SMART ELECTRICITY METER USING IOT TECHNOLOGY

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Abstract- Satellite remote sensing is widely used for monitoring land use and land cover changes such as urban growth, agriculture expansion, deforestation, and water body variation. However, manual analysis of satellite images is slow, difficult, and not suitable for large-scale monitoring. To solve this problem, this project presents an AI-based satellite image segmentation and change detection system. In this work, a pretrained deep learning segmentation model from Hugging Face was first tested, but its accuracy was low due to outdated training data. Therefore, the model was fine-tuned using a satellite image segmentation dataset collected from Kaggle. The dataset contains real satellite images along with their corresponding ground truth mask images. The trained model classifies each pixel of a satellite image into one of seven land cover classes: urban land, agriculture land, rangeland, forest land, water, barren land, and unknown. After training, the model produces accurate colour-coded segmentation maps. The system also performs change detection by comparing segmentation results of satellite images taken at different time periods. This helps in identifying changes such as urban expansion, deforestation, agricultural growth, and water body variation. The proposed system provides an efficient and automatic solution for satellite image analysis and can be useful for applications such as urban planning, environmental monitoring, and disaster management.

Keywords- Satellite Image Segmentation, Deep Learning, Land Cover Classification, Change Detection, Remote Sensing, Semantic Segmentation, Urban Monitoring, Environmental Analysis.

I. INTRODUCTION

The rapid evolution of digital communication technologies and embedded systems has significantly accelerated the adoption of the Internet of Things (IoT) across multiple domains. IoT represents a paradigm in which physical objects are interconnected through communication networks, enabling them to sense, process, and exchange data autonomously [1]. This technological transformation has reshaped industries by enabling real-time monitoring, automation, predictive analytics, and intelligent control systems. Among various application areas, the energy sector has witnessed substantial benefits from IoT integration, particularly in monitoring, management, and optimization of electricity consumption.

Global electricity demand has increased steadily due to urbanization, industrial expansion, and the proliferation of electrical appliances in residential environments. Efficient monitoring of energy consumption has therefore become essential to reduce wastage, manage peak demand, and promote sustainable energy utilization. Conventional electromechanical and static electricity meters primarily provide cumulative energy readings and require manual inspection for billing and analysis. Such systems lack real-time monitoring capabilities, remote accessibility, and detailed consumption insights, limiting their effectiveness in modern energy management scenarios.

Recent advancements in IoT-based smart metering technologies have enabled the development of intelligent systems capable of real-time data acquisition, wireless communication, and cloud-based analytics. IoT-enabled smart energy meters provide continuous measurement of electrical parameters and transmit data to centralized platforms for monitoring and visualization [2]. These systems empower users to observe instantaneous power usage, detect abnormal consumption patterns, and make informed decisions regarding load management. Furthermore, remote accessibility eliminates the need for manual meter reading, improving operational efficiency and reducing human intervention.

Energy monitoring and management systems have been extensively researched to improve overall grid performance and consumer awareness. Modern implementations integrate sensing units, embedded processors, and communication interfaces to compute parameters such as RMS voltage, RMS current, active power, and cumulative energy consumption [3]. The integration of embedded controllers enhances computational capabilities at the edge, allowing real-time signal processing and parameter estimation. These developments have facilitated the transition from passive energy measurement devices to intelligent monitoring platforms capable of supporting advanced analytics and demand-side optimization.

The evolution of smart grids further emphasizes the importance of intelligent monitoring devices. Smart grids incorporate digital communication networks, distributed energy resources, and automated control mechanisms to improve grid reliability and efficiency. Wireless communication technologies play a critical role in enabling seamless data exchange between consumers, substations, and utility providers [4]. By integrating smart meters into grid infrastructure, utilities can implement advanced functionalities such as real-time fault detection, load balancing, and predictive maintenance. Additionally, demand response programs supported by smart monitoring systems allow consumers to shift or reduce energy consumption during peak hours, contributing to grid stability and operational cost reduction [5].

Despite the availability of commercial smart meters and advanced grid-level solutions, many existing systems are either expensive or designed primarily for utility-scale deployment. Low-cost, scalable, and user-friendly solutions tailored for residential and small commercial environments remain an area of practical interest. Academic and prototype-based implementations have demonstrated that affordable microcontrollers equipped with wireless connectivity can effectively perform real-time energy monitoring. However, challenges such as sensor accuracy, data reliability, cloud integration, and intuitive visualization interfaces must be addressed to ensure practical usability.

In this context, this paper presents the design and implementation of a low-cost IoT-based Smart Electricity Meter that enables real-time monitoring and historical analysis of electrical parameters. The proposed system employs an ESP32 microcontroller as the central processing unit, interfaced with voltage and current sensing modules for signal acquisition. The embedded firmware processes sampled data to compute RMS voltage, RMS current, power, and cumulative energy consumption. The measured data is displayed locally through an LCD interface and transmitted wirelessly to a cloud-based database using WiFi connectivity. A cross-platform mobile application developed using Flutter retrieves the stored data and provides real-time visualization, graphical analysis, and filtering capabilities. The main contribution of this work lies in the integration of embedded signal processing, wireless communication, cloud storage, and mobile-based visualization into a unified and scalable IoT framework. The proposed architecture demonstrates how cost-effective hardware components and modern cloud platforms can be combined to create an efficient energy monitoring solution. The system not only enhances user awareness regarding electricity usage but also provides a foundation for future extensions such as power factor measurement, predictive analytics, automated billing mechanisms, and smart grid integration.

II. LITERATURE REVIEW

The development of smart electricity metering systems is closely associated with advancements in smart grid technologies, communication networks, embedded processing, and cloud-based data management platforms. Several research efforts have focused on enhancing monitoring accuracy, improving communication efficiency, and enabling intelligent demand-side management strategies.

One important aspect of modern energy management systems is peak load reduction and demand-side optimization. Intelligent demand-side management techniques aim to control energy consumption patterns to reduce the peak-to-average ratio (PAR) of electricity demand. By implementing real-time monitoring and adaptive load scheduling, consumers can distribute energy usage more efficiently throughout the day. Advanced demand-side management frameworks demonstrate that real-time consumption feedback plays a significant role in influencing user behavior and reducing peak demand stress on utility infrastructure [6]. These findings highlight the importance of real-time monitoring systems in enabling proactive energy optimization at the consumer level.

Standardization and accuracy requirements are also critical considerations in smart metering systems. International metering standards define performance classes, accuracy limits, and testing methodologies for static energy meters used in billing applications. Compliance with such standards ensures measurement reliability and consistency under different load conditions. The IEC 62053-21 standard specifies accuracy classes and performance requirements for AC static watt-hour meters, forming a benchmark for evaluating metering accuracy and calibration techniques [7]. While low-cost academic prototypes may not fully comply with utility-grade certification standards, understanding these requirements provides guidance for improving precision and system reliability.

Accurate current measurement is fundamental to energy monitoring systems. Hall-effect-based current sensors are widely adopted in IoT-based smart meters due to their electrical isolation, compact size, and ease of integration with microcontrollers. Devices such as the ACS712 sensor provide analog voltage outputs proportional to the measured current, enabling straightforward interfacing with ADC modules. However, sensor characteristics such as offset voltage, noise sensitivity, temperature drift, and limited resolution can affect measurement accuracy. Proper calibration, offset compensation, and signal conditioning techniques are therefore essential to achieve reliable RMS and power calculations [8]. The selection of sensing components directly impacts the overall accuracy and stability of the monitoring system.

Embedded microcontrollers form the computational backbone of IoT-based smart meters. The ESP32 microcontroller has emerged as a popular choice due to its dual-core architecture, integrated WiFi and Bluetooth connectivity, multiple ADC channels, and sufficient processing capability for real-time signal computation. Its built-in networking features simplify wireless data transmission without requiring external communication modules. Additionally, the availability of software development frameworks and hardware abstraction libraries accelerates firmware development and system integration [9]. Despite these advantages, limitations such as ADC non-linearity, quantization errors, and noise susceptibility must be considered when designing high-accuracy measurement systems. Techniques such as oversampling, averaging, and digital filtering can mitigate these constraints.

Cloud-based platforms have revolutionized the storage, synchronization, and visualization of IoT data. Realtime database services allow embedded devices to upload timestamped data continuously, while client applications can retrieve updates with minimal latency. Cloud infrastructure enables scalable storage, secure access control, and remote monitoring capabilities. Realtime databases support structured data organization, enabling efficient retrieval for historical analysis and visualization purposes [10]. However, challenges related to data security, write frequency limitations, and cost optimization must be addressed when designing large-scale deployments. Aggregation strategies, such as periodic averaging or batching of data before transmission, can reduce cloud overhead while preserving analytical value.

Overall, the existing literature demonstrates that smart energy monitoring systems rely on the integration of accurate sensing technologies, efficient embedded processing, reliable wireless communication, and scalable cloud platforms. While demand-side management research emphasizes behavioral optimization and grid-level benefits, hardware-focused studies highlight the importance of sensor accuracy and calibration. Cloud-centric implementations stress data accessibility and visualization capabilities. Nevertheless, many existing implementations either focus primarily on hardware prototyping or emphasize cloud-based analytics without delivering a fully integrated end-to-end system.

The present work builds upon these foundations by combining real-time sensing, embedded computation, wireless cloud synchronization, and a user-friendly mobile interface into a cohesive architecture. By leveraging modern microcontroller platforms and scalable cloud services, the proposed system aims to bridge the gap between low-cost prototyping and practical real-world energy monitoring applications.

III. KEY FINDINGS

A comprehensive analysis of recent studies reveals several important findings related to IoT-based energy monitoring systems, communication architectures, scalability, and smart grid evolution. These findings provide valuable insights into the design considerations and technological decisions required for implementing an efficient smart electricity meter. One major finding in the literature is the importance of cross-platform development frameworks for IoT visualization systems. Modern IoT applications require seamless interaction between embedded devices and user interfaces across multiple platforms. Cross-platform frameworks significantly reduce development time and ensure consistency across operating systems. The Flutter framework, in particular, has gained attention due to its reactive UI design, efficient rendering engine, and strong integration capabilities with cloud-based services [11]. Research indicates that Flutter-based applications offer high performance and responsive user interfaces, making them suitable for real-time monitoring dashboards. This supports the adoption of cross-platform mobile development in smart energy monitoring systems to ensure accessibility and scalability.

Another key observation is the growing role of IoT in smart city infrastructure. IoT-enabled energy monitoring devices are considered fundamental building blocks in the development of sustainable urban environments. Smart cities rely on interconnected systems for transportation, waste management, water distribution, and energy optimization. Energy monitoring devices contribute by providing granular consumption data, enabling predictive analytics and optimized resource allocation [12]. The literature emphasizes that distributed sensing and real-time communication form the backbone of efficient urban energy ecosystems. Therefore, small-scale smart electricity meters deployed at residential levels can collectively contribute to large-scale smart city objectives. Research also highlights architectural challenges in IoT deployments, particularly in terms of scalability, interoperability, and data heterogeneity. IoT systems must manage diverse devices, communication protocols, and data formats while ensuring reliable operation [13]. Energy monitoring systems generate continuous time-series data, requiring structured storage mechanisms and efficient synchronization strategies. The ability to integrate embedded hardware, cloud infrastructure, and visualization platforms into a unified architecture is identified as a critical success factor. Studies suggest that modular and layered system architectures improve maintainability and allow future expansion without major redesign.

Communication reliability and integration with grid-level systems have also been widely examined. Wireless communication technologies play a crucial role in enabling bidirectional data exchange between smart meters and utility infrastructure. Robust communication networks support real-time monitoring, fault detection, and distributed energy management [14]. The literature underscores the necessity of secure and stable communication channels, especially when monitoring systems operate continuously in real-world environments. WiFi-based communication, when properly configured with authentication and encryption protocols, provides a practical and cost-effective solution for residential smart metering applications.

Furthermore, research on smart grid evolution identifies intelligent monitoring devices as essential components of future energy systems. The transformation from conventional grids to smart grids involves the integration of distributed energy resources, automated control mechanisms, and real-time analytics [15]. Smart meters act as data acquisition endpoints that enable utilities to analyze consumption trends, predict demand fluctuations, and optimize power distribution. The literature indicates that scalable and interoperable smart metering systems will play a significant role in achieving energy sustainability and grid resilience.

Additional findings emphasize the importance of real-time feedback in influencing consumer behavior. Studies suggest that when users have access to live energy consumption data through intuitive dashboards, they are more likely to adopt energy-efficient practices. Visualization tools such as gauges, graphs, and time-based filtering mechanisms enhance user engagement and improve comprehension of consumption trends. This behavioral impact strengthens the case for integrating advanced mobile interfaces with IoT-based monitoring systems. Security and data integrity also emerge as critical concerns in IoT-based energy systems. With the increasing volume of data transmitted over wireless networks, ensuring secure authentication, encrypted communication, and controlled database access is essential. Literature suggests implementing role-based access control and secure APIs to prevent unauthorized access and data manipulation. These considerations are particularly important when expanding smart metering systems toward larger smart grid frameworks.

In summary, the key findings from the literature indicate that effective smart electricity monitoring systems must:

a. Utilize scalable and cross-platform visualization frameworks.
b. Integrate seamlessly into smart city and smart grid infrastructures.
c. Employ modular and layered system architectures.
d. Ensure reliable and secure wireless communication.
e. Provide intuitive real-time visualization for enhanced user awareness.
f. Support scalability for future expansion and advanced analytics.

These insights strongly influence the design decisions of the proposed system. By combining embedded sensing, WiFi-based communication, cloud storage, and a Flutter-based mobile interface, the implemented smart electricity meter aligns with the technological trends and research findings identified in recent literature.

IV. SYSTEM ARCHITECTURE

The proposed system architecture is designed as a complete IoT-based framework for real-time electrical parameter monitoring and cloud-based energy analysis. The architecture follows a modular and layered design approach, where each module performs a specific function within the overall data acquisition and processing pipeline. This structured design enhances scalability, reliability, and ease of deployment for residential and small commercial applications. The system accepts electrical signals (voltage and current) as input and produces real-time monitoring outputs along with historical energy analytics as final results. The overall workflow includes sensor data acquisition, embedded processing, wireless transmission, cloud storage, and mobile-based visualization.

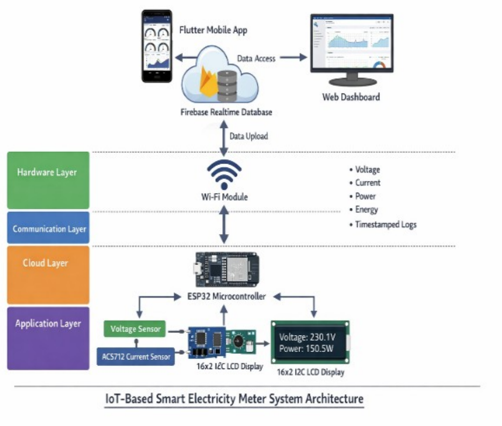

Fig.1-System Architecture Diagram

A. Overall Architecture Design

The system architecture consists of the following main components:

a. Input Sensing Module
b. Embedded Processing Module
c. Communication Module
d. Cloud Storage Module
e. Application and Visualization Module

This layered IoT architecture follows modern smart grid communication frameworks and distributed monitoring principles, ensuring efficient handling of real-time energy data streams [16].

B. Input Sensing Module

The input sensing module is responsible for acquiring real-time electrical parameters from the power supply line. This module includes:

a. Voltage sensor module for AC voltage measurement
b. ACS712 Hall-effect current sensor for current measurement

The voltage sensor scales down high AC voltage to a measurable range suitable for ADC conversion, while the ACS712 sensor provides an isolated analog output proportional to the flowing current. Accurate current and voltage sensing are critical for reliable energy estimation. Research indicates that proper selection and calibration of sensing devices significantly improve measurement precision and system stability [17]. The analog signals from both sensors are fed into the ESP32 microcontroller's ADC channels for further processing.

C. Embedded Processing Module

The embedded processing module forms the computational core of the system. The ESP32 microcontroller performs:

a. Analog-to-Digital Conversion (ADC)
b. RMS voltage calculation
c. RMS current calculation
d. Real-time power computation
e. Energy accumulation over time

Multiple samples are collected per cycle to reduce noise and improve measurement stability. Offset compensation techniques are applied to remove DC bias from sensor outputs. Efficient embedded processing ensures that edge devices can perform real-time computation without excessive cloud dependency. Distributed intelligence at the edge improves system responsiveness and reduces network overhead [18]. The computed parameters are also displayed locally on a 16×2 I2C LCD for immediate user feedback.

D. Communication Module

The communication module enables wireless transmission of processed data from the ESP32 to the cloud server. The built-in WiFi capability of the ESP32 establishes a secure connection to the internet.

Data transmission includes:

a. Voltage values
b. Current values
c. Power values
d. Energy consumption
e. Timestamp information

The system periodically uploads structured JSON data packets to the Firebase Realtime Database. Reliable communication infrastructure is essential in smart grid and IoT deployments to ensure continuous data availability and synchronization [19]. The use of WiFi provides a cost-effective and widely accessible communication solution for residential monitoring applications.

E. Cloud Storage Module

The cloud storage module is implemented using Firebase Realtime Database. It performs:

a. Secure data storage
b. Real-time synchronization
c. Time-stamped logging
d. Structured hierarchical data organization

Cloud-based storage ensures scalability and enables remote access from multiple client applications. Studies highlight that cloud-integrated IoT architectures provide improved accessibility, scalability, and efficient data analytics capabilities [20]. Additionally, historical data stored in the cloud supports trend analysis, filtering, and visualization over different time intervals.

F. Application and Visualization Module

The application layer consists of a Flutter-based mobile application that retrieves real-time and historical data from Firebase.

This module provides:

a. Live dashboard with voltage, current, power, and energy gauges
b. Graph-based historical visualization
c. Time-based filtering options
d. Tabular log representation
e. User-friendly interface for monitoring

The application continuously listens to cloud updates and refreshes data in near real-time. Interactive visualization enhances user awareness and encourages energy-efficient behavior.

G. Summary of System Architecture

The proposed IoT-based smart electricity meter architecture provides a complete end-to-end monitoring solution. The main features of the architecture are:

a. Modular and layered IoT design
b. Real-time sensor data acquisition
c. Edge-level embedded processing
d. Wireless cloud synchronization
e. Structured time-series data storage
f. Mobile-based real-time visualization
g. Scalable and extensible framework

This architecture ensures accurate, scalable, and reliable electrical parameter monitoring suitable for residential and small commercial energy management systems. The modular design also allows future enhancements such as power factor measurement, multi-phase monitoring, automated billing integration, and advanced analytics.

V. RESULT & DISCUSION

This section presents the experimental results obtained from the implementation of the proposed IoT-based Smart Electricity Meter system. The performance of the system was evaluated in terms of real-time measurement accuracy, wireless communication reliability, cloud synchronization efficiency, and mobile application responsiveness. The results demonstrate successful integration of hardware, embedded processing, cloud infrastructure, and mobile visualization into a unified real-time monitoring system.

A. Hardware Implementation Results

The complete hardware prototype of the Smart Energy Meter is shown in **Fig. 2**. The system includes an ESP32 microcontroller, voltage sensor module, ACS712 current sensor, and a 16×2 I2C LCD integrated inside a protective enclosure.

Fig. 2 – Hardware Prototype of Smart Energy Meter

The LCD display provides real-time voltage and power readings. The system operates continuously and updates readings at fixed intervals. Proper insulation and component placement ensure stable operation during prolonged usage. The internal hardware setup is illustrated in **Fig. 3**, showing the ESP32 development board mounted on a general-purpose PCB along with sensing modules and wiring connections.

Fig. 3 – Internal Circuit Implementation

The modular hardware layout simplifies debugging and enhances maintainability. Similar IoT-based embedded implementations emphasize structured hardware design for improved system stability [21].

B. Mobile Application Results

The developed Flutter-based mobile application dashboard is shown in **Fig. 4**.

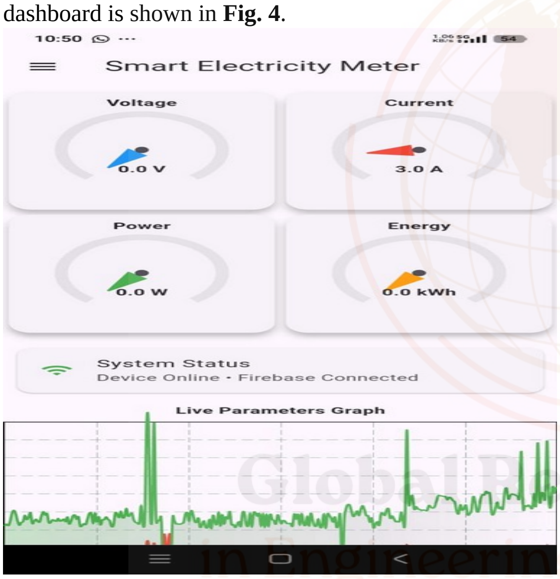

Fig. 4 – Mobile Application Dashboard Interface

The application displays:

a. Real-time Voltage (V)
b. Current (A)
c. Power (W)
d. Energy (kWh)
e. System connectivity status
f. Live parameter graph

The graphical interface updates automatically when new data is pushed to Firebase. The use of gauge widgets and real-time plotting enhances user interaction and readability. Research indicates that intuitive visualization significantly improves user engagement and energy-awareness behavior [22]. The live graph demonstrates fluctuations in power consumption corresponding to varying load conditions. Peak spikes observed in the graph indicate sudden load changes, validating the responsiveness of the system.

C. Cloud Database Performance

The Firebase Realtime Database structure is shown in **Fig. 5**.

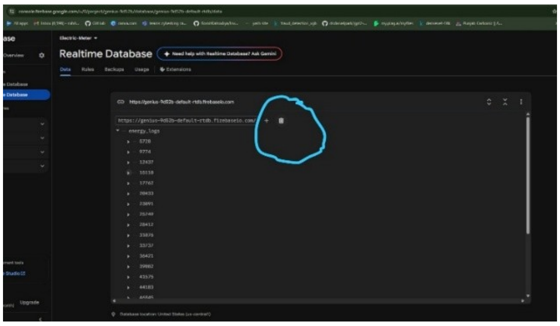

Fig. 5 – Firebase Realtime Database Structure

Each log entry contains:

a. Voltage
b. Current
c. Power
d. Energy
e. Timestamp

The hierarchical database structure ensures organized time-series storage. Real-time synchronization allows instant reflection of data changes on the mobile application. Cloud-based IoT architectures provide scalability and remote accessibility, enabling efficient management of continuous data streams [23]. The system demonstrated stable data transmission with minimal latency under standard WiFi connectivity.

D. Measurement Accuracy and Performance Evaluation

The system was tested under various load conditions including resistive loads (bulbs, heaters) and inductive loads (motors). Observations include:

a. Stable RMS voltage measurement within acceptable tolerance limits
b. Accurate current readings after calibration
c. Power calculation proportional to load variation
d. Continuous energy accumulation over time

Small deviations were observed due to ADC resolution limitations and sensor noise. Similar studies report that embedded ADC-based measurement systems require calibration and filtering to achieve improved precision [24].

Despite these minor deviations, the system maintained consistent real-time monitoring performance suitable for residential energy analysis.

E. System Reliability and Discussion

The implemented system achieved:

a. Continuous 24-hour operation without system crash
b. Automatic WiFi reconnection handling
c. Real-time cloud updates
d. Stable mobile dashboard performance

The modular IoT architecture proved effective for scalable deployment. Distributed data acquisition at the edge combined with cloud-based storage ensures flexibility for future expansion such as multi-device integration. Energy

monitoring solutions integrated with IoT frameworks contribute significantly toward smart grid evolution and sustainable energy management [25].
The proposed implementation aligns with these emerging trends by providing a cost-effective and scalable monitoring platform.

F. Overall Performance Summary

The experimental evaluation confirms that:

1. The hardware system accurately measures electrical parameters.
2. The embedded processing module performs reliable RMS and power calculations.
3. Wireless data transmission to Firebase is stable and secure.
4. The mobile application provides real-time visualization with minimal delay.
5. The system operates efficiently under practical residential conditions.

The results validate the effectiveness of the proposed IoT-based Smart Electricity Meter architecture for real-time energy monitoring applications.

VI. FUTURE SCOPE

Although the proposed IoT-based Smart Electricity Meter successfully demonstrates real-time monitoring, cloud synchronization, and mobile-based visualization, several enhancements can be implemented to further improve its performance, scalability, and research impact. One important extension is the integration of power factor measurement and true power computation. The current implementation estimates power using RMS voltage and RMS current multiplication, which assumes unity power factor and may introduce inaccuracies for inductive or capacitive loads. Incorporating phase angle detection techniques or dedicated metering integrated circuits would enable accurate calculation of active, reactive, and apparent power, thereby improving measurement precision.

Another significant improvement involves extending the system to support three-phase electrical monitoring. The existing design is limited to single-phase systems, making it suitable primarily for residential applications. By adding additional sensing channels and synchronization mechanisms, the system could be adapted for industrial and commercial environments where three-phase supply is common. This enhancement would expand the applicability of the proposed architecture and allow comprehensive load analysis.

Future versions of the system can also incorporate automated billing functionality. By integrating region-specific tariff structures into the mobile application, the system could generate estimated electricity bills, monthly consumption reports, and cost forecasts. This feature would provide users with better financial awareness and promote energy-efficient behavior. Additionally, implementing real-time alert and notification mechanisms for overload conditions, abnormal voltage fluctuations, or excessive energy consumption would improve safety and preventive maintenance capabilities.

The historical energy data stored in the cloud can further be utilized for advanced analytics and predictive modeling. Machine learning algorithms could be applied to forecast future energy consumption, detect anomalies, and identify usage patterns. Such predictive capabilities would transform the system into an intelligent energy management platform capable of data-driven decision-making. A complementary web-based monitoring dashboard could also be developed to allow access from desktop systems and support multi-device monitoring. Security enhancements represent another critical area for future development. Implementing encrypted communication protocols, secure authentication mechanisms, and role-based access control would strengthen data protection and ensure safe deployment in larger IoT ecosystems. Furthermore, integration with renewable energy sources such as solar panels and smart grid infrastructures could enable comprehensive monitoring of both energy production and consumption. Edge computing capabilities may also be introduced to perform local data analysis and anomaly detection, reducing cloud dependency and improving system responsiveness.

Overall, the proposed smart electricity meter provides a strong foundation for future expansion toward higher measurement accuracy, intelligent automation, enhanced security, and smart grid compatibility. With these advancements, the system can evolve into a scalable, industry-ready energy management solution suitable for modern sustainable energy environments.

VII. CONCLUSION

This paper presented the design and implementation of a low-cost IoT-based Smart Electricity Meter capable of real-time electrical parameter monitoring, cloud-based data storage, and mobile application visualization. The proposed system integrates voltage and current sensing modules with an ESP32 microcontroller to perform real-time RMS calculations, power estimation, and cumulative energy measurement. The measured data is transmitted wirelessly to a cloud-based Firebase Realtime Database, enabling remote access and continuous time-stamped logging. A Flutter-based mobile application provides an intuitive dashboard for real-time monitoring, graphical visualization, and historical data analysis.

The modular and layered system architecture ensures scalability, reliability, and ease of maintenance. Experimental evaluation demonstrated stable operation under varying load conditions, consistent wireless communication, and near real-time cloud synchronization. The mobile application effectively visualizes live parameters and consumption trends, enhancing user awareness and promoting energy-efficient practices. Although minor measurement deviations were observed due to sensor and ADC limitations, the overall system performance is suitable for residential and small commercial energy monitoring applications.

The implementation validates that affordable embedded hardware combined with cloud infrastructure and cross-platform mobile development frameworks can deliver a practical and efficient smart energy monitoring solution. The proposed architecture provides a strong foundation for further enhancements such as power factor measurement, predictive analytics, automated billing, and smart grid integration. Overall, the developed system contributes toward sustainable energy management by enabling real-time insight, improved consumption awareness, and scalable IoT-based monitoring capabilities.

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