ESP32-Based Prepaid Electricity Energy Meter with Remote Monitoring and Security Features: A Review

Santosh Kumar Tripathi[1][a], Vaibhav Shukla[1][b], Anusha Baranwal[2][c], Anubhav Pandey[2][d] and Vindu[2][e]

[1] *Department of Electrical Engineering, Rajkiya Engineering College, Kannauj, U.P., India*

[2] *B.Tech Scholar, Department of Electrical Engineering, Rajkiya Engineering College, Kannauj, U.P., India*

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Abstract: The inclusion of Internet of Things (IoT) technology in energy measurement systems has changed the monitoring and management of electricity consumption in residential, commercial, and industrial sectors. Although traditional meters are effective for basic operations, they are not enough to provide the advanced features required by modern energy systems, such as real-time data collection, remote accessibility, and advanced security. This review focuses on ESP32 microcontrollers as a cost-effective and powerful platform for next-generation smart energy meters. This article highlights information from the existing literature, including dynamic tariff adjustment, fault detection, anti-theft mechanisms, and cloud-based applications through platforms such as Thingspeak and Blynk. We are also looking at innovative features such as monitoring of network traffic. Research highlights the importance of visualizing real-time data to improve energy management and user engagement, while theft detection and accurate billing are highlighted as key tools for reducing energy losses, especially in developing regions. The review concludes by proposing a scalable and efficient ESP32-based IoT-enabled smart energy meter framework that integrates remote monitoring, data analysis and automated control to address the limitations of traditional systems. This approach aims to provide a sustainable and safe solution for future power management needs.

1 INTRODUCTION

The advent of smart energy meters has changed the way electricity consumption is managed and monitored in the residential, commercial, and industrial sectors. Traditional meters are functional but lack the real-time data collection and remote control capabilities required by modern energy systems. Integrating Internet of Things (IoT) technology into energy metering provides advanced features such as advanced monitoring, accurate billing, and anti-theft protection. Among the important innovations in this field, ESP32 microcontrollers have emerged as a powerful and cost-effective platform for developing the next generation of smart energy meters.

The most recent smart meters surpass the potential of a smartphone-based wireless energy monitoring system using the Blynk application. They go beyond basic electrical measurement and remote monitoring, dynamic tariff adjustment, fault detection, and anti-theft mechanisms(Othman and Zakaria, 2020). The author emphasized the importance of real-time data representation in improving energy management. Similarly, this paper has studied the use of ESP32 microcontrollers to monitor energy consumption via a cloud platform such as Thingspeak and introduced features that enable reliable data transmission and visualization(M. Anusha and Shaik, 2024).

Energy theft continues to be a serious challenge, especially in developing regions. This paper has launched a theft detection mechanism that allows quick response to unauthorized power consumption using the GSM (Global System for Mobile Communication) module built into the smart meter(J. Astronomo and Regidor, 2020), also highlighting the role of IoT-enabled meters in reducing energy losses

[a] https://orcid.org/0000-0002-4917-0110
[b] https://orcid.org/0009-0007-8606-5436
[c] https://orcid.org/0009-0004-4038-5272
[d] https://orcid.org/0009-0005-1954-5654
[e] https://orcid.org/0009-0007-2350-2408

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in smart cities(Q. Malik and Javed, 2019).

The modern energy meter is mainly used for remote monitoring and control. In response to the growing demand for transparency in energy consumption (D. N. M. Rao and Mrudhula, 2023), this paper has introduced an IoT-enabled smart energy meter designed to provide accurate billing and real-time usage tracking. Also shows how ESP32-based systems can improve user engagement by enabling real-time monitoring to support energy-efficient applications (A. S. Salunkhe and Patil, 2022).

Integration of flaw detection algorithms in systems based on the Internet of Things (T. Tony and Sasi, 2016) and the use of the MCP39F501 sensor to monitor power is an example of innovative solutions in this field (G. Spasov and Tsvetkov, 2019). In addition, in order to ensure the adaptability to different user requirements in IoT-based energy measurement systems (Yaghmaee and Hejazi, 2018), emphasized the importance of real-time connectivity and analytics.

Despite significant progress and difficulties such as non-standard calibration conditions (T. Hengyu and Yuan, 2020) and the need for robust model detection algorithms for the interpretation of accurate energy data (N. Funde and Balande, 2018). It is important to address these issues because smart energy meters are widely adopted and scalable in various operational environments.

The ESP32-based prepaid electric power meters with features like increased security and remote monitoring are the main subject of this review. MQTT-based cloud communication, theft detection, low balance alerts, and the integration of user-friendly charging mechanisms are some of the key discussion areas that aim to provide a comprehensive overview of the technology development, implementation strategies, and challenges in designing such systems by integrating existing research. This makes ESP32 a smart metering solution. It plays a significant role in the system's creation and execution.

2 LITERATURE REVIEW

The existing limitations in terms of traditional energy metering through manual reading and delay reporting are slowly getting integrated with the IoT-based energy management system. Through ESP32 NodeMCU, in this very system, one can integrate capabilities such as Wi-Fi and Bluetooth; thus, the system can support real-time data collection and remote monitoring. For instance, the sensors for voltage and current like ZMPT101B and ACS712 are well known for reliable measurements while also being read with very friendly-to-use interfaces, such as LCDs, and even through Blynk mobile apps on various platforms. Automatic protection through overload protection and controlling the load from a distance would also characterize these systems, reducing human intervention. This further leads to increased efficiency in the transparency with regard to energy use. Another interesting potential improvement includes secure integrations for payments, as well as theft detection and other upgraded features, which can arm the system with more robust safety features, such as voltage anomaly detection (Mondal and Ch, 2022). For instance, in the works of IoT-based energy management systems such as Smart Energy Meter and Monitoring System Using IoT, various parts with a prime objective of adding automation to monitoring and control functions have been integrated. In such part forms, there exist Arduino microcontrollers, energy meters, Wi-Fi modules, and relays, which enhance real-time monitoring of electricity consumption, remote controlling of appliances through smartphone applications, and automated billing processes. The data from current, voltage, and power is relayed to the cloud for analysis, and the user can view his consumption patterns on both mobile and web interfaces. A good advantage of these points is reduced interference from humankind, greater transparency, and ease of billing. Further development could include enhanced safety features, some connectivity, and possibly more sophisticated analytics about the utilization of the data in an attempt to consume energy better and realize cost reduction (N. Sulthana and Kumar, 2020). In the paper titled ”Energy Meter Based Wireless Monitoring System Using Blynk Application via Smartphone,” an IoT-based real-time energy monitoring system using an ESP32 microcontroller having Wi-Fi communication is proposed. It facilitates sharp communication with the Blynk application. Basic features include tracking of live power consumption and alerts regarding usage of energy with the backup power in case of a blackout. The application can track the desired data such as RMS values, current, voltage, and energy consumption in kilowatt-hours. This system increases the awareness of users and better decision-making capability through the historical data of consumption. Future upgrades would include AI techniques for prediction of energy bills to ascertain the self-energization of smart cities with minimum dependencies on personal meter readings (Othman and Zakaria, 2020).

Electricity theft is a big issue to be countered by utility providers. It characterizes much in terms of severe losses and ineptitude in the process. The system proposed for detecting electricity theft is discussed here by utilizing a GSM module and an alarm. The anomaly-detecting capability of electricity utilization has been based on the microcontroller along with an integrated GSM module and alarm, which sends SMS alerts along with raising an audible alarm. This system, using sensors, microcontrollers, and GSM modules, makes it possible to monitor in real time and know exactly when something is stolen. Analytical results have proven it to be reliable, error-free, and scalable to both domestic and industrial applications, making it an effective loss-gain reduction utility management solution (J. Astronomo and Regidor, 2020). The other paper described how the ever-present problem of energy theft has motivated a great amount of research into ways of lowering losses from utility systems at minimal cost. The paper ”Development of Electricity Theft Detector with GSM Module and Alarm System” is a microcontroller-based system with a GSM module and alarms allowing the real-time anomaly detection and SMS alerts sent to utility providers; hence, it can be used as a scalable product for domestic and commercial use. Similarly, Both demonstrate energy management potential by improving efficiency, reducing loss, and making modern technologies available in scalable and cost-effective manners (G. Spasov and Tsvetkov, 2019). Recent studies discuss solutions for advanced technologies in energy monitoring and management to facilitate better efficiency, a reduction in costs, and allowance for real-time monitoring. One paper illustrates the microcontroller-based system embedded with GSM along with an alarm mechanism to detect the electricity theft with an SMS, besides audible alarms for real-time alerts. Another paper, A Smart Solution for Electrical Power Monitoring Based on the MCP39F501 Sensor, proposes an IoT-based system utilizing the MCP39F501 sensor integrated with open-source platforms such as ESP32-EVB and Raspberry Pi towards real-time and historical energy data for it to be well-suited for smart home energy management. Aside from the papers above, in ”Arduino-Based Smart Energy Meter using GSM, a smart meter with instant billing and load management over remote has been developed, which reduces running costs and enhances efficiency in its operations (H. K. Patel and Goyal, 2019). Though many research works on advanced smart metering systems are performed with an intention to enhance electric energy consumption with reduced power in household applications, some more focused research has developed recommendations and even suggested some approaches, including one Modbus SDM 120 energy meter, Arduino Uno microcontrollers, and RS485-to-TTL converters for efficient data communication. The system provides live energy monitoring and sends alerts through Twilio messaging once the consumption breaks the threshold that has been set, therefore improving user awareness and energy management (C. Komathi and Vignesh, 2021). The rapid development in the domain of smart energy monitoring shows how IoT technologies can be used to better manage energy use. The paper ”Design and Implementation of an Internet of Things-Based Smart Energy Metering” shows a system that integrates the smartness from plugs, gateways, and cloud servers for power consumption surveillance and control in real-time. Key features include power usage tracking with associated cost estimation and analytics suited to individual users with the possibility of remote control of appliances during peak times (Yaghmaee and Hejazi, 2018). The other paper described about In a modern energy management system, the integration of renewable energy, smart appliance control, and bidirectional communication plays a significant role. A smart meter is an important component that allows real-time monitoring and communication with the utility provider. Advanced Metering Infrastructure (AMI)-enabled smart meters can offer the capability to collect the data for energy consumption correctly and free from manual error while allowing dynamic pricing and demand response programs. The advent of distributed generation (DG), where consumers generate their electricity using renewable sources, has necessitated the development of net meters. These devices measure bidirectional energy flows—tracking electricity consumed from and exported to the grid. This system transforms traditional consumers into ”prosumers,” fostering renewable energy adoption while ensuring energy balance in the grid. Net metering policies further incentivize this model by providing financial benefits for excess energy contribution. However, issues like grid cost recovery and user cross-subsidization have called for ongoing policy discussions (T. Tony and Sasi, 2016). The development of energy metering systems has been driven by the need to address inefficiencies in traditional systems, to combat energy theft, and to enhance general energy management. Traditional metering systems, such as electromechanical meters, relied on manual data collection and expressed energy consumption in terms of the rotation of an aluminum disc. Inefficiencies were common among these systems, including human error, logistical challenges, and security vulnerabilities. Energy theft, such as tampering or tapping, was a particular major issue that led to massive revenues losses for utilities, mostly in developing countries. Second, the reliance of this system on personnel to make meter readings and cut supply connections made it both very expensive and inefficient. Here is where smart energy meters come in, offering accuracy, security, and efficiencies by combining digital and communications technologies. The AMI systems automated data transmission to central servers and hence obviated the necessity for manual readings and subsequently reduced the operational costs (A. S. Metering and Sandeep, 2017). Use of smart meter data is the newer, non-intrusive methodology in the field of building management systems. Unlike infrared motion detectors and carbon dioxide monitors, earlier methods require dedicated installations and maintenance and are cost-effective and somewhat limited in capability. Smart meters, on the other hand, have achieved very wide usage in both residential and commercial buildings; thus, this methodology integrates more in it by utilizing already existing infrastructure. This indicates that an activity in a building has some power-consumption patterns—periodic peaks associated with high-power appliances and pulses when the activity is high in a particular period. Such energy-use patterns can be evaluated with techniques like pattern recognition and machine learning to infer about the occupancy of a building. However, renewable energy systems installed into a building, such as photovoltaic installations, cause a two-way nature in energy flows. Renewable energy generation causes fluctuations in the energy data, which needs to be accounted for to avoid false positives or negatives in occupancy detection. Advanced algorithms differentiate between energy consumption caused by human activity and variations due to renewable energy production (A. Allik and Pihlap, 2020). Recent studies discuss Smart energy metering systems have evolved a lot with the integration of IoT and automation technologies. Although traditional meters are workable for measuring and billing energy consumption, they have their inefficiencies, such as susceptibility to tampering and no automation. Researchers have proposed IoT-enabled solutions with features such as load management, theft detection, and outage notifications using GSM technology. However, such systems are limited in the fact that they are not very precise in tracking the locations of consumers or handling overload conditions. Recent attempts have focused on the integration of GPS modules and advanced microcontrollers such as Arduino to improve functionality for better overload control and location-based services (Ntambara and Umuhoza, 2021). Though many research works on advanced smart metering systems are performed Smart metering systems have evolved significantly to address the limitations of traditional methods like manual meter reading (MMR), which required physical visits and was prone to inefficiencies and errors. The introduction of electronic meter reading (EMR) marked a shift towards automation, enabling remote data collection through technologies such as radio frequency (RF) communication. This was further advanced by Automated Meter Reading (AMR), which facilitated real-time consumption monitoring and data transmission via wireless or power-line communication. Advanced Metering Infrastructure (AMI) built upon AMR, incorporating two-way communication between utilities and consumers, enabling features like remote connect/disconnect, dynamic pricing, and enhanced load management. These innovations not only improved energy efficiency but also supported the integration of renewable energy sources into smart grids (N. S. ˇ Zivic and Ruland, 2015).

3 COMPARATIVE STUDIES

After analyzing various published research papers, two primary approaches to energy metering services have been identified: the conventional method and the smart method. The conventional approach involves the use of traditional electromechanical meters, while the smart method primarily relies on IC-based meters. Within the domain of smart energy metering, significant advancements have been made in developing GSM-based and IoT-based models.

4 SYSTEM DESCRIPTION

Smart Energy Meters (SEM) are advanced systems that provide real-time monitoring and management of power usage. It integrates various components, including energy measuring devices, communication modules, and software platforms for data analysis and calculations. The system is designed to improve energy efficiency, automate the billing process, and detect anomalies in energy consumption, such as theft.

4.1 Proposed Methodology

The proposed ESP32-based prepaid electricity energy meter system aims to leverage IoT technologies for efficient energy management and enhanced security. Drawing insights from existing methodologies, the system incorporates remote monitoring and control capabilities through IoT platforms such as Blynk or Thingspeak, enabling users to track real-time electricity consumption and balance levels via mobile or web interfaces. It employs GSM and Wi-Fi technologies to facilitate remote balance recharges and automated

Table 1: Comparison of Smart Energy Meters and Conventional Energy Meters.

Feature	**Smart Energy Meter**	**Conventional Energy Meter**
Data Collection	Real-time data.	Cumulative, static data.
Communication(Ntambara and Umuhoza, 2021)	Two-way communication; Remote (IoT, GSM, RF).	One-way communication; Manual.
Monitoring and Control(R. Hariharan, 2022)	Allows remote monitoring of energy usage through apps or web portals.	Requires manual monitoring; No remote control functionality.
Billing(I. Mujawar and Karbhari, 2023)	Enables accurate and automated billing based on real-time consumption.	Billing is based on manual readings, prone to errors or delays.
Energy Management(R. Hariharan, 2022)	Provides detailed insights into energy usage patterns.	Only shows total energy usage; Offers no insights for optimization.
Integration	Can integrate with smart home systems and renewable energy sources (e.g., solar panels).	Not compatible with smart systems.

Table 2: Comparison of IoT-Based SEM and GSM-Based SEM.

Feature	**IoT-Based SEM**	**GSM-Based SEM**
Connectivity(R. Hariharan, 2022)	Operates over broader networks, including Wi-Fi, NB-IoT, or cloud-based systems.	Restricted to areas with GSM coverage.
Features and Functionality(Maity and Das, 2011)	Advanced features like real-time energy monitoring; user-friendly dashboards.	Basic functionalities like meter reading and bill generation.
Scalability	Highly scalable, suitable for large-scale deployments.	Limited scalability, especially for high-demand applications.
Cost(S. Kumar and Gill, 2023)	Higher initial cost due to complex hardware/software.	Lower initial cost, but recurring SIM-related charges.
Use Cases(A. Allik and Pihlap, 2020)	Smart cities, smart homes, industrial automation.	Remote areas with minimal infrastructure.
Theft Detection(S. K. Tripathi and Rawat, 2024)	Can detect instant energy theft.	Does not support instant energy theft detection.

notifications for low balance or disconnection events. Security is enhanced through tamper-detection mechanisms and theft-reporting systems that identify and alert users and service providers about unauthorized activities. The system automates power management by disconnecting and reconnecting supply based on balance levels, ensuring uninterrupted operation while preventing misuse. Data logging and analytics are integrated to provide detailed consumption insights, enabling users to optimize energy usage and supporting service providers in resource planning. A user-friendly interface simplifies monitoring and recharge processes, making the system accessible for diverse users. Designed for smart city integration, the system contributes to energy-efficient infrastructure with a cost-effective approach using ESP32 hardware. Though in the conceptual stage, this methodology provides a robust foundation for future implementation and refinement based on real-world feedback and testing.

4.2 Block Diagram of Proposed Work

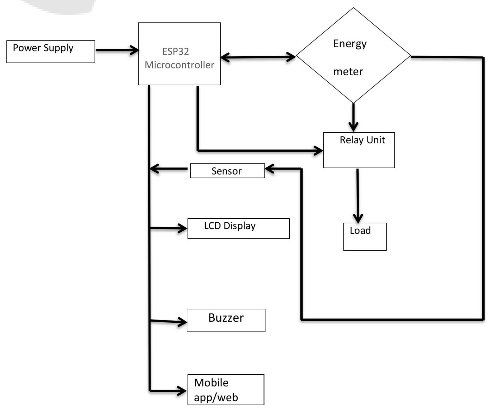

Figure 1: Block Diagram(A. S. Salunkhe and Patil, 2022).

The block diagram shows a smart energy metering system with an ESP32 microcontroller as the core. The power supply powers all components, while the energy meter measures real-time consumption and sends data to the ESP32. Based on this data, the ESP32 controls the relay unit to manage the load (appliances).

A sensor monitors parameters like tampering and shares the data with the ESP32. An LCD displays energy usage and alerts, while a buzzer signals events like low balance. The system also supports a mobile app or web interface for remote monitoring, balance recharging, and notifications via Wi-Fi or GSM, ensuring efficient energy management and security.

4.3 Flow Chart of Proposed Work

The meter is a smart prepaid energy system that monitors electricity usage and manages supply based on the balance. It keeps track of the remaining units and alerts users when the balance is low. If the balance reaches zero, the meter automatically disconnects the power supply to prevent further usage. Upon recharge, it restores the power supply and notifies the user in fig. 2(b). The system is equipped with theft detection capabilities, such as identifying bypass currents and responds by disconnecting the supply and triggering an alert fig 2(a). Real-time information, like remaining units and consumption cost, is displayed on an LCD screen, while the system communicates alerts and updates remotely and logs events for future reference.

5 APPLICATIONS

- Allows users to monitor their electricity consumption in real time(A. S. Salunkhe and Patil, 2022)(D. N. M. Rao and Mrudhula, 2023).
- Offers valuable insights into peak usage periods and areas of excessive energy consumption.(A. Allik and Pihlap, 2020)(N. S. ˇ Zivic and Ruland, 2015).
- Helps users track their electricity consumption in real time(S. Kumar and Gill, 2023)(S. K. Tripathi and Rawat, 2024).
- Provides insights into peak usage times and excessive consumption.
- Can integrate with platforms like Google Home, Amazon Alexa, or other IoT-based smart home systems(T. Tony and Sasi, 2016)(V. Phapale and Jadhav, 2024).
- Users can automate actions such as turning off lights or switching off high-power appliances when consumption reaches a threshold(Ntambara and Umuhoza, 2021)(M. Aboelmaged and Ghany, 2017).

6 LIMITATIONS AND FUTURE WORK

The ESP32 consumes more power than other microcontrollers, especially when the Wi-Fi or Bluetooth function is constantly active. This may lead to limitations for battery-powered, low-power energy meter applications. ESP32 relies primarily on Wi-Fi for IoT connections, which may be unstable or inaccessible in some regions, resulting in data loss and poor communication reliability. ESP32 relies primarily on Wi-Fi for IoT connections, which may be unstable or inaccessible in some regions, resulting in data loss and poor communication reliability. Future efforts may focus on improving security by integrating advanced encryption protocols, secure boot mechanisms, and secure radio (OTA) firmware updates to protect against possible cyberattacks and data breaches.You can use edge calculation to address transaction limitations. ESP32 can reduce bandwidth usage and latency by processing the initial data processing and analysis locally and sending only the relevant or collected data to the cloud.

7 CONCLUSION

This review highlights the potential of an IoT-enabled prepaid electricity meter using ESP32 to address inefficiencies in traditional systems. Key features include remote balance recharge, real-time monitoring, automatic alerts, power control, and anti-theft detection. With a user-friendly interface and data analytics, the system improves energy management for users and utility providers, offering a scalable, innovative solution for modern electricity challenges.

8 CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

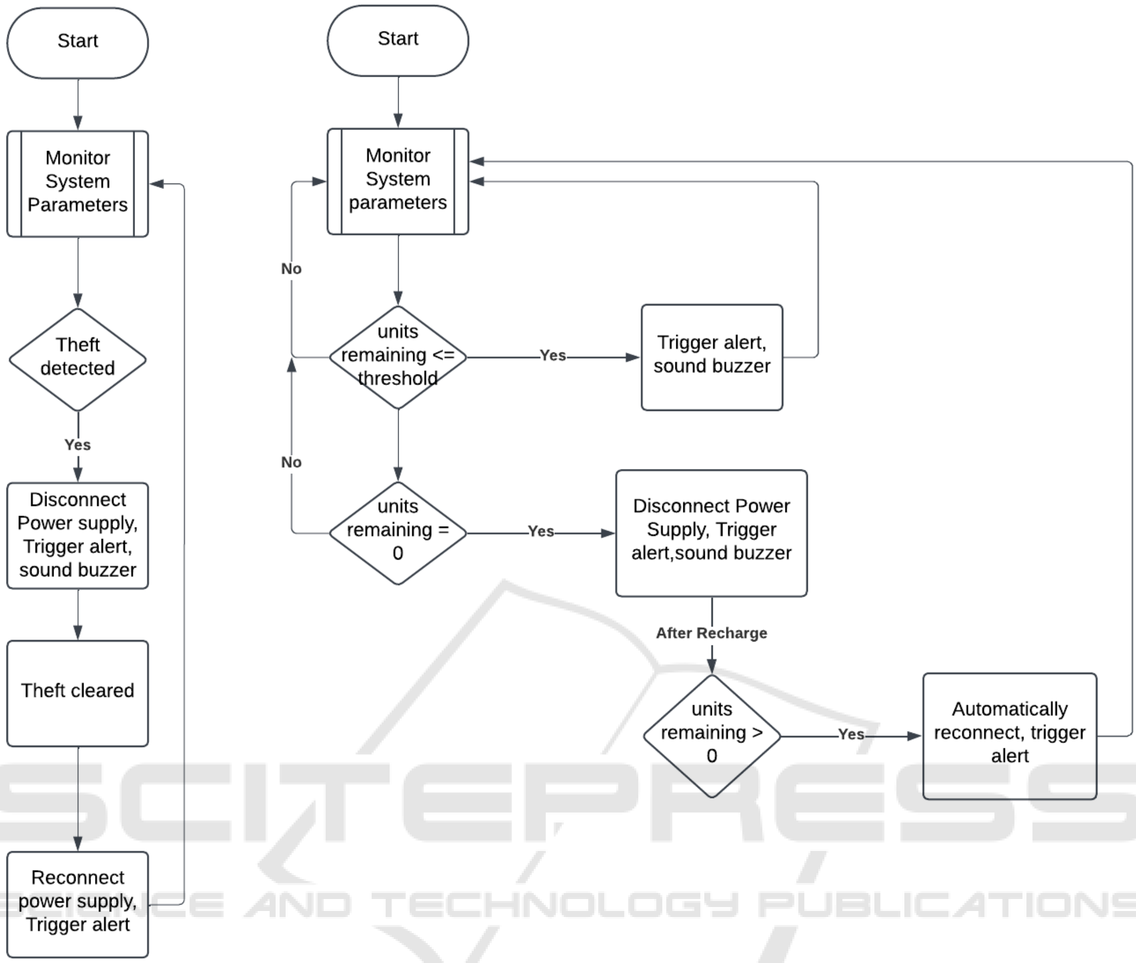

Figure 2: Flow Chart (a,b)(A. S. Metering and Sandeep, 2017).

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