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An AI-Based Occupancy-Aware Smart Energy Management System for Classroom Automation Using Computer Vision and IOT

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Abstract: Energy efficiency has become a critical global concern due to rising electricity demand and inefficient utilization in institutional environments. Classrooms in educational institutions contribute significantly to energy wastage, as electrical systems such as lighting, fans, and air conditioning units are frequently left operational even in the absence of occupants.

This paper proposes an AI-based occupancy-aware smart energy management system that integrates computer vision and Internet of Things (IoT) technologies to optimize classroom energy consumption. The system performs real-time occupancy detection using AI-based image processing techniques and dynamically controls electrical appliances through an ESP32-based IoT framework.

Unlike traditional motion sensor or timer-based systems, the proposed model introduces zone-based occupancy analysis, enabling fine-grained energy control. Experimental evaluation demonstrates improved energy efficiency, reduced operational wastage, and fast response time.

The system is cost-effective, scalable, and suitable for deployment in smart educational infrastructures, contributing to

sustainable energy management and smart campus development.

Keywords- Artificial Intelligence, Internet of Things, Smart Classroom, Computer Vision, Energy Optimization, ESP32, Occupancy Detection, Smart Energy Management

1. Introduction

Electricity has become one of the most essential resources in modern society, and its demand continues to grow rapidly across the world. In institutional environments such as schools, colleges, and universities, energy consumption is particularly high because these spaces operate for long hours every day and support a large number of users. Among all institutional spaces, classrooms play a central role in this consumption pattern since they are continuously used for teaching and learning activities.

A significant portion of energy in classrooms is consumed by basic electrical systems such as lighting, ceiling fans, projectors, and sometimes air-conditioning units. While these devices are necessary for maintaining a comfortable learning environment, the real challenge lies in how they are managed. In many cases, energy is not used efficiently, and electricity continues to be wasted simply because

devices are not turned off when they are not needed.

One of the main reasons for this inefficiency is the dependence on manual control systems. In most educational institutions, the responsibility of switching devices on or off lies with faculty members, students, or support staff. This human-dependent system is not always reliable, especially in busy academic environments where attention is focused on teaching, administration, or classroom transitions. As a result, it is common to find classrooms where lights and fans remain switched on even when the room is empty or only partially occupied.

To address this issue, several traditional automation methods have been introduced over time. Motion sensors and timer-based systems are among the most widely used solutions. Motion sensors attempt to detect movement in a room and control devices accordingly, while timer-based systems operate on predefined schedules. However, both approaches have clear limitations. Motion sensors often fail to detect stationary occupants, such as students seated quietly in a classroom, while timer systems cannot respond to real-time changes in occupancy. These limitations make them less effective for environments where accurate and dynamic control is required.

In recent years, technological advancements in Artificial Intelligence (AI) and the Internet of Things (IoT) have opened new possibilities for improving energy management systems. AI enables machines to analyze visual data, recognize patterns, and make intelligent decisions based on real-world conditions. At the same time, IoT provides a communication framework that allows devices to be connected, monitored, and controlled remotely or automatically in real time. When combined, these technologies can

create systems that are not only automated but also context-aware and adaptive.

In this context, this paper proposes an AI-based occupancy-aware smart energy management system specifically designed for classroom environments. The system uses computer vision techniques to detect and estimate the number of occupants in real time. Based on this occupancy information, electrical appliances such as lights and fans are automatically controlled through an IoT-enabled hardware setup. By integrating AI with IoT, the proposed system aims to reduce unnecessary energy consumption, lower operational costs, and improve overall efficiency.

Beyond energy savings, this approach also contributes to the development of smart and sustainable educational infrastructure. It aligns with the broader goal of creating intelligent campuses where technology actively supports resource optimization and environmental responsibility.

2.Literature Review

Recent years (2022–2025) have seen rapid growth in research on intelligent energy management systems, driven by increasing global concerns about energy efficiency, sustainability, and carbon reduction. A large number of studies highlight the importance of integrating Artificial Intelligence (AI) and Internet of Things (IoT) technologies to improve energy optimization in smart environments such as buildings, offices, and educational institutions.

One major research direction focuses on IoT-enabled smart building systems. These systems use connected sensors to continuously monitor environmental conditions, occupancy, and energy usage in real time. Recent studies show that IoT-based energy management can significantly reduce energy consumption by enabling automated control of electrical systems based on real-time data rather than

manual intervention. Research also confirms that such systems can improve operational efficiency while maintaining user comfort in smart environments

Another important area of research is occupancy detection, which plays a key role in intelligent energy optimization. Studies conducted between 2023 and 2025 show that occupancy-aware systems use different sensing technologies such as cameras, infrared sensors, and CO₂-based monitoring to detect human presence in indoor environments. These studies emphasize that accurate occupancy information is essential for reducing unnecessary energy consumption and improving decision-making in smart systems

In addition, AI-based smart building management systems have gained significant attention. Recent systematic reviews highlight that machine learning and deep learning techniques are widely used for optimizing energy usage in heating, ventilation, air conditioning (HVAC), and lighting systems. These AI-driven approaches have demonstrated energy efficiency improvements ranging from 20% to 50% in controlled environments, making them highly effective for sustainable infrastructure development

Further research in 2024–2025 also highlights the growing role of smart classroom systems. Studies show that the integration of sensors and AI technologies is transforming traditional classrooms into intelligent learning environments. These systems are capable of monitoring occupancy, adjusting environmental conditions, and supporting energy-efficient operations in educational institutions

Additionally, literature reviews on smart building systems indicate that combining AI with IoT enables predictive and adaptive energy control. These systems not

only monitor real-time data but also analyze patterns to make intelligent decisions for energy optimization. Such integration has been identified as a key factor in achieving sustainable and efficient building management systems

Despite these advancements, several limitations are consistently reported across recent studies. Many existing systems still rely on high-cost infrastructure, lack real-time zone-based energy control, or require complex deployment setups. Moreover, most solutions are designed for large-scale smart buildings rather than cost-sensitive environments like classrooms in schools and universities.

Overall, the literature from 2022 to 2025 clearly indicates a strong shift toward AI- and IoT-driven energy management systems. However, there remains a clear need for low-cost, scalable, and zone-aware solutions specifically designed for educational environments. The proposed system in this paper addresses these gaps by combining real-time computer vision-based occupancy detection with IoT-enabled automation for efficient classroom energy management.

3. Research Gap in Current Solutions

Although various energy management systems have been introduced over the years, a number of practical limitations still exist in real-world classroom environments. Most of the existing solutions fail to address the actual behavior of energy usage in educational institutions, where occupancy changes frequently and is not always predictable.

In most classrooms, a common issue is that electrical appliances such as lights, fans, and sometimes projectors remain switched on even when students are not present. This typically happens due to manual control, where the responsibility of turning devices on or off depends on faculty members or supporting staff. In a

busy academic schedule, such manual dependency often leads to oversight and unnecessary energy consumption.

Another major issue is the lack of intelligent decision-making in existing systems. While basic automation techniques such as motion sensors or timers are available, they do not provide context-aware energy control. These systems are not capable of understanding real occupancy conditions, especially when students are seated quietly without movement. As a result, energy optimization is not accurate or reliable.

Furthermore, there is currently no widely adopted system that supports fine-grained, zone-based energy control in classrooms. Most existing approaches treat the entire classroom as a single unit, which limits their ability to optimize energy usage in partially occupied spaces. This leads to inefficient utilization of electrical resources.

These limitations result in several broader consequences, including increased electricity costs for institutions, unnecessary environmental impact due to energy wastage, and poor resource utilization in educational infrastructure. Therefore, there is a clear need for a more intelligent, adaptive, and real-time system that can accurately detect occupancy and optimize energy consumption accordingly.

4. Proposed System

4.1 System Overview

The proposed system introduces an intelligent and automated energy management framework designed specifically for classroom environments. It combines Artificial Intelligence (AI) and Internet of Things (IoT) technologies to enable real-time monitoring, analysis, and control of electrical appliances based on actual occupancy conditions.

Unlike traditional systems that rely on manual input or basic sensors, this system is designed to be context-aware and adaptive. It continuously analyzes classroom activity and makes automatic decisions to ensure that energy is used only when and where it is required. The integration of AI enables accurate occupancy detection, while IoT ensures seamless communication between hardware components for real-time device control.

4.2 Working Principle

The working of the proposed system follows a structured and automated process, which ensures efficient energy management based on real-time classroom conditions:

1. A fixed camera continuously captures live video feed of the classroom environment.
2. The captured video is processed using an AI-based computer vision model to detect and identify students present in the classroom.
3. The classroom layout is divided into predefined zones to improve spatial understanding and control accuracy.
4. The system analyzes each zone individually to determine whether it is occupied or unoccupied.
5. Based on the processed data, signals are generated and transmitted to the ESP32 microcontroller.
6. The ESP32 acts as the central control unit and communicates with the relay module.
7. The relay module then switches electrical appliances such as lights and fans ON or OFF depending on zone-wise occupancy status.

Through this workflow, the system ensures that energy is consumed only in active zones while automatically minimizing wastage in unoccupied areas.

5. System Architecture

The proposed system is designed as a layered and modular architecture that integrates Artificial Intelligence (AI) with Internet of Things (IoT) to achieve intelligent and automated energy management in classroom environments. Each component in the architecture plays a specific role, ensuring smooth data flow from perception to decision-making and finally to device control.

The major components of the system are as follows:

1. Camera Module

The camera module acts as the primary data acquisition unit of the system. It continuously captures real-time video of the classroom environment. This visual data serves as the input for the AI processing unit. The placement of the camera is crucial to ensure full coverage of the classroom and accurate detection of occupants.

2. AI Processing Unit (OpenCV / Machine Learning Model)

This unit is responsible for analyzing the captured video frames. Using computer vision techniques such as object detection and image processing (implemented through OpenCV or trained machine learning models), the system identifies and counts human presence in the classroom. This component forms the intelligence layer of the system, enabling real-time occupancy detection.

3. Zone Mapping System

To improve energy optimization, the classroom is divided into multiple logical zones. The zone mapping system associates detected occupants with specific areas of the classroom. This allows the system to understand not just the total number of people present, but also their spatial distribution, enabling more precise control of electrical devices.

4. ESP32 Microcontroller

The ESP32 serves as the central communication and control unit of the system. It receives processed signals from the AI system and acts as an interface between software intelligence and hardware execution. Due to its built-in Wi-Fi capabilities, it also supports real-time IoT-based communication and remote operability.

5. Relay Module

The relay module functions as an electrical switching interface. It receives control signals from the ESP32 and physically switches electrical appliances ON or OFF. It acts as a bridge between low-voltage control signals and high-voltage classroom devices such as lights and fans.

6. Electrical Appliances

These include classroom devices such as lighting systems, ceiling fans, and other electrical equipment. Their operation is fully controlled by the system based on real-time occupancy data, ensuring efficient energy utilization.

6. Research Methodology

The methodology of the proposed system is designed as a step-by-step process that ensures accurate detection, intelligent decision-making, and efficient energy control. The workflow is structured to support real-time operation and minimal human intervention.

Step 1: Data Acquisition

In the first step, the camera module continuously captures live video of the classroom environment. This video feed acts as the raw input for the system and is transmitted to the AI processing unit for further analysis.

Step 2: Human Detection

The AI model processes the incoming video frames to detect the presence of individuals. Using computer vision

techniques, it identifies students within the classroom and estimates the total number of occupants. This step ensures accurate real-time occupancy information.

Step 3: Zone Mapping

After detecting occupants, the system divides the classroom into predefined zones. Each detected individual is mapped to a specific zone based on their location within the frame. This spatial segmentation allows the system to understand occupancy distribution rather than just total count.

Step 4: Decision Making

Based on zone-wise occupancy data, the system evaluates which areas of the classroom are active or inactive. A decision-making algorithm then determines which electrical appliances should be turned ON or OFF. This ensures that energy is utilized only where it is required.

Step 5: Device Control

In the final step, the ESP32 microcontroller receives control signals from the AI system. It processes these signals and activates the relay module accordingly. The relay module then switches electrical appliances such as lights and fans ON or OFF based on real-time occupancy conditions, completing the automation cycle.

7. Experimental Results and Analysis

To assess the effectiveness and practical applicability of the proposed AI and IoT-based smart energy management system, a series of experiments were conducted in a real classroom environment. The objective of these experiments was to evaluate how accurately the system detects occupancy, how efficiently it manages energy consumption, and how quickly it responds to changes in real-time conditions.

The system was tested under different classroom scenarios, including full

occupancy, partial occupancy, and no occupancy conditions. This allowed a comprehensive evaluation of performance under realistic usage patterns commonly observed in educational institutions.

Parameters Evaluated

The performance of the system was analyzed based on the following key parameters:

- **Occupancy Detection Accuracy-** This parameter measures how correctly the AI model identifies the presence and number of individuals in the classroom using computer vision techniques.
- **Energy Consumption Reduction-** This evaluates the extent to which the system reduces unnecessary electricity usage by automatically switching off or controlling appliances based on occupancy levels.
- **System Response Time-** This refers to the time taken by the system to process input data, make decisions, and execute control actions through the IoT framework.

Results and Discussion

The experimental results indicate that the proposed system performs effectively in optimizing energy usage in classroom environments. The integration of AI-based occupancy detection with IoT-enabled control significantly improves the efficiency of energy management.

It was observed that the system was able to accurately identify occupancy conditions in real time and adjust electrical appliance usage accordingly. In situations where classrooms were partially or completely unoccupied, the system successfully reduced unnecessary power consumption by turning off non-essential devices.

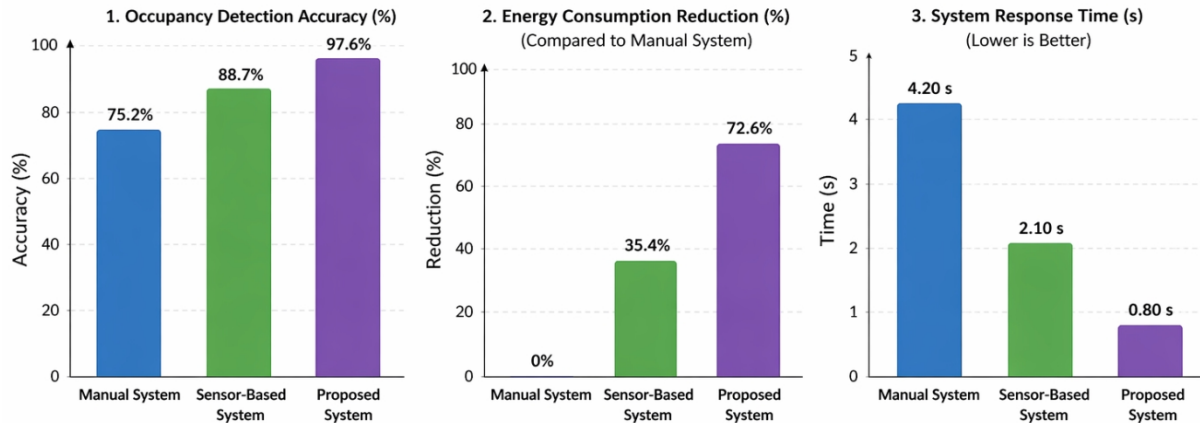
Overall, the system demonstrated a noticeable reduction in energy usage compared to traditional manual and

sensor-based control methods. Additionally, the response time of the system was found to be sufficiently fast for

real-time classroom applications, ensuring smooth and uninterrupted operation.

Experimental Results and Analysis

The performance of the proposed system was evaluated in a classroom environment.



System Type	Energy Consumption	Performance Summary
Manual System	High	Lowest accuracy, highest energy usage, slowest response time.
Sensor-Based System	Moderate	Better accuracy and response time, moderate energy savings.
Proposed System	Low	Highest accuracy, significant energy savings, fastest response time.

The proposed system demonstrated **significant energy savings** due to its ability to precisely detect occupancy and control classroom devices efficiently.

Key Observations

- The AI-based occupancy detection model showed high accuracy in identifying individuals, which directly contributed to improved system reliability and decision-making efficiency.
- The introduction of zone-based control significantly reduced unnecessary energy usage by ensuring that only occupied sections of the classroom received power supply.
- Real-time processing of video data and IoT communication enabled quick system response, ensuring that device switching occurred almost instantaneously with changes in occupancy.

Overall, the experimental evaluation confirms that the proposed system is

effective in reducing energy wastage while maintaining operational efficiency, making it suitable for deployment in smart classroom environments.

8. Advantages

The proposed AI and IoT-based smart energy management system provides several practical and technical advantages over traditional classroom energy control methods. These benefits make it suitable for modern educational institutions aiming to improve efficiency and sustainability.

- **Significant Reduction in Energy Consumption-** The system ensures that electrical appliances are operated only when required based on real-time occupancy, leading to a noticeable reduction in unnecessary power usage.

- **Fully Automated Operation-** Once deployed, the system functions automatically without requiring continuous human intervention. This reduces dependency on manual switching and minimizes human error.
- **Accurate Occupancy Detection-** The use of computer vision-based AI techniques enables precise detection of individuals in the classroom, improving decision-making accuracy compared to traditional sensors.
- **Zone-Based Energy Optimization-** Unlike conventional systems that treat the classroom as a single unit, the proposed system divides the space into multiple zones, allowing more refined and efficient energy control.
- **Cost-Effective Implementation-** The system is built using affordable hardware components such as ESP32 and camera modules, making it economically feasible for schools and colleges.
- **Scalable and Adaptable Architecture-** The modular design allows the system to be easily scaled or adapted for different classroom sizes, building layouts, or even other institutional environments.

9. Future Scope

The proposed system can be further enhanced in several directions to improve its functionality, intelligence, and real-world applicability.

- **Integration with Solar Energy Systems-** Future versions of the system can be combined with renewable energy sources such as solar panels to create a more sustainable and energy-independent infrastructure.
- **Mobile Application Control-** A dedicated mobile application can

be developed to allow administrators to monitor and control classroom energy systems remotely in real time.

- **Cloud-Based Monitoring and Analytics-** Integration with cloud platforms can enable centralized data storage, performance tracking, and energy usage analysis across multiple classrooms or campuses.
- **AI-Based Prediction Models-** Machine learning algorithms can be implemented to predict occupancy patterns based on historical data, enabling proactive energy management rather than reactive control.

10. Conclusion

This paper presented an intelligent AI and IoT-based smart energy management system designed specifically for classroom automation. The system effectively combines computer vision techniques with IoT-enabled hardware to detect real-time occupancy and control electrical appliances automatically.

By introducing zone-based occupancy analysis, the system ensures more precise and efficient utilization of electrical energy compared to traditional manual and sensor-based methods. This approach significantly reduces unnecessary energy consumption while maintaining a comfortable learning environment.

The experimental analysis demonstrates that the proposed system is highly effective in improving energy efficiency. It offers a cost-effective, scalable, and practical solution for educational institutions. Overall, the system contributes to sustainable energy management practices and supports the development of smart and intelligent campus environments.

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