IoT Based Smart Energy Meter

Real-Time Monitoring and Control for Efficient Power Management

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Abstract—**This article outlines the creation and execution of an energy monitoring system based on the Internet of Things (IoT), incorporating the Blynk platform for live data display and Firebase for data storage in the cloud. The system can measure important electrical values like voltage, current, power, frequency, power factor, and total energy usage. Continuous monitoring of these parameters enables users to access real-time data from anywhere using the Blynk mobile app. Furthermore, Firebase stores historical data for future analysis, allowing users to monitor energy usage trends. This real-time monitoring and cloud storage combination is vital for energy efficiency and cost management in residential and industrial settings. The suggested system is affordable, able to expand, and simple to implement, making it appropriate for a variety of settings. This paper also covers the structure, system incorporation, and future growth opportunities, like adding machine learning models for predictive analysis.**

Index Terms— **IoT, Energy Monitoring, Real-Time Monitoring, Blynk, Firebase, Power Measurement, Cloud Storage, Predictive Analytics, Smart Energy Systems**

I. INTRODUCTION

Global energy consumption has sharply increased due in large part to the fast expansion of urban infrastructure and the growing dependence on electronic gadgets. The International Energy Agency (IEA) estimates that the rise in population, industrialization, and the use of smart home equipment has caused the world's power demand to rise at a rate of about 4% annually. Nevertheless, traditional energy meters, which are essentially passive energy recording devices, are unable to offer insights into usage in real time or support effective energy management [1] [2].

Traditional analog and digital energy meters are still widely used in many residential and commercial areas. These meters suffer from several key drawbacks. It might be challenging to monitor daily usage or optimize consumption patterns when consumers get electricity bills at the end of the billing cycle [3]. A lot of power companies manually gather consumption data using meter readers, which can lead to mistakes and inaccuracies [1]. It is challenging to detect energy waste when consumers lack direct knowledge of their daily or hourly energy consumption [4] [5]. Traditional meters are susceptible to energy theft, which costs utility companies money. According to a World Bank analysis, electricity theft costs India alone some $16.2 billion every year [6] [7]. Given these limitations, there is a growing need for smart metering solutions that offer real-time monitoring, automation, and cloud-based analytics to improve energy management and efficiency [8] [9].

By allowing items to connect via the internet, the Internet of Things (IoT) has completely transformed a number of businesses. IoT-based smart energy meters (SEMs) combine sensors, microcontrollers, and cloud computing to provide data-driven decision-making [2] [10], remote access, and real- time energy tracking. IoT-enabled smart meters offer the following advantages over conventional meters. By wirelessly sending real-time data, IoT-based SEMs do away with manual meter readings [8]. Through a web dashboard or mobile app, users may view their energy usage statistics and monitor trends in consumption [4] [5]. IoT-enabled SEMs are able to anticipate possible electrical system defects by continually monitoring voltage, current, and power factor [5]. Any anomalous spikes or efforts to circumvent meters can be quickly identified and re- ported [6].

The development of smart grids, which seek to modernize electrical distribution networks, depends heavily on IoT-based smart energy meters. Digital technology is employed by smart grids to increase the effectiveness of energy distribution by dynamically balancing supply and demand [1] [11], promote the integration of renewable energy sources so that wind and solar can be easily added to the grid [10] and turn on demand- side management (DSM), which lets customers modify their usage in response to current electricity prices [7]. In time- of-use (TOU) pricing schemes, for instance, peak and off- peak hours determine how much electricity costs. By setting up non-essential appliances (such water heaters and washing machines) to run during cheaper times, a smart energy meter may automatically modify energy consumption and lower electricity costs [9].

Numerous studies have shown how well IoT-based smart meters work to increase energy efficiency. An analysis of IoT- based energy management systems installed in commercial buildings in 2021 revealed a 15-20% decrease in energy waste [8]. Through the use of AI-driven analytics and real-time monitoring, a pilot project in Singapore's Smart Nation effort optimized electricity use, resulting in annual savings of around $10 million [5]. By 2030, at least 80% of EU countries must have smart meters installed, as required by the European Union's Smart Metering Directive [2].

The design and implementation of an Internet of Things (IoT) based smart energy meter that uses the PZEM-004T multimeter module, CT sensor, NodeMCU ESP32 microcontroller, and cloud-based Firebase storage for real-time energy monitoring is presented in this paper. The following are the goals of this study. Creating an IoT-based energy metering system that is both affordable and scalable. Putting in place real-time electrical parameter monitoring, which includes energy usage, power, voltage, and current. Enabling easy access to real-time energy statistics through a web-based and mobile user interface through the Blynk application. Storing past energy data in Firebase for examination of trends and predictive analytics in the future. By bridging the gap between conventional energy meters and next-generation smart metering systems, this study hopes to create a model of energy use that is more intelligent, economical, and efficient.

II. PROPOSED METHODOLOGY

The proposed IoT-based Smart Energy Meter is designed as in Fig. 1 to monitor real-time energy consumption by utilizing sensors, microcontrollers, cloud storage, and mobile applications for seamless tracking and analysis. This section provides a detailed overview of the system architecture, working mechanism, and data flow, ensuring a comprehensive understanding of the implementation.

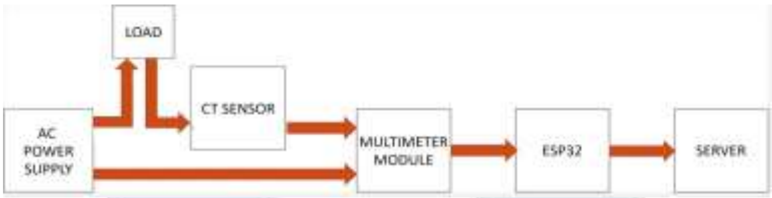

Figure 1 Block Diagram

System Overview

The IoT-based Smart Energy Meter (SEM) is designed to provide a real-time, remote, and intelligent energy monitoring system that enables users to track and manage their electricity consumption effectively. Unlike traditional energy meters, which require manual reading and post-consumption billing, this system integrates advanced sensor modules, microcontrollers, cloud storage, and a mobile application to deliver instantaneous energy tracking, automated data logging, and predictive analytics.

The proposed system focuses on accuracy, affordability, scalability, and ease of implementation, making it suitable for residential, commercial, and industrial applications. It continuously measures voltage, current, power, energy usage, and frequency, transmitting the data to a cloud-based storage system (Firebase) via an ESP32-based IoT module. Users can access this data in real time through the Blynk mobile application, allowing them to monitor consumption trends, receive alerts, and optimize electricity usage for cost savings and energy efficiency.

System Architecture

The proposed system is designed for real-time energy monitoring by integrating hardware and software components. It enables users to remotely track energy consumption through IoT-based connectivity. The system operates by measuring electrical parameters such as voltage, current, power, and energy consumption of a load, represented by a bulb that consumes power, which the system monitors using dedicated sensors and modules. The CT sensor and PZEM-004T module measure the electrical parameters, while the NodeMCU ESP32 microcontroller acts as the central processing unit, collecting and transmitting data to a cloud-based server via Wi-Fi for remote access.

The bulb serves as the electrical load in the system, representing a typical power-consuming device making it a reference for monitoring energy usage. It can be replaced with any electrical appliance for broader applications. The CT sensor measures the current flowing through the load, producing a proportional signal that indicates real-time energy consumption. Helps in energy consumption estimation by continuously monitoring cur- rent variations. PZEM-004T Multimeter Module is a specialized power measurement module that provides precise readings of voltage, current, power, and energy consumption. It communicates with the ESP32 microcontroller to transfer the collected data thereby enhances accuracy in energy monitoring by offering direct electrical parameter measurement. NodeMCU ESP32 Microcontroller serves as the central control unit of the system. It receives data from the CT sensor and PZEM-004T module, processes it, and prepares it for transmission. It is equipped with built-in Wi-Fi connectivity, enabling seamless data transfer to an IoT cloud platform which ensures efficient communication between sensors and the server, making real-time monitoring possible. The ESP32 micro- controller connects to the internet via Wi-Fi, facilitating real-time data transmission. Data is uploaded to a cloud- based server (e.g., Firebase), ensuring easy access from anywhere. This provides a secure and scalable storage solution for energy monitoring data. Users can monitor power consumption through an IoT-based application like Blynk or a web dashboard. It provides a user- friendly interface to visualize energy usage trends and track efficiency. This enables remote monitoring and potential control of electrical loads, optimizing energy consumption.

Working Mechanism

The system operates in multiple stages, from data collection to real-time user interaction, ensuring accurate and timely monitoring of energy consumption. Below is a detailed breakdown of each stage:

Data Collection: At this stage, the system gathers electrical parameters using sensors and measurement modules. CT (Current Transformer) Sensor measures the current flowing through the electrical load (e.g., a bulb or any appliance). It works by inducing a proportional current in a secondary winding, providing a low-voltage output signal corresponding to the actual current passing through the load. This output signal is fed into the ESP32 micro- controller for processing. PZEM-004T Multimeter Module measures key electrical parameters such as voltage (V)(Determines the potential difference across the load),current (A)(Cross-verifies cur- rent readings from the CT sensor), power (W)(Calculates real-time power consumption) and energy (kWh)(Tracks cumulative energy usage over time). Uses UART communication to send data directly to the ESP32 microcontroller for further processing. These two sensors work together to provide a comprehensive dataset on energy consumption.

Data Processing: Once the data is collected, the ESP32 microcontroller processes and prepares it for remote access. The ESP32 receives raw data from the CT sensor and the PZEM-004T module, applying necessary conversions and calibrations.

Power Calculation using the formula:

$$P = V \times I \qquad (1)$$

where, P is power (W), V is voltage (V), and I is current (A).

Energy Calculation:

$$E = P \times t \qquad (2)$$

where, E is energy consumption (kWh) over time t.

Cost Estimation: If the electricity tariff is known (rupees per kWh or $ per kWh), the cost is estimated as:

$$\text{Cost} = E \times \text{Tariff Rate} \qquad (3)$$

The ESP32 organizes the processed data into a structured format suitable for transmission. Then it uploads the data to Firebase via Wi-Fi, enabling real-time cloud storage and access.

Real-Time User Interaction: Users can remotely monitor energy consumption using an IoT-based mobile application like Blynk or a web interface. The ESP32 continuously updates the Blynk app dashboard via Firebase, ensuring real-time visibility. Users can view the Voltage (V), Current (A), Power (W), Energy (kWh), Cost Estimation and Live Graphs (Trend analysis of power consumption over time). The system provides access from anywhere via smartphones or web browsers.

Hardware Components

The system consists of various hardware components as shown in Fig. 2 that work together to monitor energy consumption efficiently. Each component plays a crucial role in measuring, processing, and transmitting data. Below is a detailed breakdown of each component and its function.

Figure 2 Circuit Diagram

PZEM-004T Multimeter Module monitors the voltage supplied to the load, accurately determines the current flowing through the circuit, computes the real- time power usage and tracks cumulative energy consumption over time. It uses UART (TX/RX) to send data to the ESP32 microcontroller. It is connected in parallel with the AC power supply and load to measure voltage. A current transformer (CT) sensor inside the module measures the current flowing through the circuit. It calculates power and energy consumption using real-time voltage and current values. The module transmits this data digitally to the ESP32 microcontroller for further processing and storage.

NodeMCU ESP32 microcontroller is responsible for processing sensor data and sending it to the cloud. It ensures the system is IoT-enabled with its built- in Wi-Fi capability. The ESP32 receives raw electrical parameter readings from the PZEM-004T module and the CT sensor. It calculates real-time power, energy consumption, and cost estimations based on received values. The processed data is uploaded to Firebase (cloud platform) using its Wi- Fi connectivity. The data is made accessible through the Blynk mobile app or a web dashboard, allowing real-time monitoring.

The CT sensor continuously monitors the current drawn by the load and provides an analog signal proportional to the current, which is then converted into a digital signal by the ESP32. It clamps around the power cable without disrupting the circuit. It provides isolation from the high-voltage AC circuit. The CT sensor detects the alternating current (AC) flowing through the load. It produces a small secondary current proportional to the actual current. The ESP32 microcontroller reads this signal, converts it into a digital value, and calculates power consumption.

The bulb functions as the load in this setup, demonstrating how power consumption is tracked and monitored by the system. It allows real-time monitoring of energy usage. It can be replaced with any household or industrial appliance. The bulb is connected to the AC power supply. As it draws current, the CT sensor and PZEM-004T module measure the electrical parameters. The system records and transmits the consumption data to Firebase, making it accessible to the user.

Software Components

A number of software components that provide data processing, cloud storage, and user interaction power the energy monitoring system. Together, these software solutions guarantee real-time electrical usage monitoring and analysis. Below is an in-depth explanation of each component and its role in the system.

The program that operates on the ESP32 microcontroller is written, compiled, and uploaded using the Arduino IDE (Integrated Development Environment). Cross-platform compatibility (Windows, macOS, and Linux) is one of the Arduino IDE's features. It supports programming in C and C++ and has a streamlined syntax and has extensive library support for sensor and module interfaces. For troubleshooting and real-time data visualization, it uses a serial monitor. The PZEM-004T module and the CT sensor provide the ESP32 with raw sensor data. It computes voltage, current, power, and energy usage by processing the data. The ESP32 has been configured to establish a Wi-Fi connection and interact with Firebase. Data about energy use is regularly uploaded to the cloud

Blynk is a robust Internet of Things platform that offers a user-friendly smartphone dashboard for remote energy consumption monitoring. One of Blynk's primary features is its intuitive smartphone interface for Internet of Things projects. It allows for the visualization of data in real time (graphs, labels, and gauges). It is compatible with Raspberry Pi, Arduino, ESP32, and other devices. It enables cloud connectivity via MQTT or Firebase and can provide alerts and push notifications for unusual energy use. Firebase receives energy data from the ESP32. After retrieving this information, the Blynk app shows the current (A), Voltage (V), Power (W), consumption of Energy (kWh) and cost estimate depending on tariff prices. The user uses Blynk widgets to create a personalized dashboard. Widget examples are value display (presents sensor readings in real time), graph (shows patterns in power usage over time) and notification widget (notifies users when energy consumption surpasses predetermined thresholds). Through mobile networks or Wi-Fi, users can obtain the energy statistics from any location. By integrating the system with home automation, customers can remotely turn off appliances that use a lot of energy. Blynk helps consumers optimize their electricity usage by visualizing previous data.

Google's Firebase is a cloud-based database platform that keeps track of energy usage in real time. The important Firebase features are for real-time synchronization it uses a NoSQL database. It provides quick and safe data storage and is scalable for Internet of Things uses. It provides simple Blynk and ESP32 integration. In real time, the ESP32 sends processed energy data to Firebase. Firebase serves as a bridge between Blynk and ESP32. The Blynk app quickly updates with any new data that is published to Firebase. Firebase makes it possible to track energy usage over time. In order to optimize electricity use and analyze usage trends, users can access historical records. Using Firebase data, the system can be configured to deliver warnings or perform automatic tasks. For instance, the system may notify the user if energy usage beyond a certain level. If a relay module is fitted, remotely turn off the load.

Flowchart of the System

The system operates according to a planned flow as shown in Fig. 3, guaranteeing smooth user interaction, data processing, storage, and collection. With the use of the system's real-time and historical energy consumption information, customers may optimize power usage and cut expenses.

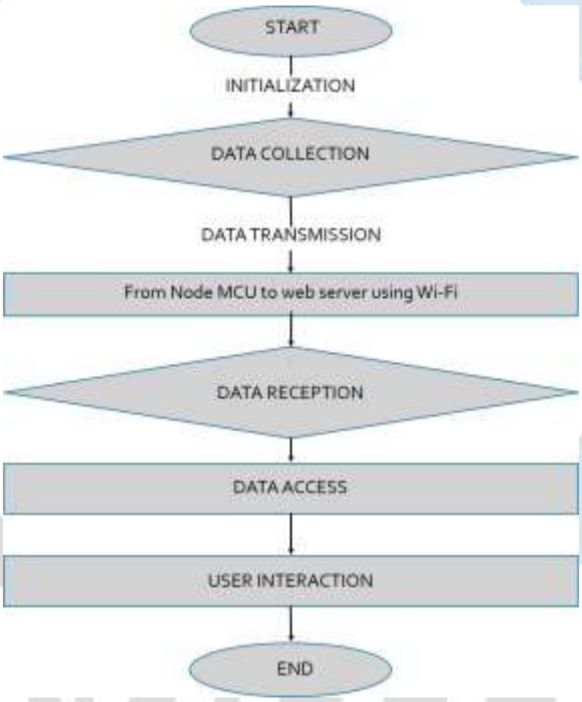

Figure 3 Flowchart

The CT sensor and PZEM-004T module continuously measure electrical parameters, including current, voltage, power, and energy consumption, from the load. The ESP32 microcontroller processes the collected data and calculates metrics such as energy usage and cost estimates. The processed data is transmit- ted to Firebase via Wi-Fi, where it is stored and made accessible for real-time and historical analysis. The Blynk app fetches the data from Firebase, allowing users to monitor energy consumption in real-time. Users can view electrical parameters, including current, voltage, power, and energy cost esti- mates, enabling efficient monitoring and control of energy usage.

III. IMPLEMENTATION RESULTS

The system was successfully implemented as per the circuit diagram shown in Fig. 2. The system successfully monitored real-time electrical parameters (voltage, current, power, and energy consumption) using the PZEM-004T module. The data was updated periodically and displayed on both the Arduino Serial Monitor and the Blynk mobile application

The Blynk app displayed live readings of energy usage. The data was shown in numerical values for voltage, current, and power, while the energy consumed was represented graphically as in Fig. 4. Users were able to see consumption patterns over time, giving them insight into how much energy was being used during different time intervals.

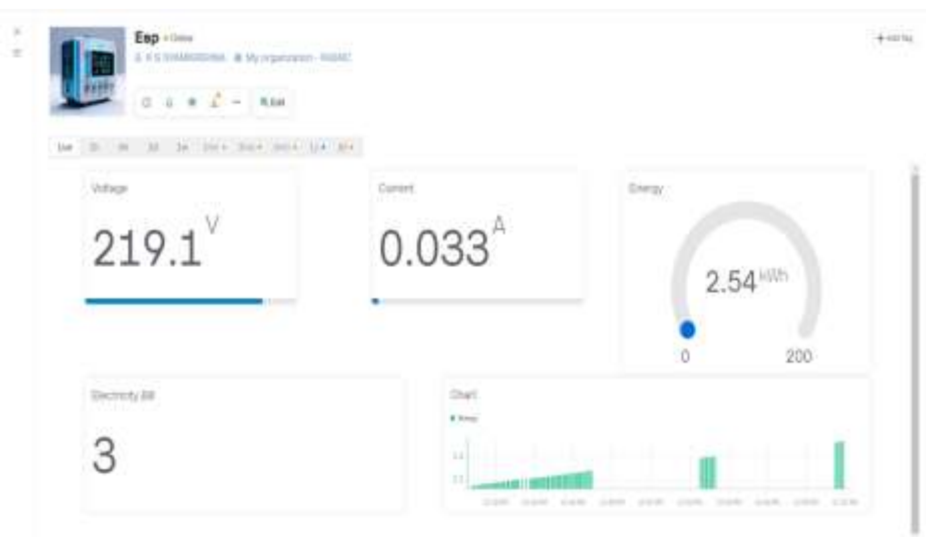

Figure 4 Blynk Website Interface

Figure 4 Blynk Application Interface

The system also calculated the approximate electricity charges using a predefined slab-based tariff. For example, the number of energy units consumed (in kWh) was used to calculate the bill. The slab-based structure applied different rates depending on the amount of energy consumed (e.g., lower rates for lower consumption, higher rates for greater usage). The Blynk application displayed the calculated bill based on the energy consumed in real-time.

The data collected was consistently accurate, reflecting the real-time consumption of the load (bulb). The system showed no significant delays in data transmission from the ESP32 to Firebase and the Blynk app. Data storage on Firebase worked effectively, allowing users to view their historical energy usage over time.

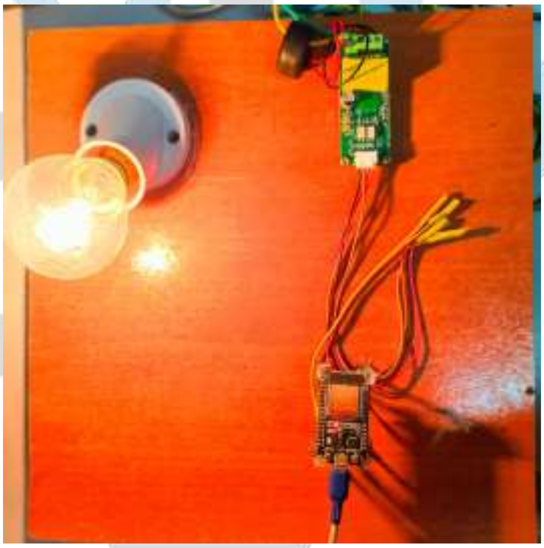

Figure 5 Final Setup

This successful implementation as in Fig. 5 showcased the potential for IoT systems to revolutionize energy management in both residential and commercial settings, allowing users to make informed decisions regarding energy usage.

IV. Conclusion

A scalable and reasonably priced Internet of Things (IoT) based energy monitoring system that combines cloud storage and real-time data visualization is presented in this research. Accurate power usage tracking is ensured by the system's efficient measurement of important electrical parameters such as voltage, current, power, frequency, power factor, and cumulative energy consumption. The main sensing components are the CT sensor and PZEM-004T multimeter module, which record electrical data in real time and process it using the NodeMCU ESP32 microcontroller. Using its integrated Wi-Fi connectivity, the ESP32 is in charge of processing the collected data and sending it to a cloud platform.

The system makes use of the Blynk mobile application, which offers an easy-to-use and interactive dashboard for real- time visualization, to improve user accessibility and remote monitoring. Furthermore, Firebase is used for cloud-based storage, which enables users to keep track of past energy usage trends. The system is ideal for both residential and commercial applications where cost control and energy efficiency are critical because of its dual-platform approach, which guarantees smooth monitoring, trend analysis, and effective energy management.

To enhance user accessibility and remote monitoring, the system leverages the Blynk mobile application, which pro- vides an intuitive and interactive dashboard for real-time visualization. Additionally, Firebase is utilized for cloud-based storage, allowing users to monitor historical patterns in energy consumption. Because of its dual-platform approach, which ensures seamless monitoring, trend analysis, and efficient energy management, the system is perfect for both residential and commercial applications where cost control and energy efficiency are crucial.

While the current implementation provides a robust foundation for energy monitoring, several future enhancements can further improve its functionality, efficiency, and intelligence. Future iterations of the system could include machine learning (ML) models for analyzing historical energy consumption data and forecasting future trends. ML algorithms can discover trends and abnormalities, which aids in problem detection, preventive maintenance, and energy waste reduction. Predictive analytics can be used to recommend optimal energy usage patterns, resulting in lower electricity bills. The system can be improved with smart relays to allow for autonomous control of electrical appliances based on real-time energy usage data. Integrating home automation platforms (such as Google Assistant, Amazon Alexa, or MQTT-based control systems) enables consumers to manage their energy consumption remotely and effectively. When energy consumption exceeds a predetermined level, a threshold-based control method can be used to turn off high-power devices. A dedicated webpage can be created to supplement the Blynk app, allowing customers to access their energy consumption data from desktop or mobile browsers. Additional customization options are available, allowing customers to create alerts, track energy bills, and receive personalized energy savings advice. The system can be customized to track energy generated by renewable sources like solar panels or wind turbines. This would allow users to measure both energy usage and energy creation, optimizing the use of renewable power sources for greater energy efficiency.

Overall, the proposed IoT-based energy monitoring system provides a scalable, cost-effective, and easy-to-implement solution for real-time power consumption tracking. By leveraging sensor technology, cloud storage, and mobile interfaces, the system enhances energy management and cost optimization. With future advancements in machine learning, automation, security, and cloud computing, this system can evolve into a comprehensive energy analytics platform, benefiting both households and industrial consumers.

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