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REHA: real-time IoT-based energy efficient home automation system using ESP8266 and PIR motion sensors

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ABSTRACT

Technological developments have improved living standards, leading to greater demand for home automation based on the internet of things (IoT) concept. This study addresses the limitations of existing home automation systems, which are often costly, complex, and lack energy-saving features. A low-cost IoT-based home automation system is developed using the ESP8266 NodeMCU and PIR motion sensors to enable both remote control and automatic operation of household appliances. It uses the Blynk platform for cloud-based monitoring with smart motion-based logic to minimize unnecessary power consumption. The evaluation is conducted through various controlled scenarios and an estimate-based energy analysis derived from standard appliance ratings. Experimental results showed a reduction in household energy consumption of about 13–15%. The proposed system offers a cost-effective, practical approach to smart home energy management by combining affordability, automation, and measurable efficiency improvements.

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1. INTRODUCTION

The internet of things (IoT) has emerged as a transformative technology in home automation, enabling real-time communication among devices, sensors, and users [1]. One of the most impactful applications of IoT is in smart energy management, where it enables the efficient use of electrical resources in residential environments [2]. Given the growing energy demand and environmental concerns, developing an IoT-based, energy-efficient system for smart homes is both pertinent and crucial. An IoT-based smart home can monitor, analyze, and control energy-intensive appliances like lights, fans, refrigerators, and HVAC systems. Automation and remote control allow users to minimize wasteful energy use and make informed energy-related decisions.

Additionally, combining sensor-based automation with web-based or smartphone interfaces improves efficiency and user comfort. According to recent research, IoT systems significantly reduce household energy consumption by using sensors and structured architectures to dynamically modify appliances based on real-time data [2], [3]. The main aim of this work is to develop an IoT-based energy management system for a smart home, with a low-cost, simple, and efficient house system as the key concentration on the Node MCU ESP8266 microcontroller to develop a home automation system. Ganga *et al.* [4] offers a low-cost, IoT-based smart home energy management system intended to increase accessibility and energy efficiency.

The system uses a NodeMCU microcontroller with built-in Wi-Fi, based on the ESP8266 system-on-chip (SoC) from espressif systems, to control household devices. All sensors are connected to the NodeMCU, which collects and transmits real-time data to the Blynk and Sinric Pro cloud servers, enabling IoT integration with Amazon Alexa for voice-based control. The NodeMCU is programmed to communicate with the Blynk servers via both local and global networks, ensuring reliable, continuous system connectivity.

The overall architecture of the IoT-based efficient energy consumption system is presented in Figure 1. The system ensures intelligent appliance operation without user intervention by integrating energy optimization techniques and motion-based automation. Particular focus is placed on inclusivity, ensuring that the system is both scalable and user-friendly for the general public and simple to use for people with physical disabilities and the elderly. Additionally, the platform's cloud integration enables safe data access, remote control, and future growth. This work helps close the digital divide and advances global objectives for smart energy conservation and sustainable living by fusing affordability, automation, and sustainability.

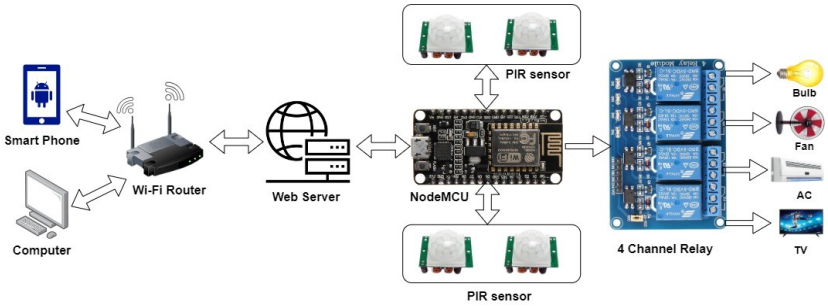


Figure 1. Overall architecture of the proposed IoT-based smart home energy management system

Although these scalable solutions address technical challenges to lower electricity costs, promote sustainability, and enable broader smart grid integration, existing IoT-based home automation systems still face several important limitations, such as the inability to operate effectively over long distances and the absence of scalable, cost-effective, and practical solutions suitable for large-scale adoption. This research aims to bridge these gaps by proposing a low-cost, sensor-driven automation system with explicit energy-saving analysis.

This paper is organized as follows: in section 1, introduce the prototype by discussing its goals, the problems with earlier approaches, and the advantages of our method. In section 2, we present background and a literature review, the goals of their studies, the algorithms used, and the distinctive features of their research. The proposed prototype discusses the systematic design, implementation, and evaluation of the IoT-based energy management system in section 3. It ensures that the research is valid from a scientific perspective, repeatable, and measurable. In section 4, presents an analysis of the proposed prototype's outcomes. Finally, we conclude the paper in section 5.

2. LITERATURE REVIEW

This section reviews existing research on IoT-based home automation and energy management systems. It critically analyzes prior approaches in terms of system architecture, communication technologies, cost, and energy optimization capabilities. Based on this analysis, the key limitations of existing systems are identified, leading to the formulation of the research gap and the contributions of this work.

2.1. Existing systems and comparative analysis

This subsection presents the benefits and drawbacks of various system architectures and covers a range of network technologies used to control household appliances, including bluetooth, Wi-Fi, and ZigBee. This section reviews and contrasts the main smart home studies on cost, communication strategies, scalability, and usability. It shows that many of the systems lacked true automation logic, had only mobile control, or were unsuitable for low-income households. Highlights significant research gaps, including poor remote access, high setup costs, limited multi-control support, and limited real-time automation. These shortcomings underscore the need for a more user-friendly, scalable, and accessible IoT-based home automation system.

Gill *et al.* [5], the author uses ZigBee as a communication protocol to design an adaptable and efficient home automation architecture. Another study introduced a Wi-Fi-based IoT framework for Internet-based home appliance monitoring and control. This approach used smartphones as control interfaces and a Raspberry Pi as the central server to ensure real-time communication and user accessibility [6], [7].

Researchers have addressed growing concerns about the security of IoT home systems by proposing onion-based multipath and split-channel gateways that circumvent Tor's scalability and bandwidth limitations [8]. These systems aim to increase security without compromising performance, especially for older users [9]. The work showed how 5G-enabled IoT can support blockchain-based smart applications across sectors such as homes, healthcare, agriculture, and transportation, while highlighting unresolved technical issues [10]. Table 1 presents a comparative analysis of some existing IoT-based home automation approaches and their components.

Table 1. Comparative analysis: existing IoT-based home automation approaches and their hardware components

SL	Author	Main focus	Components
1	Atzori *et al.* [1]	Uses Arduino and Bluetooth for gesture-based and smartphone control via Android device.	⋆ Arduino Mega 2560 ⋆ 16x2 LCD display ⋆ Google Assistant App
2	Kim *et al.* [2]	Smart meters for energy monitoring, control, and billing on the demand side.	⋆ TM4C129x MCU ⋆ MSP430 ⋆ ESP32 module
3	Shaikh *et al.* [3]	Integrates non-smart appliances using the homergy box.	⋆ Arduino Mega 2560 ⋆ ESP8266 ⋆ 4-channel relay board
4	Sureshkumar [4]	Smart meter with web/mobile control of energy loads.	⋆ Arduino ⋆ Raspberry Pi ⋆ I2C LCD adapter
5	Gill *et al.* [5]	Real-time energy display via smart meter and GPRS.	⋆ ARM Cortex M4 MCU ⋆ GSM/GPRS module ⋆ Relay driver
6	Pavithra and Balakrishnan [6]	Efficient scheduling algorithm with privacy.	⋆ 4-channel relay ⋆ ADMM algorithm
7	Kor *et al.* [7]	Bluetooth-enabled Arduino system with sensors for automation.	⋆ PIR sensor ⋆ Relay board ⋆ RTC module (DS1307)
8	Yang *et al.* [8]	Low-cost general home automation via Bluetooth.	⋆ Arduino Uno ⋆ HC-06 Bluetooth ⋆ Ultrasonic sensor
9	Kor *et al.* [9]	Real-time EMS using mesh and BI tools.	⋆ Temp/Humidity sensor ⋆ Microcontroller ⋆ Servers
10	Mistry *et al.* [10]	RECoS smart socket system to minimize energy use.	⋆ ELC module ⋆ PTC module ⋆ Zigbee

On the other hand, mobile sink path-planning techniques in IoT-based wireless sensor networks (WSNs) were thoroughly examined, and their usefulness in fields such as home automation, smart cities, healthcare, and weather monitoring was demonstrated [11]. Kaur *et al.* [12], it is also suggested that lower latency and increased network longevity can be achieved with a deep reinforcement learning-based routing algorithm. Edge computing and IoT concepts were used to create an integrated, affordable smart home platform. The system's goal is to combine various home automation features, such as energy efficiency, appliance control, and security, into a single, user-friendly architecture [13]. Vulnerabilities in device communication and cloud-based service integration were identified in a thorough security analysis of home automation systems, necessitating improved system design protections [14], [15]. Several studies developed low-cost IoT-based home automation prototypes using microcontrollers and mobile apps, employing Bluetooth for indoor control and Ethernet for outdoor connectivity [16]-[18].

Multi-protocol wireless gateways using ESP have now been developed and tested, enabling multi-hop communication and demonstrating reliable extended coverage for smart home automation [19]. The integration of IoT cloud services offers significant benefits for smart homes but requires robust security measures to mitigate vulnerabilities [20], [21]. Low-cost microcontroller-based prototypes using Bluetooth and Ethernet have been developed to enable affordable local and remote smart home control [22]. Smart home systems increasingly emphasize personalized mobile-based interfaces that allow users to remotely control home functions according to individual preferences [23]. Comprehensive smart home systems that integrate automation, safety, security, and energy efficiency while operating with minimal computational and network resources. Low-cost Arduino and Bluetooth-based solutions have demonstrated that real-time home control through Android applications is both practical and effective [24].

2.2. Research gap and problem statement

Existing IoT-based home automation systems still face several important limitations. One major challenge is the inability to operate effectively over long distances, as many studies have not adequately addressed reliable remote connectivity for smart home control. In addition, current systems often lack reliable motion-detection mechanisms, which leads to missed automation triggers and reduced responsiveness in smart-home environments. Another significant limitation is the absence of scalable, cost-effective, and practical solutions suitable for large-scale adoption. These gaps highlight the need for improved IoT architectures that support long-distance communication, dependable motion-based automation, and scalable designs that are easy to implement in real-world smart home applications.

2.3. Contributions of this work

To address the identified limitations, this study proposes a comprehensive, practical IoT-based smart home solution that enhances connectivity, reliability, and scalability. Hence, this paper highlights three key aspects. First, it proposes a hybrid control architecture that integrates manual switching, PIR-based occupancy detection, and cloud-based remote control within a unified low-cost framework. Second, it introduces a context-aware energy estimation model tailored to residential usage patterns in developing countries, incorporating locally relevant appliance data and behavioral assumptions. Finally, the system demonstrates a practical balance between affordability, automation, and energy efficiency, making it suitable for large-scale adoption in resource-constrained environments. This analysis helped to identify optimization points in system design and improve energy management logic.

3. METHODOLOGY AND SYSTEM DESIGN

This section presents the overall methodology and system design of the proposed IoT-based home automation system. It describes the system architecture, hardware and software components, and data collection procedures. In addition, the operational logic of the system is explained to ensure clarity, reproducibility, and systematic evaluation.

3.1. System overview and architecture

The functional block diagram in Figure 2 illustrates the overall operation of our proposed IoT-based energy management system, which integrates automatic and manual control of home appliances via a centralized microcontroller and wireless communication.

3.2. Hardware and software components

To complete our system development, we require some software and hardware components. The hardware components that we used to develop our home automation system are listed in Figure 3. The software tools include the Arduino IDE for coding and uploading programs, web browsers such as Google Chrome or Mozilla Firefox for accessing web interfaces, and Blynk servers for enabling real-time communication and remote control through the Blynk mobile application.

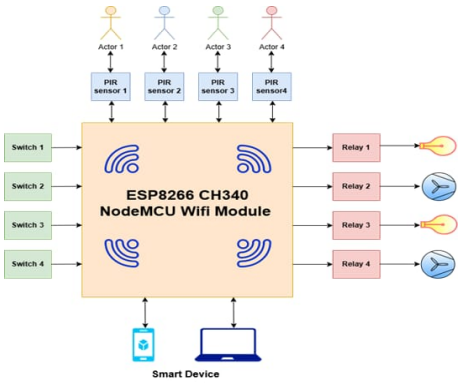


Figure 2. Functional block diagram of the proposed IoT-based home automation system



Figure 3. Hardware components of the proposed IoT-based home automation prototype

3.3. Data collection and evaluation methodology

To validate the system's performance, data were collected using the following methods:

- Surveys: conducted with users who interacted with the prototype system to assess usability and user satisfaction.
- Experiments: multiple test scenarios were created in controlled environments to measure system behavior, delay, and accuracy.
- Direct measurements: power usage, device runtime, and PIR detection activity were measured using multimeters, timers, and data logs from the Blynk app.

To evaluate the performance of the proposed Prototype, a quantitative experimental methodology is employed in a controlled residential environment, as described in the study. The system is tested using four household appliances connected through a NodeMCU (ESP8266), PIR sensors, relay modules, and manual switches. Motion detection is performed using PIR sensors with a detection range of approximately 5–7 meters and a 120° field of view. Each relay channel supports a maximum load of 220V/10A, enabling safe control of typical household appliances. This ensures that appliances operate only when user intent and occupancy are both satisfied. PIR sensors were selected for their low cost, low power consumption, and suitability for indoor occupancy detection, compared with alternatives such as ultrasonic or camera-based systems. However, energy consumption and cost savings are estimated analytically using standard appliance power ratings and assumed daily usage hours, rather than real-time energy meters. The comparison between these two conditions showed an approximate energy reduction of 13–15%, depending on household size. This methodology ensures a balance between experimental validation of system behaviour and analytical estimation of energy efficiency, providing a practical and reproducible evaluation framework.

3.4. System operation

This prototype uses Algorithm 1 to create an IoT-based, energy-efficient home automation system using the ESP8266 and the Blynk platform.

Algorithm 1 IoT-based smart home automation system

```
Initialize WiFi credentials, Blynk, and SinricPro services
Configure RELAY1–RELAY4 as OUTPUT and BUTTON1–BUTTON4 as INPUT_PULLUP
Set all relays to OFF state
Connect to Wi-Fi, Blynk cloud, and SinricPro server
while system is running do
    Execute Blynk.run() and SinricPro.handle()
    for each button i = 1 to 4 do
        if button i is pressed then
            Toggle relay i, update output, and synchronize state with Blynk
        end if
    end for
    if command received from SinricPro then
        Identify device ID, update corresponding relay state, and apply change
    end if
    if command received from Blynk app then
        Read virtual pin value, update corresponding relay state, and apply change
    end if
end while
```

4. IMPLEMENTATION AND RESULT ANALYSIS

This section presents the implementation of the proposed system and analyzes its performance under various experimental conditions. It includes experimental setup, system workflow, control logic, load capacity analysis, performance evaluation, cost analysis, and energy consumption assessment. In addition, a comparative analysis with existing systems is provided to validate the effectiveness of the proposed approach.

4.1. Experimental setup

Developing the proposed IoT-based home automation system requires specific hardware and software components. Figure 4 and Figure 5 show the circuit diagram and the physical implementation of our proposed prototype, respectively. The evaluation is conducted over multiple experimental cycles, with 50 trials per load condition and 24-hour usage scenarios repeated according to typical household patterns.

A comparative analysis is performed between the baseline conditions (manual operation without automation) and IoT-based conditions (automated control using motion detection, mobile application, and manual override).

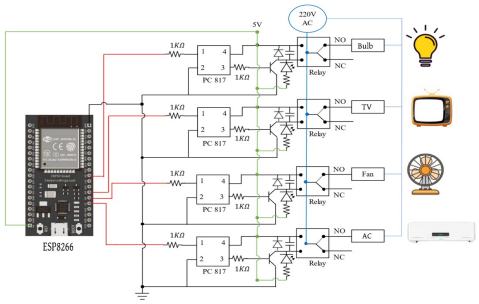


Figure 4. Circuit diagram of the proposed prototype in Proteus software

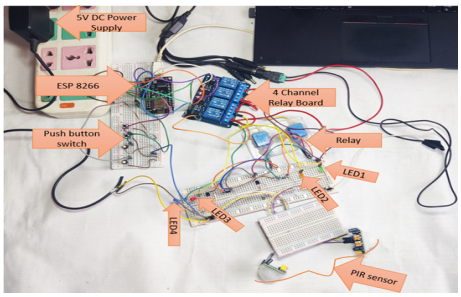


Figure 5. Physical implementation of the developed IoT-based home automation prototype

In the baseline case, appliances operate on fixed schedules, often leading to unnecessary energy consumption, whereas in the IoT-enabled system, appliances are activated only when occupancy is detected, improving efficiency. System performance metrics, including response time (approximately 0.5–2.0 seconds), switching accuracy, and PIR sensor activity, are measured directly using Blynk logs, Arduino serial monitoring, and manual observation.

4.2. System implementation and workflow

After connecting all hardware components and completing the programming setup, we tested the system by running all components according to the proposed system design shown in Figure 6.

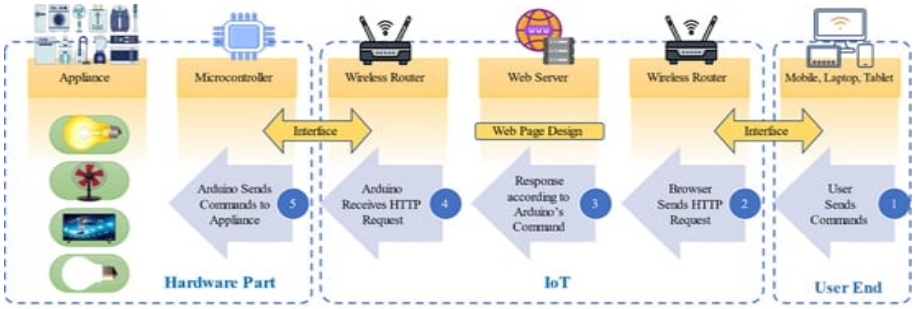


Figure 6. Operational workflow of the proposed system demonstrating data flow

4.3. Load capacity analysis

This prototype was successfully implemented and tested under real-world conditions. During the prototyping phase, several electronic components (transistors, optocouplers, and diodes) were damaged by high-voltage spikes. To ensure that all components minimize operating voltage and current to prevent failure.

Total load capacity: we used a $1.5\,\text{mm}^2$ copper wire, which supports a maximum current of $15\,\text{A}$. With a standard line voltage of $220\,\text{V}$, the total supported load capacity is:

$$\text{Total Power} = 220\ \text{V} \times 15\ \text{A} = 3300\ \text{W} = 3.3\ \text{kW} \tag{1}$$

Thus, the system can safely handle up to $3.3\,\text{kW}$ of connected electrical load under ideal conditions.

Per-channel load capacity: each relay channel used in the system is rated for $220\,\text{V}$, $10\,\text{A}$. Therefore, the maximum power capacity per relay-controlled channel is:

$$\text{Channel Power} = 220\ \text{V} \times 10\ \text{A} = 2200\ \text{W} = 2.2\ \text{kW} \tag{2}$$

This implies that each appliance or circuit connected to a single relay channel should not exceed $2.2\,\text{kW}$.

4.4. Control logic and system scenarios

Figure 7 presents the experimental results of the proposed home automation system under various operating scenarios using both the web server and the Blynk mobile application. The sequence of images illustrates the complete control workflow, including interface initialization, remote load activation, and motion-based control mechanisms. Specifically, Figure 7(a) shows the web-based control interface after establishing the server connection, while Figure 7(b) presents the initial state of the Blynk application with all loads turned OFF. The activation of Load 1, Load 2, Load 3, and Load 4 is demonstrated in Figures 7(c), 7(d), 7(e), and 7(f), respectively. Figure 7(g) illustrates the condition in which all loads are activated simultaneously through the mobile application. Finally, Figures 7(h) and 7(i) demonstrate the system behavior under motion-based operation, where selective deactivation occurs when motion is not detected and full activation is achieved when motion is detected. These results confirm that the proposed system performs consistently across different operating scenarios.

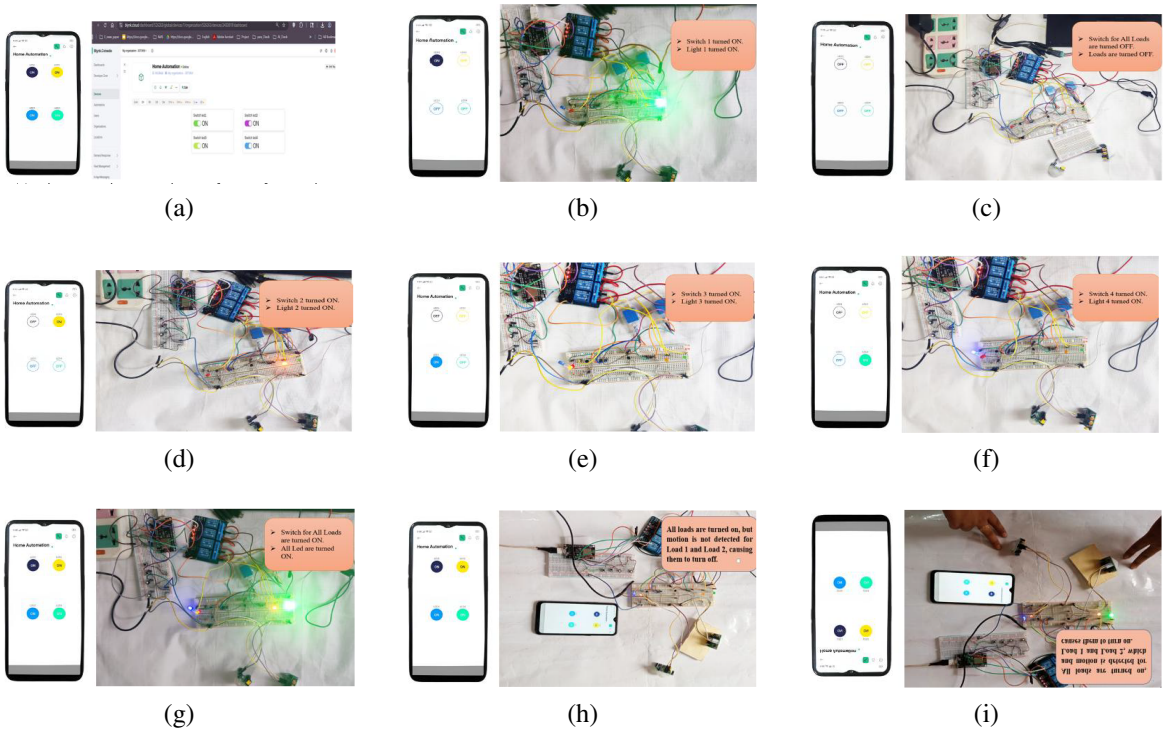


Figure 7. Experimental results demonstrating real-time control operations through web and mobile interfaces under different switching scenarios. (a) Phone and control interface after web server connection, (b) Initial Blynk interface (all OFF), (c) Load 1 ON via Blynk and Load 1 remote activation, (d) Control of Load 2 using the Blynk mobile interface, (e) Activation of Load 3 using the Blynk mobile application, (f) App-based control and activation of Load 4, (g) Full load activation using the Blynk mobile interface, (h) Load status with all switches ON but selective deactivation based on motion, and (i) Load status with all switches ON and all motion detected

The web interface and our observation of the system's response to ON/OFF commands. These are the system's real-time control functionality and responsiveness. The results of each control operation were captured as images and are discussed below:

Table 2 shows the logic for light control based on three inputs: a physical switch, a mobile app switch, and a PIR motion sensor. Various operational scenarios were tested after connecting the system to actual appliances. The control operations for each appliance's output are given below for visual validation of images.

- Physical switch: manually, when ON (1), the Light turns ON, and the PIR sensor detects that motion.
- Mobile app switch: in remote control (Smartphone), when ON (1), the Light turns ON based on motion detection.

– PIR sensor: in-room motion is detected when the return value is 1.
– Output (Light ON/OFF): if motion is detected, the Light is turned ON (1) (PIR = 1), and the mobile app switch is ON.

The boolean expression of this logic is:

$$\text{Light} = (\text{Physical Switch} \vee \text{Mobile App Switch}) \wedge \text{PIR Sensor}$$

Table 2. Logic truth table for system inputs (switch, mobile, PIR sensor) and resulting appliance state

Physical switch	Mobile app switch	PIR sensor	Light (ON/OFF)
0	0	0	0 (OFF)
0	0	1	0 (OFF)
0	1	0	0 (OFF)
0	1	1	1 (ON)
1	0	0	0 (OFF)
1	0	1	1 (ON)
1	1	0	0 (OFF)
1	1	1	1 (ON)

4.5. Performance evaluation

The system's performance was assessed for both individual loads and for all loads running simultaneously under a variety of conditions. To ensure reliability and response accuracy, each scenario was tested multiple times. Table 3 summarizes the comprehensive testing results. As demonstrated, every load was completed successfully, achieving a 100% success rate. The average control delay was approximately 1 second from the command to the load response. For safety reasons, we have included a 1-second delay in our ESP8266 code. Therefore, it takes about a second to execute a load after sending a command under normal circumstances. There are times, though, when the delay might be less than 0.5 seconds. This occurs when the user sends a command just before the ESP8266 updates the server. However, because our system uses the internet, the maximum network latency we saw was about 2 seconds. On the other hand, since our system operates over the internet, the maximum delay we observed due to network latency is around 2 seconds.

Table 3. Performance evaluation of the proposed system in terms of response accuracy, efficiency, and control delay

No.	Loads	Number of attempts	Successful attempts	Efficiency	Avg. Delay (sec)
1	LED 1	50	50	100%	1
2	LED 2	50	50	100%	1
3	LED 3	50	50	100%	1
4	LED 4	50	50	100%	1
5	All Loads	50	50	100%	1

4.6. Cost analysis

The system cost of the IoT-based home automation prototype is shown in Table 4. The approximate total cost of our prototype is 1,500 BDT (Taka). This study assesses the usefulness of an IoT-based smart home automation system across different-sized residential settings.

Table 4. Cost breakdown of hardware components used in the proposed IoT-based home automation prototype

No.	Component	Quantity	Price (BDT)
1	NodeMCU Wi-Fi module	1	420
2	4-Channel 5V relay board	1	290
3	PIR sensor	4	380
4	1N4007 diode	5	20
5	10 kΩ resistor	10	20
6	5V 2A adapter DC power supply	1	250
7	Push button switch (4-pin)	5	20
8	Male and female jumper wires	–	100
		Total estimated cost	1,500

4.7. Energy consumption and saving analysis

Complementing the performance evaluation presented in subsection 4.5, this section analyzes daily household appliance usage to quantify energy consumption using the appliance power ratings and estimated daily usage summarized in Table 5. The resulting energy consumption estimates are then used to evaluate the potential cost savings presented in Table 6.

Table 5. Household appliance power ratings and estimated daily usage for energy consumption analysis

Room/Appliance type	Device details	Power (W)	Daily usage (Hrs)
Bedroom	Light + Fan	Light = 25	14
Dining	Light + Fan	Fan = 80	14
Drawing	Light + Fan	TV = 100	8
Living	Light + Fan	Electric Iron & Rice Cooker = 1000	10
Veranda	Light	Refrigerator = 150	6
Kitchen	Light + Ex. Fan	Microwave = 1200	6
Bathroom	Light + Ex. Fan	Exhaust Fan = 45	4

Table 6. Comparative analysis of energy consumption, cost savings under conventional and IoT-based automation

Category	Appliance Type	Daily (Wh)	Monthly (kWh)	Conv. Cost (BDT)	IoT Save/Day (Wh)	IoT Save/Mon (kWh)	IoT Cost Save (BDT)	Final Cost (BDT)
Small home	Bedroom (2)	2560	76.80	687.36	320	9.6	85.92	601.44
(700 sq. feet)	Dining	1280	38.40	343.68	160	4.8	42.96	300.72
	Drawing	1280	38.40	343.68	160	4.8	42.96	300.72
	Kitchen	720	21.60	193.32	90	2.7	24.17	169.16
	Bath (2)	1440	43.20	386.64	180	5.4	48.34	338.32
Total		—	1954.68	—	—	244.34	—	1710.35
Medium home	Bedroom (3)	6975	209.25	1872.78	930	27.9	249.72	1623.09
(1000 sq. feet)	Drawing	3900	117.00	1047.15	520	15.6	139.62	907.53
	Dining	2550	76.50	684.68	340	10.2	91.29	593.39
	Kitchen	560	16.80	150.36	140	4.2	37.59	112.77
	Bath (2)	440	13.20	118.14	220	6.6	59.08	59.08
	Veranda (2)	240	7.20	64.44	80	2.4	21.48	42.96
	Entrance	240	7.20	64.44	80	2.4	21.48	42.96
Total		—	4001.99	—	—	620.24	—	3381.76
Large home	Bedroom (5)	11625	348.75	3121.30	1550	46.5	416.20	2705.15
(2000 sq. feet)	Drawing	3900	117.00	1047.15	520	15.6	139.62	907.53
	Dining	2550	76.50	684.68	340	10.2	91.29	593.39
	Living	3525	105.75	946.46	470	14.1	126.20	820.27
	Kitchen	560	16.80	150.36	140	4.2	37.59	112.77
	Bath (3)	660	19.80	177.21	330	9.9	88.62	88.62
	Veranda (2)	480	14.40	128.88	160	4.8	42.96	85.92
	Entrance	240	7.20	64.44	80	2.4	21.48	42.96
Total		—	6320.49	—	—	963.92	—	5356.58

Appliance level power ratings and usage durations form the basis for estimating baseline energy demand and evaluating the impact of the proposed IoT-based energy management system.

Daily energy consumption for each appliance is calculated using (3).

$$\text{Energy (Wh)} = \text{Power (W)} \times \text{Usage (Hours/Day)} \quad (3)$$

Which provides the baseline energy demand under conventional operation. Building on this baseline, Table 6 assumes that the proposed IoT-based prototype enables approximately 2 hours of average daily energy savings per appliance through motion-based automation, intelligent scheduling, and remote control. The assumed reduction of approximately 2 hours/day is based on observed idle-time elimination during controlled experiments and supported by typical occupancy-driven automation behavior reported in prior IoT energy management studies [25].

The power consumption values of individual household appliances listed in Table 5 are adopted from publicly available data published by the Bangladesh Power Development Board (BPDB/PDB) [26], ensuring that the electrical ratings reflect locally relevant standards and grid conditions. These ratings include commonly used residential appliances such as lights, fans, televisions, refrigerators, microwave ovens, electric irons, rice cookers, and exhaust fans. Using official BPDB data enhances the reliability and applicability of the energy consumption analysis for Bangladeshi households. The daily usage hours presented in Table 5 are intentionally assumed to be approximately two hours higher than the reference values reported in the Lighting Research Centre (LRC), Rensselaer Polytechnic Institute, USA [27]. This adjustment is based on realistic socio-economic and cultural conditions in Bangladesh, where women, children, and elderly family members typically remain at home for longer periods than in households in the United States. As a result, lighting, fans, and household appliances are operated for extended periods, particularly during daytime hours. The energy and cost savings shown in Table 6 demonstrate that the proposed system can significantly reduce daily and monthly electricity consumption across small, medium, and large residential settings. These findings validate the effectiveness of the IoT-based automation framework in achieving measurable energy and cost reductions while maintaining user comfort under realistic residential usage conditions in Bangladesh.

Figure 8 illustrates a comparative analysis of energy costs across small, medium, and large homes, with and without IoT-based automation over 12 months. First, a 700-square-foot small house shows an annual energy cost reduction of about 4,700 BDT, or 13%. This illustrates how small monthly savings add up to significant annual benefits. Then, for a medium-sized home with 1000 square feet, annual electricity costs drop from 48.02 thousand BDT to 40.58 thousand BDT, saving 7.44 thousand BDT (15.5%), mostly because of environment-responsive fan control, automated lighting, and optimized appliance usage. Additionally, IoT automation reduces the unnecessary operation of lighting and air conditioning systems in a larger 2000-square-foot home, where energy inefficiency is more noticeable under manual control. This results in annual savings of about 11,570 BDT, or a 15.25% reduction in electricity costs. All things considered, these results show that IoT-based home automation significantly increases energy efficiency and offers growing financial benefits as home size and energy demand grow.

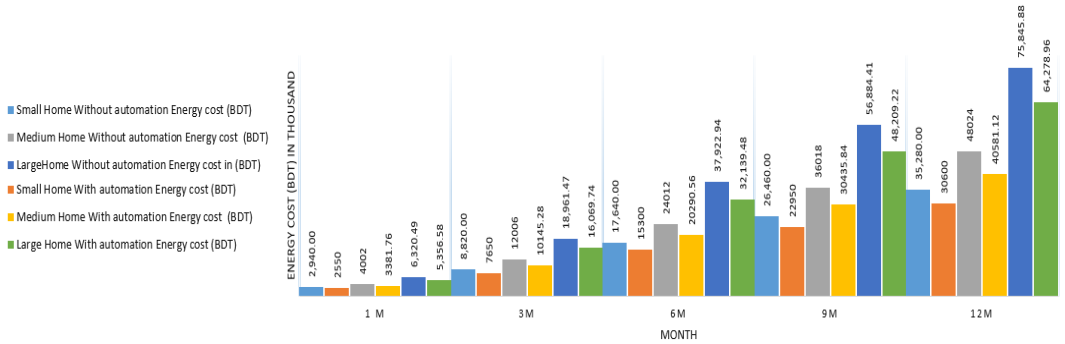


Figure 8. Compression of energy costs for small, medium, and large home energy costs

4.8. Comparative analysis with existing systems

Table 7 compares the proposed system with several existing IoT-based home automation solutions. The comparison covers key aspects such as hardware platform, communication method, sensors, cloud integration, energy optimization, evaluation approach, response delay, and overall cost. While most previous systems either lack proper energy-saving features or involve higher costs and complexity, the proposed ESP8266 NodeMCU-based system delivers effective motion-based energy optimization at a very low cost and with good response time (∼1 s). This makes it a highly practical and affordable solution, especially for resource-constrained environments in developing regions.

Table 7. Comparison of existing IoT-based home automation systems with the proposed system

Ref.	Platform	Comm.	Sensors	Cloud	Energy Opt.	Evaluation	Delay	Cost
[5]	ARM Cortex MCU	ZigBee	Limited sensing	No	Smart meter	Proto.	–	Medium
[6]	Microcontroller	Wi-Fi	No sensors	Yes (mobile)	Basic control	Proto. Test	–	Low
[13]	Edge IoT Arch.	Wi-Fi	Multiple sensors	Cloud	Energy-aware	Sim./Proto.	∼1–2 s	High
[16]	Arduino	Wi-Fi	No	Android App	None	Exp.	1–2 s	Low
[18]	Arduino	Bluetooth	No	Local control	None	Proto.	<1 s	Very low
[19]	ESP Gateway	Wi-Fi / BLE	Limited sensors	Yes	Limited	Exp.	1–3 s	Medium
[22]	ESP8266/Arduino	Wi-Fi	Basic sensors	IoT cloud	Partial	Exp.	–	Low
Proposed	ESP8266 NodeMCU	Wi-Fi	PIR sensors	Blynk cloud	Motion-based	Proto. + Est.	∼1 s	Very low

5. CONCLUSION

This work presents a low-cost, hybrid architecture integrating ESP8266, PIR-based occupancy sensing, and cloud-enabled control, validated via real-world prototype implementation and analytical energy modeling. The system demonstrates robust performance with low response latency (≈ 1 s) and achieves an estimated 13–15% reduction in household energy consumption. The proposed approach offers a scalable and context-aware energy management framework, particularly in resource-constrained environments. However, the energy savings were calculated using estimation-based analysis rather than direct real-time measurements, which may introduce some variation relative to actual household conditions. The system also relies on stable internet connectivity and can experience latency during network congestion. In addition, PIR motion sensors may occasionally trigger false alarms due to environmental factors. Future work will focus on integrating real-time energy-monitoring hardware, improving sensor accuracy, strengthening system security, and enhancing scalability for larger deployments.

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C : **C**onceptualization
M : **M**ethodology
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Su : **Su**pervision
P : **P**roject Administration
Fu : **Fu**nding Acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this paper.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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