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Design and implementation of an iot-based energy consumption monitoring system in smart homes

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ABSTRACT

The development of Internet of Things (IoT) technology provides great opportunities for creating efficient and integrated smart home systems. This study aims to design and implement an IoT-based energy consumption monitoring system to improve the efficiency of electricity use in households. The developed system consists of a current sensor, an ESP32 microcontroller, and a cloud platform as a medium for data storage and visualization. The sensors will read energy consumption from various electrical appliances in real time, then send the data to the server using a Wi-Fi connection. The data is analyzed and displayed in a web-based interface so that users can monitor and control energy consumption remotely. The research methods include system design, hardware and software development, and system testing in a real home environment. The implementation results show that the system can record energy consumption with high accuracy and provide notifications in case of unusual spikes in usage. Users can also access daily, weekly, and monthly consumption data history. With this system, homeowners can make data-driven decisions to save energy and reduce electricity costs. In conclusion, this IoT-based monitoring system is effective in supporting the concept of an energy-efficient and environmentally friendly smart home.

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1. INTRODUCTION

In the 21st century, the rapid advancement of digital technologies has significantly influenced various aspects of human life, particularly in the areas of automation, control, and connectivity. Among the most transformative trends is the Internet of Things (IoT), which refers to a network of interconnected physical devices embedded with sensors, software, and other technologies to exchange and analyze data with minimal human intervention. IoT has become a foundational element in modern technological ecosystems, enabling real-time monitoring, remote control, and intelligent decision-making across multiple domains, including healthcare, agriculture, manufacturing, transportation, and especially residential environments.

One of the most promising applications of IoT is in the development of smart homes, where everyday appliances and systems are integrated into a centralized network to enhance comfort, security, efficiency, and sustainability. Smart homes leverage the capabilities of IoT to offer automated control over lighting, heating, ventilation, air conditioning (HVAC), security systems, and household appliances. Among these features, energy management stands out as a critical aspect, considering the growing global concerns about energy scarcity, rising electricity costs, and environmental sustainability. Energy consumption in residential sectors constitutes a substantial portion of global electricity usage. According to the International Energy Agency (IEA), residential buildings account for nearly 20–30% of total energy consumption in many developed and developing countries. Much of this consumption is inefficient due to outdated appliances, poor user behavior, and lack of real-time awareness of energy usage patterns. In response, there is an increasing demand for systems that not only automate energy control but also monitor, analyze, and optimize energy consumption in real time.

Despite advancements in smart home technologies, many residential users remain unaware of their energy consumption behavior. Conventional energy meters only provide cumulative consumption data, typically at the end of billing cycles, offering little insight into detailed usage patterns of individual appliances or real-time monitoring capabilities. This lack of transparency often leads to energy wastage and higher electricity bills. Moreover, in many households, energy consumption spikes during certain periods of the day due to the simultaneous use of high-power devices such as air conditioners, water heaters, washing machines, and kitchen appliances. Without proper monitoring and analytical tools, residents have limited ability to identify these trends or adjust their behavior accordingly. Furthermore, in the absence of automated or semi-automated systems, controlling and reducing energy consumption remains largely a manual and reactive process.

The need for a cost-effective, scalable, and real-time monitoring system that enables residents to visualize, understand, and manage their energy consumption is therefore evident. Integrating such systems into smart homes using IoT technology presents a viable and practical solution to this issue. However, designing and implementing an IoT-based energy monitoring system that is affordable, user-friendly, and accurate requires a careful balance between hardware efficiency, software integration, data security, and user interface design. The significance of this research lies in its potential contribution to energy efficiency and sustainability in residential settings. As the world increasingly faces the dual challenges of rising energy demand and environmental degradation, small yet impactful technological interventions in everyday settings can play a major role. The ability to monitor and control household energy consumption in real time empowers users to reduce waste, lower electricity costs, and contribute to broader environmental goals.

From a technological perspective, this study contributes to the growing body of knowledge on IoT system design, particularly in the domain of smart energy management. It demonstrates the integration of low-cost hardware (e.g., microcontrollers and sensors) with open-source software platforms and cloud technologies to create a reliable, real-time monitoring system. Moreover, the findings of this research can serve as a foundation for further development of predictive energy optimization systems, integration with renewable energy sources, and advanced home automation. On a societal level, promoting energy literacy through technology can foster more responsible consumption habits. Providing users with meaningful and actionable insights into their electricity usage promotes behavior change and encourages a culture of energy mindfulness. The proposed system also has potential implications for utility providers and policymakers seeking to implement demand-side energy management strategies and incentive programs.

This research focuses on the design and implementation of an IoT-based system for energy consumption monitoring in smart homes. The scope includes hardware selection and configuration, software development, data communication protocols, cloud storage integration, and visualization through a web or mobile interface. The study emphasizes real-time monitoring, historical data analysis, and alert systems. The system is designed primarily for small-to-medium residential environments and may not scale optimally to large buildings or commercial settings without further modifications. The current implementation focuses on monitoring rather than control of energy-consuming devices, although future versions may integrate automated control capabilities. External factors such as network connectivity, power outages, and sensor calibration may affect system performance. The study does not include economic analysis such as return on investment (ROI) or cost-benefit analysis in different geographic or socioeconomic contexts. Data privacy and cybersecurity considerations are acknowledged but not addressed in depth in this initial prototype.

In recent years, numerous studies have been conducted on smart energy systems leveraging IoT technologies. Many researchers have explored the use of microcontrollers such as Arduino, ESP8266, and ESP32 for monitoring household energy use. For example, systems employing current sensors (e.g., ACS712 or CT sensors) in conjunction with cloud platforms such as Firebase, ThingSpeak, or AWS IoT have shown promising results in real-time energy tracking and visualization. Other studies have proposed the integration of machine learning algorithms for predictive analytics and optimization in energy consumption. While such advanced functionalities are valuable, they often require higher processing power and complex data models, which may not be suitable for low-cost home systems.

Commercial solutions, such as smart plugs and energy monitoring devices (e.g., Sense, Neurio, and TP-Link Kasa), are available in the market, but they are often expensive or limited in customization. Furthermore, many of these systems require proprietary software and infrastructure, which restricts flexibility for research and development. Thus, there is a clear need for open-source, modular, and cost-effective solutions that can be tailored to diverse household environments and user preferences. This research builds upon existing knowledge while aiming to address current gaps in accessibility, scalability, and user-centered design in smart home energy monitoring.

2. RESEARCH METHOD

This research employs a design-based engineering methodology that integrates both hardware and software development processes to create a functional prototype of an IoT-based energy consumption monitoring system tailored for smart homes. The methodology consists of five key stages: requirement analysis, system design, development, testing, and evaluation. The study begins with identifying system requirements through a literature review and benchmarking existing smart energy systems. Key functional requirements include real-time data acquisition, wireless transmission, cloud storage, user interface visualization, and data logging. Non-functional requirements such as system accuracy, scalability, affordability, and ease of use are also considered. Based on the requirements, a system architecture is designed comprising three core components: (a) sensing module using current sensors (e.g., ACS712 or SCT-013), (b) processing and communication module using ESP32 microcontroller for data processing and Wi-Fi connectivity, and (c) cloud platform for real-time data storage and visualization (e.g., Firebase or ThingSpeak). The data flow and communication protocols (MQTT/HTTP) are defined at this stage. The hardware is assembled, and firmware is developed using Arduino IDE. Sensor calibration is performed to ensure measurement accuracy. The frontend dashboard is created using a web-based interface with real-time data visualization features, including graphs, alerts, and energy usage summaries. The system is deployed in a simulated smart home environment to monitor actual appliances. Data is collected over several days to evaluate system performance, including accuracy, latency, and reliability. Benchmarking is conducted by comparing with conventional energy meters.

3. RESULTS AND DISCUSSIONS

3.1. Overview of System Implementation

The proposed IoT-based energy consumption monitoring system was successfully designed, developed, and deployed in a controlled smart home environment for testing. The system comprised a set of calibrated current sensors (SCT-013), an ESP32 microcontroller for data processing and transmission, and a Firebase cloud platform for data storage and visualization. A custom web dashboard was also developed to enable real-time energy monitoring, device-level tracking, and historical data analysis.

The implementation process proceeded as follows: Each sensor was connected to a major appliance (e.g., refrigerator, air conditioner, washing machine, lighting system). The ESP32 collected analog data from the sensors, converted it to digital format, and transmitted it to the cloud every 5 seconds. The cloud platform aggregated the data, timestamped each record, and provided APIs for data retrieval. The web dashboard visualized total and per-device energy usage, daily/weekly summaries, and alert notifications for unusual consumption patterns. This section discusses the performance of the system across several key dimensions: measurement accuracy, real-time responsiveness, system stability, user interaction, and energy-saving potential.

3.2. Measurement Accuracy

Table 1. Measurement Accuracy

Appliance	Wattmeter (W)	IoT System (W)	Error (%)
Refrigerator	142	138	2.81
Air Conditioner	1050	1035	1.42
Washing Machine	480	465	3.12
Lighting System	90	88	2.22
Microwave Oven	1200	1183	1.42

The average deviation was 2.2%, which is acceptable for household energy monitoring purposes. These results demonstrate that the current sensors, once calibrated properly, are reliable for practical energy measurement in smart homes. Slight deviations were mainly caused by fluctuations in voltage, temperature drift in sensors, and ADC resolution limitations.

3.3. Real-Time Monitoring and Data Transmission

Real-time responsiveness was tested by observing the system's ability to reflect changes in energy consumption immediately after switching appliances on or off. On average, the delay between an event (e.g., appliance being turned on) and its reflection in the dashboard was 3.7 seconds, depending on the Wi-Fi signal strength and cloud server latency. The data flow was handled via MQTT protocol for minimal overhead, and Firebase Realtime Database enabled seamless streaming of updates to the dashboard. Even during high-frequency data transmission (every 2 seconds), the system maintained stability with no data loss or buffer overflow on the ESP32. Real-time graphs, power usage alerts, and notification features functioned reliably across different test conditions.

The custom dashboard was built using React.js and integrated with Firebase APIs to fetch and display energy data. Features included: Real-time current and voltage display per appliance., Daily and weekly consumption summaries (in kWh), Pie chart showing percentage contribution of each device to total usage, Alert popups and email notifications for threshold breaches, Toggle view between "live" mode and "historical" mode, A usability test was conducted with 10 household users, who were asked to interact with the dashboard for a week. A post-test survey using the System Usability Scale (SUS) yielded an average score of 84.5, indicating high usability, Users particularly appreciated the ability to identify which appliances consumed the most energy and reported being more conscious of their electricity usage as a result.

The system stored data in 5-second intervals, aggregated into hourly and daily logs. Over a two-week deployment, the following trends were observed: Peak consumption occurred between 6 PM and 9 PM due to lighting and kitchen appliance use. The air conditioner was the single largest contributor to energy use (32.8%), followed by the washing machine (18.5%) and refrigerator (14.3%). Weekends showed higher consumption, especially in households with more occupants during the day. Using this data, the dashboard recommended behavioral changes, such as shifting laundry usage to off-peak hours and limiting simultaneous high-load device usage. Users who followed these recommendations reported 5–12% lower daily energy consumption in the second week.

3.4. Comparative Analysis

The performance of the proposed system was compared with two commercial smart energy monitoring products.

Table 2. Comparative Analysis

Feature	Proposed System	TP-Link Kasa Smart Plug	Sense Energy Monitor
Appliance-Level Monitoring	Yes	Limited (per plug only)	Yes
Real-Time Data Interval	5 sec	~60 sec	2–5 sec
Cloud Integration	Firebase	Proprietary	Proprietary
Cost per Node (USD)	~$15	~$30	~$300 (whole home)
Open-Source Customization	Full	None	Limited

While commercial products offer higher plug-and-play convenience, they are often less flexible and significantly more expensive. The proposed system provides a balance between affordability, accuracy, and customization for research or personal use.

3.5. Impact on User Behavior and Energy Awareness

A key objective was to evaluate whether real-time monitoring affects user behavior. Interviews and surveys showed that: 90% of users checked the dashboard at least once per day, 80% stated that they became more conscious of their energy use, 60% reported changing usage patterns, such as unplugging unused devices or reducing A/C use, 40% enabled daily email alerts to track trends. These findings support the behavioral aspect of smart energy systems-not only do they provide data, but they also promote awareness and action.

Despite the success of the implementation, several technical and practical challenges were encountered: Sensor Calibration Drift: Some current sensors exhibited drift over time and required periodic recalibration. Wi-Fi Stability: In areas with weak signals, packet loss occurred, affecting data continuity. Data Synchronization: Timestamp mismatches occurred occasionally due to device RTC (Real-Time Clock) discrepancies, which were later corrected using NTP servers. User Interface Scaling:

On mobile devices, the dashboard layout required additional optimization for usability. These challenges were mitigated through firmware updates, error-handling routines, and frontend improvements.

Discussion

The implementation of an IoT-based energy consumption monitoring system for smart homes has revealed several key insights into the feasibility, reliability, and practical utility of integrating low-cost IoT solutions into residential energy management. The results of this research demonstrate that the system successfully achieved its objective of enabling real-time monitoring of household energy use, providing users with actionable insights, and promoting energy-efficient behaviors. One of the most significant findings is the system's measurement accuracy, with an average deviation of approximately 2.2% compared to a commercial wattmeter. This level of accuracy is acceptable for non-critical residential applications and validates the use of SCT-013 current sensors in low-voltage settings when properly calibrated. The use of the ESP32 microcontroller, known for its built-in Wi-Fi and sufficient processing power, proved to be an effective and cost-efficient choice for real-time data acquisition and transmission.

The system's real-time monitoring capability, with a response delay of around 3–5 seconds, ensures that users receive timely updates on their energy usage. The integration of Firebase as the cloud platform enabled fast and reliable data synchronization, while the use of a web-based dashboard offered users an accessible and visually intuitive means of understanding their energy patterns. Beyond technical performance, the system had a measurable impact on user behavior. A majority of participants reported increased awareness of their energy consumption, with some adjusting their appliance usage to avoid peak hours or high-load simultaneous usage. These behavioral changes led to a noticeable reduction in daily energy usage-up to 10% in some cases-demonstrating that real-time feedback can act as a catalyst for conservation efforts.

Compared to commercial solutions, the proposed system offers a compelling balance between affordability, customizability, and functionality. While some commercial devices provide appliance-level monitoring and sleek user interfaces, they are often expensive, proprietary, and not open to customization. In contrast, the system presented in this study is open-source, modular, and cost-effective, making it especially suitable for further academic research or deployment in low- to middle-income settings. Despite its success, the research also identified several technical challenges, including sensor drift, occasional Wi-Fi disruptions, and timestamp mismatches. These issues were mitigated through software-based recalibration, watchdog timers, and time synchronization protocols, but they highlight areas for future refinement. Additionally, while the system currently supports monitoring, future iterations could incorporate control functions-such as turning devices on/off remotely-to increase its utility within home automation ecosystems. In summary, the research confirms that a well-designed IoT-based monitoring system can contribute meaningfully to household energy management. By providing accessible and real-time data, such systems empower users to become more informed and responsible energy consumers. Furthermore, the open-source nature of the system supports ongoing development and adaptation, ensuring its relevance in evolving smart home environments.

4. CONCLUSION

This research successfully designed and implemented an IoT-based energy consumption monitoring system tailored for smart home environments. Through the integration of low-cost sensors, the ESP32 microcontroller, cloud services (Firebase), and a user-friendly web dashboard, the system demonstrated the feasibility and effectiveness of real-time energy monitoring in residential settings. The system achieved a high degree of accuracy in measuring appliance-level energy usage, with an average deviation of only around 2.2% compared to standard wattmeters. Real-time responsiveness was consistently maintained, with minimal delay between changes in appliance status and their reflection in the dashboard. These performance metrics indicate that the proposed solution is technically sound for continuous residential energy tracking. One of the most valuable outcomes of this study was its impact on user behavior. By providing clear and immediate feedback on energy consumption, the system encouraged users to become more aware of their usage patterns. As a result, many participants reported improved energy-saving habits and a measurable reduction in electricity usage during the study period. This demonstrates the system's potential not only as a monitoring tool but also as a behavioral change agent that supports energy conservation at the household level. Furthermore, the system was developed with a strong emphasis on affordability, flexibility, and open-source accessibility. These qualities make it a viable solution for broader deployment, particularly in developing regions or among households with limited access to commercial smart energy products. Unlike many proprietary systems, this research offers a platform that can be customized, scaled, and integrated with additional functionalitiessuch as device control, predictive analytics, or renewable energy management. Nevertheless, several limitations were identified, including occasional connectivity issues, sensor drift, and the lack of remote control capabilities. These limitations provide opportunities for future development and refinement, such as the integration of smart switching, AI-driven energy forecasting, and enhanced data security measures. In conclusion, the research highlights the practical value of IoT in enhancing residential energy efficiency. The proposed system not only meets current needs for monitoring and visualization but also lays the foundation for more intelligent, autonomous, and sustainable smart home energy systems in the future..

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