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Energy Efficiency Optimization in Smart Buildings Using NodeMCU and Cloud Monitoring

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ABSTRACT

Inefficient energy management in modern building infrastructure is often caused by a lack of real-time visibility of power consumption and reliance on manual controls that are unresponsive to environmental dynamics. This study proposes the design of an integrated Internet of Things (IoT)-based Smart Building system for energy efficiency optimization. This system was developed using the NodeMCU ESP8266 microcontroller architecture, which orchestrates DHT11 and ACS712 sensors for the acquisition of precise data related to environmental parameters and electrical loads. The main contribution of this research lies in the implementation of a non-blocking programming algorithm to ensure stable sensor readings without interruption, as well as the application of a hysteresis control method in air conditioning (AC) units with thresholds of 30°C (ON) and 28°C (OFF). This hysteresis approach is designed to mitigate compressor short-cycling, which wastes energy. System testing shows that the integration of the RemoteXY mobile interface and OLED display is capable of presenting data telemetry with a response latency of less than 2 seconds. This system has proven effective in providing stable hybrid (automatic and manual) control, offering a low-cost but significant solution for reducing the operational energy consumption of buildings.

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INTRODUCTION

In the era of rapid industrial digitalization and urbanization, energy efficiency has transformed from merely an operational option into an urgent global imperative (Ba et al., 2025; Nazari & Musilek, 2023; Sghiri et al., 2025). Commercial and residential buildings currently contribute significantly to total global energy consumption, where inefficiencies frequently arise due to passive and manual load management practices (Akram et al., 2022; Gheouany et al., 2023; Williams et al., 2023). A fundamental issue hindering energy sustainability in conventional infrastructure is the lack of real-time visibility into power consumption profiles and the dependence on manual control mechanisms that are unresponsive to environmental dynamics and room occupancy (Alsharafa et al., 2024; Brambilla et al., 2021; Yayla et al., 2022). The inability of building managers to precisely monitor electrical load fluctuations often results in substantial energy waste (Goudarzi et al., 2021; Pan et al., 2022; Patsakos et al., 2022), such as the operation of air conditioning (AC) systems and lighting in unoccupied rooms that goes undetected. Therefore, the infrastructure development paradigm is now shifting toward the concept of Smart Buildings,

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which integrate information technology to create adaptive and energy-efficient building ecosystems.

The development of Internet of Things (IoT) technology offers a disruptive solution to overcome the limitations of conventional Building Management Systems (BMS), which tend to be expensive and complex (AL KARKOURI et al., 2025; Poyyamozhi et al., 2024; Uzair et al., 2022). IoT enables the transformation of physical objects into interconnected smart devices (Fatima et al., 2022; Paolone et al., 2022; Sharma et al., 2021), creating data networks that facilitate evidence-based decision-making (Abba Ari et al., 2024; Kang, 2022; Malik, 2024). In a broader context, (Szpilko et al., 2024) emphasized that IoT literacy and adoption are fundamental foundations for realizing the Smart City concept, where the efficiency of urban resource management, including energy, can be significantly improved through system interconnectivity. This premise is supported by the empirical findings of (Szpilko et al., 2024), whose research on smart home monitoring systems concluded that providing users with real-time electricity consumption data can alter energy consumption behavior toward greater efficiency, confirming that data visibility is the key to energy optimization.

Several previous studies have explored the technical implementation of IoT for energy efficiency using various approaches. (Kadang et al., 2023) demonstrated the effectiveness of a NodeMCU ESP8266-based remote switch system, achieving household electricity savings of up to 17.02%. This study validated that low-cost microcontroller-based technological interventions can generate tangible economic impacts. Furthermore, the flexibility of NodeMCU as a System on Chip (SoC) integrating both a microcontroller and Wi-Fi connectivity has been proven across various domains. For instance, (Tiyas et al., 2025) showed that integrating NodeMCU with cloud platforms improved the accuracy of DHT11 environmental sensors through remote calibration, while (Romadan et al., 2024) and (Manullang et al., 2021) demonstrated the reliability of this architecture in precision agriculture monitoring systems and responsive vehicle security systems.

Although these studies have provided significant contributions, there remains a technical gap that must be addressed to achieve the standards of a robust Smart Building system. Most existing low-cost energy monitoring implementations are still limited to basic data handling functions or simple manual ON/OFF remote control operations (Wibowo et al., 2023). There is still limited literature discussing software architecture stability on single-core microcontrollers such as the ESP8266 when handling concurrent multitasking operations (Akbar et al., 2024). The use of sequential programming methods (blocking code) with delay functions, commonly found in beginner-level research, often results in high latency, where the system fails to respond to user interventions while processing sensor data (Akbar et al., 2024). Moreover, automatic control strategies for large inductive loads such as air conditioners frequently apply simple threshold logic, which is vulnerable to triggering short-cycling phenomena (rapid compressor ON/OFF cycles), ultimately shortening device lifespan and causing energy-inefficient inrush currents (Jiang et al., 2024).

To address these challenges, this study proposes the design and development of an intelligent energy monitoring and control system that focuses not only on connectivity but also on the intelligence of control algorithms. The system is developed using the NodeMCU ESP8266 as the central processing unit, orchestrating the DHT11 sensor for environmental parameters and the ACS712 sensor for real-time power measurement based on the Hall effect principle. The primary novelty of this research lies in two technical aspects. First, the implementation of a non-blocking programming algorithm using internal time management (millis) ensures that the microcontroller can perform sensor data acquisition, OLED display updates, and data communication to the RemoteXY server in a pseudo-parallel manner with response latency below 2 seconds. This approach overcomes the lag issues commonly encountered in conventional IoT systems.

Second, this research implements a hysteresis control method in air conditioning automation. Unlike simple if-else logic, this algorithm establishes a deadband zone with an upper threshold of 30°C for activation and a lower threshold of 28°C for deactivation. This strategy is specifically designed to mitigate compressor short-cycling, thereby optimizing energy efficiency while maintaining the durability of electromechanical devices. In addition, the system offers hybrid flexibility, allowing users to switch between fully autonomous mode and manual intervention through the cloud-connected RemoteXY mobile interface. Through the integration of precision sensors, efficient code architecture, and control logic that prioritizes device safety, this research is expected to provide both theoretical and practical contributions to the development of reliable, affordable, and sustainable building energy management systems.

RESEARCH METHOD

This research method describes the systematic framework used in the development of an Internet of Things (IoT)-based intelligent energy management system, starting from the hardware architecture design stage to the implementation of automatic control algorithms, in order to ensure system reliability in optimizing power usage within smart building infrastructure.

2.1 Modular Architecture and System Design

The research began with the design of a modular system architecture to separate the functions of data acquisition, processing, and actuation.

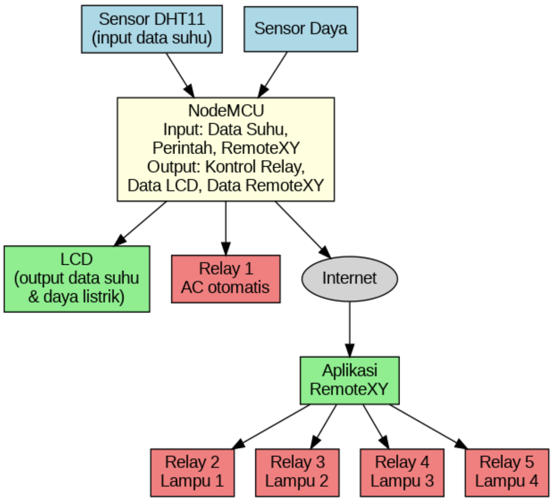

Figure 1. Block Diagram of the Energy Monitoring and Control System

The system architecture represented in Figure 1 demonstrates the structured integration between physical components and the digital platform. This architecture is divided into three main blocks: an input block, a processing block, and an output block. The input block relies on a DHT11 sensor for thermal parameters and an ACS712 sensor for electrical current detection. The central processing unit uses a NodeMCU ESP8266 that processes raw sensory data, receives external commands via internet protocol, and provides instruction logic to the output block. The system output is distributed locally through an OLED display and mechanically through a 6-channel relay module to control electrical loads such as lights and automatic air conditioners. This block diagram emphasizes the bidirectional data flow between the hardware and the RemoteXY application, which enables real-time monitoring of energy consumption while providing remote control for smart building managers.

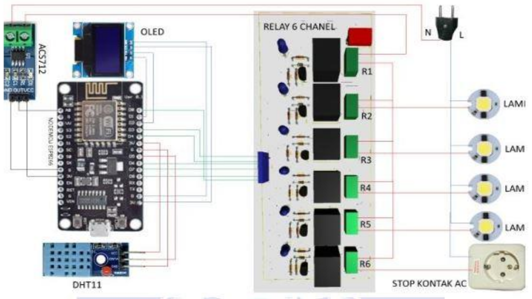

Figure 2. Schematic of the Monitoring System Circuit.

The details of the electrical interconnections between the components are presented explicitly in Figure 2, the Monitoring System Circuit Schematic. This schematic maps the data communication and power distribution paths, with the NodeMCU ESP8266 microcontroller serving as the main hub. The DHT11 sensor is connected to digital pin D5 using a one-wire protocol, while the ACS712 current sensor supplies an analog signal to pin A0 for energy data processing. For visual output, an OLED display is connected via an I2C line to pins D1 (SDA) and D2 (SCL). The most critical part is load control, which is managed through a 6-channel relay module, where pins D3, D4, D6, D7, and D8 control four lamps and the main power source, respectively, while pin D0 is specifically dedicated to the automatic activation of the air conditioning unit. This schematic arrangement ensures that each component receives the appropriate operating voltage (3.3V or 5V) and minimizes the risk of interference between the digital and analog data lines during system operation.

2.2. Algorithmic Procedures and Operational Logic

The system operates through a non-blocking timer programming logic based on the millis() function to ensure high responsiveness to user commands while maintaining periodic sensor monitoring.

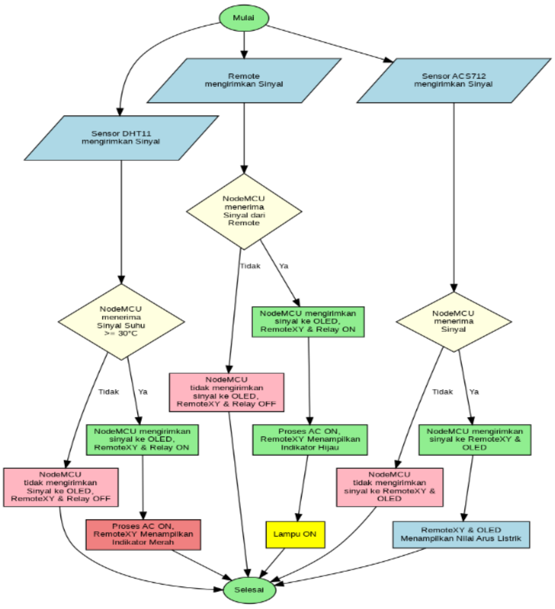

Figure 3. Program Flowchart

The system's decision-making logic is presented in detail in Figure 3, where the operational flow begins with hardware initialization and the establishment of a WiFi connection to the RemoteXY cloud server. Once the connection is established, the system simultaneously executes three logic paths: reading the DHT11 sensor, monitoring the ACS712 current sensor, and checking manual commands from the application. In the AC automation path, the system implements a hysteresis method where if the temperature is detected ≥30°C, the microcontroller will send an active signal to relay 6. Conversely, the system will only cut off the power supply if the temperature drops to ≤ 28°C to prevent the cycling phenomenon that damages the device. This flow ensures that any changes in environmental parameters are immediately converted into control actions or status updates on the graphical user interface, thus creating an adaptive and energy-efficient building ecosystem.

RESULTS AND DISCUSSION

This section presents empirical data from comprehensive system functionality and performance testing, followed by an in-depth analysis to highlight the innovative value and technical implications of implementing automated control for efficient electricity consumption.

3.1. Interface Responsiveness and Remote Control

User interface testing demonstrated high connectivity stability between the hardware and the RemoteXY cloud server. Observations showed that the average response time for each manual control command (such as turning on or off a light) was under 2 seconds. Users can monitor current consumption, temperature, and humidity through visual elements such as gauges and status indicators within the app.

Figure 4. RemoteXY Mobile Application Interface

Real-time visualization of user interaction and system performance is explicitly presented through the RemoteXY Mobile Application Interface in Figure 4, which integrates all control and monitoring parameters into a single, functional dashboard. The interface includes manual control for Main Power and four light points (L1-L4) with color-based visual feedback (orange for ON and gray for OFF), real-time current consumption (A) monitoring, and gauge displays for temperature (°C) and humidity (%) with a range of 0-100. Furthermore, experimental results confirmed that this interface provides a responsive AC status indicator (red for OFF and green for ON) to the DHT11 sensor automation logic, with high connectivity stability and an average response time of under 2 seconds.

3.2 Physical Implementation and Prototype Validation

The system's functional efficacy was validated through hardware implementation in a scaled smart building mockup prototype, as shown in Figure 5.

Figure 5. Hotel mockup.

The controller circuit, consisting of a NodeMCU and a 6-channel relay module, is assembled modularly in Figure 6. to ensure ease of maintenance and scalability. Test results show that the hardware is capable of continuous operation without significant thermal disruption, with the DHT11 sensor providing real-time temperature readings on the OLED display without significant latency. This physical integration demonstrates that the system design is not only theoretically superior but also reliable in practical implementation in confined environments.

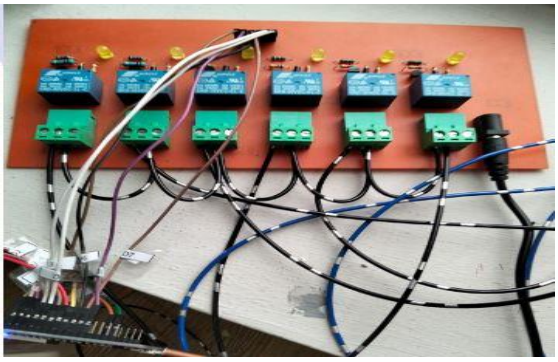

Figure 6. Module Assembly

3.3. Innovation, Implications, and Sustainability

This system offers new value in the form of comprehensive energy visibility for building managers. By providing real-time electricity consumption data, occupants can make more informed decisions to reduce overall power usage, which, according to related literature, can achieve efficiencies of up to 17.02% (Kadang et al., 2023). The implications of this research extend beyond operational cost savings to supporting climate change mitigation efforts by reducing unnecessary energy consumption. The system's modular flexibility allows for future development into a multi-channel system for monitoring broader load distribution across more complex building infrastructures.

CONCLUSION

This study concludes that the implementation of an IoT-based energy monitoring and control system using the NodeMCU ESP8266 successfully achieved optimal performance in managing smart building efficiency. The integration of the DHT11 and ACS712 sensors demonstrated high sensor data accuracy with an average synchronization latency of under 2 seconds on both the local OLED interface and the RemoteXY application. The key innovation, the hysteresis-based AC automatic control, proved effective in mitigating power waste while maintaining the device's lifespan.
However, this system suffers from major limitations, including the lack of historical data storage for long-term trend analysis and the limited monitoring channel capacity for a single load. Therefore, further research should focus on integrating cloud storage services (such as Firebase) for data recording, developing multi-channel architectures for more complex load distribution, and enhancing aesthetics and reliability through professional PCB design and ready-to-use product enclosures.

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