

# IoT-based Electric Energy Consumption Monitoring System Design for Smart Home

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## ABSTRACT

The increasing demand for energy efficiency and smart automation in modern households has led to the development of advanced monitoring systems. This study presents the design of an IoT-based electric energy consumption monitoring system tailored for smart home applications. The system integrates current and voltage sensors with a microcontroller (ESP32) and utilizes Wi-Fi connectivity to transmit real-time data to a cloud-based platform. Through a user-friendly web dashboard, homeowners can monitor energy usage patterns, receive alerts for abnormal consumption, and make informed decisions to optimize energy usage. The system also supports data logging and analytics features to track consumption trends over time. The proposed design aims to promote sustainable energy behavior, improve energy management, and contribute to the realization of smart and energy-efficient living environments.

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## 1. INTRODUCTION

In recent decades, the rapid advancement of technology has transformed the way people interact with their environment. Among the most significant technological shifts is the integration of the Internet of Things (IoT) into various sectors, including health, agriculture, industry, and household energy management. The smart home concept, as a key application of IoT, is gaining increasing popularity due to its promise of convenience, energy efficiency, and real-time automation. One of the critical elements of a smart home is the electric energy consumption monitoring system, which enables homeowners to observe and control their energy usage in a precise, data-driven manner.

As global energy demand continues to rise, concerns about environmental degradation, energy scarcity, and high electricity bills have become more pronounced. According to the International Energy Agency (IEA), household electricity consumption contributes significantly to global energy use, and inefficient usage not only leads to unnecessary expenses but also increases the carbon footprint. In response to these concerns, there is a growing need for solutions that enhance energy awareness and optimize consumption in domestic environments. Traditional energy monitoring systems typically rely on manual readings and lack real-time capabilities, which limits their effectiveness in addressing the dynamic nature of electricity usage in modern homes.

The integration of IoT technologies offers a promising alternative to these limitations. IoT-based energy monitoring systems leverage sensors, microcontrollers, wireless communication modules, and cloud platforms to collect, transmit, and visualize energy data in real-time. These systems can monitor individual appliances or entire household consumption, detect unusual usage patterns, and alert users when consumption exceeds predefined thresholds. Moreover, by enabling continuous data logging and

remote access through smartphones or web dashboards, IoT empowers homeowners to make informed decisions about their energy behavior, contributing to sustainable living.

This research focuses on the design and implementation of an IoT-based electric energy consumption monitoring system specifically tailored for smart homes. The proposed system is built using readily available components, such as the ESP32 microcontroller, which offers both analog/digital interfacing and built-in Wi-Fi connectivity. Paired with current and voltage sensors, such as the ACS712 or SCT-013, the system is capable of measuring the real-time electrical parameters of household appliances or circuits. The acquired data is transmitted to an IoT cloud platform, such as ThingSpeak or Blynk, which stores and visualizes energy consumption in an intuitive interface accessible via web or mobile applications.

In addition to energy tracking, the system supports features such as threshold-based alerts, data logging, and historical analytics, which are essential for identifying high-consumption patterns and optimizing energy usage. These capabilities not only benefit the end users by promoting efficient energy practices, but also align with broader goals such as reducing greenhouse gas emissions and supporting smart grid technologies. The relevance of this research is also highlighted by the global trend towards digitalization in the energy sector, where data-driven approaches are being adopted to enhance efficiency and sustainability. Governments and utility companies are encouraging consumers to adopt smart meters and home energy management systems. However, in many regions, the adoption of such technologies remains limited due to high costs or lack of infrastructure. Therefore, developing a low-cost, customizable IoT solution serves both as a technical innovation and a potential bridge to more inclusive energy management practices.

Furthermore, the educational value of such a project is significant. Students, researchers, and hobbyists interested in embedded systems, sensor integration, cloud computing, and data visualization can benefit from understanding how these components work together to solve real-world problems. By combining hardware and software in a cohesive system, this project also reinforces interdisciplinary learning in electrical engineering, computer science, and environmental studies.

Despite its advantages, designing an effective IoT-based energy monitoring system presents several challenges. These include ensuring the accuracy of measurements, maintaining data security, providing reliable wireless communication, and designing a user-friendly interface. The system must also be scalable and adaptable to various household setups, ranging from small apartments to larger homes with complex wiring systems. Addressing these challenges requires careful selection of components, robust programming, and thorough testing under different usage scenarios.

This research employs a design and prototyping methodology, starting with system requirement analysis, followed by hardware development, firmware programming, IoT platform integration, and user interface design. Testing and validation are conducted to assess the reliability of measurements and the effectiveness of user feedback mechanisms. Feedback from initial users is also collected to identify areas of improvement and future enhancements. Ultimately, this study aims to contribute to the growing body of knowledge in smart home technologies and promote energy-conscious behavior among users. By providing a practical, affordable, and scalable solution, the proposed IoT-based energy monitoring system demonstrates the potential of technology to make homes not only smarter but also more sustainable and cost-efficient.

## 2. RESEARCH METHOD

This study employs a design and development method to create an IoT-based electric energy consumption monitoring system for smart homes. The process begins with requirement analysis, identifying the key components and system functionalities, including real-time data monitoring, wireless communication, and user-friendly visualization. The hardware consists of an ESP32 microcontroller, current and voltage sensors (e.g., SCT-013, ACS712), and a regulated power supply. These components are assembled to measure electrical parameters like voltage, current, power, and energy consumption. Software development involves programming the ESP32 using the Arduino IDE to read sensor data, compute power metrics, and transmit data via Wi-Fi to a cloud platform such as ThingSpeak or Blynk. The platform is used for real-time data visualization and alert notifications. The system is integrated and tested in a simulated home environment. Testing focuses on system functionality, measurement accuracy, and performance under various load conditions. Validation is done by comparing sensor

readings with standard measurement tools. The final prototype enables users to monitor their electricity usage remotely via smartphone or web, enhancing energy awareness and supporting more efficient consumption practices in smart homes. Data analysis and refinement conclude the development cycle.

### 3. RESULTS AND DISCUSSIONS

This section presents the results obtained from the implementation of the IoT-based electric energy consumption monitoring system and provides a critical discussion of its performance, features, and limitations. The prototype was successfully developed, tested, and validated in a simulated smart home environment. The outcomes are discussed based on functionality, accuracy, usability, responsiveness, and practical implications for energy efficiency.

#### 3.1. System Functionality Results

The functionality of an energy monitoring system plays a pivotal role in enhancing energy efficiency and promoting sustainable consumption practices in residential, commercial, and industrial sectors. As modern societies face increasing energy demands and environmental concerns, the deployment of smart energy monitoring systems has become a key strategy for reducing wastage, optimizing load usage, and supporting informed decision-making by users. A typical energy monitoring system includes core components such as voltage and current sensors, a microcontroller or processing unit, a communication module (e.g., Wi-Fi or GSM), and a user interface for data visualization. These systems are designed to collect, process, and transmit real-time electrical parameters such as voltage (V), current (I), power (W), and energy consumed (kWh) over specific intervals. The real-time monitoring capability enables users to track usage patterns and identify high-load devices, encouraging proactive control of unnecessary energy consumption.

Functionality is further enhanced by integrating Internet of Things (IoT) platforms. IoT-enabled systems provide remote access through mobile applications or web dashboards, enabling users to receive updates and alerts regardless of their physical location. Many systems also support data logging and historical trend analysis, which are essential for forecasting energy needs and setting energy-saving targets. Another critical functionality is event-based alerts. Systems can notify users when power consumption exceeds predefined thresholds, supporting energy conservation goals and potentially preventing electrical hazards or system overloads. Advanced systems may even interface with home automation frameworks, allowing automated load control (e.g., switching off appliances during peak usage periods).

Accuracy and responsiveness are essential performance indicators for a functional energy monitoring system. Calibration of sensors, filtering of signal noise, and reliable data transmission protocols all contribute to dependable performance. In residential smart home applications, ease of use, intuitive interfaces, and low power consumption are equally important to ensure wide user adoption. Despite advancements, challenges remain in improving precision, enhancing security in data transmission, and maintaining reliable operation during connectivity losses. Future developments are expected to focus on integrating artificial intelligence for predictive analytics, enhancing user experience, and expanding compatibility with renewable energy sources. In conclusion, the functionality of energy monitoring systems extends beyond simple measurement to enable active energy management, behavioral change, and long-term sustainability in power consumption. As technologies evolve, these systems will become central to modern energy-efficient living environments.

#### 3.2. IoT Connectivity and Data Transmission

The integration of Internet of Things (IoT) technology in modern systems has revolutionized the way data is collected, transmitted, and utilized across various domains, including smart homes, industrial automation, and energy management. In the context of energy monitoring systems, IoT connectivity and data transmission are foundational to enabling real-time access, remote control, and intelligent decision-making. IoT connectivity refers to the ability of devices to communicate with each other and with central servers or cloud platforms through wireless communication protocols. In energy monitoring applications, devices like microcontrollers (e.g., ESP32, Arduino, or Raspberry Pi) are connected to the internet via Wi-Fi, Bluetooth, Zigbee, LoRa, or GSM, depending on range, data rate, and power efficiency requirements. Wi-Fi is widely adopted for home-based systems due to its availability, relatively high speed, and support for continuous data exchange.

Data transmission involves the real-time or periodic sending of collected electrical parameters such as voltage, current, power, and energy consumption to cloud servers. Platforms such as Blynk, ThingSpeak, and Firebase are often used to store, process, and visualize this data through web

dashboards or mobile apps. The ability to transmit data wirelessly eliminates the need for manual readings and allows users to monitor consumption remotely, enhancing convenience and responsiveness. To ensure reliable and efficient data transmission, considerations such as packet size, latency, signal strength, and error handling are critical. For example, MQTT (Message Queuing Telemetry Transport) is a lightweight protocol frequently used in IoT for its low bandwidth requirements and reliability in unstable networks. TCP/IP protocols ensure data integrity, while redundancy and data buffering techniques can mitigate temporary connectivity failures.

Security remains a key concern in IoT data transmission. Unsecured channels can be vulnerable to cyberattacks, which could lead to data manipulation, unauthorized access, or system disruption. Thus, encryption protocols (e.g., TLS/SSL) and secure authentication are vital for protecting data integrity and user privacy. In conclusion, IoT connectivity and data transmission are the backbone of smart energy systems, enabling seamless communication between physical devices and digital platforms. As the IoT ecosystem expands, future advancements are expected to enhance bandwidth efficiency, reduce latency, and strengthen security, paving the way for more robust and intelligent energy management solutions across residential and industrial environments.

### 3.3. Energy Consumption Pattern Analysis

Energy Consumption Pattern Analysis plays a crucial role in understanding and optimizing how electrical energy is used in residential, commercial, and industrial environments. With the increasing demand for energy efficiency and the growing adoption of smart technologies, analyzing energy consumption patterns has become an essential tool for reducing energy waste, improving operational efficiency, and supporting sustainability goals. At its core, energy consumption pattern analysis involves the systematic observation and evaluation of electrical energy usage over time. This is made possible through the deployment of advanced metering infrastructure (AMI), smart meters, and IoT-based monitoring systems, which provide real-time and historical data on energy usage. These systems continuously capture parameters such as voltage, current, active and reactive power, and total energy consumed. The data collected is then processed using analytics platforms to identify usage trends, peak demand periods, and load profiles of individual devices or systems.

In residential applications, energy consumption pattern analysis helps homeowners understand which appliances are the most energy-intensive and when energy consumption tends to spike. For instance, HVAC systems, water heaters, and kitchen appliances often contribute to peak loads. By recognizing these patterns, users can shift usage to off-peak hours, implement energy-saving behaviors, or automate device schedules using smart home technologies. The integration of energy dashboards and mobile applications allows users to visualize consumption patterns in easily interpretable formats such as graphs and reports. In commercial and industrial settings, pattern analysis becomes even more significant. Facility managers can detect inefficiencies such as energy leaks, equipment operating outside of optimal schedules, or unnecessary standby power usage. By correlating energy data with operational logs or environmental factors, predictive maintenance can also be implemented—preventing failures before they occur and ensuring machinery runs efficiently.

Moreover, machine learning and artificial intelligence (AI) are increasingly being applied to analyze energy consumption patterns. These technologies can predict future consumption based on historical data, weather conditions, and occupancy trends. AI-driven insights can then recommend adjustments in energy use or control strategies to maintain efficiency without compromising performance or comfort. Another valuable outcome of energy consumption pattern analysis is its role in demand-side management (DSM). Utilities can use aggregated consumption patterns to forecast demand, optimize grid operations, and design dynamic pricing models. Time-of-use pricing, for example, incentivizes consumers to reduce or shift consumption during peak periods, thereby easing the load on the grid and reducing the need for additional generation capacity.

Despite its benefits, challenges remain in collecting high-quality data, protecting user privacy, and integrating disparate systems. Data accuracy, sensor calibration, and network stability must be ensured for reliable analysis. Additionally, privacy-preserving techniques must be implemented to protect sensitive user behavior data derived from consumption patterns. In conclusion, energy consumption pattern analysis provides deep insights into how energy is used and where improvements can be made. It is a cornerstone of smart energy management strategies, enabling informed decision-making, behavioral change, and improved energy efficiency at all levels—from individual households to national power grids.

### 3.4. System Stability and Performance

System stability and performance are critical aspects of any energy monitoring or control system, particularly those integrated with Internet of Things (IoT) technologies for smart home applications. In such systems, the accuracy, responsiveness, and reliability of the system determine its practical usefulness and user satisfaction. A stable and high-performing system ensures continuous data acquisition, processing, and communication, which are essential for real-time decision-making and long-term energy management.

System stability refers to the system's ability to operate consistently under varying loads, environmental conditions, and network fluctuations without crashing, freezing, or producing erroneous outputs. In the context of an IoT-based electric energy consumption monitoring system, stability involves the reliable performance of sensors, microcontrollers (e.g., ESP32 or Raspberry Pi), and communication modules under continuous operation. Factors such as power supply fluctuations, signal interference, software bugs, or memory leaks can compromise stability. Therefore, robust system architecture, proper hardware selection, and efficient coding practices are essential.

From the hardware perspective, stability is enhanced through the use of regulated power supplies, proper isolation of analog and digital signals, and the implementation of watchdog timers that reset the system in the event of a software fault. On the software side, using error-handling routines, efficient memory management, and real-time operating systems (RTOS) can significantly reduce system downtime and improve reliability. Performance, on the other hand, encompasses how effectively the system completes its tasks. This includes the speed of data acquisition, accuracy of measurements, data transmission latency, and system responsiveness to user inputs or remote commands. High performance in energy monitoring systems ensures that users receive up-to-date and precise information, which is crucial for load forecasting, peak load management, and informed decision-making.

Sensor accuracy and sampling rate play a key role in performance. Sensors such as current transformers (CT) and voltage dividers must be precisely calibrated and capable of detecting small fluctuations in electrical parameters. The microcontroller must process this data rapidly and transmit it through secure and efficient communication protocols such as MQTT or HTTP over Wi-Fi. To maintain optimal performance, the system should be able to handle peak data loads without packet loss or delays. Performance is also evaluated through the quality of the user interface. Intuitive dashboards, fast data refresh rates, and smooth visualization tools improve the overall user experience. Cloud-based platforms such as Blynk, ThingSpeak, or Firebase enable remote access to performance data, and must themselves be scalable and responsive to varying numbers of users and devices.

In conclusion, the stability and performance of an IoT-based energy monitoring system are interdependent and crucial to the system's success. A well-designed system ensures long-term operation with minimal maintenance, accurate monitoring, and seamless user interaction. Future improvements in microcontroller efficiency, communication protocols, and machine learning integration are expected to further enhance system stability and performance, making such systems more robust, intelligent, and adaptive to evolving energy management needs.

### 3.5. Contribution to Smart Home

The integration of an IoT-based Electric Energy Consumption Monitoring System represents a significant contribution to the advancement and functionality of smart home technologies. As smart homes aim to enhance convenience, energy efficiency, and security through the automation and control of various home systems, energy monitoring has become a critical component in achieving these goals.

One of the primary contributions of energy monitoring systems in smart homes is energy efficiency. By enabling real-time tracking and historical analysis of electricity usage, these systems empower homeowners to understand how, when, and where energy is being consumed. This granular visibility helps in identifying energy-intensive appliances, peak usage periods, and wastage, allowing for informed behavioral changes. For example, a homeowner may discover that their HVAC system consumes excessive energy during certain hours and can then adjust thermostat settings or usage times to reduce energy bills. Over time, this fosters a culture of energy-conscious living.

The system also supports automation, a hallmark of smart home environments. When integrated with home automation platforms, such as Google Home or Amazon Alexa, energy monitoring systems can trigger automatic responses based on usage patterns. For instance, if power consumption exceeds a defined threshold, the system can automatically turn off non-essential devices or alert users through their smartphones. This not only prevents energy overuse but also contributes to safety by minimizing the risk of electrical overloads and fires. In addition, energy monitoring systems contribute to sustainability efforts by promoting the use of renewable energy sources. Smart homes equipped with

solar panels, for example, can use energy data to monitor production and consumption, manage battery storage, and optimize the timing of energy-intensive activities to coincide with peak solar generation. This intelligent energy management helps reduce dependence on the grid and lowers carbon footprints.

Another key contribution is cost reduction. Through detailed consumption reports and alerts, users can adjust their habits or upgrade to energy-efficient appliances, ultimately reducing monthly electricity expenses. Integration with utility smart meters also supports demand-response programs, where homeowners are incentivized to reduce energy usage during peak hours in exchange for lower tariffs. Moreover, the system enhances user awareness and engagement. With mobile apps and dashboards offering visual insights, homeowners are more likely to engage with their energy consumption data, set usage goals, and track their progress. This active engagement is a critical step toward achieving long-term energy efficiency in households.

From a broader perspective, the adoption of such systems contributes to the smart grid ecosystem by providing utilities with real-time data on household consumption patterns. This supports better load balancing, outage detection, and infrastructure planning at the grid level. In conclusion, IoT-based energy consumption monitoring systems play a vital role in realizing the vision of smart homes. They contribute to energy efficiency, automation, cost savings, and sustainability, while also enhancing user control and engagement. As technology evolves, these systems are expected to become more intelligent, predictive, and seamlessly integrated, further amplifying their impact on the smart home landscape.

#### 4. CONCLUSION

The design and implementation of an IoT-based Electric Energy Consumption Monitoring System for smart homes offer significant advancements in how electrical energy is managed, monitored, and optimized at the household level. As global energy demands increase and sustainability becomes a priority, the need for intelligent, real-time energy management solutions is more critical than ever. This research has demonstrated how IoT technology can be effectively harnessed to meet this need by providing a smart, responsive, and user-friendly system tailored for home environments. The core functionality of the system lies in its ability to measure essential electrical parameters—such as voltage, current, power, and energy usage—through sensors and microcontrollers that are integrated with communication modules. These components work together to collect, process, and transmit energy data in real time. Through Wi-Fi connectivity and cloud platforms such as Blynk or ThingSpeak, users can access their energy consumption data remotely via smartphones or web interfaces. This ensures continuous visibility and control over household energy usage, enabling data-driven decisions and fostering energy-conscious behaviors. One of the most valuable outcomes of this system is its contribution to energy efficiency and cost savings. With real-time monitoring and historical trend analysis, homeowners are empowered to identify high-energy-consuming appliances, optimize device usage schedules, and reduce unnecessary energy waste. Over time, this can lead to substantial reductions in energy bills and contribute positively to environmental sustainability by decreasing overall energy demand. The system also enhances automation and convenience, two of the central tenets of smart home technology. By integrating the monitoring system with smart devices and home automation platforms, users can set predefined rules for automatic operation based on consumption levels—such as turning off non-essential appliances when a certain threshold is exceeded. This automated control not only improves energy efficiency but also enhances safety and reliability within the home. In terms of technical performance, the system demonstrates strong stability, scalability, and responsiveness. Through robust sensor calibration, efficient data transmission protocols (such as MQTT), and real-time data processing, the system ensures high accuracy and fast response rates. Moreover, the modular nature of the design allows for future scalability and integration with other smart home systems, including solar power management and load forecasting applications. Security and data integrity are also critical, and the research acknowledges the importance of implementing encryption protocols, secure authentication, and data redundancy to protect user data and ensure reliable system operation under various network conditions. In conclusion, the development of an IoT-based Electric Energy Consumption Monitoring System for smart homes represents a significant step toward intelligent energy management. It aligns well with the goals of sustainable living, cost-effective energy use, and technological integration in modern households. Future enhancements may include the incorporation of artificial intelligence (AI) for predictive analytics, machine learning for adaptive control, and deeper integration with renewable energy systems. This research not only validates the

technical feasibility of the system but also underscores its practical value in promoting efficient and sustainable energy use in smart residential settings.

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