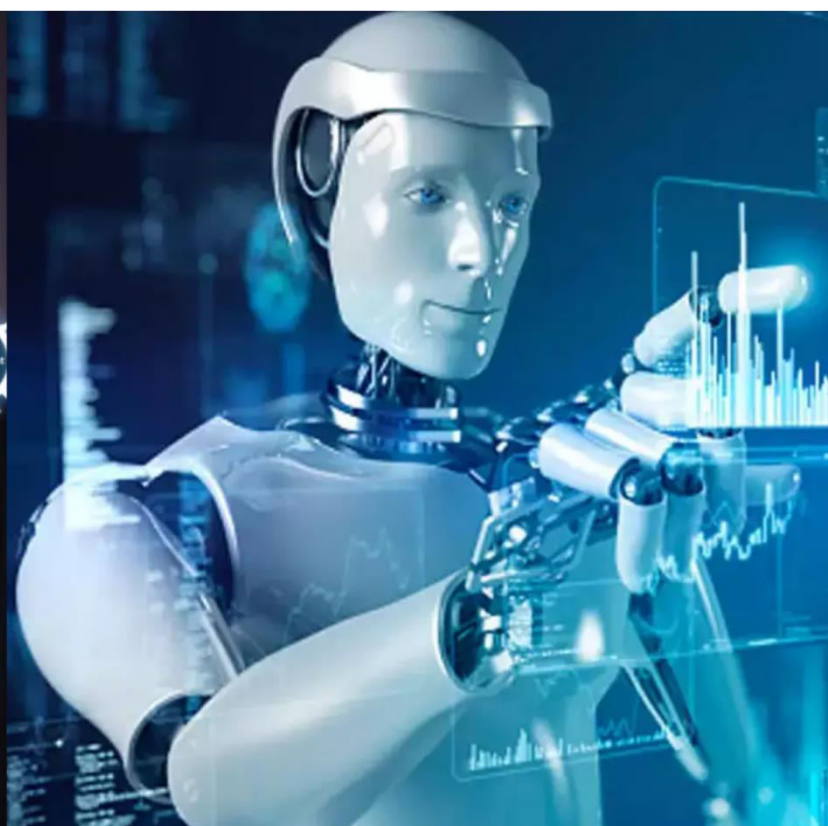




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Smart Prepaid Energy Meter

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ABSTRACT: The increasing demand for efficient energy management and prevention of electricity theft has led to the innovation of smart metering systems. This paper presents the design and implementation of an IoT-based Prepaid Energy Meter using the ESP32 WROOM-32 microcontroller, integrated with GSM-based communication and theft detection capabilities. The proposed system allows users to prepay for energy usage, enabling real-time energy consumption monitoring and alerts. The energy consumption is calculated based on real-time readings from voltage and current sensors, and the total available balance is decremented accordingly. When the energy usage reaches critical thresholds, such as 50% and 80% of the balance, the system sends automated SMS alerts to the registered user through the GSM 800L module. Upon complete consumption of the prepaid balance, the system automatically disconnects the load (DC motor) and remains inactive until the user recharges via SMS. The GSM module enables both sending of status alerts and receiving recharge commands from users, creating a two-way communication channel. A 16x2 I2C LCD module is used to display real-time voltage, current, power, and balance status. To ensure security, an ultrasonic sensor is installed within the meter box to detect any unauthorized access or tampering. If intrusion is detected, the system sends an immediate alert SMS to the concerned authority. The integration of GSM technology for remote access, real-time power consumption tracking, and anti-theft mechanisms offers a smart, secure, and scalable solution for future energy management systems. This system aims to reduce human intervention in energy billing and provide consumers with a transparent and secure method to monitor and manage electricity usage efficiently.

KEYWORDS: ESP32 WROOM-32, IoT-based energy metering, GSM 800L module, voltage and current sensors (ZMPT101B, ACS712), real-time power consumption, prepaid energy management, SMS alerts, ultrasonic sensor, theft detection, I2C 16x2 LCD, relay switching, Arduino IDE.

I. INTRODUCTION

In the era of growing digitalization and automation, traditional methods of energy metering and billing are increasingly proving to be inefficient, error-prone, and susceptible to energy theft. Conventional postpaid energy meters require manual reading and billing, which not only results in operational delays but also creates opportunities for tampering and unauthorized consumption. Prepaid energy meters have emerged as a promising alternative by enabling users to pay in advance for the electricity they consume, similar to prepaid mobile plans. This paper explores the development of a comprehensive prepaid energy meter system enhanced with theft detection and real-time monitoring capabilities.

The core of our proposed system revolves around the ESP32 WROOM-32 microcontroller, which serves as the central processing unit for integrating various sensors and modules. The system continuously monitors energy consumption using voltage and current sensors and calculates power and energy units consumed based on the load connected—represented in our prototype by a DC motor. The use of a prepaid architecture means that users need to recharge the meter balance before consuming electricity. The GSM 800L module is used to create a two-way communication channel: it sends SMS alerts to the user at key thresholds (50%, 80%, and 100% of the balance) and receives SMS-based recharge commands from the user, which allows remote management of the meter without the need for physical interaction. This user-friendly approach not only improves transparency but also ensures uninterrupted power supply as long as there is sufficient prepaid balance.

A critical aspect of energy infrastructure is the detection and prevention of energy theft. To address this challenge, the proposed system incorporates an ultrasonic sensor installed inside the meter casing to detect unauthorized access

attempts. If the sensor detects any movement or if the meter box is opened, it triggers an alert and sends an SMS to the utility authority, warning them of a potential intrusion. This anti-tamper feature enhances the security of the system and discourages attempts at theft, ultimately protecting revenue and infrastructure integrity. By integrating this security feature with the prepaid model, the system provides a holistic solution that combines energy management with physical security monitoring.

In addition to theft detection and prepaid management, the system includes a 16x2 I2C LCD module that displays real-time data to the user. This includes values for voltage, current, power consumption, and remaining balance. The LCD display provides immediate feedback to users and technicians on-site and is particularly helpful for troubleshooting or for ensuring system functionality without needing access to the cloud or mobile interface. The visual interface makes the system more interactive and helps users understand their consumption patterns, encouraging more responsible and informed energy use.

The proposed prepaid energy meter system addresses multiple challenges associated with energy consumption, including accurate billing, user awareness, and energy theft. By integrating IoT technologies and smart sensors, it presents a scalable and cost-effective solution that can be deployed in residential, commercial, or industrial sectors. With increasing emphasis on sustainable energy usage and the adoption of smart grids, such systems can play a pivotal role in reshaping how energy is consumed, monitored, and managed. This paper provides a comprehensive insight into the design, implementation, and functionality of the prepaid energy meter system, detailing its hardware components, logic architecture, user interaction mechanism, and benefits in real-world deployment scenarios.

II. RELATED WORK

Several research initiatives and development efforts have been undertaken over the past decade to enhance energy metering systems, transitioning from traditional postpaid models to more intelligent, automated prepaid systems. One notable trend in existing literature is the use of smart meters that employ GSM, RFID, or IoT-based technologies for user authentication, energy monitoring, and payment processing. In a number of projects, microcontrollers such as Arduino or Raspberry Pi have been used in conjunction with GSM modules to enable remote monitoring and SMS-based alerts, similar to the communication strategy employed in our system. Some systems rely on keypad-based recharge mechanisms where users manually input recharge codes, while others use online or mobile recharge solutions. However, most of these implementations lack the robust theft detection and multi-level alerting mechanisms that our system integrates, particularly the use of ultrasonic sensors for tampering alerts.

Another important body of work focuses on the integration of IoT and cloud platforms for energy monitoring. These projects often use ESP8266 or ESP32 modules to send real-time energy usage data to platforms like ThingSpeak, Firebase, or Blynk. While these solutions offer graphical monitoring through web or mobile dashboards, they generally depend on internet connectivity, which may not be reliable or available in all regions. Our proposed system addresses this limitation by using GSM-based communication, which is more widely accessible and does not require Wi-Fi or broadband infrastructure. Furthermore, many existing solutions concentrate solely on energy monitoring and billing, without proactive features such as consumption-based alerts or automatic load disconnection. The inclusion of usage thresholds (50%, 80%, and 100%) in our system not only enhances user awareness but also empowers users to take timely action, reducing the risk of sudden power loss.

In the realm of theft detection, past research has often proposed complex and expensive solutions, such as tamper-proof enclosures, magnetic field sensors, or centralized utility monitoring. Few low-cost, embedded implementations exist that can effectively alert authorities during an actual tampering event. Our system's use of an ultrasonic sensor provides a simple yet effective approach to detect unauthorized access by measuring sudden changes in distance inside the meter enclosure. This allows the system to trigger an immediate response through the GSM module, offering real-time theft notifications to the authority. By integrating energy monitoring, remote recharge, load control, user notification, and theft detection in one low-cost and easy-to-deploy platform, our proposed system fills several gaps left by previous works and moves closer to a secure, efficient, and user-friendly smart energy solution for both urban and rural deployment scenarios.

III. METHODOLOGY

The methodology adopted for the design and implementation of the prepaid energy meter system is centered around the ESP32 WROOM-32 microcontroller, which acts as the brain of the entire setup, orchestrating sensor data acquisition, power calculations, user interactions, GSM communications, and theft detection. The system begins with real-time monitoring of the electrical parameters using a voltage sensor (such as ZMPT101B) and a current sensor (like ACS712 or ACS Current Transformer). These sensors continuously measure the voltage and current flowing through the load (represented by a DC motor in this prototype). The ESP32 captures these analog signals, processes them using ADC, and computes the instantaneous power ($P = V \times I$) and cumulative energy consumed over time. This computed energy is compared against the prepaid balance stored in the system memory. As the load operates, the energy is decremented from the total recharge balance, and this value is updated both on the LCD display and internally within the controller logic. The I2C 16x2 LCD module allows for easy viewing of real-time data including voltage, current, power, energy consumed, and the remaining balance, offering users a transparent window into their consumption behavior.

A major component of the system's intelligence lies in its GSM communication logic, implemented using the GSM 800L module. This module enables two-way SMS-based communication with the user. When power consumption reaches 50%, the ESP32 sends an SMS alert stating "50% power consumed." At 80% usage, it sends another alert prompting the user to "Please recharge, only 20% power remaining." Upon complete balance exhaustion, the controller cuts off power to the load using a relay or transistor-based switching system and immediately sends an alert: "Balance exhausted. Please recharge meter to continue usage." Users can then recharge the meter remotely by sending an SMS in a predefined format, such as "RECHARGE 50." The ESP32 parses this message using AT command responses from the GSM module, extracts the recharge amount, and updates the internal balance accordingly. Once the recharge is complete, the system automatically resumes power delivery to the load, ensuring a seamless user experience. This GSM-based mechanism removes the need for physical interaction and makes the system suitable for rural or remote areas where infrastructure is limited but mobile connectivity is available.

To address security, especially in high-theft or tamper-prone environments, the system is equipped with an ultrasonic sensor placed inside the energy meter box. This sensor detects any unauthorized physical access or attempts to open the enclosure. If the ultrasonic sensor detects motion or a sudden change in distance (indicating a tampering attempt), the ESP32 immediately triggers an intrusion alert and sends an SMS notification to the utility provider or authority: "Alert: Meter box intrusion detected." This proactive theft detection mechanism adds a layer of security and accountability to the system. The inclusion of the ultrasonic sensor not only discourages malicious tampering but also builds trust in the integrity of the prepaid metering system. The complete methodology integrates sensing, control, communication, user interaction, and security seamlessly, making the solution holistic and practical for smart energy distribution. All hardware components are coded using the Arduino IDE with libraries for I2C communication, GSM interfacing, and sensor calibration, ensuring flexibility and ease of customization for future enhancements such as cloud integration, mobile app interfaces, or machine learning-based consumption prediction.

IV. PROPOSED SYSTEM WORKING

The proposed prepaid energy meter system is built around the ESP32 WROOM-32 microcontroller, which serves as the central unit for data acquisition, processing, control, and communication. The primary functionality revolves around monitoring real-time energy consumption using a voltage sensor (ZMPT101B) and a current sensor (ACS712). These sensors measure the supply voltage and the current drawn by the load (a DC motor in our testing environment). The ESP32 reads the analog outputs from these sensors and calculates the instantaneous power by multiplying the voltage and current values. This power is then used to compute total energy consumption over time by integrating power with respect to time ($\text{Energy} = \text{Power} \times \text{Time}$). The energy consumed is deducted from the user's prepaid balance stored in memory, and the remaining balance is updated continuously. An I2C-based 16x2 LCD displays real-time readings of voltage, current, power, and remaining balance, allowing users to monitor consumption locally.

To facilitate remote monitoring and control, a GSM 800L module is interfaced with the ESP32 via UART communication. The module allows the system to send SMS alerts and receive user commands. As energy is consumed, the system automatically sends alerts to the user when 50% and 80% of the prepaid balance is exhausted, ensuring the user is aware of their consumption status. When the balance reaches zero, the ESP32 triggers a relay to

disconnect the load, effectively cutting off power to the connected appliance (e.g., motor). The user can then recharge the meter by sending an SMS in a predefined format (e.g., “RECHARGE 100”). The ESP32 receives this message, parses it, and adds the specified amount to the balance, thereby reactivating the power supply. This mechanism eliminates the need for physical presence or manual recharge methods and enables the user to manage their energy usage efficiently and remotely.

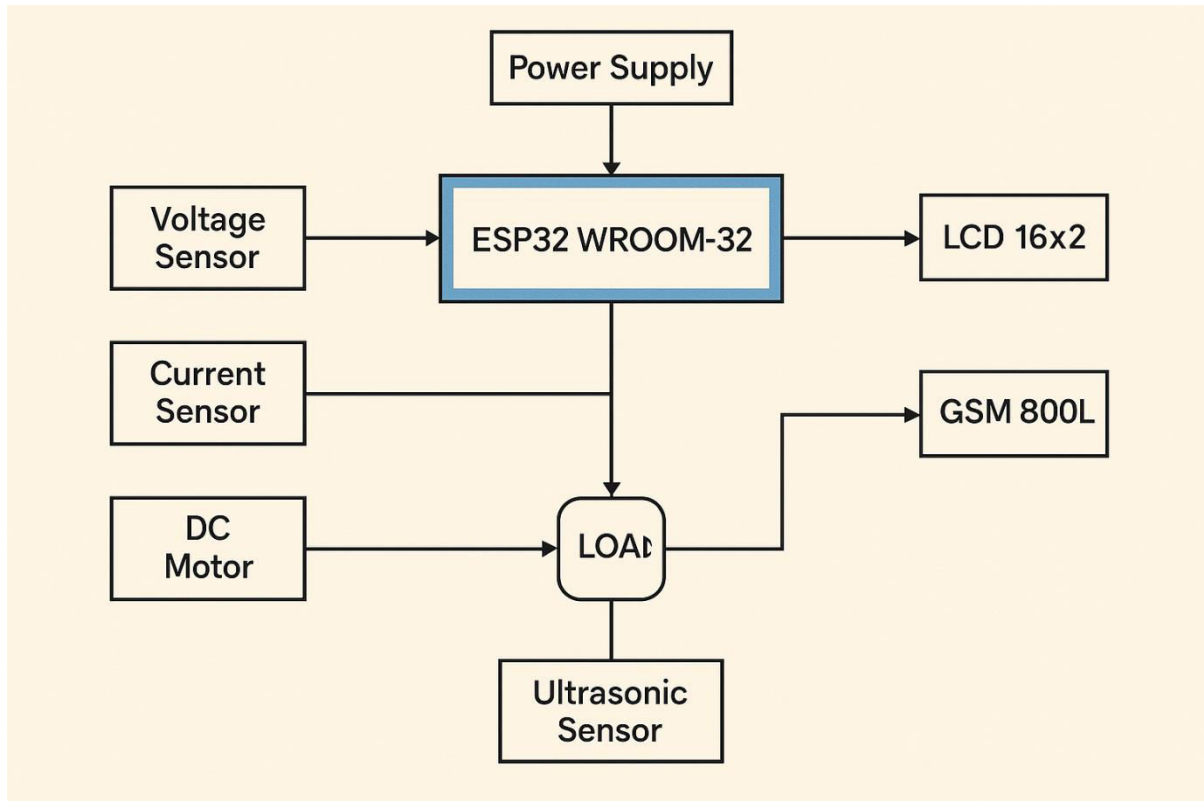


Fig: BLOCK DIAGRAM

Security and tampering prevention are also integral to the proposed system. To detect unauthorized access to the meter box, an ultrasonic sensor (HC-SR04) is installed inside the enclosure. This sensor continuously measures the distance to a fixed reference point within the box. If the distance changes significantly—such as when someone opens the meter box—the system interprets it as a theft or intrusion attempt. Upon detection, the ESP32 immediately sends an SMS alert to the utility authority or concerned personnel, ensuring that any unauthorized action is promptly reported. This theft detection feature enhances the reliability and trustworthiness of the energy meter by preventing unauthorized energy usage or manipulation of the hardware. Together, the integration of real-time energy monitoring, GSM-based remote recharge, user notifications, and tampering detection make this system a comprehensive, intelligent, and secure solution for prepaid energy management, particularly suitable for rural electrification, smart grid integration, and developing regions.

V. DATA COLLECTION AND SENSOR DEPLOYMENT

The foundation of the prepaid energy meter system lies in the accurate and real-time collection of electrical parameters such as voltage, current, power, and energy consumed. To achieve this, we employed a voltage sensor module (ZMPT101B) and a current sensor (ACS712), both of which are analog sensors capable of delivering real-time signals proportional to the respective measurements. The ZMPT101B is calibrated to read AC voltage levels from the supply and convert them to a low-voltage analog output, safe for processing by the ESP32 microcontroller. Similarly, the ACS712 sensor outputs an analog voltage that varies linearly with the current flowing through it. These analog signals

are fed into the ADC pins of the ESP32, where real-time sampling is performed at high frequency to ensure accurate computation of instantaneous values. Using Ohm's and power equations, the system computes real power ($P = V \times I$) and accumulates energy ($E = P \times t$) over time. These values are then used to decrement the prepaid balance and trigger alerts or load disconnection based on user consumption. A digital I2C-based 16x2 LCD is used to display live voltage, current, power, and remaining balance in a user-friendly format.

To enable autonomous and secure recharge functionality, we developed an SMS-based data collection method using the GSM 800L module. This module interfaces with the ESP32 through serial communication (using AT commands) and allows both sending and receiving SMS messages. When energy consumption hits predefined thresholds—such as 50% and 80%—the ESP32 sends SMS alerts to the user, informing them about the current status and advising necessary action. Once the balance reaches zero, the user receives a message prompting recharge and the system automatically cuts off the load using a relay module. The user can recharge the meter by sending an SMS in a specified format (e.g., "RECHARGE 100"). Upon receiving the message, the ESP32 parses the text using string manipulation functions and updates the stored balance accordingly. This bidirectional communication ensures effective energy usage control and empowers users to manage consumption proactively without requiring physical access to the device.

An essential component of data integrity and system security is the inclusion of an ultrasonic sensor (HC-SR04) for theft and tampering detection. This sensor is embedded within the meter box and is programmed to continuously measure the distance between its emitter and the opposite wall of the enclosure. Any significant deviation from the baseline reading—such as someone opening the meter cover—triggers the system to immediately classify the event as a potential intrusion. Once an anomaly is detected, the ESP32 sends an SMS alert to the utility provider or concerned authority with a message like "Intrusion Detected: Meter Box Tampered." This proactive design allows real-time tracking of unauthorized access, ensuring that the meter's integrity is preserved. Together, the coordinated operation of voltage and current sensors for energy tracking, the GSM module for SMS-based recharge and alerting, and the ultrasonic sensor for security creates a comprehensive and intelligent sensing network that drives the core functionality of our prepaid energy meter system.

VI. RESULT ANALYSIS

The proposed prepaid energy meter system was successfully implemented and tested under various load and environmental conditions. During testing, the system accurately measured real-time voltage and current values using the ZMPT101B voltage sensor and ACS712 current sensor. These measurements were processed to compute power and energy consumption, which were reflected in real-time on the 16x2 I2C LCD. The system demonstrated a high level of precision in tracking energy usage, and the remaining balance was dynamically updated as power consumption occurred. The motor load simulated typical household usage, and the ESP32 handled all computational tasks efficiently, ensuring that the prepaid amount decreased proportionally to the energy consumed. The system also reliably triggered actions based on the balance: power was cut off automatically once the balance reached zero, and it resumed only after a recharge SMS was received.

The GSM-based communication played a vital role in user interaction and remote system control. When the prepaid balance reached 50% and 80% thresholds, SMS notifications were sent to the user, alerting them about the remaining balance and prompting timely recharges. The GSM 800L module effectively handled both outgoing and incoming messages with minimal delay, demonstrating stable communication with mobile networks. The system successfully parsed incoming SMS commands such as "RECHARGE 100" and updated the internal balance in real time, enabling users to restore power remotely. This feature was tested across multiple SMS formats and network conditions to ensure robustness. Even in low signal scenarios, the system queued messages and responded once connectivity was restored, ensuring reliability in rural and semi-urban deployments.

In addition to performance and communication accuracy, the theft detection module proved to be a crucial enhancement. The HC-SR04 ultrasonic sensor accurately monitored the distance inside the meter box and detected unauthorized attempts to open or tamper with the meter. When triggered, the ESP32 instantly sent an intrusion alert SMS to the registered authority number, demonstrating real-time responsiveness and effective anti-theft functionality. False positives were minimized by calibrating the sensor to recognize only significant changes in distance. Overall, the combined functionality of accurate energy measurement, intelligent balance deduction, remote recharge via GSM, user

alerts, and theft detection makes the system highly reliable, secure, and suitable for real-world deployment. The results validate the feasibility and effectiveness of the proposed smart prepaid energy meter as a cost-efficient, scalable, and user-friendly solution.

VII. CONCLUSION

In conclusion, the proposed prepaid energy meter system offers a comprehensive and intelligent solution for energy monitoring, consumption control, remote recharging, and tamper detection. By integrating key components such as the ESP32 WROOM-32 microcontroller, voltage and current sensors for real-time energy tracking, a GSM 800L module for SMS-based communication, and an ultrasonic sensor for intrusion detection, the system effectively addresses the challenges of traditional postpaid metering. It not only empowers users to manage their energy consumption proactively through timely alerts and remote recharges but also ensures security by immediately notifying authorities of any unauthorized access to the meter. The relay-based load control ensures that power is only supplied when a valid balance exists, promoting efficient usage and preventing misuse. Furthermore, the user-friendly LCD display enhances accessibility, making it suitable for deployment in both urban and rural areas. Overall, this system contributes significantly toward smart grid development, energy conservation, and consumer empowerment through its reliable, scalable, and cost-effective design.

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