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

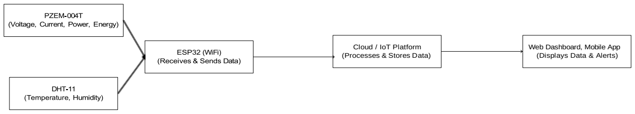

Fig. 1. IoT-Based Energy Monitoring System Architecture

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.

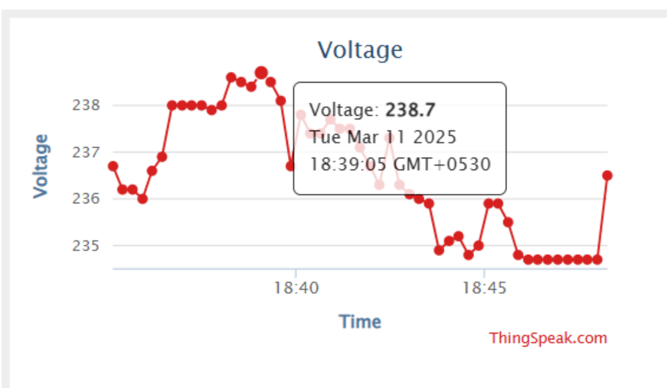

Fig. 5. Voltage

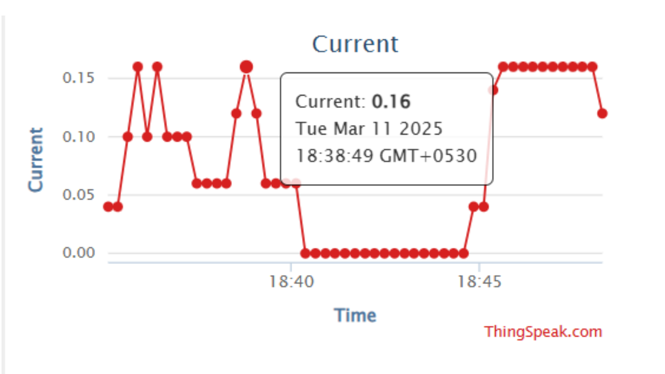

Fig. 6. Current

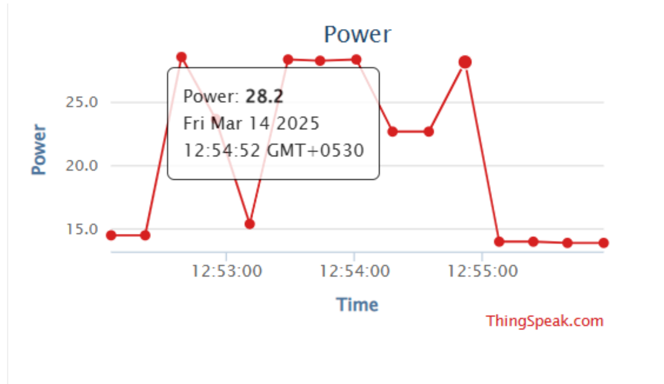

Fig. 7. Power

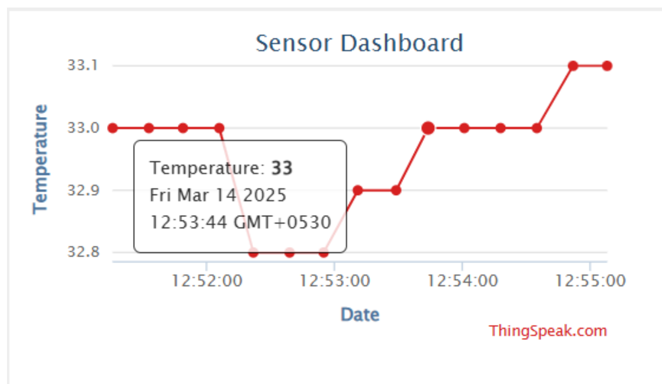

Fig. 8. Temperature

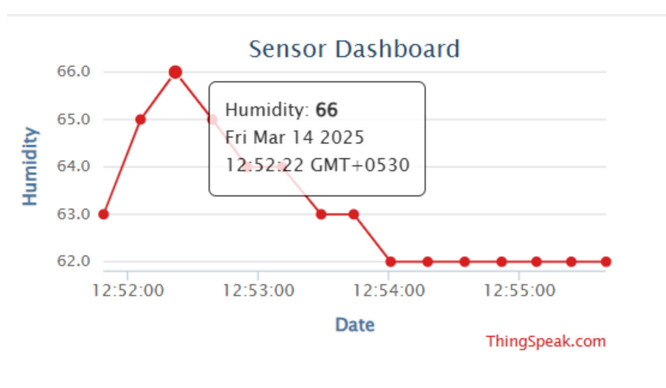

Fig. 9. Humidity

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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