iJRASET
International Journal For Research in Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** IV **Month of publication:** April 2025

DOI: https://doi.org/10.22214/ijraset.2025.68513

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue IV Apr 2025- Available at www.ijraset.com

Smart Energy Meter and Theft Detection Using ESP32

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Abstract: ***A smart energy meter is a device that tracks electricity usage in real time and sends the data directly to utility companies. It helps consumers monitor and control their energy consumption more effectively. These meters also detect energy theft by identifying tampering, unusual usage patterns, and voltage irregularities. If any suspicious activity is detected, the meter sends alerts to the utility provider. Smart meters improve billing accuracy, grid management, and help prevent electricity theft, making them an important tool for modern energy systems.***
Index Terms: Real-time monitoring, ESP32, Microcontroller, Tamper detection, Billing accuracy, Electricity theft detection.

I. INTRODUCTION

Smart energy meters provide real-time monitoring of electricity consumption and automatically send data to utility companies. This ensures accurate billing and efficient energy management. One of the key benefits of smart meters is their ability to detect electricity theft. They do this through features like tamper detection, monitoring unusual usage patterns, and sending remote alerts. These theft detection capabilities help reduce revenue loss and ensure a more reliable and secure energy supply.

II. LITERATURE REVIEW

[1] Faruqui, A., Sergici, S., & Sharif, A. (2010):This study reviews the impact of smart meters on electricity usage. It shows that real-time consumption data and time-based pricing reduce peak demand and total energy use. The study emphasizes that results vary with consumer behavior and regional policy. [2] Kothari, D., & Mollah, M. (2017):-The paper explores machine learning techniques—supervised, unsupervised, and hybrid—for detecting anomalies like tampering in smart meters. It finds that ML improves meter accuracy, security, and performance.[3] Gupta, S., & Kumar,
R. (2015):- This research uses historical energy data to detect irregular usage patterns. It highlights how past trends help in spotting faults and theft, improving billing and grid reliability.[4] Mohale V.P., Babar D.G.:- This paper proposes a smart system for monitoring and managing energy supply. The system automates control, enhances load management, and improves energy efficiency.[5] Patel Darshit, Patel H.B. The study presents a GSM-based energy meter that supports remote monitoring and load control. It improves billing, reduces human effort, and helps manage electricity consumption.[6] Govindak:-This project designs a smart meter using an Atmel 89S52 microcontroller. It enables real-time energy tracking and theft detection, helping in efficient power usage and secure metering.

III. DEFINITION AND COMPONENTS

A smart energy meter records electricity usage in real time and sends the data to utility companies automatically. This helps ensure accurate billing and better energy management. Theft detection in smart meters involves identifying unauthorized electricity use through tamper detection, monitoring irregular usage patterns, and voltage inconsistencies. When theft is detected, the meter sends alerts to utilities for quick action, reducing losses and improving grid security. The primary components include:

A. Current Sensor



Figure 1: Current Sensor

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The SCT-013 is a non-invasive current sensor widely used in smart energy meters for measuring AC current without cutting the wire. It operates on the principle of electromagnetic induction and provides an analog output proportional to the current passing through the conductor. When combined with voltage measurements, it enables accurate power and energy calculations. In smart meters, the SCT-013 helps monitor real-time energy usage and plays a key role in detecting electricity theft by identifying irregular current patterns or tampering. It is often paired with microcontrollers like Arduino or ESP32 and requires proper signal conditioning, such as burden resistors, for accurate readings, making it a reliable component for efficient and secure energy monitoring systems.

B. Voltage Sensor

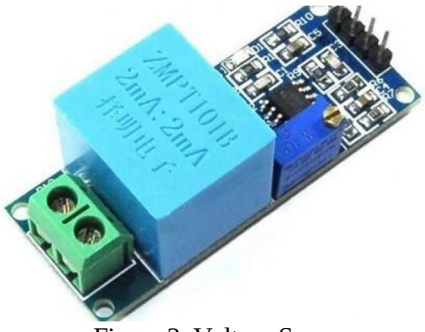


Figure 2: Voltage Sensor

The ZMPT101B is a high-precision voltage sensor used in smart energy meters to measure AC voltage accurately. It is based on a voltage transformer that isolates and scales down the mains voltage to a safe level, providing an analog output proportional to the actual voltage. This sensor is essential for calculating real-time power consumption when used alongside a current sensor like the SCT-013. In smart energy meters, the ZMPT101B enables accurate voltage monitoring, load analysis, and helps detect anomalies in the power supply. For theft detection, it plays a vital role by identifying inconsistencies between voltage and current readings, which can indicate tampering or illegal tapping. It is commonly interfaced with microcontrollers such as Arduino or ESP32, and with proper calibration and filtering, it contributes to building reliable and tamper-resistant energy monitoring systems.

C. LED Display



Figure 3: LED Display

The I2C 16x2 LCD Display is an enhanced version of the standard 16x2 LCD, featuring an I2C (Inter-Integrated Circuit) interface for easier connectivity with ESP32, Raspberry Pi, and others. Unlike the standard parallel 16x2 LCD, which requires multiple data pins for communication, the I2C version uses just two data lines (SDA for data and SCL for clock), significantly reducing the number of pins needed and simplifying wiring. This makes it a popular choice in projects with limited GPIO pins or when reducing complexity is a priority. The display can show 16 characters per row on 2 rows, typically with a blue or green backlight, and it allows for easy control of text and custom characters.

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The I2C interface also allows for more efficient communication, making it a great choice for embedded systems, sensors, and other compact electronics projects.

D. Buzzer



Figure 4: Buzzer

A buzzer in a smart energy meter with theft detection serves as an audible alert for abnormal activities, such as energy theft or power usage irregularities. When the system detects potential tampering or unauthorized power consumption, the buzzer sounds an alert, providing immediate feedback. This helps users or security personnel respond quickly to suspicious activity. The buzzer can be controlled by the ESP32 microcontroller, which triggers it based on sensor readings (from devices like SCT-013 and ZMPT101B). In addition to theft detection, it can also notify users of system errors, making it an essential part of the smart meter's feedback system.

E. ESP32



Figure 5: ESP32

The ESP32 is a powerful microcontroller with built-in Wi-Fi and Bluetooth, making it ideal for smart energy meters. It reads data from sensors like SCT-013 (current) and ZMPT101B (voltage) to calculate real-time power usage. Its wireless capabilities allow remote monitoring and data logging. In theft detection, the ESP32 can analyze abnormal patterns, detect tampering, and send alerts to the utility provider, helping ensure accurate and secure energy tracking in smart grid systems.

F. Block Diagram

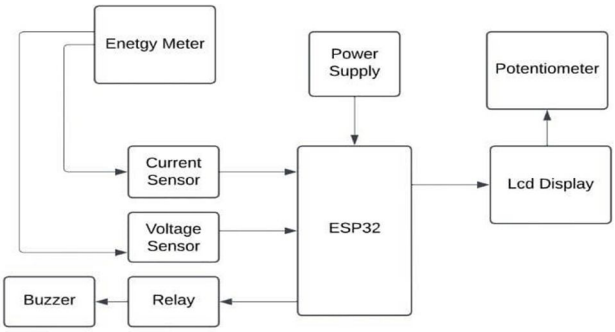


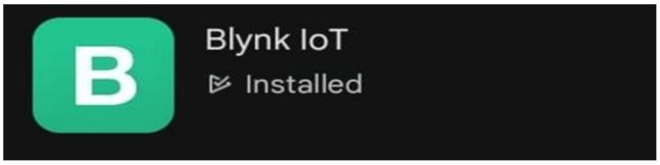
Figure 6: Block Diagram of Smart Energy Meter And Theft Detection

This block diagram represents a smart energy monitoring and theft detection system using an ESP32. The energy meter provides input to both a current sensor (like SCT-013) and a voltage sensor (like ZMPT101B), which send real-time data to the ESP32. The ESP32 processes this data to calculate power usage and detect anomalies. If theft or abnormal activity is detected, it activates a relay connected to a buzzer for an alert. The system is powered by a dedicated power supply, and an LCD display—adjustable with a potentiometer—shows the measured values and status updates. The ESP32 also enables smart control and wireless communication if needed.

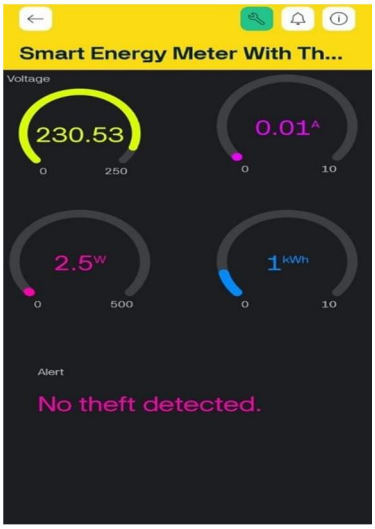
IV. SOFTWARE AND APP

A smart energy meter with theft detection measures electricity usage using current and voltage sensors. It sends the data to a microcontroller like the ESP32, which calculates power and checks for unusual patterns. If theft or tampering is detected, it triggers a buzzer and can alert the user. The system also displays readings on an LCD and helps ensure accurate and secure energy monitoring.

A. APP



The Blynk IoT app is used to monitor smart energy meter data on a smartphone. It connects with the ESP32 to show voltage, current, and power usage in real time. If any theft or tampering is detected, Blynk sends an alert to the user. It also allows remote control of devices like buzzers or relays, making the system smart and easy to manage from anywhere.



This screen from the Blynk IoT app shows live data from a smart energy meter system. It displays voltage, current, power, and energy usage. The ESP32 sends this data using sensors. The app also shows alerts—here, it says "No theft detected," meaning everything is normal. If theft happens, the alert will change, helping users monitor and react quickly.

V. BENEFITS OF SMART ENERGY METER

1) Real-time energy monitoring: Provides up-to-date data on energy consumption, helping users track and manage their usage more efficiently.
2) Improved billing accuracy: Eliminates estimated billing by transmitting precise, real-time data directly to utility providers.
3) Cost savings: Enables consumers to better understand their energy usage patterns, potentially reducing their energy bills.

VI. THEFT DETECTION

A. *Definition and Characteristics*

Theft detection in smart energy meters is the ability of the meter to identify unauthorized electricity use. By tracking real- time energy consumption and spotting irregular patterns, smart meters can detect illegal activities like tampering or bypassing the meter. This helps prevent electricity theft, ensuring accurate billing and reducing energy losses for utility companies.

1) Anomaly detection: Monitors real-time energy usage and detects irregular consumption patterns that may indicate theft.
2) Tamper detection: Identifies physical tampering with the meter, such as opening the meter box or altering its components.
3) Unauthorized access alerts: Sends immediate notifications to utility providers when unauthorized connections or bypasses are detected

B. *Benefits of Theft Detection*

1) Reduced financial losses: Effective theft detection minimizes revenue losses for utility companies, ensuring that legitimate consumers are not burdened with the costs of stolen energy.
2) Improved billing accuracy: By accurately detecting consumption, theft detection systems ensure fair billing for all customers, preventing inflated costs due to unaccounted theft.
3) Enhanced grid stability: By identifying and preventing electricity theft, utilities can maintain a more stable and reliable energy grid, reducing outages and improving service quality.
4) Timely interventions: Immediate alerts for potential theft allow utility providers to respond quickly, reducing the time that illegal connections or tampering can go undetected.

VII. CASE STUDIES

A. *India - Tata Power*

Tata Power, one of India's largest private power companies, deployed smart meters to tackle energy theft and enhance billing accuracy. Key Features:

1) Automated data collection: Smart meters eliminated manual reading errors, providing accurate consumption data.
2) Alerts for irregular usage: The system detected unauthorized connections and tampering.

B. *California, USA - Pacific Gas and Electric (PGE)*

PGE implemented smart meters across its service area to enhance energy management and reduce electricity theft. Key Features:

1) Real-time monitoring: Smart meters provided real-time data on energy consumption, allowing for immediate detection of anomalies.
2) Theft detection capabilities: The system analyzed usage patterns to identify potential theft.

VIII. QUANTITATIVE DATA

1) Reduction in non-technical losses: Smart energy meters can reduce electricity theft (non-technical losses) by up to 50
2) Accuracy improvement: Smart meters are up to 99
3) Cost savings: Utility companies can save 10
4) Theft detection rate: Advanced algorithms used in smart meters can detect up to 80

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
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IX. TECHNICAL SPECIFICATIONS

A. *Power Supply*

1) Operating Voltage: Usually operates on a standard voltage range (e.g., 220-240V AC).
2) Battery Backup: Some models may include a battery backup for data retention during power outages

B. *Tamper Detection Features*

1) Tamper Sensors: Physical sensors to detect unauthorized access or manipulation of the meter.
2) Alarm System: Automatic alerts to utility providers in the event of tampering or unauthorized connections.

X. SOCIAL IMPLICATIONS

A. *Increased Awareness*

Smart energy meters provide consumers with real-time data on their energy usage, leading to greater awareness and encouraging energy conservation behaviors. This can result in reduced consumption and lower energy bills.

B. *Fair Pricing*

By accurately measuring consumption and detecting theft, smart meters help ensure that all consumers are billed fairly. This can help prevent legitimate customers

XI. GLOBAL EXAMPLES

A. *India - Tata Power*

Tata Power deployed smart meters in urban and rural areas to combat high rates of electricity theft and improve service delivery.

B. *United States - Pacific Gas and Electric (PGE)*

PGE implemented smart meters across California as part of a statewide initiative to modernize the energy grid.

XII. FUTURE TREND

1) IoT Connectivity: Smart meters will increasingly use IoT technology for real-time data transmission, enabling better monitoring of energy usage and quicker detection of theft.
2) Data Analytics and AI: Advanced analytics and AI will be employed to analyze energy consumption patterns, helping identify unusual activity that may indicate theft.
3) Automated Alerts: Future smart meters will feature automated alerts for utility companies about irregular consumption patterns, facilitating prompt investigation of potential theft.

XIII. POLICY IMPLICATIONS

A. *Regulatory Framework*

Clear regulations are needed to establish standards for smart meter accuracy, security, and consumer data protection.

B. *Incentives for Adoption*

Governments may provide subsidies or tax breaks to encourage the adoption of smart meters by utilities and consumers.

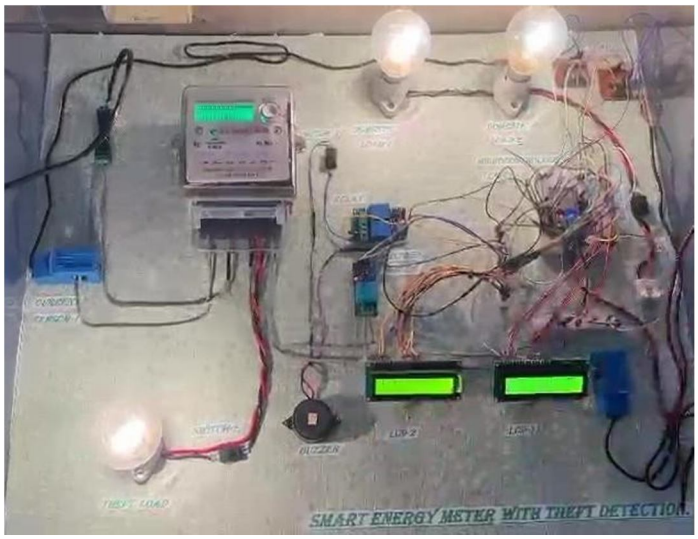
C. *Stakeholder Collaboration*

Effective policies require collaboration among government agencies, utilities, technology providers, and consumer groups.

XIV. RESULT AND EVALUATION

The Smart Energy Meter with Theft Detection worked well in tracking electricity use and spotting any tampering. It showed energy usage in real-time and sent the data to a central system for easy monitoring. When fake thefts were tested, the system caught most of them correctly. It helped save time, reduced manual checks, and made it easier to respond to theft. The system was also low-cost and could be used in many places.

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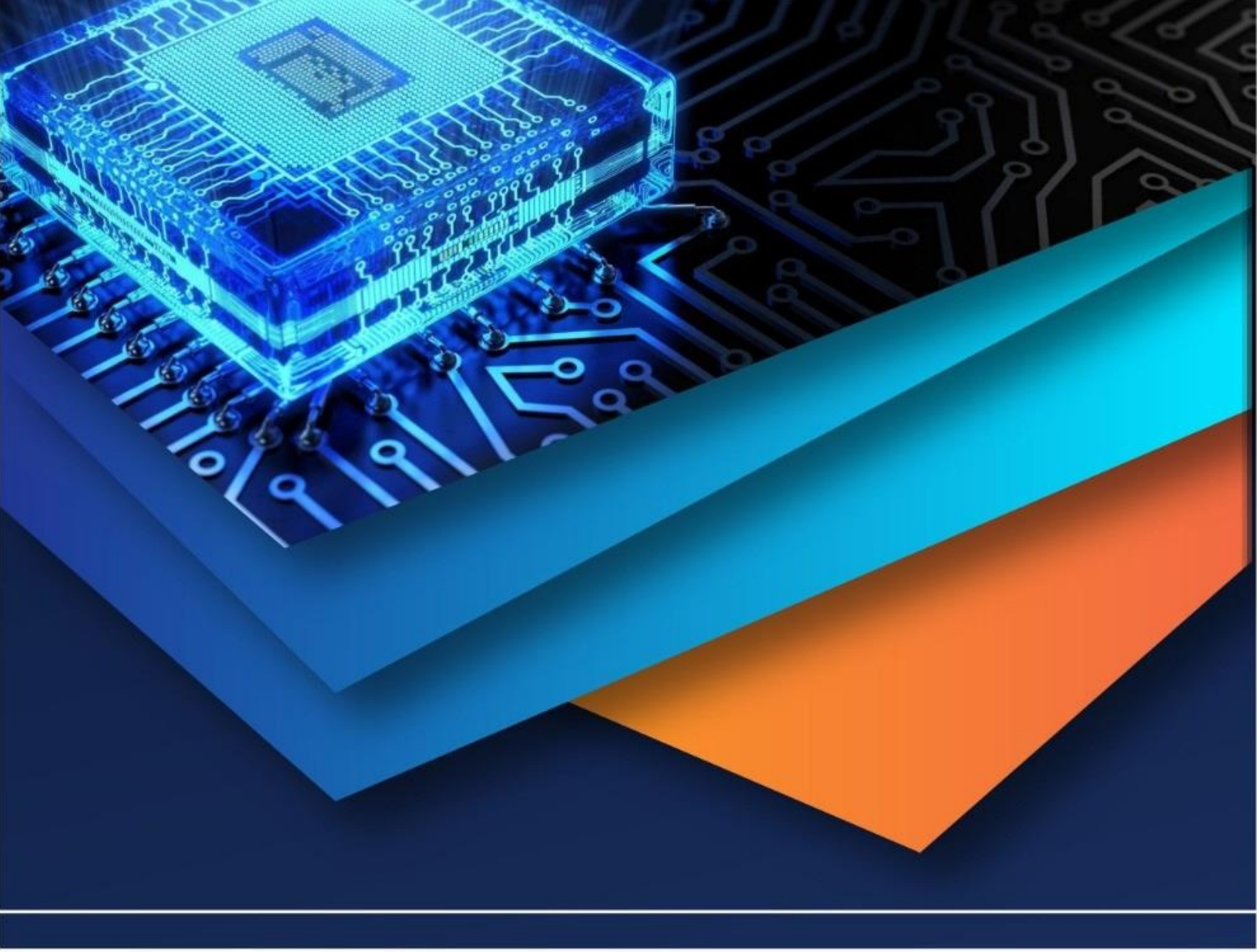


XV. CONCLUSION

Smart energy meters and theft detection systems greatly improve how we manage and secure energy use. They use internet technology and data analysis to provide accurate monitoring and help consumers manage their energy better. These systems also help utility companies find and prevent energy theft, protecting their revenues. To make these technologies work well, we need clear rules, strong privacy protections, and teamwork among different groups. Overall, using smart energy meters and theft detection can lead to a more efficient, secure, and sustainable energy future.

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