Room energy management utilizing internet of things technology for decreasing electricity consumption

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ABSTRACT

This paper proposes a novel internet of things (IoT)-based control system for energy management to reduce electricity consumption from the two most dominant loads in buildings: air conditioners (AC) and lighting. The proposed system provides a comprehensive operational control strategy that integrates scheduling, human detection, ambient temperature, and light intensity for optimal room-level energy management employed. The proposed system employs wireless fidelity (WiFi)-enabled temperature, presence, and light sensors for comprehensive room conditions monitoring. Additionally, a WiFi-connected infrared module serves as an actuator to regulate the AC unit. Testing results demonstrate compelling energy savings, achieving up to 36% for the AC and 72% for the lighting while maintaining a comfortable indoor environment. These results were obtained from an experimental test in a private room within a residence over an 8-hour daytime period with 50% occupancy time. The proposed IoT system offers a highly effective and easily deployable solution for sustainable energy reduction in residential settings.

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1. INTRODUCTION

In recent years, the swift escalation of global energy consumption has garnered significant interest due to its profound effects on both the environment and society. This concern is amplified by the fact that around 80% of current energy needs are still met by the use of fossil fuels [1], which drive greenhouse gas emissions and environmental pollution. To mitigate this global challenge, attention must be shifted toward sectors with high energy demand. According to the International Energy Agency (IEA), electricity is a crucial target, since it contributes 20% to global final energy consumption and is expected to raise to more than 50% by the middle of the century [2]. Consequently, reducing electricity consumption, particularly through effective building energy management, plays an important role, as buildings account for approximately 60% of total electrical energy consumption [3].

Within the building sector, the highest energy waste is often concentrated in specific equipment and user behavior. The most electric energy-consuming equipment in a typical building are air conditioners (AC) and lighting. AC consume about 70% of building electricity [4], whereas lighting accounted for accounts for approximately 15 % of the global electric energy consumption [5]. Furthermore, the growing desire for optimal thermal comfort can lead to excessive energy consumption [6]. Crucially, this consumption is exacerbated by people's unenergy-efficient behaviors in operating equipment, such as failing to turn off unused devices or setting AC temperatures excessively low [7]. These behavioral patterns lead directly to wasted energy and increased electricity costs.

The emergence of information and communication technology (ICT) and the rise of smart buildings are expected to play an important role in conserving and optimizing the use of electrical energy [8]. The use of building internet of things (BIoT) based monitoring and control systems has become a key technology for energy saving solution [9]. Several studies have developed IoT-based systems to monitor room conditions [10], [11], measure electric energy [12], [13], and enable users to remotely control electrical equipment [14]–[16]. Specific efforts include reducing energy consumption through smart lighting control [17], [18], simple efficiency measures like lamp replacement and motion sensors [19], [20] and automatically controlling AC operation to reduce human error [7], [21]. However, many of these early control strategies rely on simple binary logic (ON/OFF) when equipment is unused. While effective for saving energy, this binary approach can negatively affect the comfort aspect, particularly when a room is quickly re-used after being turned off.

To address the comfort trade-off, more advanced systems have been developed. This includes systems that regulate AC based on thermal comfort metrics, such as predicted mean vote (PMV) [22] and systems that implement optimal pre-cooling strategies considering renewable energy surplus or time-varying pricing [23]. Other research focuses on comprehensive energy management through pattern observation and strategic scheduling of appliances [20].

Most existing studies focus on optimizing a single parameter (either comfort atau pure energy saving via ON/OFF), or they employ complex, computational scheduling that does not dynamically or simultaneously address the non-linear interaction between human presence, varying schedules, and the rapid restoration of comfort during room re-use. This paper aims to develop a new IoT system configuration incorporating internet-connected sensors (presence, temperature, and lighting) and actuators to monitor and manage room environmental conditions, design new control strategies that minimize electricity consumption of both AC and lighitng equipment, and ensure room comfort is maintained or rapidly restored when the room is in use or re-used, by considering a unique set of constraints, including schedules, human presence, temperature, and lighting levels. This paper is structured as follows: section 2 describes the proposed IoT system architecture and method. Section 3 presents the results and analysis of the developed control strategies. Finally, section 4 concludes the paper and outlines future work.

2. RESEARCH METHOD

2.1. Design configuration and components

Figure 1 illustrates the configuration of the proposed system. The architecture of the internet of things (IoT) typically comprises three primary layers: a perception or sensing layer, a network layer, and an application layer [24]. Several sensors were used including temperature, humidity, light intensity, presence, and energy sensor. Then we used an infrared module and wireless fidelity (WiFi) tuneable lamp as the actuator. In the middle layer, the WiFi router provides a local network connection for all devices to connect to the internet. The home assistant energy management application was installed on a Raspberry Pi mini-computer, which also functions as a local system server. Table 1 presents the details of the components used.

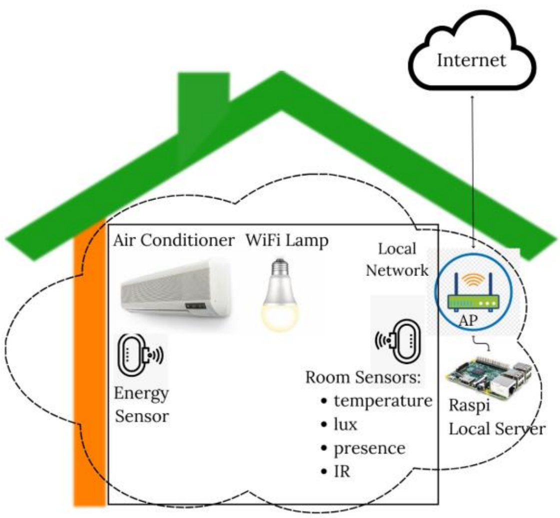
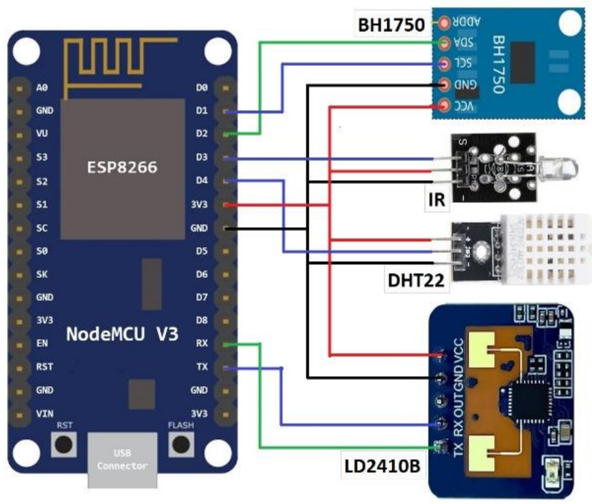


Figure 1. System configuration

Table 1. Hardware components and the functions

No	Hardware	Component	Function
1	Temperature and humidity sensor	DHT22	Read temperature and humidity data
2	Light sensor	BH1750	Read lux data
3	Presence sensor	LD2410B	Read presence (moving and still target)
4	Energy sensor	TP-Link P115	Read equipment electric power and energy data
5	Infrared remote control	Infrared module	Sent infrared command to AC equipment
6	Node processor	NodeMCU ESP8266	Process sensor data and sent them to IoT server
7	Access point	WiFi router	Provide all devices network connectivity
8	IoT local server	Raspberry Pi	Local server and database; application to control the system

Room sensors were used to monitor room conditions and device energy consumption. In this work, we used: the DHT22, LD2410B, and BH1750 module to sense room environmental data. DHT22 is an accurate, low-cost digital temperature and humidity sensor [25] for reading room temperature and humidity data. The H-Link LD2410B presence sensor was used to detect human presence in the room. This sensor employs frequency-modulated continuous wave (FMCW) technology, integrating radar signal processing with sophisticated algorithms to precisely detect human targets within a designated area. Compared to passive infra-red (PIR) sensors which cannot perceive small movements like a person who is still and sleeping [26], FMCW radar can detect very small motion [27], enabling the high-sensitivity detection of human presence, with the capability to recognize both moving and stationary human bodies. To acquire ambient light quantity, we used the BH1750 module, an integrated circuit which offers an extensive light measurement range and achieves high resolution of up to 65535 lx [10], [28]. The NodeMCU collects and sends data from these sensors to the server via a local network connection. The sensor-to-nodeMCU connection circuit is shown in Figure 2.



Pin Connection	
NodeMCU Pin	Component Pin
D1	SCL BH1750
D2	SDA BH1750
D3	S KY-005
D4	Out DHT22
RX	TX LD2410B
TX	RX LD2410B
3V3	VCC
GND	GND

Figure 2. Node–sensors connection

In the Raspberry Pi-based server, an energy management application was utilized to facilitate data logging, data analysis, and the execution of action measures in accordance with the implemented management strategies. Control operations were conducted using an infrared remote controller in conjunction with a network-connected smart lamp. Various control scenarios were devised to oversee the functioning of the AC and lamp, with a focus on analyzing their usage to minimize electrical energy consumption. To accurately measure electrical energy usage, Wi-Fi-enabled smart plugs were installed on the sockets of the AC and lamp.

2.2. Air conditioner control strategies

The IoT-based smart energy management system is designed to optimize energy utilization by facilitating real-time monitoring and analysis of power consumption patterns across IoT network [29]. Various factors influence the usage of AC electrical energy, including climate conditions, the characteristics of the building envelope, the equipment within the building, the indoor environment, user behavior, maintenance status, and social factors [30]. From the perspective of user behavior, it is common for individuals to operate their AC units according to a set schedule, maintaining a constant room temperature throughout the day. Additionally, many users tend to leave the AC running even when the room is unoccupied. In order to address these inefficiencies and mitigate human errors that contribute to excessive AC operation, several control strategies have been implemented. An overview of these control strategies is presented in Table 2.

Table 2. Control strategies for AC energy management

No	Trigger	Condition	Action
1	Scheduled to on	-	Power on AC
2	Scheduled to off	-	Power off AC
3	Presence being occupied	On schedule	Set mode auto with lower comfort set temp (23 °C)
4	Presence being not occupied	On schedule	Scenario 1: sleep mode Scenario 2: auto mode with higher set temp (26 °C)
5	Temperature rise above the upper limit	On schedule; presence detected	Auto mode with lower comfort set temp (23 °C)
6	Temperature rise above the upper limit	On schedule; presence clear	Scenario 1: sleep mode Scenario 2: auto mode With higher set temp (26 °C)
7	Temperature drop below lower limit	On schedule	Mode sleep

The controlling strategies implemented encompass monitoring schedules, assessing human occupancy, and regulating room temperature. Initially, the AC system is programmed to activate or deactivate according to a pre-established timetable. Subsequently, upon detecting human presence, the system is designed to issue automatic operational commands for the AC, ensuring settings are adjusted to maintain a comfortable temperature. Generally, individuals feel comfortable when room temperature and humidity are kept within the thermal comfort zone, specifically between 22 °C and 27 °C [31]. Conversely, when no occupants are identified, two separate strategies are utilized. The first strategy entails activating the sleep mode on the AC unit. The second strategy involves raising the temperature setting of the AC to the upper limit of the comfort zone.

The controlling strategies used include checking schedules, human presence, and room temperature. First, the AC turned on or turned off according to a predetermined schedule. Then, in the event of presence, the system was designed to send AC automatic operating mode commands with comfortable temperature settings. On the other hand, in conditions where there is no presence, two scenarios were applied. The first scenario was to send a command to change the AC mode to sleep mode. Meanwhile, in the second scenario, the AC temperature setting will be raised to the upper limit temperature of the comfort zone.

2.3. Room lighting control strategies

Users generally manage lighting by activating and deactivating lights according to predetermined schedules or specific triggers. The system discussed herein incorporates additional factors such as presence detection and ambient room lighting levels into its control mechanisms. Table 3 outlines various lighting control strategies aimed to minimize energy consumption while ensuring that the necessary illumination levels are upheld.

Table 3. Control strategies for lights energy management

No	Trigger	Condition	Action
1	Presence being occupied	Lux below requirement	Lamp on
2	Presence being occupied	Lux above requirement	Lamp off
3	Presence being not occupied	-	Lamp off
4	Light raise above upper limit	-	Decrease lamp until light within requirement
5	Light drop below lower limit	Presence detected	Increase lamp until light within requirement
6	Light drop below lower limit	Presence clear	Lamp off

The lights are turned on only when there is presence and natural light is insufficient. Instead the lamp turned on to meet lighting needs. The augmentation of illumination from natural sources is counterbalanced by a decrease in lamp wattage, which aims to minimize electrical energy consumption while ensuring that lighting intensity remains within the specified thresholds. Conversely, when the natural light levels drop, the system will boost the lamp's power to ensure the lighting stays above the designated minimum threshold. For testing, this study used a room lighting level of 200 lux with a tolerance of 5%.

3. RESULTS AND DISCUSSION

The proposed system was implemented in a private room within a residence equipped with a 400 W AC and a 12 W smart lamp. Testing was conducted over a scheduled 8-hour daytime period with an established occupancy rate of 50% to evaluate the performance of the implemented system. Then the effectiveness of controlling strategies was analyzed. Room conditions—including temperature, humidity, illumination, and occupancy—alongside the energy consumption metrics of the equipment, were monitored in real-time via a server application dashboard (illustrated in Figure 3). This initial implementation confirms the system's capability to effectively monitor room parameters as the foundation for the control strategies.

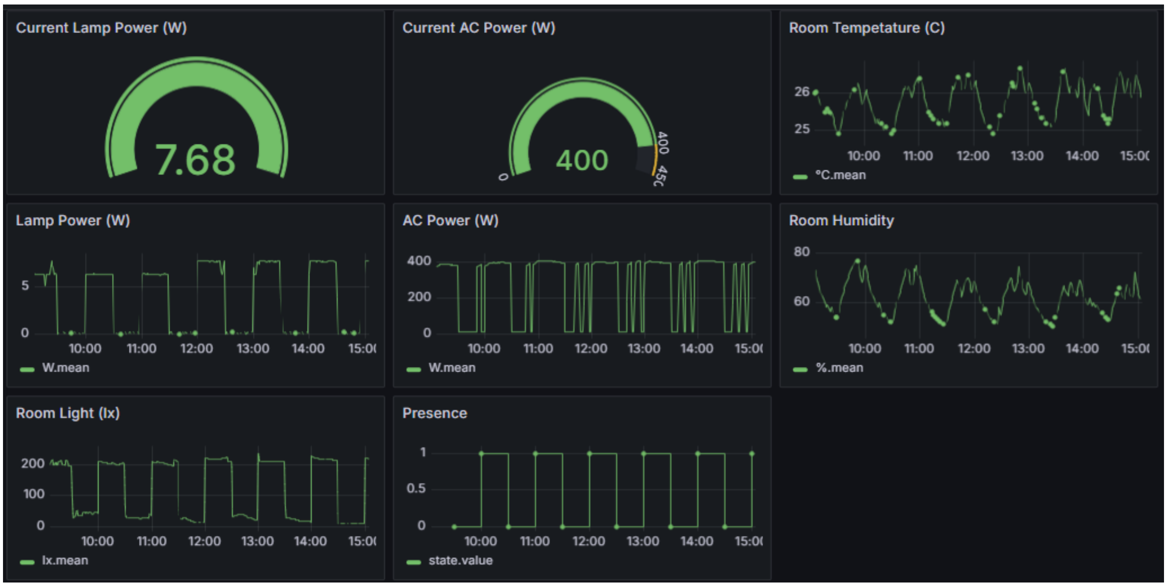


Figure 3. Monitoring dashboard

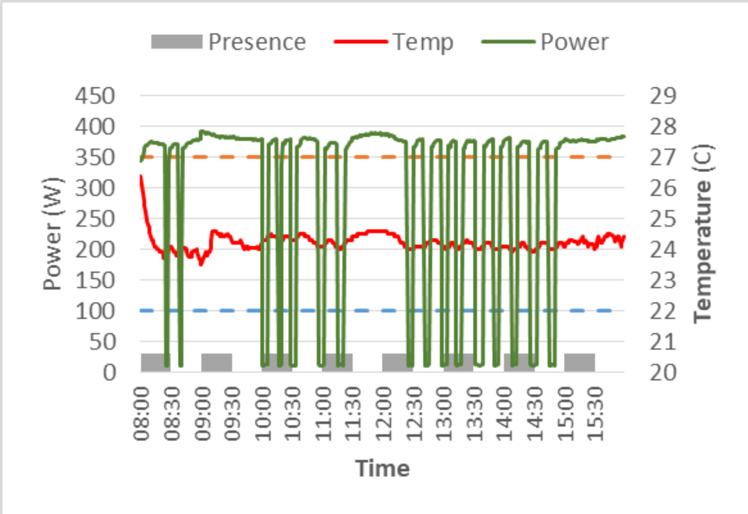
3.1. Air conditioner control strategy analysis

Figure 4 illustrates the operation of the AC unit over an eight-hour period in an environment with an occupancy time of 50%. In the base scenario depicted in Figure 4(a), occupant presence was not taken into control consideration, and a constant temperature setting was employed to ensure that the room temperature remained as close as possible to the specified comfort level. For this assessment, the target temperature was established at 23 °C.

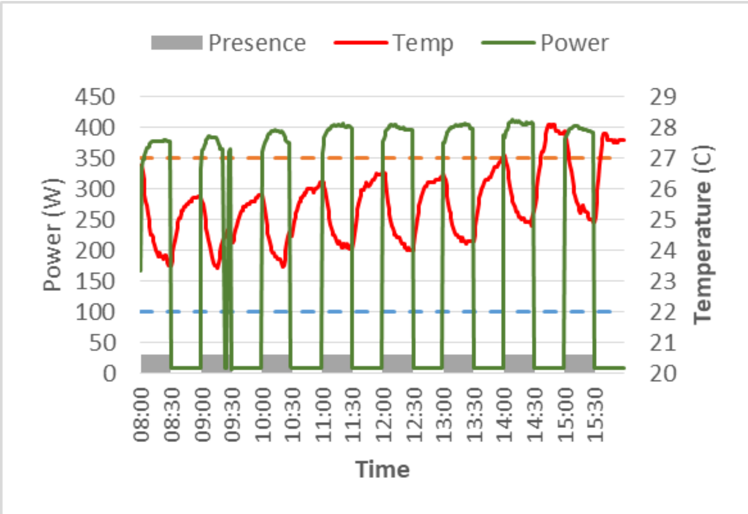
The results of the AC operation in control scenario 1 are illustrated in Figure 4(b). It can be seen that when presence changes to absence, the AC switches to sleep mode which is indicated by a significant reduction in power consumption. During this phase, the energy usage of the AC is minimal. Concurrently, the temperature of the room will rise. This continues until the sensor detects presence again. Conversely, when a presence is identified, the AC unit reverts to its automatic mode, resulting in a significant increase in energy consumption as it works to cool the room. The disadvantage of this scenario is that when absence lasts too long, the room temperature can rise beyond the comfort level. As a result, it may take a long time to cool the room again after someone re-enters.

Setting the AC system to a higher temperature within the acceptable range for unoccupied conditions, as illustrated in Figure 4(c), ensured a comfortable room temperature, even in the absence of occupants. In this second scenario, when the room temperature remained below the newly established higher set point, the AC consumed less energy. Once the temperature increased beyond this set point, the AC would automatically activate to cool the room, preventing it from exceeding the acceptable temperature threshold. Table 4 summarizes the performance analysis of the AC units in a comparison of three scenarios.

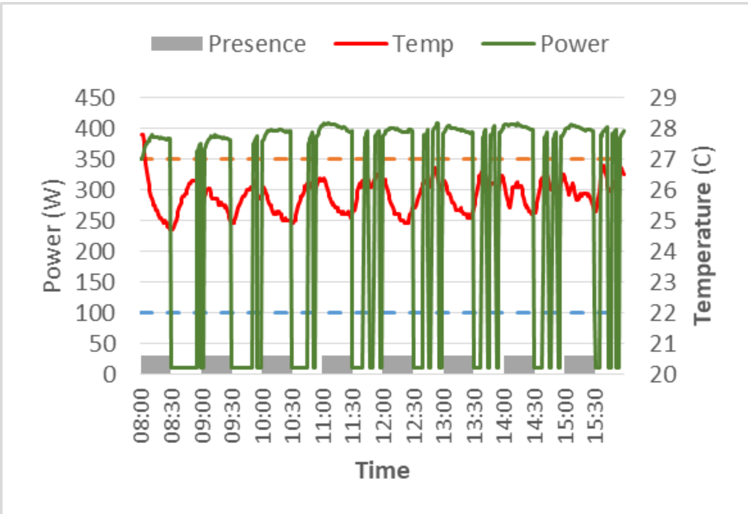
Based on the results depicted in Figure 4, it is clear that the baseline condition offers an optimal level of room comfort, as the temperature is consistently regulated at 23 °C without considering occupancy. However, this condition also results in the highest energy consumption as shown in Table 4. With an energy usage of 2.43 kWh for 8 hours, it results in an average power consumption of 303 W or a load factor of 0.76.



(a)



(b)



(c)

Figure 4. AC operation on; (a) base case, (b) scenario 1, and (c) scenario 2

Table 4. Comparison of AC energy consumption

No	Scenario	Energy (kWh)	Energy reduction	Load factor	Impact on comfort	Critical analysis
1	Base case	2.43	0% (benchmark)	0.76	Highest	Offers optimal comfort but is the least energy efficient.
2	Scenario 1	1.55	Maximum (36.2%)	0.49	Lowest	Room temperature to rise beyond the comfort zone during absence. Required re-cooling time upon re-entry.
3	Scenario 2	2.18	Moderate (10.4%)	0.68	Balanced/high	Offers the best compromise between energy efficiency and maintained thermal comfort.

The first scenario results in the highest energy reduction of 36.2% compared to the base case, yielding an average power consumption of 194 W or reduced load factor to 0.49. However, however this scenario results in the lowest impact on comfort due to significant temperature fluctioation. When absence is detected, the AC is turned off or set to sleep mode, causing room temperature to rise beyond the comfort zone. Upon re-entry, the time required to restore comfort is prolonged (re-cooling time), negatively impacting user experience.

Compared to the first scenario, the second scenario offers the best compromise between energy efficiency and maintained thermal comfort. Although energy savings are lower (10.4% from base case), raising the temperature set point in this scenario prevents the room temperature from exceeding an acceptable threshold, mitigating extreme temperature swings.

3.2. Room lighting control testing results

Figure 5 presents how the lighting control strategy was applied to lamp operation. It can be seen that the system can control the lighting device according to the predetermined scenario. When there is no presence, the light device is always turned off so the device does not use electricity. During the presence conditions, it is important to maintain the quantity of lighting above standard values according to the type of room and work being carried out. In this test, we used a value of 200 lux. This value was obtained from a combination of light from natural sources (the sun) and lamp light. In this case, we increased the lamp power to add the lights needed when the sunlight was weak. Conversely, when the natural light source is strong, the lamp power is reduced so electrical energy consumption is lower. This operation ensures the room's lighting needs are met without a shortage or wasting lamp energy.

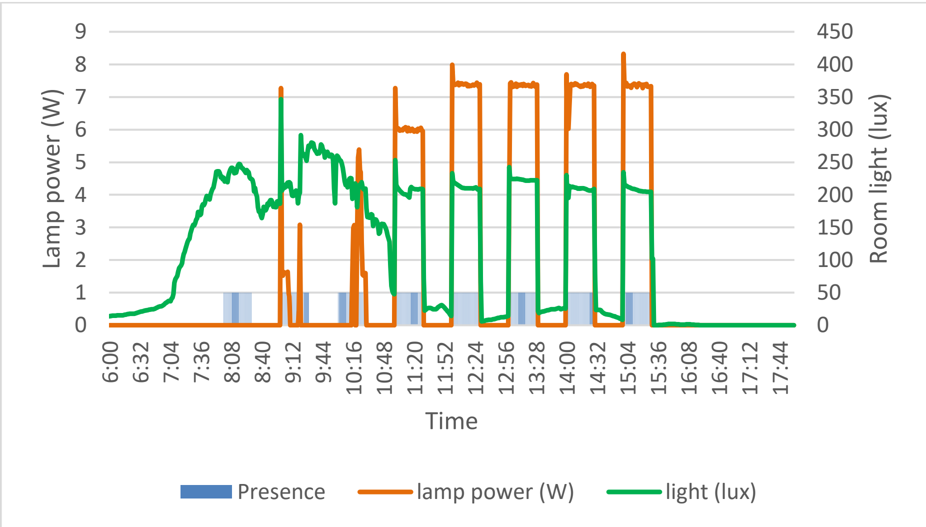


Figure 5. Light lamp operation

Table 5 provides an overview of the lamp's performance as illustrated in Figure 5. Under the implemented control strategy, the lamp activates below its rated power when occupancy is detected, dynamically adjusting to the available natural light to achieve the desired illumination level of 200 lux. The lamp's maximum operational power is 8.34 W, which accounts for 69% of its total rated power. Throughout an 8-hour operational period, the lamp consumes 18.72 Watt-hours of energy, resulting in an average power usage of 2.34 W. The lighting control strategy achieved energy savings of 72% (relative to maximum lamp usage of 12 W for 8 hours). This saving is derived from two sources:

a. 50% efficiency from the capability to switch off the lamp when unoccupied.
b. 22% additional efficiency from dimming the lamp's power (maximum operational power of only 8.34 W) when adequate natural light is available, yet supplementary light is needed to reach 200 lux.

This strategy proved highly effective in achieving energy efficiency. Concurrently, by maintaining illumination above the 200 lux standard during occupancy, the visual comfort of the room is maintained, eliminating the risk of under-illumination.

Table 5. Comparison of lamp energy consumption

Description	Value	Unit
Lamp power	12	W
Maximum operating power	8.32	W
8 h-energy	18.72	Wh
8 h-average power	2.34	W
Load factor	0.28	

3.3. Challenges in internet of things network and sensor implementation

In both AC and lighting control strategies a key challenge was linked to sensor accuracy and IoT network latency. The accuracy and response speed of the presence sensor directly influence the time taken for comfort restoration. Delays in detecting re-entry (WiFi network latency) in the scenario 1 of AC control strategy can extend the AC's waiting time to return to full cooling mode, exacerbating the discomfort caused by prolonged absence-induced temperature rise. For lighting control, the primary implementation challenge is ensuring the light sensor can react quickly and smoothly to changes in natural light intensity (without sudden fluctuations in lamp brightness) to ensure a comfortable user experience. Implementation in a residential environment highlights the critical need for stable WiFi network connectivity and fast sensor data processing to ensure the control strategy operates effectively in real-time.

Overall, the proposed IoT system achieved its goal of significantly reducing energy consumption, but with varying degrees of compromise on comfort. From lighting, high energy savings (72%) were achieved without sacrificing visual comfort during occupancy. Meanwhile, for AC control strategies where comfort is the primary consideration, scenario 1 (36.2% savings) offers the largest reduction but with a significant negative impact on thermal comfort due to the long re-cooling time. Scenario 2 (10.4% savings) proves to be a more practical solution for environments requiring continuous thermal comfort, offering adequate savings while maintaining thermal comfort levels nearly equivalent to the base scenario. In conclusion, the most effective combined strategy is to use adaptive lighting control (maintaining 200 lux) and adopt scenario 2 for AC control, which successfully balances energy efficiency and maintaining a stable thermal comfort zone.

4. CONCLUSION

An IoT-enabled system for managing energy in AC and room lighting has been successfully implemented, operating effectively in alignment with the proposed design and specified control strategies. This system adjusts the operational patterns of lighting and AC units in response to the human presence and the environmental conditions within the room, utilizing data collected from wireless sensor devices. Two new distinct scenarios have been assessed to evaluate the effectiveness of the established management strategies. Test results showed energy savings up to 36% from AC operation and 72% from lights operation can be obtained without reducing room comfort. However, this research was limited in controlling load side i.e., a single AC unit and lighting in a room and the 8-hour test was conducted during the day with constant room occupancy. Further research can develop IoT-based building control systems that integrate load-side in complex building and source-side management with renewable energy means to achieve net-zero energy buildings and improve overall building energy performance.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
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Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [W], upon reasonable request.

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