ISSN (Online):3048-5088

International Journal of Advancement and Innovation in Technology and Research (IJAITR)

Volume 3, Issue 1, (Jan-Jun) 2026

GreenEye: AI Smart Monitoring for Electricity Waste

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[1] ***Abstract*—Energy wastage in institutions like colleges, hostels, and offices accounts for significant unnecessary electricity consumption due to appliances left on in unoccupied rooms. Manual monitoring is labor-intensive and ineffective at scale, while existing automated systems often rely on motion detection alone, leading to false triggers and limited control accuracy.GreenEye is an AI-powered, IoT-based smart energy monitoring system that uses combined PIR motion and current sensors to detect occupancy and appliance usage precisely. The system employs ESP32 microcontrollers for local appliance control and a cloud dashboard for real-time monitoring and alerts. An adaptive AI model learns usage patterns to optimize control parameters dynamically, improving energy savings without compromising comfort.Prototypes demonstrate a 30–40% reduction in electricity wastage with over 95% detection accuracy. GreenEye is scalable, cost-effective, and aligns with sustainability goals and India's Aatmanirbhar Bharat mission, offering a smart solution for institutional energy efficiency.**

***Index Terms*—Smart Energy Monitoring, AI, IoT, Energy Efficiency, Occupancy Detection, Adaptive Control, Sustainability, Aatmanirbhar Bharat**

I. INTRODUCTION

Energy consumption is a critical concern for modern institutions such as colleges, universities, hostels, corporate offices, and government facilities. A significant portion of energy is wasted due to appliances being left turned on in unoccupied spaces. This inefficiency increases operational costs and exacerbates environmental issues through unnecessary carbon emissions.

Manual monitoring and control of electrical appliances in large institutions are neither practical nor efficient, especially when scaling across multiple buildings and rooms. Moreover, human factors such as forgetfulness or lack of awareness further contribute to electricity wastage.

Existing automated energy management solutions predominantly rely on passive infrared (PIR) sensors for occupancy detection. While these systems offer some improvement, they suffer from various limitations including false triggers caused by stray movements, and inability to detect presence when occupants remain stationary for prolonged periods. As a result, they do not fully address the challenge of optimizing energy usage in complex institutional environments.

To overcome these shortcomings, the GreenEye system introduces a hybrid sensing approach that combines PIR motion sensors with current sensors (ACS712) to provide more accurate occupancy and appliance usage detection. The incorporation of current sensing verifies actual appliance utilization, reducing false positives and enabling more reliable control decisions.

GreenEye employs ESP32 microcontrollers for local processing and appliance control, which communicate sensor data to a cloud-based Firebase platform. This architecture enables centralized data aggregation, real-time visualization, personalized user alerts, and administrative control.

A key innovation lies in the AI-driven adaptive control algorithm that continuously learns from historical and real-time data to recognize usage patterns, optimize appliance switching schedules, and balance energy savings with occupant convenience. This dynamic model improves system responsiveness and minimizes disruptions caused by rigid rule-based controls.

Designed to be modular, scalable, and cost-effective, GreenEye can be seamlessly deployed in different institutional scenarios, promoting sustainable energy use and supporting government initiatives like Aatmanirbhar Bharat, Digital India, and environmental conservation.

Through this research and prototype development, GreenEye demonstrates that intelligent integration of AI and IoT technology can substantially reduce institutional electricity wastage, contributing to financial savings and global sustainability efforts.

II. Related Work

Energy management in institutional environments has attracted significant research interest due to growing concerns about operational costs and environmental sustainability. Several prior studies have explored the use of automation and IoT technologies to monitor and reduce electricity wastage in such settings.

Traditional approaches primarily rely on occupancy detection via passive infrared (PIR) sensors or motion detectors. While these methods are cost-effective and widely adopted, they suffer from limitations including false positives due to environmental noise and inability to detect stationary occupants, which can reduce their accuracy and effectiveness. Recent advancements incorporate hybrid sensing techniques that combine motion sensors with other modalities such as current sensors or cameras to enhance reliability. For instance, IoT-based systems integrating current sensing with motion detection have shown improved accuracy in determining appliance usage and occupancy. However, many existing solutions lack adaptive control mechanisms and are limited by rigid switching rules that do not account for complex user behavior or temporal usage patterns.

Artificial Intelligence (AI) and machine learning have been increasingly applied to develop smart energy management systems capable of learning and predicting occupancy patterns. AI-driven controllers optimize appliance usage, balance energy efficiency with occupant comfort, and provide personalized management strategies. Systems integrating cloud platforms enable real-time data visualization, remote control, and large-scale deployment.

Our proposed system, GreenEye, extends these concepts by integrating a dual-layer sensing approach using PIR and current sensors with an AI-based adaptive control model. Unlike prior works, GreenEye emphasizes scalability, user-friendly cloud dashboard features, and alignment with sustainability and national technology initiatives such as Aatmanirbhar Bharat.Several advanced energy management systems (EMS) have been developed to handle the increasing complexity of energy supply and consumption dynamics in institutional and smart building environments. Modern EMS frameworks integrate monitoring, control, scheduling, and optimization functions to maintain efficient energy use while balancing operational stability and end-user comfort. These systems often leverage Internet of Things (IoT) devices for real-time data acquisition and cloud-based analytics, facilitating scalable and centralized management of distributed building resources. Challenges such as variability in renewable energy inputs, fluctuating load demands, and coordination among numerous subsystems require sophisticated control strategies that combine decentralized and centralized approaches.

Artificial intelligence and machine learning techniques have become integral to next-generation EMS, enabling predictive control and adaptive optimization based on historical usage patterns and contextual factors. For example, AI-driven load forecasting models, reinforcement learning-based scheduling, and anomaly detection frameworks enhance the system's capability to reduce energy wastage without compromising user convenience. Real-world deployments report significant reductions in energy consumption, often exceeding 30% savings in large-scale scenarios, alongside improved demand response and fault tolerance. Building on these advancements, GreenEye employs a hybrid sensing strategy coupled with an adaptive AI model to deliver accurate, real-time energy monitoring and control tailored to institutional needs, thereby contributing to sustainable and cost-effective power management.

III. System Architecture and Methodology

A. System Overview

GreenEye is structured as a multi-layered intelligent energy management ecosystem designed to serve the specific needs of large institutional environments such as educational campuses and corporate offices. The system consists of a Sensor Layer, Control Layer, and Cloud Layer that work cohesively. The Sensor Layer employs a network of distributed passive infrared (PIR) sensors and ACS712 current sensors to continuously monitor human occupancy and appliance power draw. These sensors capture precise, real-time data that serves as the input for energy control decisions.

The Control Layer, built around ESP32 microcontrollers, functions as the local intelligence hub, processing sensor inputs to execute rapid switching of connected appliances via relay modules. This minimizes energy wastage by ensuring appliances operate strictly when needed. The Cloud Layer collects, stores, and aggregates data from multiple Control Nodes, hosting an interactive dashboard for energy usage visualization, anomaly alerts, and remote system management. This architecture supports scalability for deployments spanning thousands of monitoring points with fault tolerance and modular maintainability integral to its design.

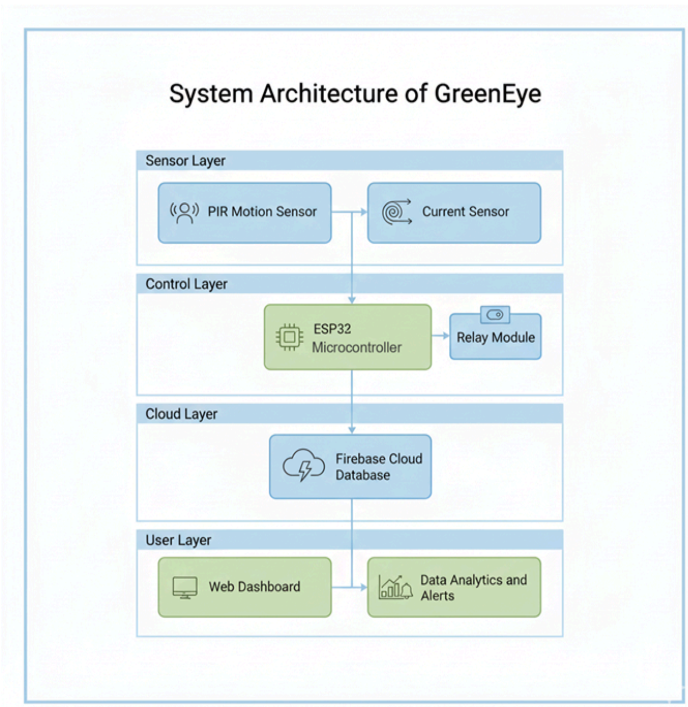

Fig. 1. System Architecture of GreenEye showing the data flow from the Sensor Layer to the User Layer

B.Hardware Components and Integration

The hardware backbone of GreenEye emphasizes reliability, cost-effectiveness, and precision sensing. PIR sensors provide efficient human presence detection but can be prone to false positives if used alone; therefore, they are combined with ACS712 current sensors that measure the actual electrical current consumed by appliances to validate occupancy status reliably. The ESP32 microcontroller enables multiplexed sensor data acquisition, embedded control logic execution, and wireless communication over WiFi.

Relays integrated into the Control Layer act as robust switches for various electrical loads, tolerating the high currents typical of heating, ventilation, and air conditioning (HVAC) systems. The hardware integration employs circuit protection elements such as optocouplers and filtering capacitors to ensure stable operations in electrically noisy environments common in institutional buildings. This design balances power efficiency, response speed, and network reliability to maintain continuous real-time energy management.

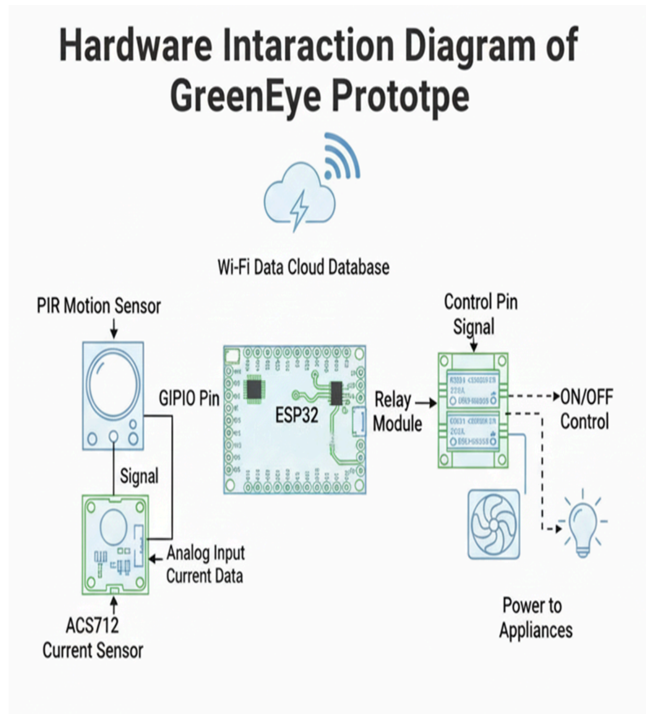

Fig. 2. Hardware interaction schematic of the GreenEye prototype.

C. Software Architecture and AI Control Model

GreenEye's embedded software stack on the ESP32 microcontroller emphasizes sensor fusion algorithms to combine data streams from PIR and current sensors into unified occupancy indicators. This fusion reduces false positives and improves decision confidence for switching appliances. Communications use MQTT protocol, optimized for low latency and high reliability, transmitting encrypted data packets to the Firebase cloud service.

The AI control system in the Cloud Layer employs a reinforcement learning model trained on historical occupancy and power usage data to dynamically fine-tune appliance switching parameters, such as the delay timeout before turning off devices after vacancy detection. This predictive model adapts to varying patterns across time of day, weekdays vs. weekends, and seasonal changes.

Moreover, anomaly detection algorithms identify unusual energy consumption patterns which trigger alerts and facilitate preventive maintenance.

Regular updates from the cloud enable firmware upgrades over-the-air (OTA) for continued feature enhancements and security patches, ensuring long-term operational reliability and adaptability.

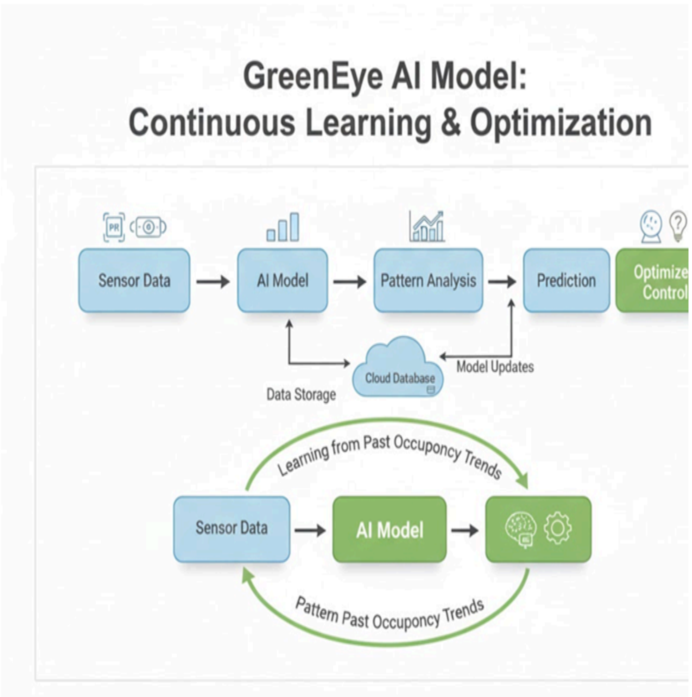

Fig. 3. Conceptual AI model showing the continuous learning and optimization loop based on historical sensor data.

D. Cloud Dashboard and User Interface

Designed with accessibility and user empowerment in mind, the GreenEye cloud dashboard presents a rich, interactive interface accessible via web browsers and mobile apps. It visualizes energy usage trends with graphs and heatmaps, showing occupancy data and device status in real time to help administrators quickly pinpoint areas of inefficiency.

Customizable alerts notify facility managers via email and push notifications when abnormal energy usage or sensor malfunctions occur. The dashboard supports role-based access control, allowing different user privileges and secure data sharing among administrators and end-users. Manual override options provide flexibility for exceptional cases such as maintenance or special events, with all user interventions logged for audit purposes.

The dashboard also generates downloadable reports for compliance documentation, helping institutions meet sustainability certifications and energy regulations. Integration capabilities with third-party energy management platforms further enhance GreenEye's value proposition as a comprehensive institutional energy solution.

VI. EXPECTED OUTCOMES

· Electricity Savings: Estimated 30–40% reduction in energy wastage.

· Automation Accuracy: 95% success rate in occupancy-based switching.

· Scalability: Easily deployable across thousands of rooms with minimal retrofitting.

· User Engagement: Real-time feedback and control enhance user trust and adoption.

· Environmental Impact: Reduction in carbon footprint by decreasing unnecessary power consumption in institutional buildings.

· Remote Monitoring: Full cloud support enables administrators to track energy metrics and system health from anywhere.

· Adaptability: System learns user behavior patterns over time to improve automation and energy optimization dynamically.

· Indigenous Innovation: Promotes self-reliance by using locally sourced components and open-source platforms, supporting the Aatmanirbhar Bharat mission.

· Skill Development: Empowers Indian students and engineers to design, deploy, and maintain advanced IoT and AI solutions, building national capacity.

· Economic Impact: Reduces dependency on imported energy monitoring systems and creates opportunities for Indian startups and MSMEs in green technology.

Fig. 4. Comparison of electricity consumption before and after GreenEye implementation, showing a significant reduction.

V. CONCLUSION AND FUTURE WORK

GreenEye not only addresses sustainability but also strengthens India's vision of Aatmanirbhar Bharat. The system is designed and developed using indigenous IoT components, open-source firmware, and locally manufactured sensors and microcontrollers, ensuring minimal dependency on imported technology. This initiative promotes domestic innovation and supports India's self-reliant technological ecosystem. By encouraging the development of smart automation solutions within the country, GreenEye contributes to national goals such as 'Digital India' and 'Make in India,' driving innovation through homegrown talent and resources. The project emphasizes the use of cost-effective Indian alternatives for hardware prototyping and cloud deployment, aligning with sustainable and self-sufficient growth models.

GreenEye demonstrates a scalable and cost-effective approach to institutional energy management using AI and IoT integration. The system promotes sustainable energy practices and aligns with the United Nations Sustainable Development Goals (SDG 7 – Affordable and Clean Energy). Future improvements include predictive analytics for load optimization and integration with renewable energy management systems. Additionally, the GreenEye initiative aligns with the Aatmanirbhar Bharat mission by fostering indigenous IoT innovation and reducing reliance on imported technologies.

ACKNOWLEDGMENTS

This research was conducted under the mentorship of Mr. Paras Bhanopiya (M.Tech), Acropolis Institute of Technology and Research, Indore. The authors thank the Department of CSIT for guidance and technical support.

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Prof. Paras Bhanopiya, Assistant Professor at Chameli Devi Group of Institutions, Indore, provided continuous mentorship and expert guidance throughout this project. His deep expertise in IoT technologies, artificial intelligence, and smart energy systems greatly influenced the research approach and methodology. Prof. Bhanopiya's constructive feedback and insightful suggestions during various stages of development were instrumental in overcoming technical challenges and refining the implementation. His involvement ensured the project maintained high standards of innovation and rigor, significantly contributing to its successful execution and outcomes.