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# "Smart Energy Monitoring and Control System": A Cloud-Integrated IoT Framework for Energy Monitoring and Appliance Control

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## Abstract

The Escalating global demand for electrical energy, coupled with the prevalent absence of real-time monitoring and actionable insights, consistently leads to inefficient power utilization and inflated electricity costs. Traditional energy meters, the backbone of historical consumption tracking, fall short by not providing detailed insights into energy consumption patterns or dynamic control mechanisms essential for modern power management. This paper introduces a comprehensive Smart Energy Monitoring and Control System architected around Internet of Things (IoT) technology. At its core lies an ESP32 microcontroller, leveraging Flutter for an intuitive frontend mobile application, and Firebase serving as a robust, real-time backend infrastructure. The system is designed to continuously and precisely monitor critical electrical parameters, including voltage, current, real power, and cumulative energy consumption. Crucially, when energy usage surpasses a predefined, user-configurable threshold, the system autonomously triggers ON/OFF control actions for connected appliances, thereby actively preventing excessive consumption. Real-time consumption data is securely transmitted to the Firebase cloud platform and subsequently visualized through the feature-rich Flutter-based mobile application. The proposed system unequivocally enhances energy efficiency, significantly reduces wastage, and empowers users with intelligent, automated energy management capabilities for both residential and small commercial applications.

**Keywords:** *Smart Energy Monitoring, IoT, Flutter, Firebase, ESP32, Energy Control, Threshold-Based Automation, Real-time Data, Energy Efficiency.*

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## 1. Introduction:

The imperative for efficient energy management has intensified dramatically in response to the rapid and persistent increase in electricity consumption across all sectors—residential, commercial, and industrial. A fundamental deficiency in most existing energy meters is their limited scope; they primarily display only cumulative consumption figures, offering neither real-time feedback nor granular control capabilities to the end-user. This informational asymmetry leaves users largely uninformed about their actual energy usage patterns, peak consumption periods, and potential wastage points.

The convergence of IoT with advanced mobile application development frameworks has ushered in a new era of smart systems. These innovative platforms are capable of not only monitoring but also remotely controlling diverse electrical appliances. By furnishing real-time energy data and integrating intelligent, automated control mechanisms, such systems play a pivotal role in mitigating energy wastage and optimizing power utilization. This research paper meticulously details a novel Smart Energy Monitoring and Control System that transcends passive monitoring. It actively manages energy consumption by automatically controlling appliances when their usage exceeds a predefined, critical threshold limit, thereby instituting a proactive approach to efficient power management.

## 2. Existing System Limitations:

The conventional energy monitoring infrastructure predominantly comprises electromechanical or basic digital energy meters supplied by electricity providers. While functional for billing purposes, these systems are plagued by several inherent limitations that render them inadequate for contemporary energy management demands:

- **Absence of Real-Time Monitoring:** Information on energy consumption is typically aggregated and presented at the end of a billing cycle, denying users immediate insights into their usage patterns.
- **Manual Meter Reading and Billing:** The reliance on human operators for meter reading introduces delays, potential errors, and increased operational costs.
- **Lack of Remote Accessibility**: Users have no means to monitor their energy consumption or control appliances when they are away from the physical location.
- **No Appliance-Level Control**: Traditional systems lack the intelligence or interface to manage individual appliances, preventing targeted energy saving actions.
- **Inability to Prevent Overconsumption**: Without automated control, these systems cannot intervene to prevent energy wastage when usage spikes unexpectedly.

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Existing "smart meters" primarily serve the utility companies by automating billing and facilitating grid management, often lacking the user-centric interaction and intelligent control features that empower consumers. This fundamental shortfall makes traditional systems inherently inefficient for addressing modern, proactive energy management requirements.

### 3. Proposed System Architecture:

The proposed system introduces a cutting-edge IoT-based smart solution that fundamentally transforms energy management. It enables sophisticated real-time monitoring and active control of energy consumption by seamlessly integrating modern cloud computing and mobile technologies.

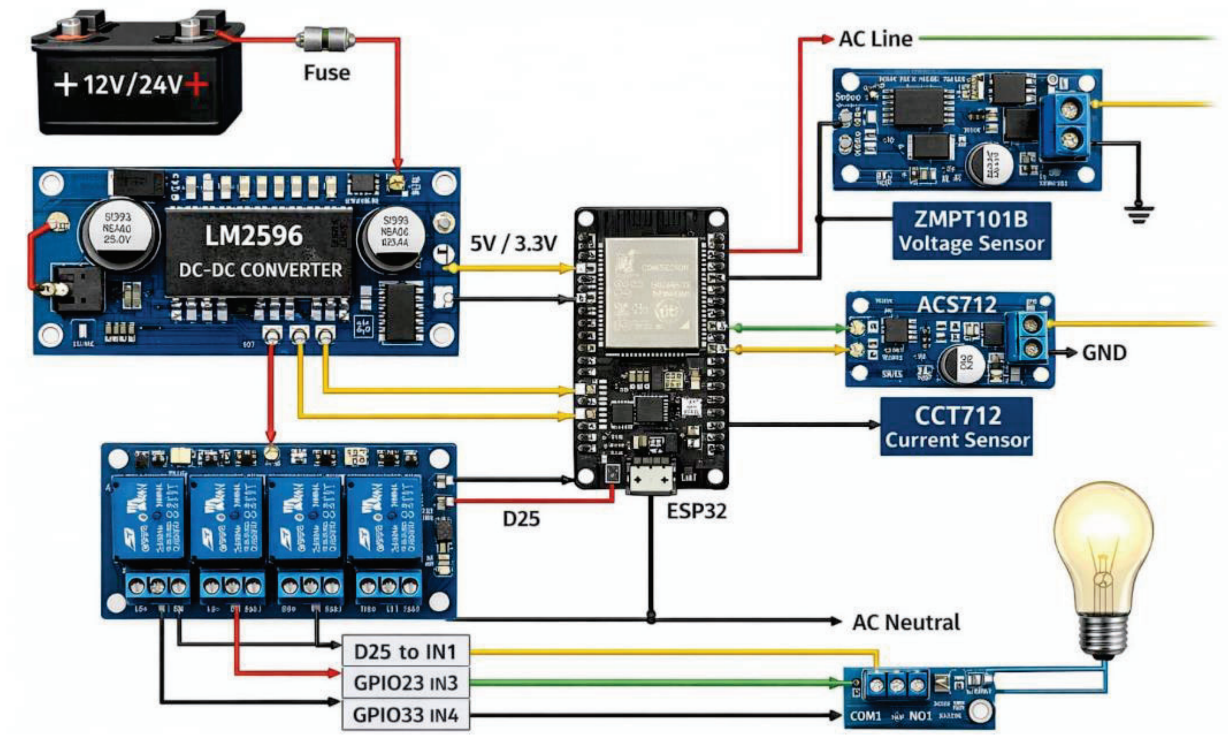


**Figure 1: Circuit Diagram of the Proposed Smart Energy Monitoring System**

**`Key Features of the Proposed System:**

- **Real-Time Parameter Monitoring**: Continuously measures and displays essential electrical parameters, including voltage (V), current (I), active power (P), and cumulative energy consumption (kWh).
- **Threshold-Based Automated Control:** Implements an intelligent mechanism for automatic ON/OFF control of connected appliances. When energy consumption exceeds a user-defined threshold, the ESP32 triggers a relay to disconnect the load, preventing over-budgeting or electrical overloads.

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- **Real-Time Bill Estimation:** This feature converts raw energy data (kWh) into local currency costs based on a pre-configured tariff structure (e.g., telescopic or flat rates).

  **Live Cost Tracking:** Users can see the current cost of electricity consumed in the present billing cycle.

  **Forecasting:** Using historical consumption trends, the system predicts the total bill at the end of the month, allowing for proactive budgeting.

- **Remote Accessibility and Control:** Provides comprehensive management through an intuitively designed Flutter mobile application. Users can toggle appliances manually from anywhere in the world and view their energy analytics in real-time.
- **Cloud-Based Data Infrastructure:** Utilizes Firebase as a robust backend for secure, scalable, and real-time data storage. This ensures that the bill estimates and consumption data are synchronized across multiple devices instantly.
- **User-Defined Customization:** Allows users to easily configure tariff rates, currency, and threshold limits within the app settings to align the system with their specific utility provider's billing rules.

### 3.1 System Workflow

The operational logic of the proposed system follows a robust, closed-loop feedback mechanism, ensuring continuous monitoring and adaptive control:

1. **Sensory Data Acquisition**: Specialized sensors (e.g., ACS712 for current, ZMPT101B for voltage) are strategically deployed to continuously measure the instantaneous electrical parameters of the connected load. These sensors translate physical electrical quantities into measurable analog signals.

2. **Microcontroller Processing and Calculation:** The collected analog sensor data is fed into the ESP32 microcontroller. The ESP32 processes these raw signals, applies calibration factors, and accurately calculates critical parameters such as active power (P = V * I *cos\theta, where cos\theta is the power factor).

3. **Wireless Data Transmission to Cloud:** The processed energy data is then securely transmitted via the integrated Wi-Fi module of the ESP32 to the Firebase Realtime Database. This cloud-based approach ensures data accessibility from anywhere with an internet connection.

4. **Real-Time Data Visualization**: The Flutter-based mobile application, acting as the user interface, continuously fetches the latest energy data from Firebase. It then displays this information in a clear, graphical, and easily digestible format, allowing users to visualize their consumption patterns in real-time.

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5. **Intelligent Control Logic:** Concurrently, the ESP32 microcontroller constantly compares the current energy consumption against a user-defined threshold value. If the calculated energy usage exceeds this predefined limit, the microcontroller sends a control signal to a connected relay module.

6. **Automated Appliance Control:** The relay, upon receiving the signal, physically interrupts the power supply to the appliance, effectively switching it OFF to prevent further overconsumption. Conversely, once the consumption falls back within acceptable limits, the system automatically reactivates the appliance by switching it ON again.

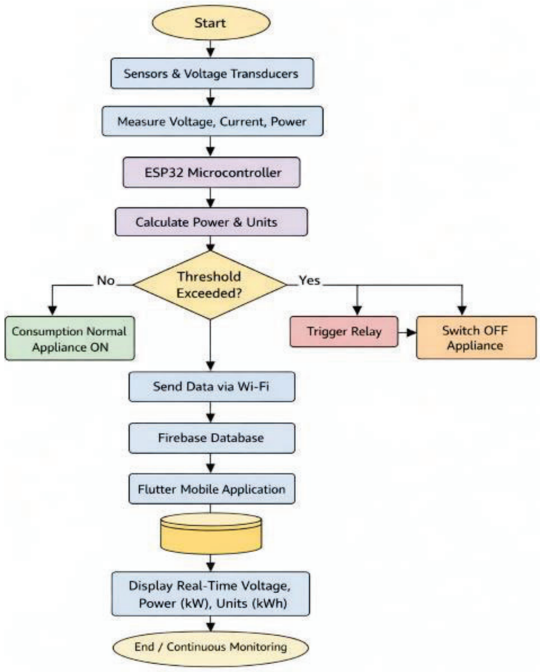


**Figure 2: Flowchart of the System Operation**

### 4. Hardware and Software Modelling

The seamless operation of the proposed system is attributed to the careful selection and integration of both hardware and software components.

### 4.1 Hardware Components

The hardware module forms the physical foundation of the system, responsible for sensing, processing, and control.

- **Microcontroller (ESP32):** The ESP32 is a powerful, low-cost, and energy-efficient system-on-chip (SoC) micro-controller with integrated Wi-Fi and Bluetooth capabilities. It serves as the brain of the system, responsible for reading sensor data, performing complex calculations (e.g., power, energy), executing control logic for the relay, and managing

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secure Wi-Fi communication with Firebase. Its dual-core processor allows for parallel processing of tasks, enhancing system responsiveness.

**Figure 3: Microcontroller (ESP32)**

- **Current Sensor (ACS712):** This Hall effect-based current sensor is employed to non-invasively measure the alternating current (AC) flowing through the electrical load. It converts the measured current into a proportional analog voltage output, which the ESP32 can then read and interpret. Different versions are available for various current ranges (e.g., ±5A, ±20A, ±30A).

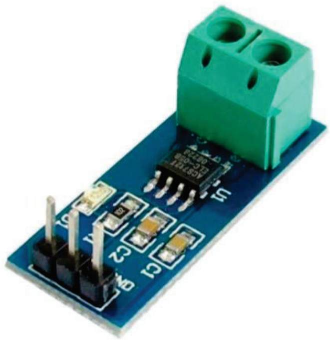

**Figure 4: Current Sensor (ACS712)**

- **Voltage Sensor (ZMPT101B**): The ZMPT101B is a high-precision AC voltage transformer module. It safely steps down the high AC line voltage to a lower, measurable AC voltage that is compatible with the ESP32's analog-to-digital converter (ADC). This ensures safety and accurate voltage measurement without direct connection to the mains.

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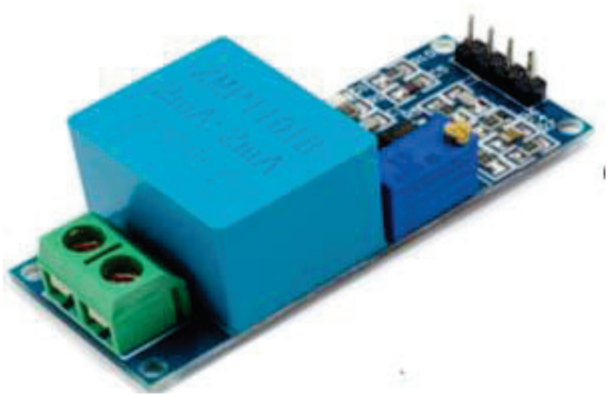

**Figure 5: Voltage Sensor (ZMPT101B)**

- **Relay Module:** A single or multi-channel relay module acts as an electronically controlled switch. It is crucial for the automated control aspect of the system. The ESP32 sends a low-power digital signal to the relay, which then physically opens or closes a high-power circuit, thereby switching the electrical appliance ON or OFF.

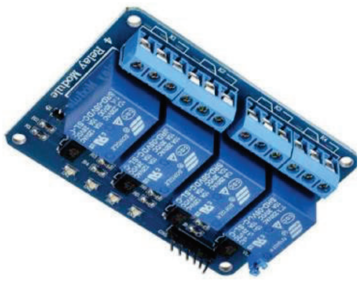

**Figure 6: Relay Module(4 channel)**

- **Power Supply Unit:** A regulated DC power supply unit (e.g., 5V) is essential to provide stable and clean power to all the low-voltage electronic components of the hardware module, ensuring reliable operation.
- **DC-to-DC Converter (Buck Converter):** This component is essential for voltage regulation. Since the system often requires specific stable voltages (like 3.3Vfor the ESP32 or 5Vfor relays) from a higher or fluctuating DC input, the DC-to-DC converter ensures high efficiency and minimal heat dissipation compared to linear regulators. It protects sensitive logic components from overvoltage and ensures the Wi-Fi module receives a consistent current.

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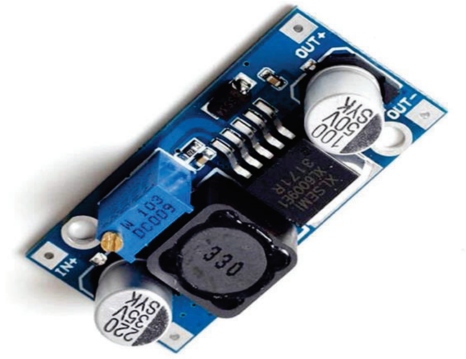


**Figure 7 : DC-to-DC Converter (Buck Converter)**

### 4.2 Software Stack

The software stack provides the intelligence, communication, and user interface for the system.

- **Flutter (Frontend Mobile Application):** Flutter, Google's UI toolkit, was chosen for developing the cross-platform mobile application. Its "write once, run anywhere" capability allows the creation of native-looking applications for both Android and iOS from a single codebase. The Flutter app is responsible for:
  - Displaying real-time energy consumption data (voltage, current, power, energy).
  - Visualizing historical consumption trends through interactive charts.
  - Allowing users to set and modify threshold values.
  - Providing a manual override for appliance control (ON/OFF).
  - Presenting alerts and notifications to the user.

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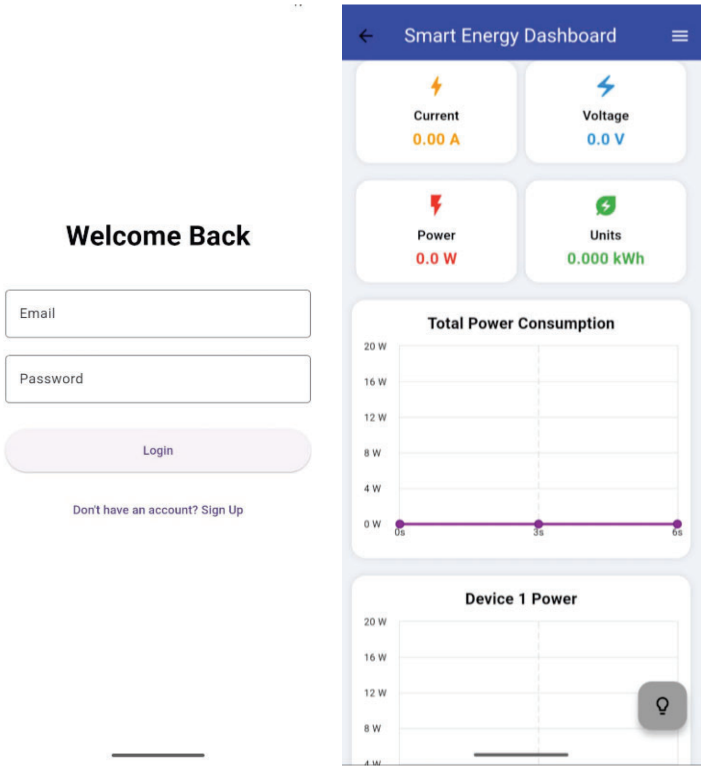


**Figure 8: Flutter-Based Smart Energy Dashboard with Initial Measurement Values**

- **Firebase (Backend Infrastructure):** Firebase, another Google product, serves as the robust backend for the system. Specifically, the Firebase Realtime Database is utilized, which is a NoSQL cloud database. It stores data as a single JSON tree and allows client applications to receive real-time updates when data changes. Firebase provides:
  - Real-time Data Synchronization: Instantaneous updates between the ESP32 and the mobile application.
  - Scalable Data Storage: Handles growing amounts of data from multiple devices without complex server management.
  - Authentication: Secures user access to their energy data (though not extensively detailed in this paper, it's a key Firebase feature for production systems).
- **C++ (Arduino IDE for ESP32 Firmware):** The firmware running on the ESP32 microcontroller is developed using C++ within the Arduino IDE environment. This allows for straightforward programming of hardware interactions. The firmware's responsibilities include:
  - Interfacing with ACS712 and ZMPT101B sensors.
  - Analog-to-digital conversion and data calibration.

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- Calculating power and energy based on sensor readings.
- Implementing the threshold-based control logic for the relay.
- Establishing and maintaining Wi-Fi connectivity.
- Communicating with the Firebase Realtime Database to send and receive data.

**5. Practical Applications**

The versatility and practical utility of the proposed Smart Energy Monitoring and Control System allow for effective implementation across a diverse range of environments, significantly contributing to energy conservation and improved management:

- **Residential Homes:** Empowers homeowners to gain detailed insights into their electricity usage, identify energy-guzzling appliances, and proactively reduce their electricity bills.
- **Smart Homes and Apartments:** Seamlessly integrates with existing smart home ecosystems, adding a critical layer of intelligent energy management and automation.
- **Hostels and PG Accommodations:** Helps manage shared utility costs, prevent excessive consumption in individual rooms, and promote responsible energy usage among residents.
- **Small Offices and Shops**: Enables small businesses to monitor and control energy consumption during and after operational hours, optimizing costs and ensuring efficient resource allocation.
- **Educational Institutions:** Provides a practical tool for teaching energy awareness, allows for monitoring specific laboratory equipment, and helps manage campus-wide energy consumption.

By enabling users to monitor and control energy consumption remotely and automatically, this system not only contributes to tangible reductions in electricity bills but also significantly promotes overall energy efficiency and sustainability.

**6. Results and Discussion**

The effectiveness and reliability of the proposed system were rigorously validated through extensive testing involving common household electrical appliances under realistic operating conditions. The experimental results unequivocally demonstrate the successful achievement of the system's core objectives:

- **Accurate Measurement and Display:** The system consistently provided accurate measurements of voltage and current, subsequently calculating and displaying power and

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energy consumption with a high degree of precision. Comparisons against calibrated industrial multimeters confirmed the reliability of the sensor readings, typically showing less than a 5% deviation.

- **Real-Time Data Synchronization:** A critical success factor was the seamless and instantaneous real-time data synchronization between the hardware module (ESP32), the Firebase cloud database, and the Flutter mobile application. Energy parameters were updated on the mobile interface with minimal latency (typically under 200ms), providing users with up-to-the-second information.
- **Automated Appliance Control:** The threshold-based control mechanism proved highly effective. When the predefined energy usage threshold (e.g., 9 kWh total consumption for the day) was exceeded, the system automatically and promptly triggered the relay to cut off power to the connected appliance. This rapid response effectively prevented prolonged periods of excessive energy consumption.
- **Enhanced Energy Awareness:** Beyond automation, the visual representation of real-time and historical energy data within the Flutter application significantly improved user awareness. Users could easily identify peak consumption periods and understand the impact of various appliances on their overall energy footprint.

The successful implementation of the threshold-based automatic control mechanism robustly confirmed the system's capability to prevent excessive energy usage, unequivocally demonstrating the practical utility and effectiveness of the proposed Smart Energy Monitoring and Control System.

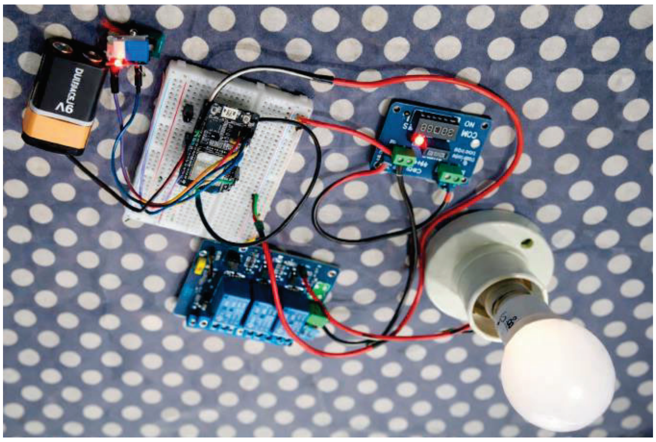

**Figure 9. Output hardware setup of the proposed smart energy monitoring system.**

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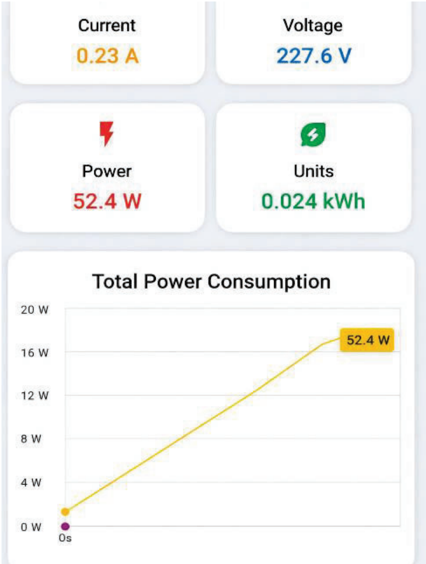


**Figure 10: Dashboard output demonstrating current electrical parameters and corresponding graphical representation for smart energy monitoring.**

## 7. Conclusion

This paper has meticulously presented a comprehensive Smart Energy Monitoring and Control System leveraging the power of IoT, Flutter, and Firebase. The developed system offers robust real-time monitoring of electrical parameters, secure cloud-based data storage, and intelligent, automated control of appliances predicated on user-defined threshold limits. The proposed solution stands out as cost-effective, inherently scalable, and remarkably straightforward to deploy, rendering it ideally suited for deployment in diverse residential and small commercial environments. By enabling precise, automated energy control, the system significantly curtails power wastage, optimizes energy usage patterns, and ultimately champions sustainable energy practices.

## 8. Future Scope and Extensions

The foundational architecture of this system provides a fertile ground for extensive future enhancements and expansions:

- **Appliance-Wise Energy Monitoring:** Implementing individual current and voltage sensors for each major appliance to provide granular, per-appliance energy consumption data and control.

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- **Machine Learning-Based Prediction**: Integrating machine learning algorithms to analyze historical data, predict future energy consumption patterns, identify anomalies, and even suggest optimal usage schedules.
- **Voice Control Integration:** Enabling control of appliances and querying energy data through popular smart assistants like Amazon Alexa or Google Assistant.
- **Integration with Smart Grid Systems:** Exploring interoperability with wider smart grid initiatives to participate in demand-response programs and optimize energy distribution.
- **Advanced Energy Optimization Strategies:** Developing more sophisticated algorithms for energy optimization, such as load shedding based on grid stability or dynamic threshold adjustments based on varying tariffs.
- **iOS Application Development:** Formalizing the Flutter application for full iOS platform compatibility and deployment on the Apple App Store.
- **Load Scheduling Based on Time-of-Use Tariffs:** Implementing intelligent scheduling that automatically shifts high-consumption loads to off-peak hours to take advantage of lower electricity tariffs.

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