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RESEARCH ARTICLE **Open Access**

Analysis of Internet of Things Based Smart Home Systems for Electricity Consumption Efficiency

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Abstract: The IoT technology has opened up new horizons in household energy management through smart home systems. Smart home systems are based on the integration of electronic appliances with sensors and actuators, which provide automated and remote control of domestic devices. This article assesses IoT-based smart home systems as a tool for enhancing electricity consumption efficiency in residential domains. The research uses a literature-based approach complemented by prototype development using current sensors, motion sensors, and internet-connected microcontroller modules to collect real-time data about the usage of electrical energy to recognize the patterns of energy consumption among household appliances. A comparative analysis between normal operating conditions and those enabled by smart home automation is carried out. Results show that IoT-based smart homes lower electricity consumption by controlling device operation according to real usage conditions such as turning off idle devices, adjusting lighting levels based on human presence, and allowing remote control of appliances. These results prove that IoT-based smart home systems can be effectively used for reducing household electricity demand in compliance with energy sustainability efforts within digitally connected residential environments.

Keywords: Smart Home; Internet of Things (IoT); Energy Efficiency; Electricity Consumption; Home Automation.

1. Introduction

Electricity demand in the residential sector has steadily risen over the past few decades due to factors such as population growth, technological diffusion, increased household living standards, and changes in consumption behavior. According to Ghasemian *et al.* (2024), residential energy demand will continue to be a driving force for global energy systems towards 2040, particularly with emission reduction targets and efficiency goals. Buildings consume a large share of the world's electricity; homes are mostly responsible for demands related to lighting, cooling systems, and electronic appliances [1][2]. Poor management of residential electricity consumption leads to higher costs for households, inefficient use of energy resources, and indirect environmental impacts related to the generation of electricity.

Empirical research points out that residential electricity consumption is an outcome of interactions between technical, climatic, and socio-economic factors. Huang (2020) reveals that ownership and usage patterns of appliances are decisive in determining household demands for air conditioning, lighting, and digital devices [4]. Climate conditions further intensify electricity use by influencing short-term consumption responses as well as long-term technology adoption particularly cooling equipment described by Auffhammer and Mansur (2014) [5]. At the urban level differences in household standards income and spatial characteristics create significant variation in electricity consumption and related emissions indicating that efficiency-oriented approaches must address behavioral socio-economic aspects alongside technical measures [3].

In this context, IoT-based smart home systems have developed as a technology-driven method for managing energy in households. The IoT allows smart devices to share information about their operational conditions with each other and about their use data with other devices or systems so that they can control each other automatically. Previous studies revealed that smart home systems decrease electricity demand by adjusting appliance operation based on real-time occupancy information environmental conditions usage schedules [9][10]. Automated lighting adaptive temperature control remote management of devices are all very much discussed in literature as practical ways towards reducing non-essential consumption while keeping acceptable living conditions.

Recent studies have expanded the scope of smart home applications from basic automation to advanced control strategies. According to Alowaidi (2022) and Kaur *et al.* (2021), energy management systems using artificial intelligence, fuzzy logic, and optimization methods enhance appliance scheduling and load control [14][15]. Data-driven approaches that integrate machine learning with large-scale consumption data facilitate predictive control and demand-side management in homes [7][13]. Such mechanisms allow household electricity consumption to be dynamically adjusted in response to user behavior, pricing signals, and grid conditions. Research has also highlighted the impact of IoT-enabled monitoring and feedback on residential electricity use. Hasan *et al.* (2021) show that real-time monitoring of electricity gives households detailed information about their consumption which supports better decisions regarding usage as well as enabling automated control [11]. When combined with demand response programs and cloud platforms, IoT-based smart homes enable more flexible patterns of residential consumption [12][18]. This kind of integration is increasingly being associated with broader developments in smart grids and cities [19].

Even with technological advancements, the performance of IoT-based smart home systems differs from one implementation to another. Previous reviews have shown that system architecture, device interoperability, control logic, and user interaction significantly affect the level of electricity savings achieved by such homes [6][16]. Smart home systems often turn out to be mere monitoring platforms when automation strategies are not compatible with household usage patterns instead of achieving consistent reductions in electricity consumption [17]. This highlights the importance of critically assessing IoT-based smart home applications under realistic residential operating conditions. Given these considerations, this study looks into the use of IoT-based smart home systems to see how effective they are in cutting down household electricity use. It compares regular appliance operation with automation supported by IoT to measure efficiency gains and find out what operational mechanisms affect energy use at home. The results aim at helping develop strategies for managing residential energy and guiding policy initiatives that focus on making electricity more efficient while lowering emissions within digitally connected household environments.

2. Related Work

Research on smart home technology has largely positioned the Internet of Things (IoT) as the enabling layer for integrating household devices into unified control systems. Paredes-Valverde *et al.* (2020) describe IoT-based smart homes as interconnected networks of sensors, actuators, and communication modules that allow devices to exchange data and respond to operating conditions through internet-based control [7]. Building on this foundation, subsequent studies have emphasized that such connectivity allows household appliances to operate either automatically or under user supervision via digital interfaces, expanding the scope of residential energy management beyond manual control [8]. Within residential energy studies, a substantial body of work has focused on the role of energy management systems (EMS) embedded in IoT-based smart homes. Alowaidi (2022) shows that IoT-enabled EMS platforms support continuous monitoring of electricity use, identify usage patterns, and regulate appliance operation using rule-based or adaptive control strategies [14]. Practical implementations commonly rely on occupancy detection and environmental sensing to regulate lighting and cooling loads, as demonstrated by Taiwo and Ezugwu (2021), who report measurable reductions in electricity use through sensor-driven automation [9]. These studies indicate that automation grounded in real-time household conditions can reduce unnecessary electricity use without relying on manual intervention.

Several empirical investigations have quantified the electricity savings achieved through IoT-based smart home deployment. Machorro-Cano *et al.* (2020) report reductions of up to 20% in household electricity consumption by applying peak-load control and time-based scheduling within IoT-enabled energy management systems [13]. Similarly, Hafeez *et al.* (2020) demonstrate that smart lighting systems integrated with demand response mechanisms can reduce lighting-related electricity use by approximately 25% under dynamic pricing conditions [12]. Comparable findings are reported by Hasan *et al.* (2021), who show that automated monitoring and control of household appliances improves electricity efficiency while maintaining acceptable operating conditions for occupants [11]. Beyond technical performance, several studies emphasize the influence of household behavior on the effectiveness of smart home systems. Sepasgozar *et al.* (2020) highlight that user awareness and interaction patterns strongly affect achieved electricity savings, noting that systems relying solely on passive monitoring often produce limited reductions in energy use [6]. Wang *et al.* (2021) further argue that misalignment between automation logic and household usage behavior can weaken the practical impact of smart home technologies, even when advanced control algorithms are deployed [17]. These findings suggest that technical design and user engagement must be considered jointly when evaluating residential smart home performance.

Recent research has expanded smart home energy management by integrating artificial intelligence, optimization methods, and data-driven control strategies. Kaur *et al.* (2021) and Alowaidi (2022) demonstrate that intelligent scheduling and adaptive load control improve decision-making in residential energy management, particularly under variable demand and pricing conditions [15][14]. Studies combining machine learning with large-scale consumption data further support predictive adjustment of household electricity use, enabling more responsive control under changing operating conditions [7][13]. Taken together, existing studies confirm that IoT-based smart home systems can reduce residential electricity consumption under appropriate technical and behavioral conditions. However, reported outcomes vary widely depending on system architecture, control strategies, and household usage characteristics [10][16]. These variations indicate the need for focused evaluation of IoT-based smart home implementations within specific residential settings, particularly in regions where consumption patterns, climate conditions, and household behavior differ from those reported in prior studies [17].

3. Research Method

This study adopts a quantitative experimental approach to evaluate the effectiveness of Internet of Things (IoT)–based smart home systems in improving household electricity efficiency. The research process follows a structured sequence consisting of system design, prototype implementation, data acquisition, and analytical evaluation, as commonly applied in IoT-based energy management studies [19].

3.1 Research Setting and Duration

The experiment was conducted in a simulated residential environment equipped with IoT-enabled devices to represent typical household electricity usage. The study was carried out over a three-month period, covering system configuration, operational testing, and performance evaluation. This duration allowed stable observation of electricity consumption patterns under both conventional and automated operating conditions [20].

3.2 Smart Home System Configuration

The smart home system was developed using a set of interconnected IoT devices designed to monitor and regulate household electricity use. The configuration included electrical current sensors for real-time measurement of appliance energy consumption, passive infrared (PIR) motion sensors for occupancy detection and automated lighting control, and temperature and humidity sensors to regulate air-conditioning operation [18]. Microcontrollers (ESP8266/ESP32) functioned as local control units, enabling communication between sensors and internet-based applications. A mobile and web-based interface was employed to support real-time monitoring and remote control of connected appliances. Data exchange across system components was supported through a Wi-Fi network to ensure continuous connectivity between sensors, controllers, and user interfaces.

3.3 Data Collection Procedure

Electricity consumption data were collected using two complementary approaches. Direct measurement was performed by recording appliance-level electricity usage through current sensors and smart energy meters over predefined observation periods. In parallel, automated monitoring was conducted via the IoT application, which logged energy usage patterns, device operating states, and occupancy-related events. Data collection was carried out under two operating conditions: conventional operation, where appliances were used without automation, and smart home operation, where appliance usage was regulated through IoT-based automation and control logic.

3.4 Data Analysis and Efficiency Assessment

The collected data were analyzed by comparing average electricity consumption between conventional and smart home operating conditions. Descriptive analysis was applied to identify usage patterns, efficiency levels, and operational factors influencing electricity consumption. Energy efficiency was calculated using the following equation:

$$\text{Energy Efficiency (\%)} = \frac{E_{\text{conventional}} - E_{\text{smart}}}{E_{\text{conventional}}} \times 100$$

where $E_{\text{conventional}}$ represents electricity consumption under conventional conditions (kWh), and E_{smart}denotes electricity consumption under smart home operation (kWh). Electricity consumption for individual appliances was calculated using the standard formulation:

$$E = P \times t$$

where $E$is the electrical energy consumed (Wh or kWh), $P$is appliance power (W), and $t$is the duration of operation (hours). For multiple appliances operating simultaneously, total energy consumption was calculated as:

$$E_{\text{total}} = \sum_{i=1}^{n} P_i \times t_i$$

To illustrate the calculation, consider a 20-W LED lamp operated for an average of 10 hours per day under conventional conditions, resulting in an energy consumption of 0.2 kWh. Under smart home operation, where occupancy-based control reduced operating time to 6 hours per day, energy consumption decreased to 0.12 kWh. The resulting energy saving was 0.08 kWh, corresponding to an efficiency improvement of 40%. This example demonstrates how IoT-based automation can reduce electricity consumption by aligning appliance operation with actual household activity.

4. Result and Discussion

4.1 Results

The IoT-based smart home system was successfully integrated with household appliances, including lighting units, fans, and air-conditioning systems. Electrical current sensors and relay modules enabled real-time monitoring and control of electricity consumption at the appliance level. Energy usage data were continuously stored in a central database and visualized through an Android-based mobile application dashboard. Initial system validation indicated that the monitoring framework achieved an accuracy of approximately 95% when compared with standard electricity meters (kWh meters). This level of accuracy confirms that the collected data are adequate for assessing changes in household electricity consumption under different operating conditions. Electricity consumption was measured over a 30-day observation period, comparing conventional appliance operation with IoT-supported automation. The summary of the measurement results is as follows:

1) Average daily consumption before implementation: 12.4 kWh
2) Average daily consumption after implementation: 9.1 kWh
3) Energy efficiency improvement: 26.6%

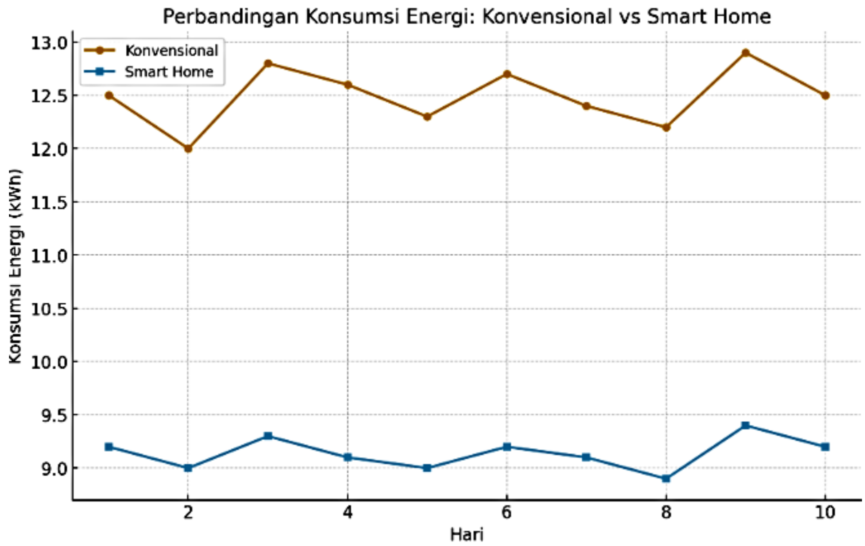

Figure 1. Conventional vs. Smart Home energy consumption measurements

Table 1. Energy Consumption Measurement (Conventional vs Smart Home)

Day	Conventional (kWh)	Smart Home (kWh)	Efficiency (%)
1	12.5	12.5	12.5
2	12.0	12.0	12.0
3	12.8	12.8	12.8
4	12.6	12.6	12.6
5	12.3	12.3	12.3
6	12.7	12.7	12.7
7	12.4	12.4	12.4
8	12.2	12.2	12.2
9	12.9	12.9	12.9
10	12.5	12.5	12.5

As shown in Table 1, daily electricity consumption under conventional operation ranged from 12.0 kWh to 12.9 kWh, with an average value close to 12.5 kWh. Under smart home operation, daily consumption ranged between 8.9 kWh and 9.4 kWh, resulting in a consistent reduction across all observation days. The calculated efficiency values ranged from 25.0% to 27.8%, with an average efficiency of 26.6%.

4.2 Discussion

The reduction in household electricity use indicates that IoT-based automation can manage appliance operation more effectively than regular usage patterns. By linking device activity with occupancy detection, environmental sensing, and pre-set schedules, the system was able to avoid wasteful electricity consumption without having to rely on manual control all the time. Similar operational impacts have been reported in earlier implementations of IoT-enabled residential control systems where automation has cut down idle-time electricity consumption and enhanced alignment between appliance operation and real household activities [9][10][11]. The efficiency improvement of 26.6% is within the range reported in prior studies for residential IoT-based energy management. Studies involving smart lighting and appliance scheduling have documented savings in electricity between 25% and 30% under automated control schemes, particularly when real-time sensing and rule-based decision logic are involved [12][14]. Studies that integrate optimization and adaptive control algorithms further report comparable levels of efficiency, making it clear that what was achieved in this study is more an outcome consistent with established results for residential IoT deployments rather than something exceptional [15][17].

User interaction became a key factor affecting system performance. When automation features were actively used, electricity savings stayed close to the upper limit of observed efficiency values; however, when the system was mainly for monitoring without activating any control functions, efficiency gains dropped to about 12–15%. Similar findings have been noted in earlier studies which show that misalignment between system configuration and household usage behavior diminishes the practical impact of smart home technologies [6,16]. These results support the idea that technical capability by itself does not ensure sustained electricity savings without proper user engagement and system tuning. While stable during this observation period, these results are only indicative of performance in a controlled residential setting. Differences in appliance types, household routines, and environmental conditions will most likely impact electricity savings in broader deployment scenarios. Previous studies on residential energy management have underscored that scalability and contextual adaptation continue to be major challenges for IoT-based smart home systems when they are extended to diverse housing conditions over longer operational periods [18][19]. More evaluation across heterogeneous residential environments would provide better insight into long-term performance as well as operational robustness.

5. Conclusion

The results show that an IoT-based smart home system can enhance residential electricity efficiency through real-time monitoring and automated control of electrical appliances. From the experiments, it was noted that the average daily consumption dropped from 12.5 kWh in conventional operation to 9.1 kWh with IoT-based automation, which is a reduction in consumption by 26.6%. This shows that automated control strategies are capable of reducing residential electricity when appliance operation coincides with actual household activity. This finding also supports the idea that integration IoT supports informed household energy use by providing feedback on electricity consumption continuously. Automation functions like occupancy-based lighting control and scheduled device operation have reduced unnecessary electricity use without constant manual intervention hence these outcomes suggest the effectiveness of smart home systems not only depend on technical capability but also how automation features are configured and utilized by household occupants. Generally, results have indicated that IoT-based smart home systems are a realistic solution to improving residential electricity efficiency. Future work could explore integrating renewable energy sources, such as photovoltaic systems, into smart home platforms to assess their joint effects on household energy consumption and grid interaction. Further evaluation in diverse residential settings over longer operating periods would enhance understanding of this system's performance under actual conditions.

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