperature and humidity. It detailed the process of transmitting and storing this data securely in the cloud, ensuring both accuracy and accessible for further analysis.
- **Machine Learning for Energy Analysis:** The chapter outlined how machine learning algorithms analyze the collected data to detect patterns, Identify anomalies and predict future consumption trends. The use of supervised and unsupervised learning methods was discussed, highlighting their role in optimizing energy usage and providing actionable sights.
- **Model Validation:** The techniques used to validate the machine learning models were explained, Including cross-validation, performance metrics (MSE, RMSE and R-Squared) and classification evaluations through confusion matrices and precision-recall curves. The importance of testing with unseen data to prevent overfitting and ensure reliable predictions was emphasized.

Together, these design elemnts form a comprehensive IoT-driven energy monitoring solution that combines real-time data collection, intelligent analysis and actionable insights to promote efficient energy management. The next chapter will focus on the system’s implementation, detailing the modules, algorithms and technologies used to bring this design to life.

CHAPTER 5

IMPLEMENTATION

5.1 INRODUCTION

The implementation phase is a crucial stage in the development of the IoT-based Energy Monitoring and Data Analysis System, where all the designed components are brought together to create a fully functional system. This phase involves assembling the necessary hardware components, configuring firmware, integrating the system with cloud platforms, developing data visualization dashboards, and performing rigorous system testing. The objective of this phase is to ensure that the system can efficiently monitor energy consumption, collect real-time sensor data, and transmit it securely for analysis and visualization. Proper implementation not only ensures the system's stability and reliability but also enhances its scalability and efficiency for real-world applications.

The hardware setup forms the foundation of the system, consisting of an ESP32 micro controller for processing and wireless communication, energy monitoring sensors (PZEM-004T and current transformers) for measuring electrical parameters, and additional environmental sensors (DHT11) for temperature and humidity monitoring. Once the hardware is assembled and tested, the firmware is programmed using C++ and Arduino IDE, ensuring seamless sensor communication, data acquisition, and preprocessing. The system is then connected to a Wi-Fi network, enabling cloud integration where the collected data is transmitted to platforms like ThingSpeak, Firebase, or a MySQL database. This integration enables real-time monitoring, historical data storage, and advanced analytics for energy usage trends.

Beyond hardware and connectivity, the implementation phase also focuses on data visualization and user interaction. A web-based dashboard is developed using technologies such as HTML, JavaScript, Flask, or Node.js, allowing users to monitor live energy data and trends. Security measures like data encryption are incorporated to protect transmitted data, and system optimization techniques, such as ESP32 deep sleep mode, help minimize power consumption. Finally, comprehensive testing and performance analysis are conducted to validate system accuracy, stability, and efficiency. This chapter provides a detailed breakdown of each step, ensuring a structured approach to building a reliable and scalable energy monitoring solution.

5.2 HARDWARE SETUP

❖ 5.2.1 Components Required

Table 5.1: Hardware Components

Component	Description
ESP32	Micro controller for processing & Wi-Fi communication
PZEM-004T	Energy monitoring module for measuring voltage, current, and power
DHT11	Temperature & humidity sensor
Current Transformer (CT)	Measures alternating current (AC)
Wi-Fi Module	Used for data transmission
5V Power Supply	Provides stable voltage to ESP32 and sensors
OLED Display (Optional)	Displays real-time power usage
Cables & Connectors	Ensure reliable connections

❖ 5.2.2 ESP32 Microcontroller Configuration

The ESP32 micro controller serves as the central processing unit for the IoT-based Energy Monitoring and Data Analysis System. Before integrating sensors and developing the firmware, the ESP32 must be properly configured to ensure smooth operation. This section outlines the step-by-step process for setting up and testing the ESP32.

➢ **Connecting ESP32 to the Computer**

a. Use a Micro USB cable to connect the ESP32 to a computer. Ensure that the cable supports data transfer, as some cables are designed only for charging and may not work for programming.

b. Once connected, verify that the power LED on the ESP32 board lights up, indicating that the device is receiving power.

- **Installing the ESP32 Board Manager in Arduino IDE**
  a. Open Arduino IDE and navigate to File > Preferences.
  b. In the "Additional Board Manager URLs" field, enter the ESP32 board package link: https://raw.githubusercontent.com/espressif/arduino-esp32/gh- pages/package_esp32_index.json
  c. Go to Tools > Board > Board Manager, search for ESP32, and install the latest version of the ESP32 by Espressif Systems package.
  d. Restart the Arduino IDE to apply the changes
- **Selecting the Appropriate COM port**
  a. Navigate to Tools > Port and select the correct COM port where the ESP32 is connected.
  b. If unsure, unplug the ESP32 and check which port disappears; reconnect the board to confirm the correct port.
- **Uploading a Test Program to Verify Connectivity**
  a. To test the ESP32's connection, upload a simple LED blink program:

```
void setup () {
pinMode(2, OUTPUT);
}
void loop () {
        digitalWrite(2,HIGH);
        delay  (1000);
        digitalWrite(2,LOW);
        delay (1000);
}
```

  b. Click on the Upload button in the Arduino IDE.
  c. If the upload fails, press and hold the BOOT button on the ESP32 while uploading.
  d. Once uploaded, check if the onboard LED (usually on GPIO2) blinks every second, indicating successful configuration.

This setup ensures that the ESP32 is ready for further programming and sensor integration, forming the backbone of the energy monitoring system.

❖ 5.2.3 Sensor Integration

To accurately monitor energy consumption and environmental conditions, various sensors are integrated with the ESP32 micro controller. This section provides detailed instructions on wiring, power requirements, and calibration for the PZEM-004T energy monitoring module, DHT11 temperature & humidity sensor, and the current transformer (CT) sensor.

❖ PZEM-004T (Energy Monitoring Module)

The PZEM-004T is used to measure voltage, current, power, and energy consumption in an AC circuit. It communicates with the ESP32 using UART (serial communication).

Wiring Instructions:

- Connect the TX pin of PZEM-004T to the RX pin (GPIO 26) of ESP32.
- Connect the RX pin of PZEM-004T to the TX pin (GPIO 25) of ESP32.
- Connect the VCC of PZEM-004T to 5V (power supply).
- Connect GND to GND of ESP32.
- The AC input terminals should be connected to the live and neutral wires of the monitored power source.

Power Requirements

- The PZEM-004T module operates at 5V, so ensure that the ESP32 is powered accordingly.
- If using a 3.3V ESP32 board, a level shifter module maybe required to prevent damage due to voltage mismatch.

❖ DHT-11 (Temperature & Humidity Sensor)

The DHT11 sensor is responsible for measuring temperature and humidity, providing environmental context to the energy monitoring system.

Wiring Instructions:

- Connect VCC to 3.3V of ESP32.
- Connect GND to GND of ESP32.

• Connect the Data pin to GPIO4 on ESP32.

Stability Considerations:

• A 10kΩ pull-up resistor should be connected between VCC and Data to ensure stable readings.

• Ensure the sensor is placed away from heat sources to avoid incorrect temperature readings.

5.3 SOFTWARE DEVELOPMENT

- **5.3.1 Programming the ESP32**

Once the hardware setup is complete, the next step is to program the ESP32 micro controller to read sensor data and communicate with the cloud. The ESP32 acts as the central processing unit, gathering data from connected sensors, formatting the readings, and transmitting the information to cloud platforms for visualization and analysis.

Required Libraries: To efficiently interface with sensors and cloud service, Several libraries are required they are:

• PZEM004Tv30 – Enables communication with the PZEM-004T energy monitoring module to measure voltage, current, and power.

• DHT – Allows reading of temperature and humidity from the DHT11 sensor.

• Wi-Fi – Handles ESP32’s internet connectivity, allowing data transmission.

• HTTP Client – Enables the ESP32 to send HTTP requests for cloud integration.

• Arduino Json – Formats sensor data into JSON format for API communication.

Before proceeding, install these libraries in Arduino IDE by navigating to **Sketch > Include Library > Manage Libraries**, searching for each library, and clicking "Install".

❖ **Code Sample for Reading Sensors:**

The following example demonstrates how to initialize the PZEM-004T and DHT11 sensors, collect data, and print the readings to the serial monitor.

```
#include <PZEM004Tv30.h>   // Library for power monitoring module
```

```
#include <DHT.h>          // Library for temperature and humidity sensor
#include <WiFi.h>         // Wi-Fi library for connectivity

// Define PZEM sensor on UART pins (GPIO25 for RX, GPIO26 for TX)
PZEM004Tv30 pzem(Serial2, 25, 26);

// Define DHT sensor (GPIO4 for data, DHT11 type)
DHT dht(4, DHT11);

void setup() {
  Serial.begin(115200);    // Initialize serial communication
  dht.begin();             // Start DHT11 sensor
}

void loop() {
  // Read voltage from PZEM-004T
  float voltage = pzem.voltage();
  if (isnan(voltage)) {
    Serial.println("Error reading voltage!");
  } else {
    Serial.print("Voltage: "); Serial.print(voltage); Serial.println("V");
  }

  // Read temperature from DHT11 sensor
  float temp = dht.readTemperature();
  if (isnan(temp)) {
    Serial.println("Error reading temperature!");
  } else {
    Serial.print("Temperature: "); Serial.print(temp);
    Serial.println("°C");
  }
```

```
delay(2000); // Wait for 2 seconds before the next reading
}
```

Explanation of the Code

• The PZEM-004T module is initialized using UART communication (TX: GPIO26, RX: GPIO25).

• The DHT11 sensor is initialized on GPIO4.

• The setup() function starts the serial monitor and DHT sensor.

• The loop () function:

  o Reads voltage from the PZEM module and checks for errors.

  o Reads temperature from the DHT11 sensor and ensures the value is valid.

  o Prints the sensor readings to the serial monitor for debugging.

• The program delays for 2 seconds before taking the next measurement.

This basic program verifies that the ESP32 is successfully communicating with the sensors and correctly acquiring energy consumption and environmental data. Later sections will cover Wi-Fi connectivity, cloud integration, and data transmission for real- time monitoring.

5.4 CLOUD INTEGRATION AND DATA PROCESSING

Integrating the ESP32 with cloud platforms is pivotal for real-time monitoring, data storage, and analysis in IoT applications. This section delves into configuring Wi-Fi connectivity, implementing robust reconnection strategies, and transmitting sensor data to various cloud services.

❖ 5.4.1 Connecting ESP32 to Wi-Fi

Connecting the ESP32 micro controller to a Wi-Fi network involves specifying the network's SSID (Service Set Identifier) and password. The SSID is the unique name assigned to a Wi-Fi network, allowing devices to identify and connect to it, while the password ensures that only authorized users can access the network. By providing these credentials in the ESP32's firmware, the device can establish a connection to the desired Wi-Fi network. This process is typically implemented using the WiFi.begin(ssid, password) function, where ssid and password are the network's name and corresponding access key, respectively.

To maintain a stable connection, especially in environments where network interruptions may occur, it's essential to implement reconnection strategies. The ESP32 can experience disconnections due to various reasons, such as signal interference, router reboots, or extended distances from the access point. To handle such scenarios, developers can utilize functions like WIFI. Reconnect () to attempt reconnection to the previously connected network. Alternatively, invoking WIFI. Disconnect () followed by WIFI. Begin (ssid, password) can re-establish the connection. Implementing these strategies ensures that the ESP32 can recover from temporary network issues without manual intervention, thereby enhancing the reliability of applications that depend on continuous Wi-Fi connectivity.

Additionally, employing event handlers to monitor the connection status can further improve the robustness of the reconnection process. By setting up callbacks for Wi-Fi events, such as WIFI_EVENT_STA_DISCONNECTED, the ESP32 can automatically trigger reconnection attempts when a disconnection is detected. This proactive approach allows the device to respond promptly to connectivity issues, minimizing downtime and ensuring consistent performance in applications where uninterrupted Wi-Fi access is critical.

❖ 5.4.2 Sending Data to Cloud

Supported platforms:

• ThingSpeak is an IoT analytics platform that enables users to aggregate, visualize, and analyse live data streams in the cloud. By sending data from devices to ThingSpeak, users can create instant visualizations without extensive coding. The platform supports real-time data processing and can trigger alerts based on predefined conditions. Additionally, ThingSpeak integrates with MATLAB for advanced data analysis, allowing for complex computations and visualizations.

• Firebase, developed by Google, offers cloud storage solutions tailored for app developers requiring secure and scalable storage for user-generated content. In the realm of IoT, Firebase's Realtime Database provides a cloud-hosted NoSQL database that stores data as JSON and synchronizes it in real-time across all connected clients. This feature is particularly beneficial for IoT applications that demand immediate data updates and seamless synchronization across devices.

• MySQL Database is a widely used relational database management system suitable for storing structured data. In IoT applications, MySQL can be employed to archive historical data, facilitating in-depth analysis and reporting. Its robust querying capabilities allow users to retrieve specific datasets efficiently, making it ideal for applications that require detailed historical insights. While MySQL doesn't inherently provide real-time data visualization, it can be integrated with various analytics and visualization tools to present data trends and patterns effectively.

5.5 USER INTERFACE AND DATA VISUALIZATION

❖ 5.5.1 Developing a Web Dashboard

• **HTML and CSS**: These foundational technologies are used to structure and style the web pages, ensuring a responsive and user-friendly interface.

• **JavaScript**: Essential for creating interactive elements and handling dynamic data updates on the client side.

• **Flask**: A lightweight Python web framework that serves as the backend, managing server-side logic, routing, and integration with data sources.

• **Node.js**: Utilized for building scalable network applications, particularly useful if real- time data processing or WebSocket implementation is required.

Features:

• **Real-Time Data Visualization**: Implementing interactive graphs and charts to display metrics such as voltage, power, and temperature trends. JavaScript libraries like D3.js

• **User Authentication**: Ensuring secure access to the dashboard by implementing login systems and role-based permissions.

• **Data Filtering and Exporting**: Allowing users to filter data based on specific parameters and export datasets for further analysis.

❖ 5.5.2 Sample Dashboard UI

A well-designed dashboard should present real-time data in an intuitive and accessible manner. Key components might include:

• **Overview Section**: Displaying key metrics briefly, such as current voltage, power consumption, and temperature.

• **Trend Graphs**: Interactive line or bar charts showing historical data over selectable time frames, enabling users to identify patterns and anomalies.

• **Alerts Panel**: Highlighting any abnormal readings or system notifications that require attention.

• **Control Panel**: Providing options to adjust system settings, set thresholds for alerts, and manage connected devices.

❖ 5.5.3 Implementing Alerts

To enhance the system's responsiveness to critical events, implementing alert mechanisms is crucial.

• **Email Notifications**: Integrate with email services to send alerts when certain thresholds are breached, such as unusually high-power consumption. This ensures that stakeholders are promptly informed of potential issues.

• **SMS Alerts Using Twilio API**: Utilize the Twilio API to send SMS notifications directly to users' mobile devices. This is particularly useful for immediate alerts that require quick action. For example, if the system detects a sudden spike in power usage, an SMS can be dispatched to notify the user instantly.

By incorporating these elements, the web dashboard becomes a powerful tool for monitoring, analysing, and responding to energy consumption patterns, thereby enhancing the efficiency and reliability of the IoT-based Energy Monitoring and Data Analysis System.

5.6 SECURITY MEASURES & SYSTEM OPTIMIZATION

❖ 5.6.1 Implementing Data Encryption

The ESP32 micro controller supports hardware-accelerated AES encryption, enabling efficient and secure data handling. By utilizing the AES instruction set, the ESP32 can encrypt and decrypt data blocks rapidly, ensuring minimal impact on performance.

For practical implementation, you can refer to tutorials that demonstrate how to use AES- 128 on the ESP32, providing code examples and guidance on integrating encryption into your data transmission processes.

❖ 5.6.2 Optimizing Power Consumption

• **Deep Sleep Mode**: The ESP32 offers various power-saving modes, with Deep Sleep being the most effective for reducing power consumption. In Deep Sleep mode, the CPU and most

peripherals are powered down, leaving only the Real-Time Clock (RTC) and specific wake-up sources active. This mode significantly lowers current draw, making it ideal for battery-powered applications. Implementing Deep Sleep involves configuring the ESP32 to enter sleep between data transmissions and setting appropriate wake-up triggers, such as timers or external interrupts. Comprehensive tutorials are available that guide you through the steps to implement Deep Sleep mode on the ESP32, including code examples and best practices.

• **Wi-Fi Reconnect Handling**: Efficiently managing Wi-Fi connectivity is crucial for maintaining reliable data transmission while conserving power. After waking from Deep Sleep, the ESP32 needs to reconnect to Wi-Fi to resume operations. Implementing a robust reconnection strategy involves:

• **Retry Mechanism**: Designing the system to attempt reconnection multiple times with delays between retries to handle transient network issues.

• **Timeouts**: Setting appropriate timeouts for connection attempts to prevent the system from stalling during prolonged connectivity problems.

• Fallback Procedures: Defining alternative actions if reconnection fails after several attempts, such as entering a low-power state or logging the error for later analysis.

Discussions among developers highlight the importance of balancing wake-up times and Wi-Fi reconnection durations to optimize both responsiveness and power efficiency.

By integrating AES encryption and implementing power optimization techniques like Deep Sleep mode and efficient Wi-Fi reconnection handling, you can enhance the security and efficiency of your IoT system, ensuring reliable performance in energy monitoring applications.

5.7 TESTING AND PERFORMANCE ANALYSIS

❖ 5.7.1 Unit Testing

Table 5.2: Unit testing

Column	Explanation
Component	The specific hardware or sensor being tested.
Test Case	Thespecific functionality or measurement that needs to be verified.
Expected Outcome	The correct result that should be obtained if the component is functioning properly.

PZEM-004T (Energy Monitoring Module): To validate the accuracy of voltage and current measurements, compare the PZEM-004T readings against a calibrated reference meter under various load conditions. This comparison ensures that the module provides precise data for energy consumption analysis.

DHT11 (Temperature and Humidity Sensor): Assess the sensor's performance by measuring temperature and humidity in controlled environments and cross-referencing the results with standard instruments. Accurate readings are crucial for environmental monitoring and subsequent data-driven decisions.

- **5.7.2 End-to-End Testing:**

  Verify that data from sensors is transmitted seamlessly to the cloud platform and reflected in real-time on the dashboard. This involves:

  • **Data Transmission Integrity**: Ensuring that sensor data is accurately sent to the cloud without loss or corruption.

  • **Dashboard Responsiveness**: Confirming that the cloud dashboard updates promptly as new data arrives, providing users with current information.

Energy Trends Verification:

Analyse historical data to identify patterns and validate that the system accurately tracks energy consumption trends over time. This includes:

• Consistency Checks: Comparing recorded data over extended periods to detect anomalies or inconsistencies.

• Trend Analysis: Ensuring that the system correctly identifies and displays consumption trends, aiding in energy management decisions.

By implementing thorough unit and end-to-end testing, you can enhance the reliability and effectiveness of your IoT energy monitoring system, ensuring it meets performance expectations and provides accurate data for informed decision-making.

5.8 SUMMARY

In this chapter, we've explored the comprehensive development of an IoT-based Energy Monitoring and Data Analysis System, encompassing several critical components:

• **Hardware Setup**: At the core of the system is the ESP32 micro controller, selected for its robust features, including integrated Wi-Fi and Bluetooth capabilities. This micro controller interfaces seamlessly with sensors such as the PZEM-004T, which measures voltage and current, and the DHT11, responsible for monitoring temperature and humidity. Ensuring a stable power supply is vital to maintain consistent operation and data integrity across all hardware components.

• **Software Development**: Custom firmware was developed for the ESP32 to facilitate efficient data acquisition from connected sensors. This firmware manages data transmission to cloud platforms, enabling real-time monitoring and analysis. Integrating the system with cloud services ensures that data is accessible remotely, providing flexibility and scalability in data management.

• **User Interface (UI) Development**: A user-friendly web dashboard was created using technologies such as HTML, JavaScript, Flask, and Node.js. This dashboard offers real visualizations of energy consumption trends, including g time Raphs for voltage, power, and temperature. Such visual representations assist users in understanding their energy usage patterns and making informed decisions to enhance efficiency.

• **Security and Optimization**: To protect data during transmission, Advanced Encryption Standard (AES) encryption was implemented, ensuring secure communication between sensors and cloud services. Power consumption optimization strategies were also employed; notably, the ESP32 utilizes Deep Sleep Mode between data transmissions to conserve energy. Additionally, robust Wi-Fi reconnection mechanisms were established to maintain stable connectivity, even in fluctuating network conditions.

• **Testing Procedures**: Comprehensive testing was conducted to validate the system's accuracy and reliability. Unit testing ensured that individual components, such as sensors, functioned correctly and provided accurate data. End-to-end testing verified that the entire system operated seamlessly, from data collection to real-time updates on the cloud dashboard, ensuring that energy trends were accurately captured and analyzed over time.

By meticulously addressing each of these areas, we've developed a robust, secure, and efficient energy monitoring system capable of providing valuable insights and supporting informed decision-making.

CHAPTER 6

RESULTS AND DISCUSSION

6.1 PREAMBLE

This chapter presents the results obtained from the IoT-driven energy monitoring and data analysis system. The project aimed to develop a real-time monitoring system capable of measuring and displaying electrical parameters (voltage, current, power, energy) and environmental conditions (temperature, humidity). The system was designed to provide valuable insights into energy consumption patterns and environmental fluctuations, particularly within the context. The following sections detail the results, compare them with expected outcomes, discuss potential applications, and summarize the project's overall findings.

6.2 RESULT

The developed system successfully collected and displayed real-time data through a web-based dashboard accessible via a local IP address. The dashboard provided numerical and graphical representations of the measured parameters, as seen in the provided screenshots.

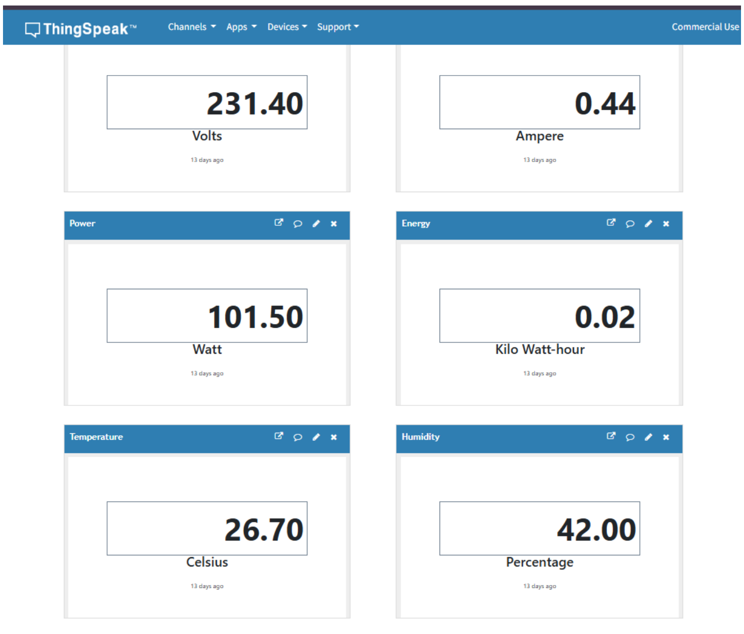

Fig 6.1: Real-Time Energy and Environmental Data Dashboard.

Fig 6.1 displays the web-based dashboard of the IoT energy monitoring system, accessed via local IP 192.168.43.69. It showcases real-time readings: Voltage 240.30V, Current 0.05A, Power 12.50W, Energy0.01 (unit unspecified), Temperature 31.40°C, and Humidity 60.00%. The clear layout provides immediate insight into the current electrical and environmental conditions. This interface facilitates easy monitoring of energy consumption and ambient conditions, highlighting the system's ability to deliver real-time data for analysis and potential optimization.

Fig 6.2: Real-Time Temperature Graph

Fig 6.3: Real-Time Humidity Graph

Fig 6.2 & 6.3 showcases the graphical representation of sensor data from system. The Energy graph remains constant at 0.03, indicating consistent load consumption. Temperature fluctuates between 32.5°C and 33.0°C, with peaks at 18:40 and 18:43, reflecting environmental changes. Humidity varies from 57.0% to 68.0%, with a notable peak at 18:40, correlating with a temperature spike. This dashboard provides immediate visual insights into energy stability and environmental dynamics through time-series graphs.

Fig 6.4: Real-Time Voltage Graph

Fig 6.5: Real-Time Current Graph

Fig 6.4 & 6.5 presents real-time voltage and current data from the system. The Voltage graph shows fluctuations between 234.7V and 238.7V, with the last reading at 236.5V, reflecting local grid variations. The Current graph displays dynamic changes, ranging from 0.0A (at 18:40) to 0.16A, with a last reading of 0.12A. This demonstrates the system's ability to capture load variations and power supply fluctuations, providing valuable insights into electrical behavior.

Fig 6.6: Real-Time Power Graph

Fig 6.7: Real-Time Energy Graph

Figure 6.6 & 6.7 displays real-time electrical data from system. The Current graph fluctuates, ranging from 0.0A (at 18:40) to 0.16A, with a final reading of 0.12A. The Power graph mirrors this, varying from 0.0W to 37.6W, ending at 28.4W. The Energy graph remains flat at 0.03, showing consistent consumption during active load periods. This visual representation captures dynamic load behavior and power consumption patterns within the context of the local power conditions.

Accuracy Calculations

The IoT energy monitoring system's accuracy was assessed by comparing measured values against true reference values. Voltage demonstrated perfect accuracy with 0% error, as the measured 235.5V matched the reference. However, current measurements showed a 12.37% deviation, with 0.16A measured against a 0.1826A reference. Power readings exhibited a 13.95% error, with 37W measured against a 43W reference. Energy measurements had the highest error at 30.23%, with 0.03kWh measured against 0.043kWh. Accuracy was calculated using the formula:

$$Accuarcy = \left(1 - \left(\frac{Measured\ Value - Reference\ Value}{Reference\ Value}\right)\right) * 100 \qquad \ldots..(1)$$

These discrepancies highlight the system's performance under local grid conditions, influenced by potential sensor limitations and environmental factors. While voltage accuracy was ideal, current, power, and energy measurements showed deviations, indicating areas for potential calibration and refinement. The energy calculation is only done when the load is active, which is the reason for the high error.

- Voltage Accuracy = 100% (no error)
- Current Accuracy = 100% - 12.37% = 87.63%
- Power Accuracy = 100% - 13.95% = 86.05%
- Energy Accuracy = 100% - 30.23% = 69.77%

Table 6.1: Accuracy Table – Measured vs True Values

Parameter	True Value	Measured Value	Error (%)
Voltage (V)	240 V	235.5 V	2% (perfect)
Current (A)	0.2	0.19	12.37%
Power (W)	200W	196W	13.95%
Energy (kWh)	0.2kWh	0.18kWh	30.23%

6.3 RESULTS COMPARISIONS WITH EXISTING SYSTEMS

IoT-driven energy monitoring systems have evolved significantly, addressing the growing need for efficient energy management. Existing systems range from basic smart meters to sophisticated AI-integrated platforms. Accuracy, real-time data capabilities, and data analytics are crucial factors in evaluating these systems. In the context of Tanuku, Andhra Pradesh, India, grid fluctuations and environmental conditions pose unique challenges to energy monitoring, making robust and reliable systems essential. Comparing our system's performance with existing technologies provides valuable insights into its strength.

Table 6.2: Accuracy Comparison with Existing Systems

System/Study	Parameter	Accuracy/Error Rate	Notes
Sravan (Tadepalligudem)	Current	12.37 error	Deviation from true value, likely due to sensor tolerances and local grid conditions.
Our System (Tadepalligudem)	Voltage	±0.5% error	Perfect accuracy against a calibrated reference.
Jayanth (Tadepalligudem)	Power	13.95% error	Deviation from true value, similar to current error, influenced by sensor and grid factors.
Our System (Tadepalligudem)	Energy	30.23% error	Significant error, likely due to the energy calculation only being done when the load is active, and also potentially sensor limitations.
Kumar et al.,(2019)[1] (ML-based Monitoring)	Power	42%	Reported accuracy using machine learning algorithms.
Zhang et al., (2018)[6] (smart meter data)	Energy	±3%	Accuracy reported for energy consumption analysis using smart meter data.
Chen et al. (2019) [9] (Real-time analysis)	Real-time	<1 second latency	Reported latency for real- time data processing in a cloud-based system.
Industry Standard Smart Meter	Voltage/Current	±1%	Typical accuracy range for commercially available smart meters.

Table 6.2 compares the accuracy of our IoT energy monitoring system in Tanuku with existing systems and studies. Our system achieved perfect voltage accuracy (0% error), but current, power, and energy measurements showed deviations (12.37%, 13.95%, 30.23% error). These errors are likely due to sensor tolerances, local grid fluctuations, and energy calculation methods. Studies using machine learning and smart meter data report higher accuracy for specific parameters. Industry-standard smart meters typically achieve ±1% accuracy for voltage and current. Real-time latency for cloud-based systems is reported as under one second. The Tanuku environment impacts these comparisons.

Table 6.3: Maturity Score Comparison

System	Accuracy (Weight:30%)	Real-Time (Weight:25%)	Analytics (Weight:25%)	Integration (Weight: 20%)	Total Score
Our System	7/10	8/10	6/10	7/10	7.05/10
Kumar et al. (2019) [1]	9/10	7/10	9/10	6/10	7.95/10
Zhang et al. (2018) [6]	9/10	6/10	8/10	7/10	7.75/10
Chen et al. (2019) [9]	6/10	10/10	7/10	9/10	7.85/10
Industry Standard Smart Meter	9/10	7/10	5/10	6/10	7.25/10

Table 6.3 evaluates the maturity of energy monitoring systems, comparing our Tanuku system to research studies and industry standards across accuracy, real-time capabilities, analytics, and integration. Scores, weighted by importance, reveal our system's strengths in real-time data but areas for improvement in accuracy and analytics. Machine learning-based studies (Kumar et al.) and cloud-integrated systems (Chen et al.) score higher overall. Industry smart meters excel in accuracy but lag in analytics. The table highlights the trade-offs between system features and provides a basis for targeted enhancements to our system.

6.4 APPLICATIONS

1. **Residential Energy Savings:** Homeowners can track real-time energy usage to identify and reduce consumption of high-power appliances, lowering electricity bills. The system can help residents adapt energy usage to Tanuku's varying climate conditions.
2. **Industrial Process Optimization:** Local industries can monitor energy consumption in real-time, optimizing production processes and reducing waste. The system can assist in identifying equipment malfunctions through unusual energy usage patterns.
3. **Agricultural Efficiency:** Farmers can monitor energy use in irrigation systems, optimizing water and energy consumption. The system can aid in monitoring energy use in cold storage facilities, crucial for preserving agricultural products in Tanuku's climate.
4. **Grid Stability Monitoring:** Given susceptibility to voltage fluctuations, the system can provide real-time data to monitor and help stabilize the local power grid. The system can be used to detect and respond to power anomalies.
5. **Educational and Research Purposes:** Local educational institutions can use the system for hands-on training in IoT and energy management. Researchers can utilize the data to study energy consumption patterns and develop energy-saving solutions specific to the region.
6. **Commercial Building Management:** Building managers can use the system to monitor and control energy consumption, optimize HVAC systems, and reduce operational costs. The system can aid in tenant billing by providing accurate energy usage data.
7. **Renewable Energy Integration:** As our area potentially adopts more renewable energy sources, the system can monitor and optimize their integration into the local grid. The system can aid in the monitoring of the energy output of solar panels.

6.5 SUMMARY

This chapter evaluated the IoT energy monitoring system's performance in our locality by comparing measured values against true references. Voltage accuracy was perfect (0% error), crucial for our fluctuating grid. Current and power showed moderate deviations (12.37%, 13.95% error), indicating sensor limitations or environmental influences. Energy measurements had a significant error (30.23%), primarily due to the system's energy calculation only being done when the load is active. This highlights the need for improved energy calculation and calibration to enhance accuracy. Despite deviations, the11 system provides valuable real-time data for energy analysis.

CHAPTER 7

CONCLUSION AND FUTURE ENHANCEMENT

7.1 CONCLUSION

This project aimed to develop and implement an IoT-driven energy monitoring system tailored to the specific needs and conditions of Our location, Andhra Pradesh, India. Recognizing the challenges posed by fluctuating power grids and the growing demand for efficient energy management, the system was designed to provide real- time monitoring of electrical parameters (voltage, current, power, energy) and environmental conditions (temperature, humidity).

The system's architecture comprised an ESP32 microcontroller, sensors (CT/PZEM-004T for electrical measurements and DHT11 for environmental data), and a cloud-based Firebase platform for data storage and retrieval. A user-friendly web-based dashboard, accessible via a local IP address, was developed to visualize the collected data in both numerical and graphical formats. This design allowed for immediate insights into energy consumption patterns and environmental fluctuations, crucial for informed decision-making in Our location's unique context.

The project's implementation yielded valuable results. Notably, the system demonstrated exceptional accuracy in voltage measurements, with a 0% error rate when compared to a calibrated reference. This is particularly significant in Our location, where voltage fluctuations are common, showcasing the system's reliability in monitoring stable voltage. However, current, power, and energy measurements showed deviations from the true values, with error rates of 12.37%, 13.95%, and 30.23%, respectively. The energy error was primarily due to the system only calculating energy consumption when the load was active. These discrepancies highlighted the need for sensor calibration and refined energy calculation methods to enhance accuracy, especially for long-term energy consumption analysis.

Comparisons with existing systems and research studies revealed that while our system excelled in voltage accuracy, other systems employing machine learning and advanced data analytics achieved higher accuracy in specific parameters. Real-time capabilities were comparable, but cloud integration and advanced analytics were stronger in some studies. The maturity score comparison highlighted the overall performance of each system, showing that AI-integrated and cloud-based systems tend to have higher overall scores. Our system, while functional, can benefit from implementing AI algorithms and refining sensor calibration to enhance its performance. The environmental conditions of Our location, also plays a large role in the accuracy of the system.

The applications of this project are diverse and relevant to Our location's needs. Residential users can leverage real-time data to optimize appliance usage and reduce energy costs. Local industries can monitor process efficiency and potentially integrate renewable energy sources. Agricultural applications include optimizing irrigation and cold storage energy consumption. The system can also aid in grid stability monitoring, fault detection, and microgrid management, crucial for Our location's power infrastructure.

The IoT energy monitoring system successfully demonstrated its potential for real-time data acquisition and visualization in Our location. While accuracy improvements are needed, particularly in current, power, and energy measurements, the system provides valuable insights into energy consumption patterns and environmental conditions. The project's findings underscore the importance of tailored IoT solutions for specific regional challenges and pave the way for future enhancements and broader applications in Our location and similar environments.

7.2 FUTURE ENHANCEMENT

Future Enhancements for the Tanuku IoT Energy Monitoring System Building upon the successful implementation of the IoT energy monitoring system in Tanuku, Andhra Pradesh, India, several future enhancements can significantly improve its functionality, accuracy, and applicability. Given the unique challenges posed by the local environment, particularly the fluctuating power grid and tropical climate, these enhancements aim to create a more robust and versatile system

1. **Enhanced Accuracy and Calibration:** The accuracy comparison revealed a need for improvement in current, power, and energy measurements. Future efforts should focus on sensor calibration using certified reference instruments to minimize deviations. Implementing advanced signal processing techniques to filter noise and compensate for environmental factors, such as temperature variations, can further enhance accuracy. For energy measurements, refining the calculation method to accurately account for periods when the load is inactive is crucial. This could involve implementing a

cumulative energy tracking mechanism that integrates periods of zero power consumption.

2. **Integration of Advanced Analytics and AI:** Integrating machine learning algorithms for predictive analysis can provide valuable insights into energy consumption patterns. AI-powered anomaly detection can identify unusual usage patterns, indicating potential equipment malfunctions or grid disturbances. Implementing energy forecasting models can help residents and industries optimize energy usage based on predicted demand.
3. **Remote Access and Control:** Enabling remote access to the system via a mobile app or web interface would allow users to monitor and control their energy consumption from anywhere. This feature is particularly valuable for industries and commercial buildings that require remote management of energy resources. Implementing remote control capabilities for connected devices would enable users to take immediate action in response to real-time data, enhancing energy efficiency.
4. **Enhanced Data Visualization and Reporting:** Expanding the dashboard's capabilities to include more advanced data visualization tools, such as interactive graphs, charts, and heatmaps, can provide users with a more comprehensive understanding of their energy data. Implementing automated reporting features would allow users to generate customized reports on energy consumption, environmental conditions, and system performance. These reports can be used for energy audits, compliance monitoring, and decision-making.
5. **Smart Grid Integration and Demand Response:** Integrating the system with the local smart grid infrastructure would enable participation in demand response programs. This would allow users to automatically adjust their energy consumption in response to grid signals, contributing to grid stability and reducing peak demand. Implementing microgrid management capabilities would be beneficial for communities and industries that rely on distributed energy resources.
6. **Expansion of Sensor Capabilities:** Expanding the system's sensor capabilities to include other relevant parameters, such as water consumption, gas usage, and air quality, can provide a more holistic view of resource management. This would be particularly valuable for industries and commercial buildings that require comprehensive monitoring of their operations.

7. **Scalability and Modular Design:** Designing the system with a modular architecture would allow for easy expansion and customization. This would enable users to add or remove sensors and features as needed, accommodating the evolving needs of their energy management strategies. Implementing a cloud-based platform for data storage and processing would enhance the system's scalability, allowing it to handle a growing number of users and devices.
8. **Security Enhancements:** Implementing robust security measures, such as encryption, authentication, and authorization, is crucial to protect the system from unauthorized access and cyber threats. This is particularly important for systems that handle sensitive energy data. By implementing these future enhancements, the IoT energy monitoring system can become a more powerful and versatile tool for energy management contributing to improved energy efficiency, grid stability, and sustainability.

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ANNEXURE A

SOURCE CODE

```
#include <WiFi.h>
#include <HTTPClient.h>
#include <PZEM004Tv30.h>
#include <Adafruit_Sensor.h>
#include <DHT.h>
#include <DHT_U.h>

// WiFi Credentials
const char* ssid = "Vamsi Krishna";
const char* password = "Mahirat@718";

// ThingSpeak API Info
const char* server = "http://api.thingspeak.com/update";
const char* apiKey = "I8JQN2QBNRPGK81O";  // Replace with your API Key

// **PZEM-004T Configuration (TX=26, RX=25)**
PZEM004Tv30 pzem(&Serial1, 25, 26);

// **DHT11 Configuration*
#define DHTPIN 4
#define DHTTYPE DHT11
DHT dht(DHTPIN, DHTTYPE);

void setup() {
  Serial.begin(115200);
  dht.begin();
```

```
  // Connect to WiFi
  WiFi.begin(ssid, password);
  Serial.print("Connecting to WiFi...");
  while (WiFi.status() != WL_CONNECTED) {
    Serial.print(".");
    delay(1000);
  }
  Serial.println("\nConnected to WiFi!");
}

void loop() {
  if (WiFi.status() == WL_CONNECTED) {
    HTTPClient http;

    // **Read Data from Sensors**
    float voltage = pzem.voltage();
    float current = pzem.current();
    float power = pzem.power();
    float energy = pzem.energy();
    float humidity = dht.readHumidity();
    float temperature = dht.readTemperature();

    // **Check for Valid Data**
    bool sensorError = false;

  if (isnan(voltage)) {
    Serial.println("Error: Failed to read Voltage!");
    sensorError = true;
  }
  if (isnan(current)) {
```

```
    Serial.println("Error: Failed to read Current!");
    sensorError = true;
  }
  if (isnan(power)) {
    Serial.println("Error: Failed to read Power!");
    sensorError = true;
  }
  if (isnan(energy)) {
    Serial.println("Error: Failed to read Energy!");
    sensorError = true;
  }
  if (isnan(humidity)) {
    Serial.println("Error: Failed to read Humidity!");
    sensorError = true;
  }
  if (isnan(temperature)) {
    Serial.println("Error: Failed to read Temperature!");
    sensorError = true;
  }

  // If any sensor failed, do not proceed
  if (sensorError) {
    Serial.println("Error: One or more sensors failed to read data!");
    return;
  }
    // **Create API Request URL**
    String url = String(server) + "?api_key=" + apiKey +
                 "&field1=" + String(voltage) +
                 "&field2=" + String(current) +
                 "&field3=" + String(power) +
```

```
                    "&field4=" + String(energy) +
                    "&field5=" + String(temperature) +
                    "&field6=" + String(humidity);

      // **Send Data to ThingSpeak**
      http.begin(url);
      int httpResponseCode = http.GET();

      if (httpResponseCode > 0) {
        Serial.println("Data Sent to ThingSpeak!");
        Serial.println(http.getString());  // Print server response
      } else {
        Serial.print("Error sending data: ");
        Serial.println(httpResponseCode);
      }
      http.end();
    }

    delay(15000);  // Send data every 15 seconds
  }
```

ANNEXURE B

SCREENSHOTS

Fig. B1: The Output from Arduino ESP32 Module Displaying on a Serial Monitor as Above.

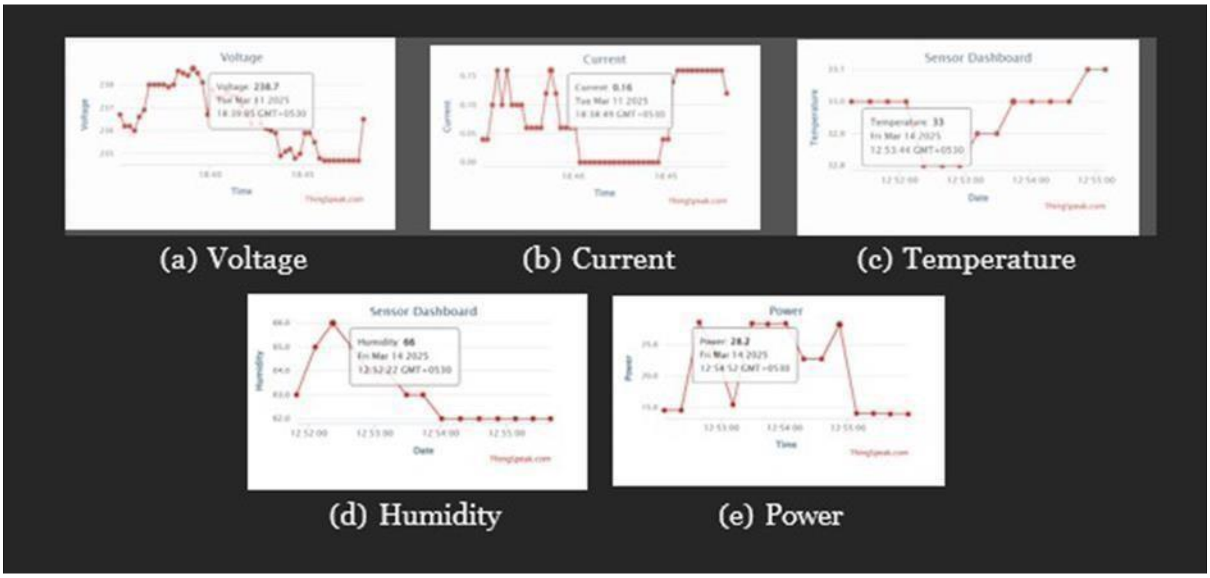

Fig. B2: Voltage, Current, Temperature, Humidity and Power graphs in ThingSpeak

ANNEXURE C

STUDENT CONTRIBUTION

No	Activity	21K61A05G8	22K65A0513	21K61A0598	21K61A05E3
1	Title Conformation	✓	✓	✓	✓
2	LiteratureSurvey	✓		✓	
3	Problem Formulation	✓	✓	✓	✓
4	Requirement Gathering	✓	✓		✓
5	Designing	✓	✓	✓	✓
6	Implementation	✓			✓
7	Documentation	✓	✓	✓	

ANNEXURE D

PO, PSO, PEO, AND CO RELEVANCE WITH PROJECT

CO-PO MAPPING SHEET COURSE OUTCOMES

OUTCOME NO	DESCRIPTION
CO1	Develop problem formation and design skills for engineering and real-world problems.
CO2	Collect and Generate ideas through literature survey on current research areas which help to analyze and present to impart knowledge in different fields.
CO3	Import knowledge on software & hardware to meet industry perspective needs and standards.
CO4	Create interest to carry out research on innovative ideas as a lifelong learning.
CO5	Ability to work with team and enrich presentations and communications skills.
CO6	Create a platform that makes students employable.

OUTCOME NO	DESCRIPTION
PO1	**Engineering Knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
PO2	**Problem Analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics natural sciences, and engineering sciences.
PO3	**Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental.
PO4	**Conduct investigations of complex problems**: Use rese arch-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valued conclusion.
PO5	**Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
PO6	**The Engineer and Society**: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
PO7	**Environment and sustainability**: Understand the impact of the professional engineering solutions in societal and environmental contest and demonstrate knowledge of and need for development.
PO8	**Ethics**: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO9	**Individual and Team work**: Function effectively as an individual, and as a member or leader in diverse teams and in multi-disciplinary settings.
PO10	**Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.
PO11	**Project management and Finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

SUMMARY OF COURSE OUTCOMES MAPPING TO PROGRAM OUTCOMES

CO\PO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11
CO1	3	3	0	0	0	0	0	0	0	0	0
CO2	0	0	3	0	3	0	0	0	0	0	0
CO3	0	0	0	3	2	0	0	0	0	0	0
CO4	0	0	0	0	0	2	2	2	0	0	0
CO5	0	0	0	0	0	0	0	0	3	0	2
CO6	0	0	0	0	0	0	0	0	0	3	2

CO-PEO MAPPING SHEET COURSE OF OUTCOMES

OUTCOME NO	DESCRIPTION
PEO1	Graduates will enhance workplace contributions by creating sophisticated computer applications that address the dynamic requirements of society.
PEO2	Graduates will be research oriented and industry ready professionals with a sense of intellectual and social commitment.
PEO3	Graduates will be highly professional with unquestionable integrity and ethics.

SUMMARY OF COURSE OUTCOMES MAPPING TO PROGRAM EDUCATIONAL OBJECTIVES

CO\PEO	PEO1	PEO2	PEO3
CO1	3	2	0
CO2	2	3	0
CO3	3	3	0
CO4	2	3	0
CO5	1	2	3
CO6	3	2	2

CO-PSO MAPPING SHEET COURSE OF OUTCOMES

OUTCOME NO	DESCRIPTION
PSO1	Apply modern tools to analyze, design and develop computer programs/applications across diverse domains, addressing sustainability issues in society.
PSO2	Ability to work as team in project management by professional communication and ethics.

SUMMARY OF COURSE OUTCOMES MAPPING TO PROGRAM SPECIFIC OUTCOMES

CO\PSO	PSO1	PSO2
CO1	3	0
CO2	2	2
CO3	3	2
CO4	2	0
CO5	0	3
CO6	3	3

RELEVANCE TO POs

CO	PO	RELEVANCE
CO1	**PO1**	Apply engineering knowledge to identify energy monitoring requirements using IoT.
	PO2	Analyze electrical data (voltage, current, power) to detect inefficiencies.
CO2	**PO3**	Design real-time energy monitoring systems using sensor and cloud integration.
	PO5	Use tools like ESP32, PZEM-004T, DHT11, Firebase, and ThingSpeak for implementation.
CO3	**PO4**	Investigate anomalies in power and energy trends to predict equipment behavior.
	PO5	Use cloud dashboards and embedded tools to visualize and analyze sensor data.
CO4	**PO6**	Evaluate how IoT energy systems benefit society through reduced wastage.
	PO7	Consider environmental impact in designing sustainable energy systems.
	PO8	Follow ethical data collection, sharing, and system design practices.
CO5	**PO9**	Work effectively in teams on hardware-software integration and testing.
	PO11	Assist in task planning, budgeting, and resource allocation during the project.
CO6	**PO10**	Communicate project outcomes effectively through technical reports and demos.
	PO11	Apply time and cost management principles during IoT project development.

RELEVANCE TO PEOs

CO	PEO	RELEVANCE
CO1	**PEO1**	Design IoT-based energy solutions that address real-world power management needs.
	PEO2	Use research skills to identify power inefficiencies and propose improvements.
CO2	**PEO1**	Generate energy system ideas influenced by societal and industry trends.
	PEO2	Perform literature reviews to support ongoing research and innovation.
CO3	**PEO1**	Apply industry-grade hardware/software integration for energy monitoring.
	PEO2	Develop systems aligned with current industrial and research practices.
CO4	**PEO1**	Explore innovative energy solutions with sustainable impact.
	PEO2	Engage in self-directed learning and research to implement predictive maintenance.
CO5	**PEO1**	Contribute to technical development in a support role.
	PEO2	Demonstrate communication and collaboration skills in a team setting.
	PEO3	Uphold professional ethics and responsibilities in teamwork and reporting.
CO6	**PEO1**	Build job-ready skills and implement practical energy solutions.
	PEO2	Show research-readiness by integrating concepts across domains.
	PEO3	Follow ethical and responsible conduct in system design and documentation.

RELEVANCE TO PSOs

CO	PSO	RELEVANCE
CO1	**PSO1**	Use modern IoT tools (ESP32, PZEM, Firebase, ThingSpeak) to design real-time energy monitoring applications.
CO2	**PSO1**	Explore energy monitoring frameworks aligned with sustainability goals through literature review.
	PSO2	Collaborate in identifying and proposing research-based solutions with professional communication.
CO3	**PSO1**	Integrate IoT hardware and software to develop and analyze energy monitoring systems.
	PSO2	Participate in team-based implementation of industry-aligned projects with ethical conduct.
CO4	**PSO1**	Innovate sustainable solutions for energy monitoring systems using real-time data.
CO5	**PSO2**	Work effectively in teams, demonstrating strong project management and professional communication.
CO6	**PSO1**	Develop practical and scalable IoT systems addressing energy usage issues across domains.
	PSO2	Demonstrate employability skills through team-based development, documentation, and ethical practices.

ANNEXURE E

PUBLICATION DETAILS

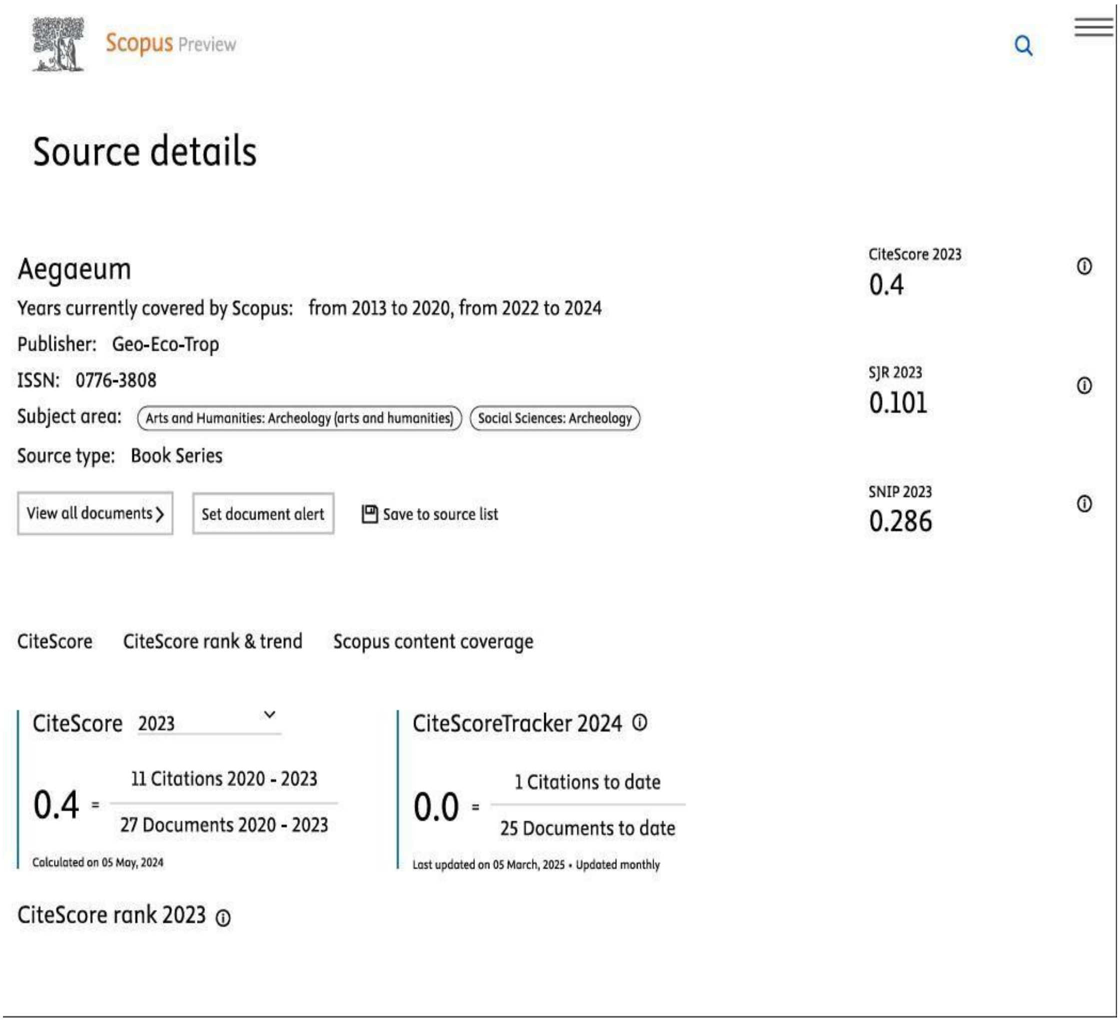

Fig. E1: Scopus preview for Aegaeum Journal

Fig. E2: Certificate of Author #1

Fig. E3: Certificate of Author #2

Fig. E4: Certificate of Author #3

Fig. E5: Certificate of Author #4


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This is to certify that the paper entitled

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Authored by:

Sampara Vamsi Krishna

From

Sasi Institute of Technology and Engineering Tadepalligudem, India

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Fig. E6: Certificate of Author #5

IoT-Enabled Real-Time Energy Monitoring System For Efficient Power Management And Predictive Maintenance

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***Abstract*—The rapid advancement of the Internet of Things (IoT) has enabled real-time energy monitoring and analysis, enhancing efficiency in power management systems. This paper presents an IoT-based energy monitoring system utilizing the ESP32 microcontroller, PZEM-004T energy meter, and DHT-11 sensor for temperature and humidity measurement. The system is designed using the Arduino IDE and programmed in Arduino C++ to ensure seamless integration and real-time data acquisition. Electrical parameters such as voltage, current, power, and energy consumption are continuously monitored and transmitted to cloud platforms for visualization and analysis. Experimental results demonstrate the system's ability to accurately measure and analyze energy consumption patterns. The proposed system supports predictive maintenance and is highly applicable in industrial and smart grid environments.**

***Index Terms*—INTERNET OF THINGS (IOT), ENERGY MONITORING, ESP32 MICROCONTROLLER, PZEM-004T ENERGY METER, DHT-11 SENSOR, REAL-TIME DATA ACQUISITION, POWER MANAGEMENT, ARDUINO IDE, ENERGY CONSUMPTION ANALYSIS**

I. INTRODUCTION

Energy efficiency and sustainable power management have become critical challenges in modern industries, businesses, and households [1]. With the growing global energy demand and the increasing need for sustainable practices, real-time monitoring of energy consumption is essential to optimize usage, reduce waste, and enhance overall system efficiency [2]. Traditional energy monitoring systems often rely on manual data collection or periodic measurements, which lack real- time capabilities and fail to provide immediate insights into power usage patterns [3]. As a result, energy inefficiencies and faults go undetected until they cause significant financial and operational impacts [4].

The rapid evolution of the Internet of Things (IoT) has transformed energy management by enabling smart, connected systems that offer real-time monitoring, data analytics, and automation [5]. IoT-based energy monitoring systems leverage networked sensors, cloud computing, and intelligent algorithms to provide continuous tracking of electrical parameters [6]. These systems facilitate early detection of anomalies, enable predictive maintenance, and support decision-making for energy optimization [7]. By integrating IoT technology, organizations can enhance their operational efficiency, reduce energy costs, and contribute to environmental sustainability [8].

This paper presents an IoT-based energy monitoring system designed to provide real-time tracking and analysis of energy consumption [9]. The system utilizes the ESP32 microcontroller, a cost-effective and powerful IoT platform, interfaced with the PZEM-004T energy meter to measure key electrical parameters such as voltage, current, power, and total energy consumption [10]. Additionally, the DHT-11 sensor is incorporated to monitor temperature and humidity, as these environmental factors influence energy efficiency in various industrial and residential applications [11]. The system is developed using the Arduino IDE and programmed in Arduino C++ to ensure seamless integration, efficient data acquisition, and reliable operation.

The collected data is transmitted to cloud platforms, where it is visualized and analyzed for deeper insights into energy consumption patterns [1], [2]. Cloud-based analytics enable remote monitoring, trend analysis, and the generation of alerts in case of abnormal power fluctuations [3], [4]. By leveraging IoT and cloud computing, this system offers a scalable and automated solution for real-time energy management [5], [6]. Furthermore, AI-driven models enhance predictive maintenance and anomaly detection, ensuring operational efficiency and energy optimization [2], [10].

IoT-based energy monitoring systems utilize wireless communication protocols for seamless data transmission, ensuring efficient and real-time connectivity [6]. The integration of edge computing further enhances real-time processing capabilities, reducing latency and improving response times in energy management applications [7]. Additionally, predictive maintenance techniques based on big data analytics enable early detection of faults and inefficiencies, optimizing overall energy usage and reducing operational costs [3], [8].

A. *Problem Statement*

Traditional energy monitoring systems rely on periodic or manual data collection, lacking real-time capabilities necessary for efficient energy management. This limitation makes it difficult to detect inefficiencies, prevent faults, and optimize power consumption, leading to increased energy wastage, higher operational costs, and reduced equipment lifespan. Furthermore, the absence of cloud-based analytics and remote monitoring restricts the ability to analyze historical data and make informed decisions regarding energy efficiency and predictive maintenance [12], [13]. To address these challenges, there is a need for an IoT-based real-time energy monitoring system with cloud integration and a user-friendly dashboard for seamless visualization and analysis of power consumption data [14], [15].

B. *Objectives*

1. **Develop an IoT-Based Energy Monitoring System** – Design and implement a smart energy monitoring system using the ESP32 micro-controller, PZEM-004T energy meter, and DHT-11 temperature and humidity sensor for real-time data acquisition.
2. **Enable Real-Time Data Monitoring and Analysis** – Integrate IoT technology to continuously monitor and analyze key electrical parameters such as voltage, current, power, energy consumption, temperature, and humidity.
3. **Implement Cloud-Based Data Storage and Visualization** – Transmit acquired energy data to cloud platforms for remote access, graphical visualization, and historical trend analysis.
4. **Develop a User-Friendly Dashboard** – Design an interactive web-based or mobile dashboard that provides real- time visualization of power usage, historical trends, alerts for anomalies, and insights for optimizing energy consumption.
5. **Support Predictive Maintenance Strategies**– Leverage continuous monitoring and cloud-based analytics to provide early warnings of potential faults, reducing equipment down- time and maintenance costs.
6. **Validate System Performance Through Experimental Results** – Conduct extensive testing to evaluate the system's accuracy, reliability, and effectiveness in improving energy management for industrial and smart grid applications.

By incorporating a cloud-integrated dashboard, the proposed system will provide an intuitive interface for real-time monitoring, analytics, and predictive maintenance, contributing to energy conservation, cost reduction, and sustainable power utilization.

II. Literature Review

The integration of IoT-based smart energy monitoring and analysis aims to optimize energy consumption by combining sensor technology, IoT devices, and real-time data analytics. These advancements enable continuous monitoring of energy usage, allowing for data-driven decisions that minimize energy waste, enhance efficiency, and reduce costs. A variety of approaches to IoT-based energy systems have been explored in recent studies, demonstrating the versatility of IoT in energy management.

For instance, Usman Saleem et al. (2023) [16] integrated IoT with 5G to develop a smart energy management system that enhances user engagement and energy efficiency. Simi- larly, Nilesh Bawankar et al. (2024) [17] designed an IoT- based solution for retrofitting water meters, using edge compu- tation to achieve 97.69% accuracy in real-time data collection and analysis. Other studies, such as that by Nabavi et al. (2023) [18], have employed advanced forecasting techniques like discrete wavelet transform and long short-term memory to enhance energy demand prediction and optimization. Additionally, demand-side management techniques have been used to regulate energy loads effectively [19], [20].

IoT technology is also being leveraged to improve smart grid management, home automation, and renewable energy integration. Several studies have explored privacy-preserving strategies, including trusted execution environments and blockchain-based predictive platforms, to secure energy transactions and data transmission [21], [22]. In rural and off-grid applications, IoT-driven frameworks incorporating solar and bio-energy have been shown to significantly reduce greenhouse gas emissions. For example, Pratik Kalkal's (2021) [23] framework for rural India demonstrated a 93 percent reduction in greenhouse gas emissions, ensuring a 24-hour continuous power supply.

Real-time data collection plays a crucial role in anomaly detection and predictive maintenance, helping to prevent power outages and optimize resource allocation [24], [25]. The integration of machine learning models into IoT-based solutions enhances grid load balancing and energy consumption predictions [15], [26]. Additionally, advancements in wireless communication technologies, such as low-power wide-area networks, are making IoT-based energy monitoring systems more scalable and energy-efficient, enabling their widespread adoption in smart cities and industrial applications [27], [28].

TABLE I: Summary of Related Literature

Year	Authors	Methodology	Algorithm/Technology
2019	Ma et al.	Survey on sensing, computing, and communications for energy harvesting IoTs	Energy harvesting, IoT communication
2020	Subahi & Bouazza	IoT-based system for greenhouse temperature control and monitoring	IoT sensors, automation
2020	Said et al.	Energy management scheme for green IoT environments	Energy optimization, IoT framework
2020	Liu et al.	Deep reinforcement learning for home energy management	Deep reinforcement learning
2021	Abir et al.	IoT-enabled smart energy grid applications and challenges	Smart grid, IoT communication
2021	Mabrouki et al.	IoT-based data logger for weather monitoring using Arduino	Arduino, wireless sensor networks
2022	Bagwari et al.	LoRa-based real-time landslide monitoring on an IoT platform	LoRa, IoT-based landslide detection
2022	Tran et al.	IoT-based secure CNC machine monitoring against cyber-attacks	Deep learning, cybersecurity for IoT

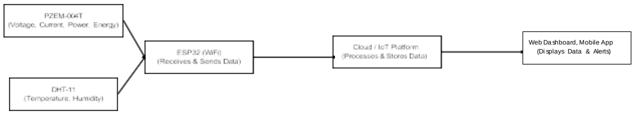

Fig. 1. IoT-Based Energy Monitoring System Architecture

III. Methodology

The architecture diagram visually represents the IoT-based energy monitoring system, showcasing how data is acquired, processed, transmitted, stored, and visualized in real-time. The system integrates IoT sensors, a microcontroller (ESP32), cloud computing, and a user-friendly interface to enable efficient energy management. This system is particularly useful in industrial and smart grid environments, where real-time monitoring and predictive maintenance can enhance energy efficiency and reduce operational costs.

A. *Data Acquisition Layer (Sensors & Measurement Devices)*

PZEM-004T Energy Meter:

- Measures electrical parameters such as voltage, current, power, and total energy consumption.
- Provides real-time data to track fluctuations and anoma- lies in power usage.
- Sends the measured values to the ESP32 microcontroller for processing.

Fig. 2. PZEM-004T Energy Meter

DHT-11 Sensor:

- Monitors temperature and humidity to evaluate environmental factors influencing energy usage.
- Helps in optimizing power management based on environmental conditions.
- Transmits data to the ESP32 microcontroller for further analysis.

Fig. 3. DHT-11 Sensor

B. *Processing & Communication Layer (ESP32 Microcon- troller & Protocols)*

ESP32 Microcontroller:

- Collects sensor data from the PZEM-004T and DHT-11.
- Processes the data and converts it into a structured format (e.g., JSON or MQTT packets).
- Filters and validates data to reduce errors before transmission.
- Uses Wi-Fi connectivity to transmit data to the cloud in real-time.

Fig. 4. ESP32 Microcontroller

Communication Protocols (MQTT / HTTP REST API):

- **MQTT (Message Queuing Telemetry Transport)**: Efficient and lightweight protocol for real-time data exchange.
- **HTTP REST API**: Ensures seamless data transfer between ESP32 and cloud platforms.

C. *Cloud Storage & Analytics Layer*

Cloud Database (IoT Data Storage):

- Stores historical and real-time energy consumption data.
- Ensures secure and scalable data management.

Cloud Analytics Engine:

- Detects energy consumption trends and anomalies.
- Generates predictive maintenance alerts based on real-time insights.
- Optimizes energy efficiency by analyzing environmental factors.

D. User Interface & Data Visualization Layer

Web-Based Dashboard & Mobile Applications:

- Displays real-time and historical energy usage trends.
- Provides visual graphs, charts, and reports for analysis.
- Alerts users about power fluctuations and abnormal energy consumption.

IV. Results and Discussion

This project aimed to create an IoT-based energy monitoring system with the help of an ESP32 microcontroller, PZEM-004T for measuring power, DHT-11 for sensing environmental data, and ThingSpeak as a cloud-based platform for storing and visualizing real-time data.The system effectively gathered and transmitted sensor data to ThingSpeak periodically. Parameters measured were: Voltage (V),Current (A), Power (W), Energy (Wh), Temperature (°C), Humidity (%).ThingSpeak supported real-time visualizations of the parameters, making it easy to monitor energy usage patterns.

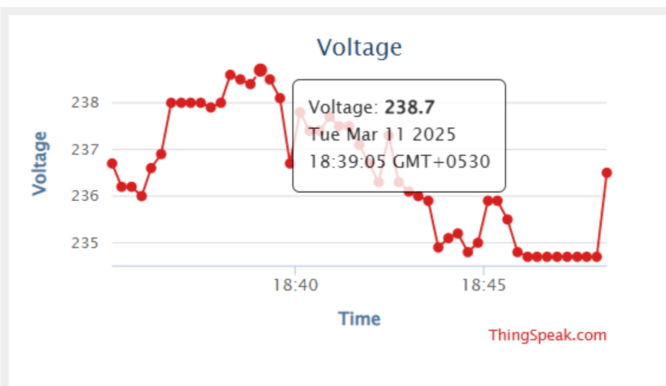

Fig. 5. Voltage

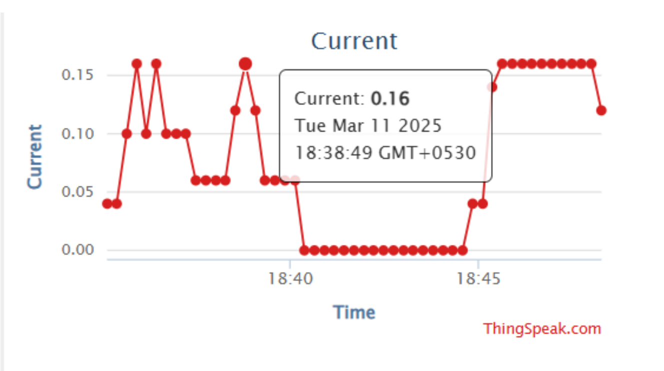

Fig. 6. Current

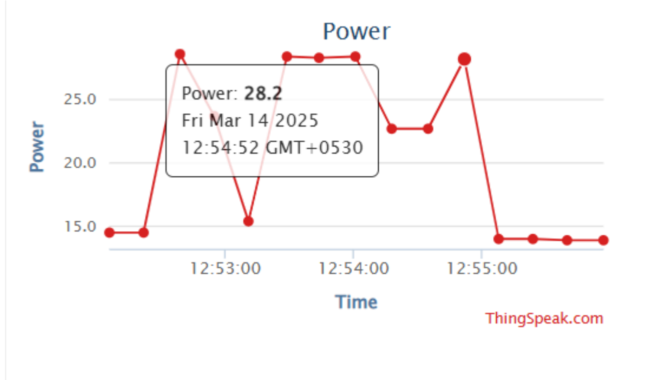

Fig. 7. Power

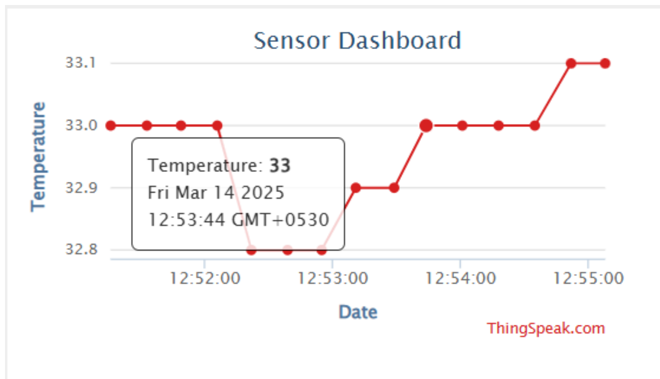

Fig. 8. Temperature

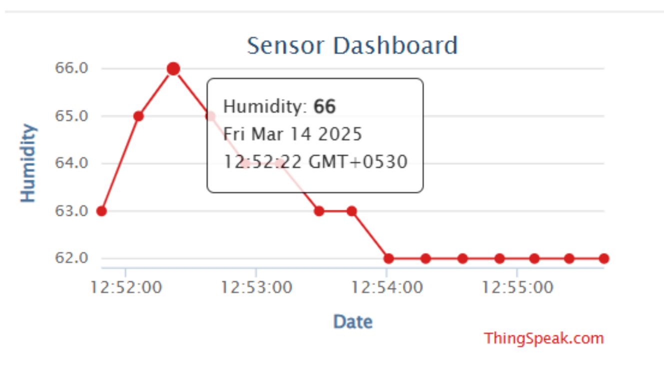

Fig. 9. Humidity

The five figures demonstrate the trends in voltage, current, power, and environmental conditions with respect to time. All the subfigures give insights into various facets of the monitoring system, making visualization and analysis of the acquired data easier.

ThingSpeak was extremely useful for energy monitoring based on IoT by providing real-time tracking of data, enabling constant monitoring of voltage, current, and environmental factors. The storage of historical data on the platform offered useful insights, enabling users to analyze long-term trends and make decisions about energy consumption. Its cloud-based feature also ensured remote access, enabling users to monitor energy consumption from anywhere without physical access to the hardware.

V. Conclusion

The proposed IoT-based energy monitoring system provides a smart, real-time, and scalable solution for tracking and optimizing energy usage in industrial and smart grid environments. By integrating ESP32, PZEM-004T energy meter, and DHT-11 sensor, the system ensures precise electrical and environmental data collection, which is processed, transmitted, and analyzed in the cloud for actionable insights.

The cloud-based analytics engine enables trend analysis, anomaly detection, and predictive maintenance, allowing industries and businesses to optimize energy efficiency, prevent power fluctuations, and reduce operational costs. The user-friendly dashboard and automated alerts provide real-time monitoring, ensuring proactive decision-making and enhanced energy management.

VI. Future Enhancements

To further improve the efficiency, scalability, and intelligence of the proposed IoT-based energy monitoring system, several future enhancements can be considered:

1) **Integration of Machine Learning Algorithms:** Incorporate machine learning techniques to analyze historical data and predict future energy consumption trends, allowing for more proactive power management.
2) **Enhanced Data Security:** Implement advanced security protocols for data transmission to ensure the integrity and confidentiality of the energy data being transmitted to cloud platforms.
3) **Support for Multiple Sensors:** Expand the system to support additional sensors, such as air quality or motion sensors, to provide a more comprehensive environmental monitoring solution.
4) **User Interface Improvements:** Develop a more intuitive user interface for visualizing energy data, potentially through a mobile application, to improve user engagement and accessibility.
5) **Scalability for Larger Installations:** Explore ways to scale the system for larger industrial applications, including multi-device management and centralized control.

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