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EnerPulse-IoT: Design and Implementation of an ESP32-Based Prepaid Smart Energy Meter with Real-Time Monitoring and Automated Load Control

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Abstract: ***Energy meters are essential devices used to measure and record electrical energy consumption in residential, commercial, and industrial environments. This paper presents EnerPulse-IoT, an ESP32-based prepaid smart energy meter designed for accurate energy monitoring, automated billing, and efficient load management. The proposed system integrates voltage and current sensing modules to acquire real-time electrical parameters and calculate power usage continuously. Energy consumption data are processed by the ESP32, enabling dynamic balance deduction based on prepaid credit. A relay mechanism automatically disconnects the electrical supply when the available balance reaches zero, preventing unpaid consumption and promoting responsible energy utilization. An integrated LCD displays consumption statistics, remaining balance, and system status for enhanced user awareness. Wireless connectivity enables remote monitoring, recharge management, and alert notifications through an IoT-enabled platform. The system also incorporates theft detection and tamper indication features using a buzzer-based warning mechanism, improving operational security. Experimental implementation demonstrates reliable performance in measuring energy usage, maintaining billing accuracy, and controlling connected loads. The proposed solution reduces manual intervention, supports transparent energy management, and sustainability.***

Keywords: ESP32, Internet of Things (IoT), Prepaid Energy Meter, Smart Metering, Energy Monitoring, Automated Load Control, Remote Monitoring, Energy Management, Theft Detection, Smart Grid.

I. INTRODUCTION

Electricity plays a fundamental role in modern society by supporting residential activities, commercial operations, industrial processes, and technological advancement. As electricity demand continues to increase, efficient monitoring and management of energy consumption have become essential for ensuring sustainable utilization of available power resources. Conventional electricity billing systems often suffer from limitations such as manual meter reading, delayed bill generation, billing inaccuracies, energy theft, and insufficient consumer awareness regarding real-time energy usage. These challenges can lead to operational inefficiencies, financial losses, and reduced transparency between utility providers and consumers. An energy meter is a device used to measure and record the electrical energy consumed by connected loads over a specified period. Traditional electromechanical and digital meters generally depend on manual inspection and periodic data collection, making them susceptible to human error and delayed processing. The emergence of Internet of Things (IoT) technologies has enabled the development of intelligent metering solutions that support automated monitoring, remote communication, and real-time data analysis. Such capabilities improve billing accuracy, enhance user awareness, and facilitate efficient energy management. This study presents an ESP32-based prepaid smart energy meter incorporating real-time monitoring and automated load control functionalities. The proposed system employs voltage and current sensing modules to continuously acquire electrical parameters and calculate energy consumption. The ESP32 microcontroller processes the measured data, manages prepaid balance information, and enables wireless communication for remote monitoring. A relay module automatically disconnects the electrical supply when the available balance reaches a predefined threshold, preventing unauthorized or unpaid energy usage. An LCD interface provides instant information regarding power consumption, balance status, and system operation. Additionally, theft detection and alert mechanisms enhance system security and reliability. By integrating prepaid billing, IoT-based communication, and automated control features into a unified platform, the proposed approach contributes to improved energy conservation, reduced manual intervention, enhanced billing transparency, and efficient utilization of electrical resources in modern smart energy management systems.

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II. LITERATURE SURVEY

Article [1] "An IoT based Real-time Low Cost Smart Energy Meter Monitoring System using Android Application" by Md Redwanul Islam and Supriya Sarker in 2020: This paper presents a low-cost IoT-enabled smart energy meter monitoring system integrated with an Android application. The proposed system automates electricity consumption monitoring and reduces manual meter reading efforts. Arduino Uno and optical sensors are utilized to collect meter pulse data. Wireless communication enables remote access to energy consumption information. The developed application provides consumers with real-time monitoring capabilities. The study highlights reduced human errors in billing processes. Experimental results demonstrate reliable performance and improved user awareness regarding electricity usage.

Article [2] "IoT Based Smart Energy Meter Monitoring and Billing System" by Manisha Tejwani and Prachi Rane in 2020: This research introduces an IoT-enabled energy meter designed for monitoring electricity consumption and automating billing operations. The system employs an ESP8266 module for wireless communication and cloud connectivity. ThingSpeak is used to visualize energy usage data in real time. Consumers can track their electricity consumption remotely. The proposed approach improves billing transparency and reduces manual intervention. Automated monitoring helps utility providers manage consumption efficiently. The study demonstrates a practical solution for smart metering applications.

Article [3] "IoT Based Smart Energy Meter using GSM" by C. Santhosh and S. V. Aswin Kumer in 2020: This paper focuses on smart energy metering through GSM communication technology. The system enables remote transmission of energy consumption data to utility providers. Real-time monitoring improves the accuracy of energy usage tracking. Automated communication reduces dependency on manual meter reading. The proposed design supports efficient billing and consumption analysis. GSM connectivity enhances accessibility in areas with limited internet infrastructure. The study demonstrates the feasibility of integrating communication modules with smart meters.

Article [4] "IOT Based Smart Energy Meter Using ESP32" by S. Gadekar and S. Kulkarni in 2021: This work presents an ESP32-based smart energy meter capable of automatically tracking residential energy consumption. The system calculates electricity usage and billing information using embedded algorithms. Sensor data are processed and transmitted wirelessly to consumers and utility providers. ESP32 enables efficient communication and data management. The design supports remote monitoring and improved consumer awareness. Automated operation minimizes manual effort in meter reading. The study validates the effectiveness of ESP32 for smart energy applications.

Article [5] "IOT Based Prepaid Energy Meter" by Ranganayaki V and Nithish Kumar S in 2021: This paper proposes a prepaid energy metering system that allows users to recharge electricity usage in advance. The system continuously deducts energy charges based on consumption. Consumers receive alerts regarding low balance conditions. Automatic disconnection occurs when the prepaid balance is exhausted. The design improves revenue collection efficiency for utility providers. Remote monitoring capabilities enhance transparency and user control. The study demonstrates effective implementation of prepaid electricity management.

Article [6] "IoT Based Smart Energy Meter Monitoring and Theft Detection" by Sunil Kumar C and Chandra Mohan Reddy P in 2021: This study presents an IoT-based smart energy meter with integrated theft detection functionality. The proposed system continuously monitors power consumption patterns. Abnormal conditions trigger alerts to concerned authorities. Real-time monitoring improves energy accountability and operational efficiency. The design helps reduce power theft and revenue losses. Wireless communication supports remote access to consumption data. Experimental results indicate improved monitoring and security performance.

Article [7] "IOT Based Smart Prepaid Energy Recharge Scheme for EB" by E. Kaliappan and S. Karthikeyan in 2022: This paper introduces a prepaid electricity recharge mechanism based on IoT technology. The system automatically disconnects power supply when the recharge balance becomes insufficient. Consumption information is displayed and updated through an IoT platform. Users can monitor expenditure and recharge status remotely. Automated notifications improve customer awareness regarding energy usage. The design minimizes manual intervention and billing disputes. Results demonstrate efficient prepaid energy management and operational reliability.

Article [8] "Pre-SEMMS: A Design of Prepaid Smart Energy Meter Monitoring System for Household Uses Based on IoT" by K. D. Irianto and M. H. Purnomo in 2023: This research proposes an IoT-based prepaid smart energy meter monitoring system for residential applications. The design integrates energy measurement, monitoring, and balance management functions. Consumers can access usage information remotely through internet connectivity. Real-time monitoring improves transparency and energy awareness. The system supports efficient billing and consumption control. IoT integration enables continuous communication between consumers and service providers. The study demonstrates suitability for modern smart home environments.

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Article [9] "IoT-based Analysis for Smart Energy Management" by Guang-Li Huang and Adnan Anwar in 2023: This paper reviews IoT-based approaches for intelligent energy management and monitoring. The study discusses energy disaggregation techniques and consumption analysis methods. Real-time monitoring enables optimized utilization of electrical resources. Various IoT communication technologies are evaluated for energy applications. The paper highlights the importance of user behavior analysis in energy conservation. Smart monitoring systems improve awareness and operational efficiency. Future research opportunities in sustainable energy management are also discussed.

Article [10] "IoT Based Smart Energy Meter" by various researchers in 2025: This study presents an intelligent energy monitoring system capable of providing real-time consumption information. Sensor modules measure voltage and current parameters continuously. Cloud connectivity enables remote visualization and analysis of energy usage. The system supports automated alerts for abnormal consumption patterns. Historical data analysis improves energy management decisions. The proposed design enhances billing accuracy and operational efficiency. Results indicate effective performance in modern smart grid environments.

Article [11] "Development of an IoT-Enabled Smart Electricity Meter for Advanced Monitoring" by H. O. Garcés and J. P. Rojas in 2025: This paper presents an advanced smart electricity meter with IoT-based communication features. The system incorporates noninvasive sensing techniques and flexible communication methods. Real-time data transmission supports continuous monitoring of electrical parameters. Improved measurement accuracy enhances energy management capabilities. The design addresses challenges related to harmonics and frequency analysis. Cloud integration enables remote access and control. Experimental evaluations demonstrate reliable and accurate performance.

Article [12] "Design and Implementation of IoT-Based Prepaid Smart Energy Meter for Efficient Power Management" by Vaishnavi Vishwas Kale and Dnyaneshwar Shivaji Waghmode in 2025: This paper proposes a prepaid smart energy meter integrated with IoT technology for efficient power management. The system enables real-time monitoring of electricity consumption and prepaid balance. Remote billing management improves operational transparency. Automated load control helps prevent unpaid energy usage. IoT connectivity facilitates communication between users and utility providers. The design supports smart grid integration and energy conservation objectives. The study concludes that the proposed solution provides a reliable and scalable approach for modern energy management systems.

III. PROBLEM STATEMENT

Conventional electricity metering systems face several challenges that affect both utility providers and consumers. Manual meter reading is time-consuming, labor-intensive, and prone to human errors, resulting in inaccurate billing and delayed payment processing. Traditional postpaid billing methods often lead to revenue losses due to unpaid bills and inefficient collection procedures. Consumers generally lack access to real-time information regarding energy consumption, making it difficult to monitor usage and control electricity expenses. In addition, electricity theft, meter tampering, and unauthorized power usage continue to be major concerns for power distribution authorities. The absence of automated monitoring and remote management mechanisms further limits operational efficiency, transparency, reliability, and accountability.

IV. OBJECTIVES

The primary objective of this study is to develop an IoT-enabled prepaid smart energy metering system capable of monitoring electricity consumption accurately in real time. The study aims to eliminate the limitations associated with conventional metering and billing methods by enabling automated energy tracking and balance management. Another objective is to provide consumers with continuous access to consumption information, allowing better control over electricity usage and expenditure. The study also focuses on implementing automated load disconnection when the prepaid balance is exhausted, reducing unpaid energy consumption. Additionally, it seeks to enhance billing transparency, minimize human intervention, improve operational efficiency, and support secure energy management.

V. METHODOLOGY

The methodology adopted in this study focuses on developing an IoT-enabled prepaid smart energy metering system for real-time monitoring, automated billing, and load control. The proposed framework integrates sensing, processing, communication, and control modules to accurately measure electrical parameters and manage prepaid energy consumption. Figure 1 illustrates the overall system architecture of the proposed EnerPulse-IoT framework, showing the interaction between sensors, ESP32 controller, display unit, relay module, and remote monitoring platform.

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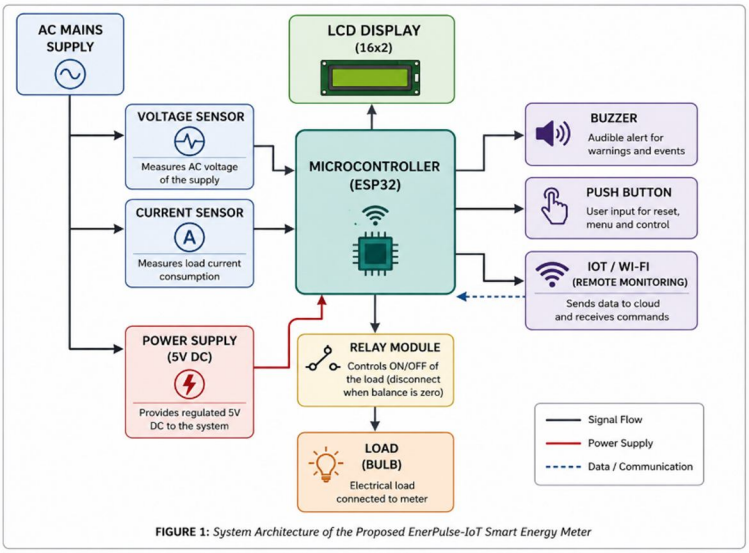


Figure 1. System Architecture of the Proposed EnerPulse-IoT Prepaid Smart Energy Meter with Real-Time Monitoring and Automated Load Control

A. Data Acquisition Using Voltage and Current Sensors

The proposed system continuously acquires electrical parameters through dedicated voltage and current sensing modules. The voltage sensor measures the AC supply voltage while the current sensor monitors the load current consumed by connected appliances. These sensors generate analog signals proportional to the measured electrical quantities and transmit them to the processing unit for further analysis. Continuous sensing enables accurate tracking of electrical behavior under varying load conditions. The acquired data form the foundation for calculating power and energy consumption. Accurate measurement is essential for reliable billing and prepaid balance management. Sensor integration improves system responsiveness and ensures that consumption information is updated in real time without requiring manual intervention.

B. Real-Time Processing Using ESP32 Controller

The ESP32 microcontroller acts as the central processing unit responsible for managing all system operations. Sensor readings obtained from the voltage and current measurement modules are processed to determine electrical parameters such as voltage, current, power, and cumulative energy consumption. The controller executes predefined algorithms to convert raw sensor values into meaningful information. Its built-in computational capabilities support rapid processing and efficient system performance. The ESP32 also coordinates communication between sensing, display, monitoring, and control units. Real-time processing enables timely decision-making and accurate consumption tracking. The controller serves as the core component that integrates measurement, communication, and automation functionalities within the proposed prepaid smart energy metering framework.

C. Prepaid Balance Management Mechanism

A prepaid balance management mechanism is implemented to regulate electricity utilization based on available credit. The system maintains balance information within the controller memory and continuously updates the remaining credit according to measured energy consumption. As electrical energy is consumed, the corresponding cost is deducted automatically from the prepaid account. This approach ensures transparency in electricity usage and expenditure. Consumers can easily monitor the remaining balance and manage energy consumption accordingly. The automated deduction process eliminates billing delays and reduces dependency on conventional postpaid systems. By linking consumption directly with available credit, the system promotes responsible energy utilization and supports efficient electricity management practices.

D. Automated Load Control through Relay Module

Automated load control is achieved through a relay module connected to the processing unit. The relay functions as an intelligent switching device capable of connecting or disconnecting the electrical supply based on predefined operating conditions.

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When the prepaid balance reaches a critical threshold or becomes exhausted, the controller activates the relay to disconnect the load automatically. This mechanism prevents unauthorized electricity consumption and ensures adherence to prepaid billing principles. The relay can also be used for remote control operations through the monitoring platform. Automated switching improves operational efficiency and minimizes manual intervention. The integration of relay-based control enhances system reliability and provides effective management of electrical loads.

E. IoT-Based Remote Monitoring and Communication

The proposed framework utilizes the wireless communication capabilities of the ESP32 to establish IoT-based connectivity. Real-time consumption data, balance information, and operational status are transmitted to a remote monitoring platform through internet communication. This functionality enables users and service providers to access system information from any location. Continuous communication improves visibility of energy usage patterns and facilitates efficient monitoring. Remote accessibility eliminates the need for physical inspection and manual data collection. Instant availability of information enhances transparency and decision-making capabilities. IoT integration transforms conventional metering infrastructure into a connected smart system capable of supporting modern energy management requirements and intelligent utility operations.

F. Alert Generation and Security Monitoring

Security and reliability are enhanced through alert generation and monitoring mechanisms integrated within the proposed framework. The system continuously observes operational parameters and predefined security conditions to identify abnormal events. When unauthorized access, meter tampering, or suspicious activity is detected, an alert notification is generated immediately. A buzzer provides local warning indications while remote notifications inform users or utility authorities regarding potential issues. Continuous monitoring improves system protection and helps reduce electricity theft. The alert mechanism also assists in maintaining operational integrity and ensuring dependable performance. These security features contribute to safer energy management and strengthen the overall effectiveness of the prepaid smart metering system.

VI. EXPERIMENTAL SETUP

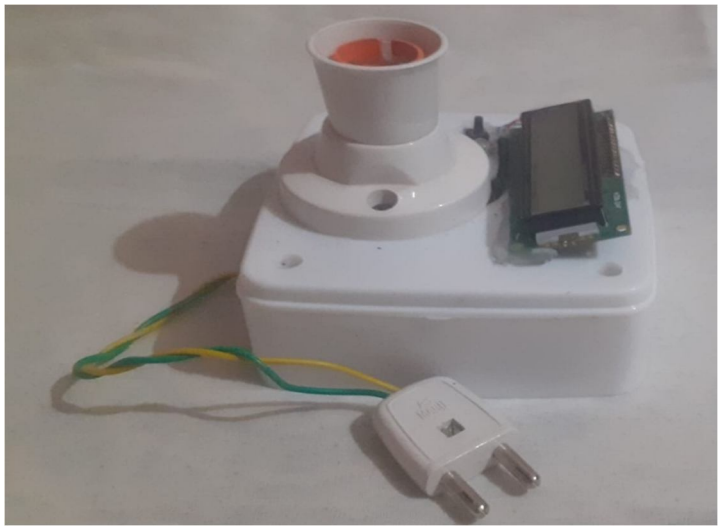


Figure 2. Prototype Kit of the Proposed EnerPulse-IoT Prepaid Smart Energy Meter

The developed prototype kit demonstrates the practical implementation of the proposed IoT-enabled prepaid smart energy metering system. The hardware setup integrates an ESP32 controller, LCD display, power management circuitry, and load interface within a compact enclosure. The kit is designed to monitor energy consumption, display system parameters, and support automated load control based on prepaid balance conditions. Its compact architecture enables reliable operation, real-time monitoring, and efficient energy management for residential and small-scale applications.

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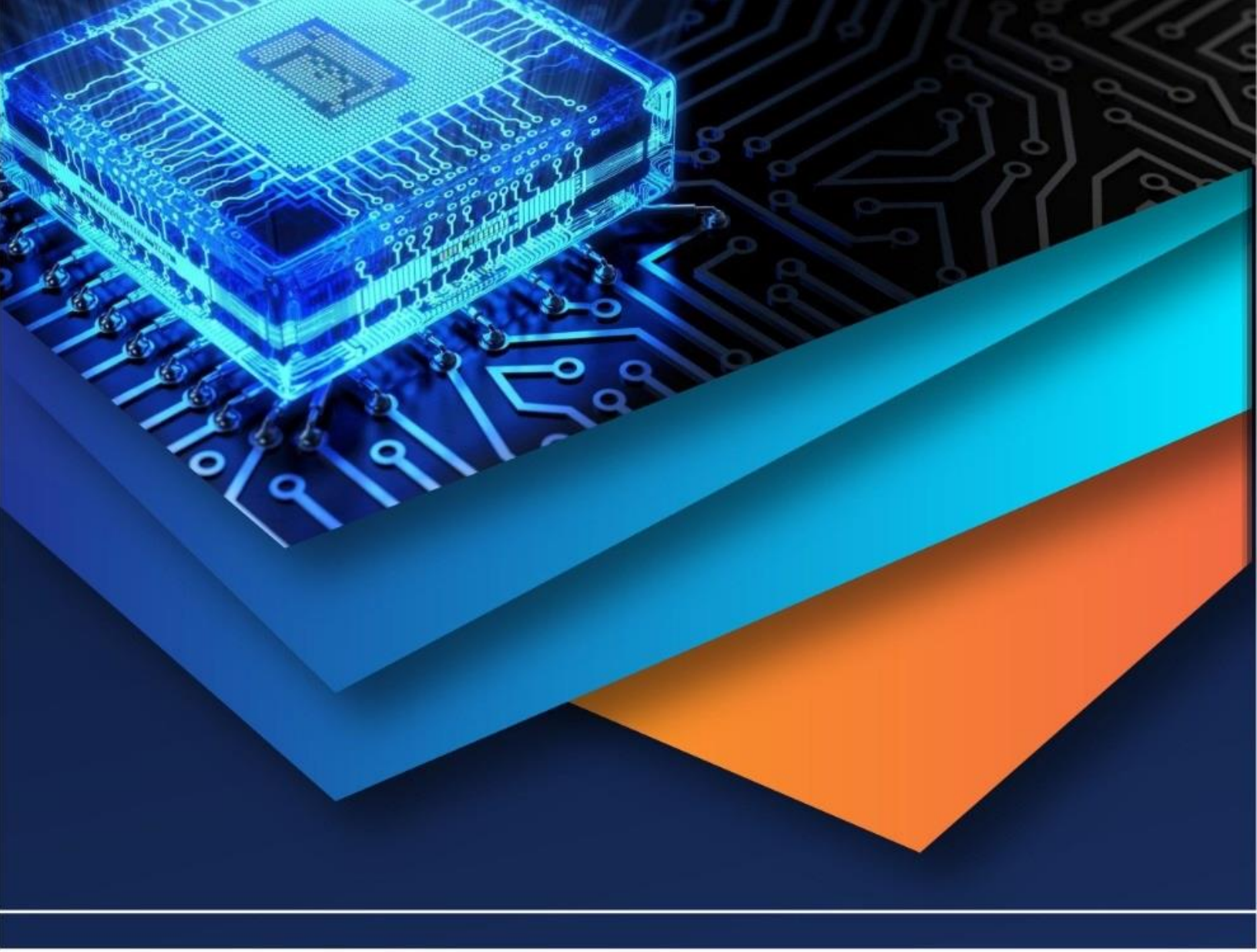
VII. CONCLUSION

In this research, an IoT-enabled prepaid smart energy metering system was successfully presented to improve electricity monitoring, billing transparency, and energy utilization efficiency. The proposed framework integrated voltage and current sensing modules, an ESP32 microcontroller, wireless communication capabilities, a relay control mechanism, and a display interface to provide continuous monitoring of electrical energy consumption. Real-time measurement and automated balance deduction enabled effective management of prepaid electricity usage while reducing dependency on conventional billing procedures. The automated load control feature ensured disconnection of supply when the available balance was exhausted, preventing unauthorized energy consumption. Remote monitoring functionality enhanced accessibility and user awareness regarding electricity usage patterns. The incorporation of alert and security mechanisms further improved operational reliability and protection against potential misuse. The study demonstrated that intelligent metering solutions can significantly reduce manual intervention, improve billing accuracy, and support efficient energy management. Future work may focus on integrating cloud-based analytics, mobile payment gateways, advanced theft detection algorithms, renewable energy monitoring capabilities, and machine learning techniques for consumption forecasting. Additional enhancements may include smart grid interoperability, multi-user billing support, and large-scale deployment for advanced energy management applications across diverse sectors and environments.

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