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Design and Implementation of IoT-Based Prepaid Smart Energy Meter for Efficient Power Management

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Abstract: The increasing demand for smarter and more efficient energy management systems has led to the emergence of prepaid smart energy meters integrated with Internet of Things (IoT) technologies. This paper presents the design and implementation of an IoT-based prepaid smart energy meter intended to enable real-time consumption monitoring, remote billing management, and automated power control. The system allows consumers to purchase electricity credits in advance and track their usage through a user-friendly mobile or web interface, fostering energy awareness and promoting conservation.

The hardware architecture incorporates a digital energy metering IC for accurate measurement, an ESP32 microcontroller for processing and control, and Wi-Fi/GSM modules to ensure seamless data transmission. The system communicates with a cloud-based platform that manages user profiles, stores consumption data, and facilitates remote credit recharges. Key functionalities include real-time usage alerts, automatic disconnection when credit is depleted, tamper detection, and support for dynamic tariff structures based on time-of-use pricing.

This IoT-enabled solution benefits consumers by providing transparency and control over their electricity consumption while also helping utility providers reduce revenue loss from manual errors, billing delays, and electricity theft. Furthermore, the integration of real-time analytics supports predictive load forecasting and demand-side energy management, contributing to the stability and scalability of smart grid infrastructures.

Performance evaluations demonstrate the system's effectiveness in energy regulation, user convenience, and operational reliability. Cost analysis indicates the feasibility of deploying such systems in both urban and rural settings, particularly in regions with unreliable billing practices or limited access to on-site utility services. Additionally, this approach aligns with global sustainability goals by encouraging responsible energy usage, facilitating renewable energy integration, and minimizing environmental impact.

It lays the foundation for the development of smart, self-regulating cities that prioritize resilience, economic efficiency, and environmental stewardship. Future improvements could include AI-based consumption forecasting, blockchain-enabled secure transactions, and integration with smart home systems for a fully automated energy ecosystem.

Keywords: IoT-based Energy, Metering Prepaid smart Energy Meter, Real-time Energy Monitoring, Smart Grid Integration

I. INTRODUCTION

The global energy landscape is rapidly evolving, driven by the increasing demand for more efficient, sustainable, and transparent energy management systems. Traditional energy metering systems, which are predominantly based on postpaid billing, manual meter readings, and centralized control, often suffer from issues such as billing inaccuracies, delays, power wastage, and the challenges associated with managing fluctuating energy demand. These inefficiencies have become particularly problematic as urban populations grow, energy consumption patterns become more dynamic, and the integration of renewable energy sources into grids increases. To address these challenges, prepaid energy metering systems have emerged as a practical alternative. By allowing consumers to pay in advance for their energy usage, prepaid systems reduce the risks associated with non-payment and provide an incentive for users to adopt more energy-efficient behaviors.

However, conventional prepaid meters often lack real-time monitoring and communication features, which limits their ability to offer comprehensive control and feedback to both consumers and utility providers.

The advent of the Internet of Things (IoT) has revolutionized the design of energy management systems by enabling real-time data collection, remote monitoring, and seamless communication between devices. IoT-based prepaid smart energy meters leverage these advancements to provide consumers with greater control over their energy usage. These meters combine advanced metering technology, microcontroller units, wireless communication protocols (such as Wi-Fi or GSM), and cloud computing to offer real-time consumption monitoring, automated billing, dynamic pricing, and immediate feedback on energy usage. This paper explores the design and implementation of an IoT-based prepaid smart energy meter aimed at improving energy management by enhancing monitoring capabilities, streamlining billing processes, and encouraging efficient energy consumption.

The proposed system includes key components such as digital energy metering ICs, an ESP32 microcontroller, communication modules, and a cloud-based platform to track and store data. By enabling remote recharges, real-time usage alerts, and automatic disconnection when the account balance reaches zero, the system promotes energy awareness while ensuring consumer convenience and operational efficiency for utility providers. The goal of this study is to evaluate the technical feasibility and effectiveness of the proposed system, providing insights into its architecture, hardware and software integration, and overall performance. Furthermore, the paper will discuss the scalability of the system for large-scale deployment, its cost-effectiveness, and its potential contribution to building smarter, more resilient energy grids in the future.

II. LITERATURE SURVEY AND RELATED WORKS

1. Existing Works and Related Studies

1.1 IoT-Enabled Smart Energy Meters
An IoT framework for smart grid communication systems was presented by Rathore et al. (2016), who emphasized how IoT makes it possible for energy systems to have automated control, data analytics, and continuous monitoring. Reducing waste, identifying irregularities early, and increasing operational efficiency are all made possible by real-time monitoring.

1.2 Prepaid Metering Systems
A microcontroller in the GSM-based prepaid energy meter created by Patil et al. (2015) tracks energy usage and subtracts user credits appropriately. Significant drawback: Although GSM offers extensive coverage, places with subpar cellular networks experience problems with data speed and dependability.

1.3 Communication Technologies Used
Numerous communication protocols, including NB-IoT, ZigBee, LoRa, and Wi-Fi, have been examined: Wi-Fi has a limited coverage area but offers high data rates. Despite its low power consumption, ZigBee is best suited for short-range uses. LoRa offers low-power, long-range communication, making it perfect for large-scale or rural deployments. NB-IoT is promising for future smart grid applications and supports a large number of low-power devices. According to Mukhtar and Shabbir (2019), Wi-Fi and NB-IoT are the most effective technologies for home smart meters.

1.4 Mobile Application and Web-Based Monitoring
A wireless sensor network (WSN) smart metering system was proposed by Teymour Zadeh et al. (2013). Users could access real-time usage data via an Android application. By raising consumers' awareness of their daily energy usage patterns and promoting energy-saving practices, these systems have been shown to increase user engagement.

1.5 Load Management and Theft Detection
Smart meters that can identify odd consumption patterns that point to energy theft or leakage were developed by Jain and Purohit (2018). Artificial intelligence (AI)-based methods were proposed to forecast customer behaviour and automatically modify tariffs or notify authorities of irregularities.

1.6 Cybersecurity and Privacy Issues
Cybersecurity issues with smart energy meters were brought to light by Zhou et al. (2019). The interconnectedness of IoT devices increases the risk of hacking, false data injection attacks, and data breaches. Therefore, blockchain and secure communication protocols (like SSL/TLS) are recommended for safe transactions and data verification.

2. Identified Gaps in Existing Systems
Absence of dynamic tariff management in real time. Inadequate IoT data cybersecurity measures. Lack of integrated payment systems for mobile wallets. Autonomous load shedding and peak load forecasting have limited support. In regions with erratic communication networks, poor performance.

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3. Motivation for Proposed System

Given the shortcomings of current systems, a solution that combines the following is desperately needed: IoT (using ESP32, GSM, or Wi-Fi modules), monitoring of balance in real time, Notifications and app recharge for users Encrypted and secure communication, load-based dynamic tariff adjustment, Data analytics for emergency disconnections, remote load control, and power usage forecasting. With the use of Internet of Things technology, the proposed system seeks to develop and deploy a prepaid smart meter that guarantees effective power management, intuitive operation, and improved system security.

III. SYSTEM ARCHITECTURE

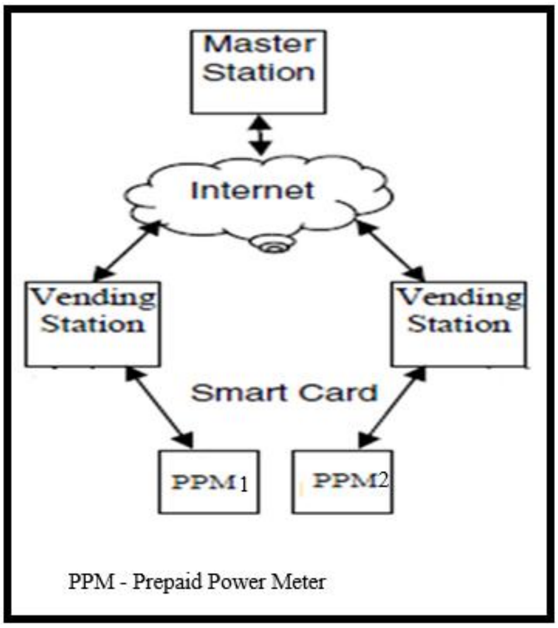

Fig. 1. System Architecture of Design and Implementation of IoT-Based Prepaid Smart Energy Meter for Efficient Power Management

The Internet of Things-based prepaid smart energy meter's system architecture is made to offer a practical and effective way to monitor and control energy use using prepaid techniques. The Master Station, which serves as the central server in charge of overseeing the system's overall operation, is at the centre of the system. It manages authentication and coordination between various nodes and keeps track of user information, transaction history, and energy usage logs. The Master Station and different Vending Stations are connected via the Internet, which enables smooth data synchronization and communication. These vending stations are well-placed service locations where customers can buy energy credit to top off their electricity accounts. As a portable data carrier between the user's location and the vending station, the smart card is essential. The smart card is taken to the user's home after being encoded with their unique credit information after they have purchased credit at the vending station. After inserting the smart card, the Prepaid Power Meter (PPM) determines the available credit and turns on the power supply in accordance with that information. The PPM continuously tracks energy consumption and subtracts the units used from the balance that is available. The PPM makes sure that consumption is strictly kept to the pre-paid amount by cutting off the power supply when the balance drops to zero. In addition to preventing electricity theft and doing away with the need for manual meter reading, this architecture gives users the ability to track and manage their energy usage in real time. The system is appropriate for contemporary smart grid environments since it also guarantees scalability, remote access, and effective energy distribution through the use of IoT and network communication.

IV. METODOLOGY

To guarantee a dependable and effective system, the research, design, development, and testing stages are all included in the methodology for the project "Design and Implementation of IoT-Based Prepaid Smart Energy Metre for Efficient Power Management." In order to comprehend the existing energy metering systems, their shortcomings, and the potential of IoT integration to address issues like billing errors, power waste, and energy theft, a thorough literature review is first carried out. This review lays the groundwork for creating a more effective system by pointing out weaknesses in current technologies.

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Fig. 2. IoT based Smart Energy meters For Efficient Energy Management

A system requirement analysis is carried out to identify the hardware and software components required for the project after the literature review. Choosing a suitable energy measurement system (like current/voltage sensors), microcontrollers (like Arduino or ESP32), communication modules (like Wi-Fi or GSM), and a relay to cut the load when credits are depleted are among the hardware requirements. A secure system for managing prepaid credit, a mobile or web application for user interaction, and an Internet of Things-based platform for real-time energy consumption monitoring are among the software requirements.

The system design, which incorporates both software and hardware architecture, comes next. While the software design describes the logic required to manage prepaid credits, data transmission to the cloud, and user notifications, the hardware design concentrates on integrating sensors with the microcontroller and relay system to measure and control energy consumption. Creating a user interface that offers real-time updates on energy consumption and credit status is another aspect of the system. In parallel, MQTT and HTTP are chosen as communication protocols to ensure effective data transfer between the cloud platform and the energy meter.

Following design completion, the hardware components are put together and the software is coded during the prototype development phase. The microcontroller is configured to gather sensor data and transmit it to an Internet of Things platform, which then shows the data on a web or mobile application. When the prepaid system logic is put into practice, credits are automatically deducted and the connection is cut off when the balance is depleted. The prototype undergoes preliminary testing to confirm the relay mechanism, sensor accuracy, and system-to-cloud platform communication.

Following validation of the prototype, all components are integrated into a fully functional unit to start the system implementation phase. This entails installing the energy meter in an actual location, configuring the Internet of Things platform for real-time monitoring, and making sure the web or mobile application has the features users need to view consumption data, top up credits, and get alerts. The prepaid system is also extensively tested to guarantee precise billing, smooth disconnections, and trustworthy alerts.

Once deployed, testing and calibration are conducted to ensure that the system functions as intended. The energy meter is calibrated against a standard meter to ensure accurate power consumption readings. Functional testing is carried out to check the reliability of the prepaid system, the accuracy of the energy readings, and the effectiveness of user notifications. The system’s performance is also evaluated under various conditions to ensure reliability and efficiency.

Once deployed, testing and calibration are conducted to ensure that the system functions as intended. The energy meter is calibrated against a standard meter to ensure accurate power consumption readings. Functional testing is carried out to check the reliability of the prepaid system, the accuracy of the energy readings, and the effectiveness of user notifications. The system’s performance is also evaluated under various conditions to ensure reliability and efficiency. Deployment, which involves installing the system in a test environment and gathering user feedback, occurs in the last stages. In order to evaluate the system's efficacy in terms of cost effectiveness, energy management, and user experience, this feedback is examined. This could be used to optimize the system for increased scalability and performance.

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The project ends with a success assessment and recommendations for future enhancements, like incorporating renewable energy sources or using advanced analytics for predictive power management.

V. CONCLUSION

The project "Design and Implementation of IoT-Based Prepaid Smart Energy Meter for Efficient Power Management" effectively illustrates how prepaid energy metering and IoT technology can be combined to improve energy efficiency and management. Through a smartphone application, the system gives users the ability to monitor and manage their power consumption in real time, which is convenient and empowers them to take proactive measures to manage their energy usage. The solution reduces power theft, avoids overuse, and ensures a more consistent consumption pattern by implementing a prepaid model. Additionally, energy providers can remotely monitor and manage the IoT-based smart meter, which lowers operating costs and improves electricity distribution efficiency.

In addition to encouraging energy conservation, the project helps users and service providers save money. All things considered, this system offers a dependable and sustainable method of managing energy, and it has the potential to completely transform energy metering on a bigger scale with additional advancements like predictive analytics and integration with renewable energy sources.

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