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Smart Mosque Prototype Based on IoT for Electrical Energy Savings Using LDR, DHT11 and PIR Sensors

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Abstract

This study examines the importance of energy efficiency in mosques in Indonesia as part of national sustainability initiatives. This research aims to develop and evaluate the performance of an IoT-based automation system designed to optimize electricity consumption. A prototype was developed using a NodeMCU ESP32 microcontroller integrated with light (LDR), temperature (DHT11), and motion (PIR) sensors. The ThingSpeak platform was utilized for real-time energy consumption monitoring and system control. Black-box functional testing indicates that the multi-sensor adaptive control mechanism operates with a 100% success rate. A comparison of energy consumption was conducted between a manual operational scenario and the automated system. Measurements show that energy consumption under manual operation reaches approximately 0.475 kWh per day. Following the implementation of the automated system, the average daily operational duration of the devices was reduced to approximately 25 minutes, resulting in a decrease in energy consumption to about 0.0396 kWh. Consequently, the system yields an estimated daily energy saving of nearly 92%. These findings demonstrate that IoT-based control has the potential to support energy management in mosques, in alignment with sustainable Green Building principles.

Keywords*: Smart Mosque, IoT-Based Automation, Energi Efficiency, Green Building.*

Abstrak

Penelitian ini mengkaji pentingnya efisiensi energi pada masjid di Indonesia sebagai bagian dari inisiatif keberlanjutan nasional. Penelitian ini bertujuan untuk mengembangkan dan mengevaluasi kinerja sistem otomatisasi berbasis IoT yang dirancang untuk mengoptimalkan konsumsi energi listrik. Prototipe sistem dikembangkan menggunakan mikrokontroler NodeMCU ESP32 yang terintegrasi dengan sensor cahaya (LDR), suhu (DHT11), dan gerak (PIR). Platform ThingSpeak digunakan untuk pemantauan konsumsi energi dan pengendalian sistem secara real-time. Hasil pengujian fungsional Black Box menunjukkan bahwa mekanisme kontrol adaptif multisensor beroperasi tingkat keberhasilan 100%. Perbandingan konsumsi energi dilakukan antara skenario operasional manual dan sistem otomatis. Hasil pengukuran menunjukkan bahwa konsumsi energi pada kondisi manual mencapai sekitar 0,475 kWh per hari. Setelah penerapan sistem otomatis, rata-rata durasi operasional perangkat berkurang menjadi sekitar 25 menit per hari, sehingga konsumsi energi menurun menjadi sekitar 0,0396 kWh. Sistem menghasilkan estimasi penghematan energi harian sebesar hampir 92%. Temuan ini menunjukkan bahwa pengendalian durasi operasional berbasis IoT mendukung pengelolaan energi pada bangunan mesjid sejalan dengan prinsip Bangunan Hijau yang berkelanjutan.

Kata kunci: Masjid Cerdas, Internet of Things, Efisiensi Energi, Bangunan Hijau.

Introduction

The strategic priorities of the Indonesian Government focus on energy efficiency as an effort to balance economic growth with environmental sustainability, aligning with the objectives of reducing carbon emissions and operational costs. This initiative encourages the adoption of green technologies and enhances public awareness through sustainable, community-based energy conservation programs. Specifically, the Ministry of Religious Affairs, through the National Research Agenda for Islamic Higher Education Institutions (PTKI) 2025–2029, has designated energy efficiency in religious buildings, including mosques, as a primary focus to support sustainable development.

In line with these initiatives, the Government, through the Ministry of Public Works and Public Housing (PUPR), enacted Regulation No. 02/PRT/M/2015, which promotes the implementation of the Green Building concept. The Green Building approach focuses on resource efficiency regarding water, materials, and electrical energy to minimize environmental impacts and improve occupant well-being [1]. The application of these principles in buildings has been proven to reduce energy consumption by up to 25% [2]. or public facilities, beyond the ecological benefits, Green Building also provides economic value through operational cost savings, making it a potential model for low-carbon development and global emission reductions.

Energy management in mosques faces unique challenges due to highly fluctuating consumption patterns [3]. Based on observations in mosques within Banda Aceh City, energy demand surges drastically during specific worship times, such as Friday prayers and the month of Ramadan; however, outside of these periods, electricity consumption is often inefficient. This issue is exacerbated by the significant growth in the number of mosques in Aceh, which, according to reports from the Ministry of Religious Affairs, increased from 4,385 in 2021 to 4,450 in 2023. This infrastructural growth directly increases the total electrical energy demand within the religious sector.

Energy waste in mosques is generally caused by manual operational systems for lighting and ventilation [4]. In mosques, various electrical devices often continue operating even when the number of worshippers is very small or when no one is present [5]. This contradicts Green Building principles, which prioritize adapting resource utilization to actual needs. Studies indicate that automation technology, particularly motion sensors, has the potential to significantly improve operational efficiency. Preliminary observational data show a substantial difference between the consumption of incandescent lamps (0.022 kWh) and energy-efficient lamps such as LEDs (0.003 kWh); however, previous studies emphasize that the effectiveness of monitoring systems in analyzing and controlling electrical energy consumption remains the primary key.

The implementation of IoT technology offers an innovative solution to address energy inefficiencies in mosques. IoT systems can monitor energy utilization in real time, analyze consumption patterns, and automatically optimize operations. Literature supports that sensor-based automation systems can reduce energy consumption by 20–30% by adjusting lighting based on user activity [6]. This technology enables proactive responses, such as early warnings for anomalies in electricity consumption, thereby minimizing the risk of energy waste.

Although the implementation of the Internet of Things (IoT) for energy efficiency in mosques has been widely explored, previous studies have generally focused on controlling a single parameter, such as lighting using LDR sensors [7] or temperature using DHT11 sensors [8], and have not yet developed an integrated automated system capable of managing both major electrical loads simultaneously. In addition, most existing research has emphasized prototype development and implementation without providing quantitative measurements of the actual energy savings achieved, leaving their effectiveness insufficiently validated through empirical evidence. Furthermore, several systems still rely on user intervention or specific devices for monitoring and control [9], which may limit the long-term optimization of energy efficiency. Therefore, there is a need for research that develops an IoT-based automatic control system integrating LDR and DHT11 sensors within a unified platform while quantitatively evaluating electrical energy savings to address these existing research gaps.

Literature Review

Energy consumption patterns in mosques are highly distinctive, as they fluctuate according to prayer schedules and congregation occupancy levels. In many mosques, the most significant energy loads typically originate from air conditioning systems (HVAC/fans) and lighting. Scientific evidence indicates that implementing sensor-based systems for automatic facility control can effectively reduce energy waste [10]. A study by Abdallah et al. (2025) found that the application of smart sensors in mosques reduced total energy consumption by 16.2% to 21.2% without requiring any modifications to the physical structure of the buildings [11], [12].

The effectiveness of the Internet of Things (IoT) is achieved through the integration of three core components: sensors, actuators, and a dashboard [13]. The system operates by continuously monitoring energy consumption in real time and automatically adjusting the operating status of electrical devices when spaces are unoccupied or when load requirements change [9]. The implementation of automatic control minimizes the limitations associated with manual human intervention. Integrated control systems, such as machine-to-machine (M2M) bridge communication, have been shown to improve operational efficiency and facilitate the management of worship schedules. Furthermore, the automatic operating mode of mosque energy management systems has demonstrated the most stable performance, achieving energy savings of up to 23.7% compared with conventional manual operation [14].

The Light Dependent Resistor (LDR) sensor is used to detect the ambient light intensity within a room. The applicability of the LDR sensor has been demonstrated by Lapi et al. (2023) through the development of a smart mosque prototype [15]. In that study, the LDR sensor was integrated with a NodeMCU ESP32 microcontroller and an electrical relay to successfully monitor light intensity and automatically control the on/off status of mosque lighting. Consequently, the LDR sensor prevents unnecessary lighting operation during daylight hours or when natural illumination is sufficient.

The DHT11 sensor is used to accurately measure indoor temperature and humidity. The application of temperature sensors, such as the DHT11, has proven to be essential for improving the energy efficiency of cooling systems. Previous research

demonstrated the effectiveness of the DHT11 sensor at Nurul Amin Lahumbung Mosque, where the system automatically activated the fans when the indoor temperature exceeded 25°C and turned them off when the temperature fell below 25°C [8]. Furthermore, the study by Kafrawi et al. (2020) confirmed that controlling mosque fans based on ambient temperature measurements is an effective approach to reducing electricity consumption [16].

Theoretical analysis indicates that although previous studies have investigated individual components separately (e.g., LDR sensors for lighting control or temperature sensors for fan control), the existing literature still lacks a comprehensive end-to-end IoT-based energy management system [11]. This study integrates the two most critical environmental parameters in mosques visual conditions (LDR) and thermal conditions (DHT11) into a unified dual-control system. By combining these sensors with automated control mechanisms, the proposed system directly addresses real-time energy inefficiency and supports the primary objective of achieving measurable electrical energy savings under actual operating conditions [14].

Method

The method used in this study is the V-Model [17]. The V-Model was selected due to its capability to minimize development risks. Each step in the V-Model is accompanied by a relevant testing (validation) phase, enabling effective problem identification and mitigation at an early stage of the process [18]. This approach is highly critical to achieving the Technology Readiness Level, which is the focus of this research, wherein sensor functionality must be tested through simulation on a mock-up.

This study employed a prototyping development approach, in which the system performance was evaluated using a small-scale prototype rather than being directly tested in a physical building. The Smart Mosque prototype was specifically designed and configured to replicate the environmental characteristics, spatial layout, and electrical load patterns of the two sample sites: T Nyak Arief Darussalam Mosque in Banda Aceh and Al Ihsan Mosque in Grong-Grong, Pidie Regency. The use of this representative model enabled the researchers to conduct system testing and evaluation under controlled conditions, allowing the responses of the LDR sensor to variations in light intensity and the DHT11 sensor to changes in ambient temperature at both sample mosques to be safely validated before full-scale field implementation.

a. System Development Method (V-Model)

The requirements analysis phase was conducted to determine the relevant hardware and software specifications for the energy optimization system. In this phase, the NodeMCU ESP32 microcontroller was selected as the central processing unit, supported by a PIR motion sensor, an LDR light sensor, and a DHT11 temperature sensor. A relay module was utilized as the actuator to control a 5W lamp load and a 90W fan load, while the energy monitoring process was executed using a watt-hour meter for the manual baseline and the ThingSpeak platform for real-time monitoring.

The system was designed based on an IoT architecture by applying a multi-sensor adaptive control logic. The prototype design was realized in the form of a mosque mockup to simulate actual operational conditions. The control mechanism was designed to

prioritize occupancy detection via the PIR sensor before activating the loads. The lamp is turned on only when motion is detected and the light intensity drops below 2,000 lux, while the fan turns on if motion is present and the ambient temperature reaches or exceeds 30°C.

During the implementation phase, the hardware was configured using the NodeMCU ESP32 with C++-based programming to ensure optimal system responsiveness. The integration of the ThingSpeak platform was carried out to provide continuous, real-time energy visualization, logging, and monitoring.

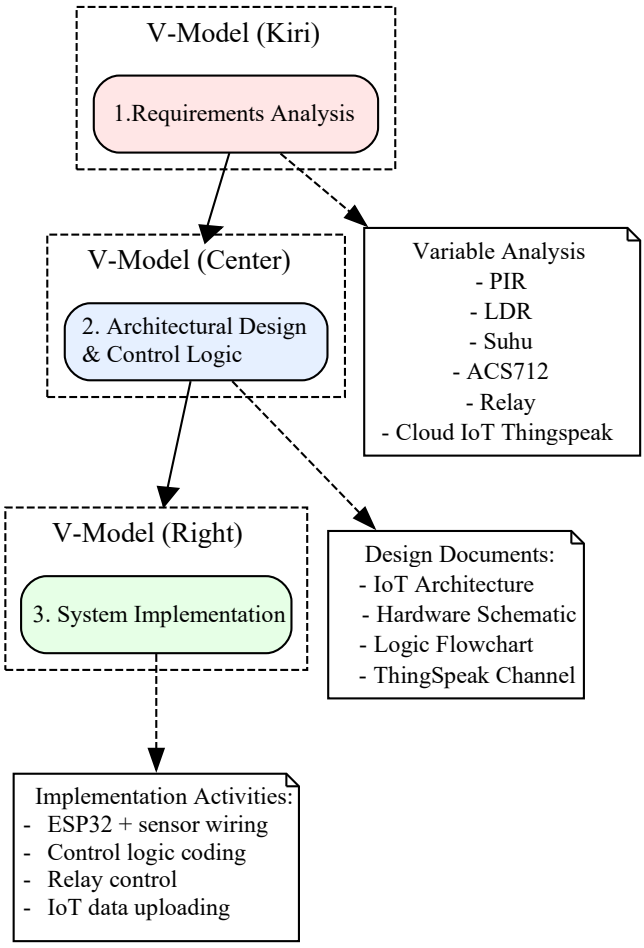


Figure 1. Research Flowchart

b. Validation Procedure

The validation and testing procedures were designed to ensure system performance in terms of technical functionality, energy efficiency, and user acceptance. Regarding the functionality aspect, testing was conducted using the black-box method to verify the compliance of system outputs specifically the status of the lamp and fan with the defined control logic. A series of test scenarios was developed utilizing six variations of sensor input conditions to simulate operational situations in a mosque environment. The efficiency calculation refers to Equation 1.

$$Energi(Wh) = V \times I \times T \quad \text{.....(1)}$$

The energy efficiency analysis was conducted by comparing the daily energy consumption between manual and automated scenarios. In the manual configuration, the

lamp and fan were assumed to operate constantly for five hours per day, resulting in a consumption of 0.475 kWh. Meanwhile, in the automated scenario, energy consumption was recorded directly via a power sensor, and the efficiency was calculated using a power- and duration-based energy formula.

The user acceptance aspect was evaluated through a Likert scale-based survey distributed to mosque administrators to measure perceptions of ease of use, automation effectiveness, and the transparency of the energy consumption monitoring process.

Result

a. Functional Verification of Control Logic

Testing using the Black-box method across six scenarios that varied the temperature, light, and motion sensor inputs demonstrated that the automation system operates with 100% accuracy in accordance with the designed control logic.

Table 1. Black-Box Testing

Temperature Sensor(^{0}C)	Light Sensor (Lux)	Motion Sensor	Lamp	Fan	Description
≤ 30	≤ 2000	yes	off	off	Normal Temperature, Enough Light, Efficiency Logic
> 30	≤ 2000	no	off	off	High Temperature, PIR Main Filter
> 30	≤ 2000	yes	off	on	Thermal Comfort Achieved
≤ 30	> 2000	no	off	off	Enough Natural Light, No Movement
≤ 30	> 2000	yes	on	off	Visual Comfort First
> 30	> 2000	yes	on	on	Full Active Condition (Maximum Comfort)

The 100% success rate across all scenarios verifies the stability of the multi-sensor control algorithm. Crucially, the motion sensor (PIR) acts as a gatekeeper, preventing fan activation despite high temperatures (Scenario 2), and effectively mitigating energy waste caused by human negligence [19].

b. Real-Time System Performance Analysis

Real-time monitoring testing via the ThingSpeak platform demonstrates the dynamic response of the system to load shedding. The log data reveals two operational phases characterized by sharp shifts in power consumption:

1. Operational Phase (Lamp On): The measured power consumption remains stable at 0.9768 Wh, with the total energy accumulating linearly.
2. Transition Phase (Lamp Off): When the system responds to changing conditions (the lamp is turned off), the power consumption immediately drops to 0.56166 Wh.

This significant reduction in power consumption quantitatively proves that the automated control system responds to environmental conditions by instantly shedding unnecessary electrical loads, thereby minimizing energy consumption. The analysis of energy escalation patterns confirms that the fan (90 W) is the dominant contributor,

indicating that the system's ability to control the fan's operational duration is the primary key to achieving efficiency.

c. Quantitative Validation of Energy Efficiency Optimization

The efficiency was calculated by comparing the daily energy consumption between the manual scenario and the automated scenario, which successfully limited the devices' runtime. In buildings that are used in continuously, residential-based HVAC (heating, ventilating and air conditioning) control saves energy by lowering system performance when the room is empty [20].

Table 2. Comparing Efficiency

Parameters	Manual Scenario	Automated Scenario
Daily Duration Assumptions	5 clocks (300 minutes	±25 minutes 0.4167 clock)
Daily Consumption (kWh)	0.475 kWh	0.0396 kWh
Absolute Savings (kWh)	-	0.4354 kWh
Efficiency Percentage	-	92%

The absolute energy savings achieved were 0.4354 kWh per day, representing an efficiency of nearly 92%. This remarkably high efficiency achievement is due to the operational duration control driven by the motion sensor (PIR). The runtime reduction of the high-power load (90 W) from 300 minutes to 25 minutes serves as the primary mechanism in achieving substantial savings, confirming that duration management is the most critical factor in optimizing energy within buildings characterized by intermittent utilization patterns.

These findings are consistent with and further reinforce the theory proposed [21] regarding the implementation of the Green Building concept, which emphasizes that the adoption of adaptive technologies and utility-based management strategies can substantially improve energy efficiency.

This figure substantially exceeds the results reported in previous empirical studies. Amri et al. (2026) found that the Automatic operating mode implemented at Taj-Al'ulum Mosque achieved energy savings of only 23.7% compared with the baseline condition [14]. Similarly, Abdallah et al. (2025) reported that the implementation of smart occupancy sensors in mosques reduced total energy consumption by approximately 16.2% to 21.2%. More broadly, the smart building literature has demonstrated that hybrid AI–IoT systems typically achieve energy efficiency improvements in the range of 20%–40% [11].

The exceptionally high energy efficiency (92%) achieved in this study is attributed to the control algorithm, which employs the Passive Infrared (PIR) sensor as the primary gatekeeper before activating the lighting or fan actuators. Even when the monitored indoor temperature exceeds 30°C or the ambient light intensity falls below 2,000 lux, the system maintains the devices in the OFF state if no human occupancy is detected. These findings demonstrate that occupancy-based control is significantly more

effective than control strategies relying solely on environmental parameters, particularly in spaces characterized by intermittent occupancy.

Occupancy-based control consistently reduces energy use compared with fixed schedules, with especially large gains for lighting and HVAC in intermittent-use spaces. Simple PIR or motion-based sensors are often the most cost-effective solution for hallways, lavatories, and small offices, delivering substantial savings with modest complexity [19].

The questionnaire results from the mosque administrators (Al-Ihsan Mosque, Grong-Grong) reinforce the technical success of the system. Most aspects of usability, installation efficiency, and automation functionality received a 'Strongly Agree' (SA) rating. Respondents perceived the system as effective in addressing congregants' negligence, as the devices automatically power down when the room is unoccupied, directly contributing to the reduction of electrical waste. The transparency of energy utilization data provided via the ThingSpeak dashboard was considered highly beneficial for the administrators to control energy in real time. This positive user support indicates that the developed system possesses a high adoption rate and excellent scalability.

Conclusion

The IoT-based Smart Mosque automation system prototype, which integrates a multi-sensor control mechanism (PIR, LDR, and DHT11), was successfully developed and validated at the prototype (mockup) scale. Functional testing using the black-box testing method demonstrated that the system's adaptive control logic operated consistently, achieving 100% accuracy across various room-condition scenarios.

The system architecture, which employs the Passive Infrared (PIR) sensor as the primary determinant of device operating duration, proved to be critical for energy optimization [21]. Based on comparative testing using the prototype simulation, the system reduced the active operating time of electrical devices to approximately 25 minutes per day. Occupancy-based sensor control has proved the potential in improve energy efficiency [22][23]. This reduction corresponded to an estimated energy efficiency improvement of up to 92%, with daily electricity consumption decreasing from 0.475 kWh/day under the manual operation scenario to 0.0396 kWh/day under the automated operation scenario.

Although the prototype system conceptually supports the Green Building principles of energy efficiency for facilities with intermittent occupancy patterns, the reported 92% energy savings represent a limited simulation-based estimate and do not yet reflect the dynamic operational load conditions encountered in real-world environments [24][25]. To comprehensively validate the effectiveness of this prototype, future research is strongly recommended to advance the technology-to-Technology Readiness Level (TRL) 4 through implementation and testing in actual mosque buildings. In addition, the scope of the control system should be expanded to include large-scale Heating, Ventilation, and Air Conditioning (HVAC) systems, complemented by more comprehensive analysis of monitoring data collected through ThingSpeak.

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