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Design And Implementation of an IOT-Based Smart Energy Management System for Student Hostels Using Edge-Enabled Automation

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ABSTRACT: *Electricity shortages, high generator costs, and persistent energy waste remain major challenges in Nigerian student hostels. These problems are largely driven by human negligence and the uncontrolled use of high-power appliances such as lights, fans, irons, and electric cookers. This paper presents the design and implementation of a low-cost Internet of Things (IoT)–based Smart Energy Management System (SEMS) tailored for shared residential environments. The system employs ESP32 microcontrollers integrated with Passive Infrared (PIR) motion sensors, light-dependent resistors (LDR), and current and voltage sensing modules to enable automated appliance control and real-time energy monitoring. A decentralized edge-based architecture was implemented across three hostel nodes, where each node operates autonomously while synchronizing operational data to a cloud platform via Wi-Fi. Experimental evaluation showed an average motion-to-actuation response time of approximately 140 ms. Field deployment demonstrated a 28.5% reduction in total energy consumption, with lighting loads reduced by over 75%. The system effectively mitigates energy waste caused by human negligence, reduces peak demand, and lowers reliance on fuel-powered generators. Its modular and affordable design makes it suitable for large-scale deployment in Nigerian campuses and similar energy-constrained environments.*

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I. INTRODUCTION

Nigeria continues to experience chronic electricity supply challenges, characterized by frequent outages, unstable voltage levels and inadequate generation capacity. As a result, millions of households and institutions rely heavily on petrol and diesel generators for basic power needs, which significantly increases operating costs and environmental pollution (Olabi et al., 2023).

Within student hostels, energy inefficiency remains a persistent challenge. Appliances such as lights, fans, irons and electric cookers are frequently left operating in unoccupied rooms due to human negligence. Previous studies have shown that the introduction of automated energy management systems can reduce residential energy consumption by between 20 % and 30 %, with lighting-related savings reaching up to 90 % when occupancy-based control is applied (Badar and Anvari-Moghaddam, 2022; Patti et al., 2022).

Smart Energy Management Systems (SEMS) employ sensing, communication and automation technologies to monitor energy consumption and control electrical appliances in real time (Mahapatra and Nayyar, 2022). In typical smart buildings, Internet of Things (IoT) technologies enable continuous monitoring of device states, remote control of appliances and data-driven optimization of energy use (Poyyamozhi et al., 2024).

However, most existing solutions are designed for single-family households in developed regions and often assume the availability of stable internet connectivity and relatively expensive infrastructure (Raza et al., 2024). In developing regions such as Nigeria, network instability and limited financial resources significantly constrain the deployment of conventional smart home platforms (Bakare et al., 2023).

To address these limitations, edge-based architectures have recently been proposed to improve responsiveness and reliability by performing control decisions locally while using cloud services only for monitoring and data analytics (Trigka et al., 2025; Andriulo et al., 2024).

This paper presents the design and implementation of an IoT-based Smart Energy Management System specifically developed for Nigerian student hostels. The proposed system embeds intelligence at the edge using ESP32 microcontrollers, enabling local decision-making based on real-time sensor inputs. Occupancy and light conditions are continuously evaluated to automate appliance control, while current and voltage sensors provide real-time monitoring of energy usage. Each node operates independently yet communicates with a central cloud platform for visualization and administrative oversight.

The main contributions of this work are:

1. The design of a low-cost, decentralized SEMS architecture suitable for hostel-scale deployment in developing regions.
2. The integration of sensor-driven automation for occupancy- and light-aware control of appliances.
3. The implementation of load monitoring and threshold-based protection for high-power devices.
4. Experimental validation in a real hostel-like environment, demonstrating significant energy savings and fast system responsiveness.

By addressing both technical and contextual challenges, this work provides a practical pathway toward sustainable energy management in Nigerian campuses and similar resource-constrained environments.

II. RELATED WORK

Smart Energy Management Systems have been widely studied as an effective approach for improving energy efficiency in residential and institutional buildings. Recent surveys show that home energy management platforms are capable of significantly reducing electricity consumption and operational costs through automation, scheduling and real-time feedback mechanisms (Mahapatra and Nayyar, 2022; Raza et al., 2024).

Commercial and academic systems commonly adopt layered IoT architectures consisting of sensing, communication and application layers for data acquisition, transmission and analytics (Pragati, 2022). Advanced approaches incorporate machine learning and model predictive control to optimize appliance scheduling and reduce peak demand (Huang et al., 2023; Péan et al., 2018).

Several recent studies have explored data-driven and cloud-assisted solutions for smart building energy optimization. Billanes et al. (2025) and Jamuna (2021) highlight the importance of reliable data acquisition and communication protocols in achieving scalable energy management platforms. Similarly, advanced monitoring and control frameworks for complex energy systems have been reported in Patti et al. (2022).

In developing countries, research efforts have focused mainly on low-cost microcontroller-based systems using Arduino or ESP platforms to implement simple occupancy-based automation for fans and lighting (Bakare et al., 2023). Although these solutions demonstrate the feasibility of reducing energy waste, they are typically limited to single-room deployments and do not provide centralized monitoring, scalable multi-node coordination or load protection mechanisms (Poyyamozhi et al., 2024).

Furthermore, many existing systems rely heavily on continuous cloud connectivity, which can be unreliable in resource-constrained environments. Hybrid and edge-centric computing paradigms have therefore been proposed to mitigate latency and connectivity issues by enabling localized decision-making while maintaining centralized monitoring through cloud platforms (Andriulo et al., 2024; Trigka et al., 2025).

This work bridges these gaps by combining low-cost hardware with a decentralized edge–cloud architecture. Each node performs local decision-making for immediate control, while cloud services are used solely for monitoring and data aggregation. The system extends beyond basic occupancy control by integrating current and voltage sensing, enabling real-time energy auditing and threshold-based protection for high-power loads. By targeting student hostels—a shared, energy-intensive environment in Nigeria—the proposed system addresses a domain largely overlooked in existing literature and provides a scalable, context-appropriate solution.

III. SYSTEM ARCHITECTURE AND METHODOLOGY

The proposed Smart Energy Management System (SEMS) is designed using a decentralized, edge-based architecture suitable for shared residential environments. Instead of relying on a single centralized controller, the system is composed of multiple autonomous nodes, each responsible for managing a specific hostel section or room cluster. This design approach improves responsiveness and fault tolerance compared with fully centralized cloud-based systems (Andriulo et al., 2024; Trigka et al., 2025).

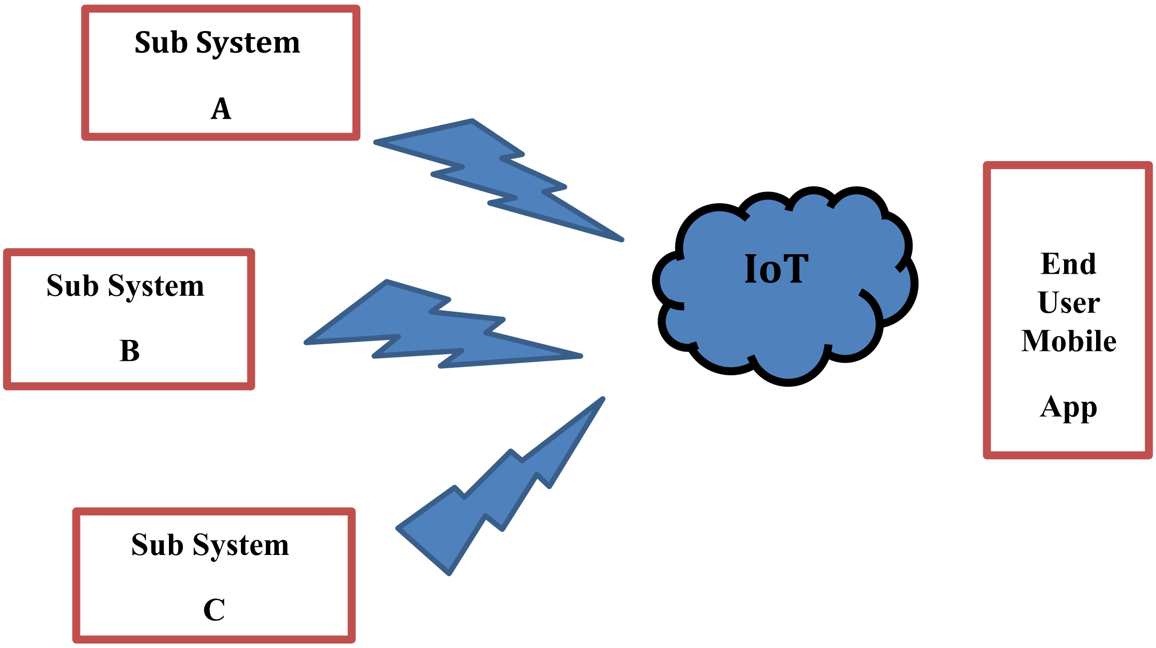

Fig. 1: Overall System Block Diagram

Each node is built around an ESP32 microcontroller, which performs real-time data acquisition and rule-based control. Occupancy and illumination information obtained from PIR sensors and light-dependent resistors are used to automate appliance operation. Similar sensing-driven automation strategies have been widely adopted in smart building applications to reduce unnecessary energy consumption (Patti et al., 2022; Mahapatra and Nayyar, 2022).The sensing layer includes:

- Passive Infrared (PIR) motion sensors for occupancy detection,
- Light Dependent Resistors (LDR) for ambient light measurement, and
- ACS712 and ZMPT101 modules for current and voltage sensing respectively.

Current and voltage monitoring using low-cost sensing modules enables real-time energy auditing and load supervision, which is a key requirement for demand-side energy management in modern smart grids (Avancini et al., 2021; Saleem et al., 2023).

Cloud services are employed only for visualization and historical analysis, thereby reducing dependency on continuous internet connectivity and ensuring uninterrupted local operation during network outages (Trigka et al., 2025).

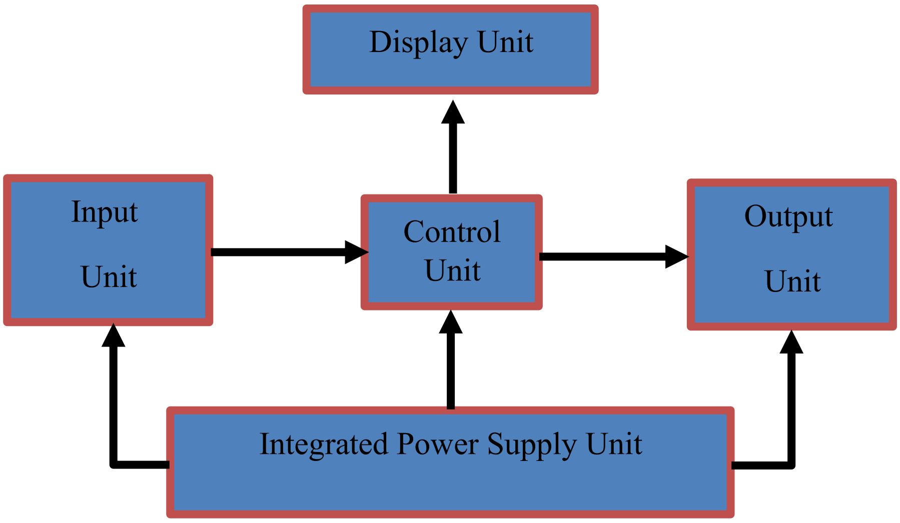

Fig. 2: Sub System Block Diagram

The actuation layer consists of relay modules that control the power supply to connected appliances such as lights, fans, irons, hotplates, and refrigerators. These relays enable the microcontroller to physically switch loads on and off based on evaluated conditions.

The architecture follows a hybrid edge–cloud model. At the edge, each node continuously reads sensor inputs and executes rule-based control logic. Typical rules include:

- Switching off lights and fans when no motion is detected for a predefined period,
- Preventing lighting operation when ambient illumination exceeds a set threshold, and
- Enforcing load limits on high-power appliances by disconnecting supply when measured power exceeds configured thresholds.

These decisions are made locally, ensuring immediate response even when internet connectivity is unavailable. At the cloud layer, nodes periodically transmit operational data—such as appliance states, current, voltage, and power consumption—to the ThingSpeak IoT platform via Wi-Fi. The cloud serves as a monitoring and visualization layer, providing administrators with real-time visibility and historical records of energy usage.

This architecture ensures that the system remains functional under network disruptions while still offering centralized oversight. The decentralized structure also enables easy expansion: additional nodes can be deployed without modifying existing units, making the system suitable for gradual campus-wide rollout.

A top-down design methodology was adopted. The system was first modeled at the block level, identifying power supply, sensing, control, communication, and output units. Each unit was then designed, implemented, and tested independently before full integration. This modular approach simplified debugging and ensured reliable operation of the complete system.

The methodology emphasizes practicality, affordability, and robustness, aligning with the constraints of Nigerian campus environments where power instability and limited budgets are persistent challenges.

IV. HARDWARE AND SOFTWARE IMPLEMENTATION

The hardware implementation of the Smart Energy Management System consists of three identical subsystems, each representing an independent smart node. Every subsystem integrates five major units: the power supply unit, input (sensor) unit, control unit, display unit, and output (actuation) unit. This modular structure ensures reliability and ease of maintenance.

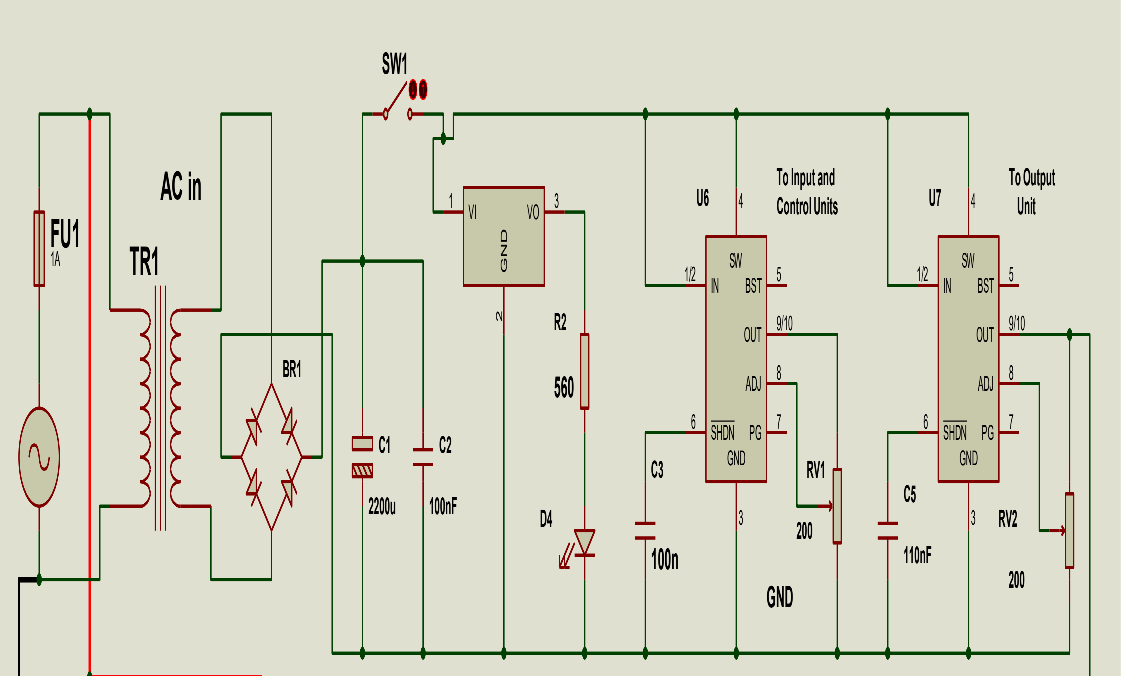

Fig. 3: Circuit Diagram of Power Supply

The power supply unit converts the 220 V AC mains voltage to regulated 5 V DC required by the ESP32 microcontroller and peripheral devices. A step-down transformer, bridge rectifier, filtering capacitors, and DC–DC buck converters were employed to provide stable output. Special consideration was given to the ESP32's current demand, ensuring adequate supply during Wi-Fi transmission.

The input unit comprises the PIR motion sensor, LDR, and the ACS712 and ZMPT101 modules. The PIR sensor detects human presence based on infrared radiation changes, producing a digital signal that indicates occupancy. The LDR measures ambient illumination, enabling automatic light control. The ACS712 current sensor measures load current, while the ZMPT101 voltage module measures AC line voltage. These values are sampled through the ESP32’s analog-to-digital converter and used to compute real-time power consumption.

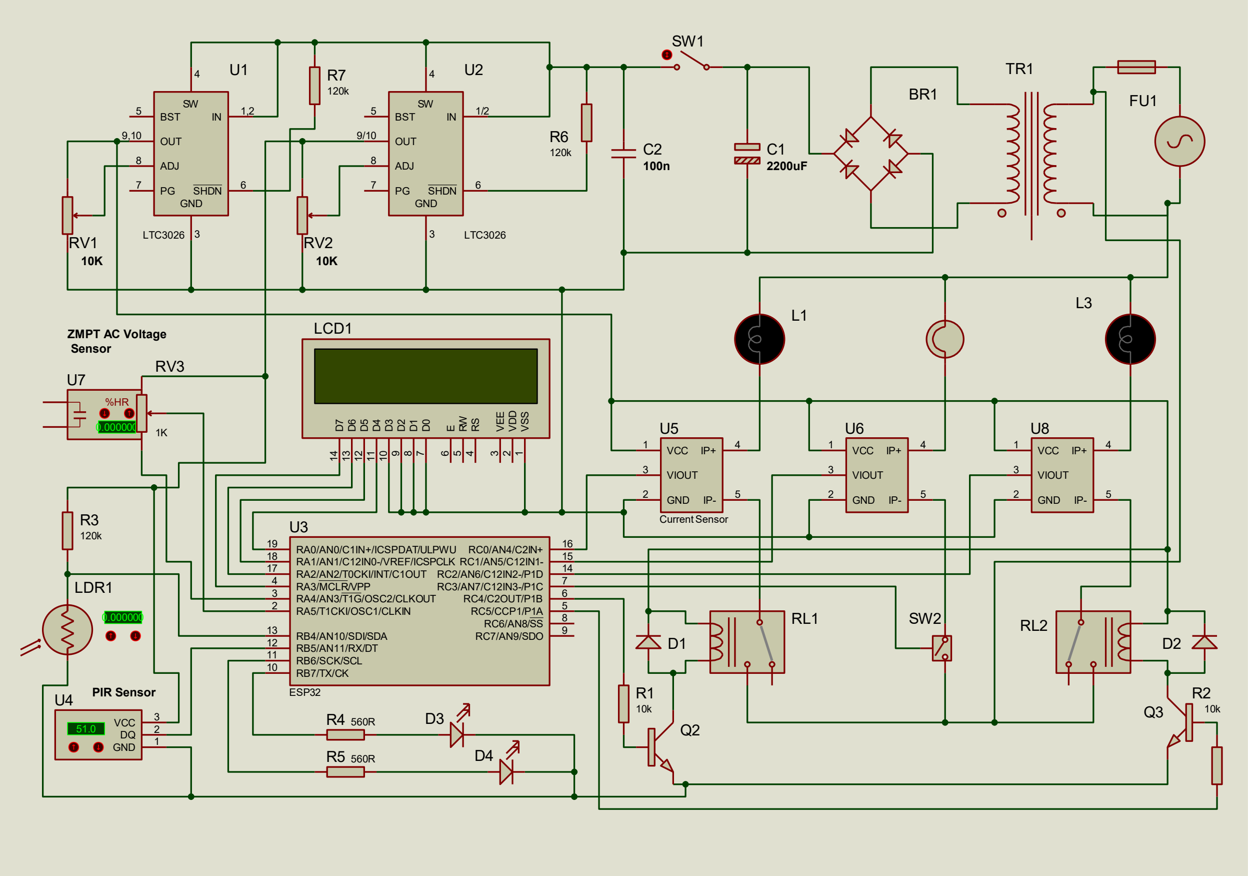

Fig. 4: Complete circuit diagram of the Smart Home and energy management module

The sensing and control framework adopted in this work follows commonly reported IoT-based smart building architectures, in which microcontrollers acquire sensor data, execute local decision logic and communicate with cloud services for monitoring purposes (Pragati, 2022; Poyyamozhi et al., 2024). The control unit is centered on the ESP32 microcontroller. The ESP32 executes all decision logic and communication tasks. Firmware was developed using the Arduino Integrated Development Environment. Upon startup, the controller initializes hardware, establishes Wi-Fi connectivity, and confirms online status via an LCD display. The main control loop continuously:

1. Reads sensor inputs,
2. Evaluates predefined rules,
3. Drives relay outputs accordingly, and
4. Transmits operational data to the IoT platform.

The integration of current and voltage sensors enables accurate real-time measurement of appliance consumption, a technique widely used in smart metering and load monitoring systems (Avancini et al., 2021). Rule-based logic governs system behavior. For example, if no motion is detected for a set duration, non-essential loads such as lights and fans are turned off. If ambient light exceeds a threshold, lighting remains disabled. For high-power appliances, measured current and voltage are used to compute instantaneous power. When this value exceeds configured limits, the corresponding relay is deactivated to prevent overload.

The output unit employs electromagnetic relays driven through transistor interfaces. These relays control AC power to connected appliances, providing electrical isolation and safe switching.

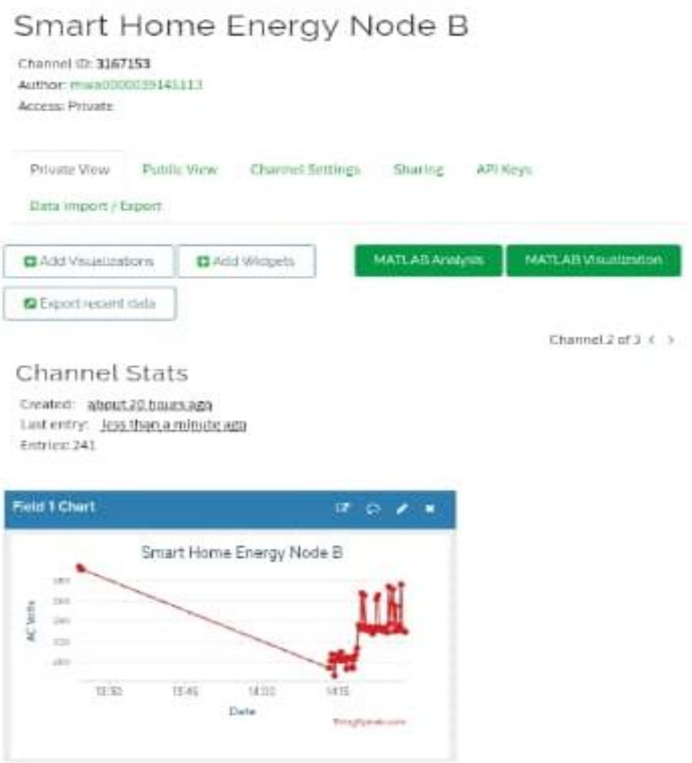

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Fig. 5: The Thinspeak IoT platform

The ThingSpeak cloud platform is employed as the monitoring layer, providing data visualization and storage for analysis. Similar lightweight cloud platforms have been successfully used in recent smart energy management deployments (Saleem et al., 2023). On the software side, the ThingSpeak IoT platform serves as the cloud interface. Each node uploads data fields representing voltage, current, power, and device state. The platform visualizes this information in real time and stores historical records for analysis. This combination of embedded control and cloud monitoring forms a complete cyber-physical energy management system.

The integration of low-cost hardware, open-source software, and cloud services ensures affordability and replicability, making the system suitable for deployment in resource-constrained educational environments.

V. EXPERIMENTAL SETUP

The observed reduction in total energy consumption of 28.5 % aligns with previously reported savings achieved by IoT-based home and building energy management systems (Badar and Anvari-Moghaddam, 2022; Raza et al., 2024). To evaluate the performance and practicality of the proposed Smart Energy Management System, three identical subsystems were constructed and deployed in a hostel-like environment. Each subsystem represented a node responsible for managing a small residential section. The deployment environment simulated typical student hostel conditions, where multiple appliances are used irregularly and often left unattended.

Fig. 6: Subsystem

Each node was equipped with three output ports: two high-power ports and one low-power port. The high-power ports were configured to accommodate appliances such as pressing irons, refrigerators, and electric cookers, while the low-power port served lighting and small loads. Threshold limits were assigned to each port based on safe operating conditions for hostel wiring. These limits ensured that excessive loads would be automatically disconnected to prevent overcurrent and system failure. The substantial reduction in lighting energy consumption is consistent with earlier findings which demonstrated that occupancy-based lighting control can yield significant energy savings in intermittently occupied spaces (Patti et al., 2022).

Fig. 7 (a): Image of the system turned on **(b): Image of system displaying it's online status**

The evaluation focused on five key performance metrics:

1. Wi-Fi and online connectivity time,
2. Motion-to-actuation response delay,
3. Relay switching and load threshold enforcement,
4. Accuracy of current and voltage measurement, and
5. Overall energy savings.

Table 1: Time for Online connection

S/N	Sub System	Time
1	System Node A	7 seconds
2	System Node B	7 seconds
3	System Node C	9 seconds

Appliances used during testing included light bulbs, standing fans, pressing irons, refrigerators, and electric cookers. Each test followed a structured procedure:

- The system was powered on and allowed to establish Wi-Fi connectivity.
- Motion was introduced by a user entering the sensor range.
- The time taken for the system to transition into its active state was recorded.
- Appliances were connected sequentially to observe relay behavior under different loads.
- Power consumption data were monitored on the ThingSpeak platform.

Table 2: **Time taken for System state activation after motion detection**

S/N	Sub System	1st Swipe	System Remark	2nd Swipe	System Remark
1	System Node A	40 seconds	System active	36 seconds	System inactive
2	System Node B	10 seconds	System active	8 seconds	System inactive
3	System Node C	15 seconds	System active	18 seconds	System inactive

For energy savings evaluation, baseline energy consumption was measured under manual operation over a defined period. The SEMS was then activated under identical usage conditions, and total energy consumption was recorded. Percentage savings were computed by comparing the two datasets.

The effectiveness of the edge-based control approach further supports recent studies which indicate that local processing significantly improves responsiveness and reliability in real-time IoT applications (Andriulo et al., 2024; Trigka et al., 2025). This structured approach ensured that both functional performance and real-world impact were quantitatively assessed.

VI. RESULTS AND DISCUSSION

CONNECTIVITY AND RESPONSIVENESS

All three nodes successfully established Wi-Fi connectivity and synchronized with the IoT platform. The average time to reach online status ranged between 7 and 9 seconds. Once online, the system displayed confirmation on the LCD, indicating readiness for operation.

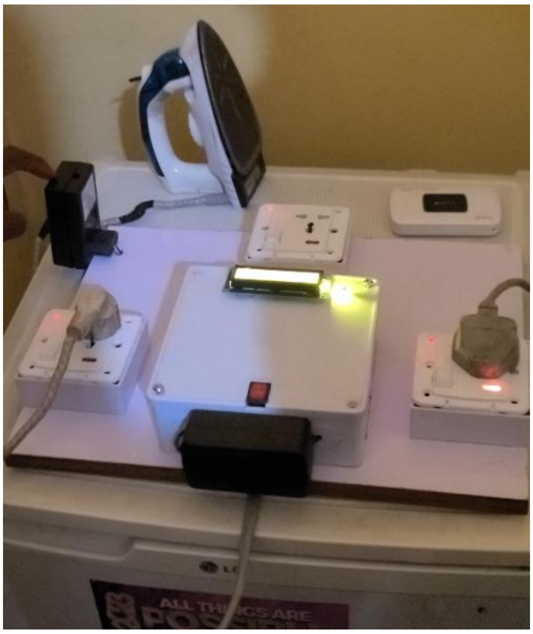

Figure 8 (a): Relay turns off after sensor detects absence. *Figure 8 (b): Relay turns on switch after sensor detects presence*

Motion detection tests revealed fast system responsiveness. The average delay between motion detection and appliance actuation was approximately 140 ms. This near-instantaneous response confirms the effectiveness of edge-based decision-making and demonstrates that automation is not hindered by network latency.

RELAY SWITCHING AND LOAD THRESHOLD ENFORCEMENT

Load threshold tests validated the system's protective capability. Appliances drawing power below configured limits remained active, while loads exceeding thresholds triggered immediate relay shutdown. For example, pressing irons rated at approximately 950–1,100 W operated normally on high-power ports configured at 1,400 W and 3,500 W. Conversely, appliances exceeding port limits were automatically disconnected.

This mechanism prevents circuit overloads and protects hostel electrical infrastructure. It also discourages misuse of high-power appliances, promoting responsible energy behavior without direct human enforcement.

SENSOR ACCURACY AND ENERGY MONITORING

Current and voltage measurements obtained from the ACS712 and ZMPT101 sensors closely matched nominal appliance ratings. For instance, a television rated at 0.65 A was measured at approximately 0.62 A, while a pressing iron rated between 4.3–4.6 A was measured at 4.35 A. These results confirm the reliability of the sensing modules for real-time energy auditing.

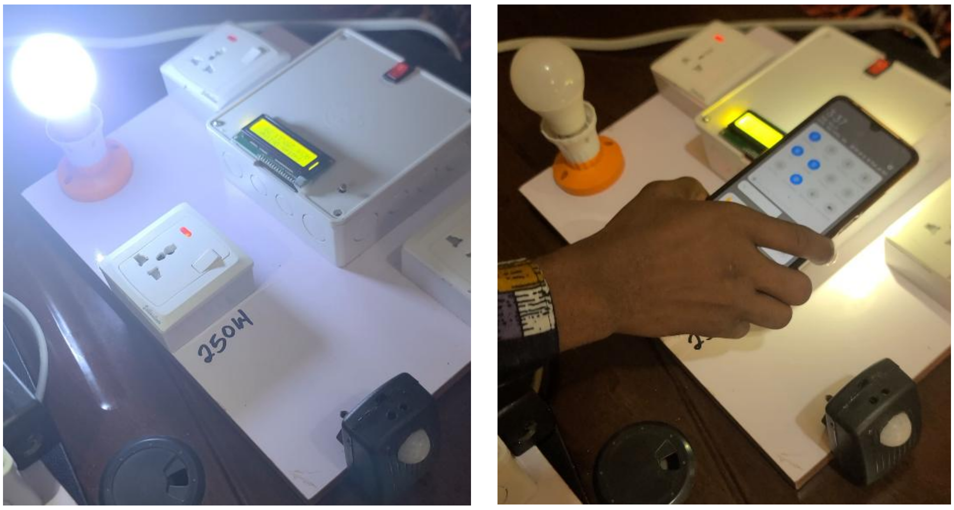

Fig. 9: Images of the light variability and control test being carried out

Data uploaded to the ThingSpeak platform accurately reflected appliance operation and power consumption, enabling remote visualization and historical analysis.

Table 3: Current Measurement Validation: Nominal vs. Measured Load Current

Appliances	Standard current ratings (Amps)	Measured current ratings (Amps)
Television	~0.65A	~0.62A
Pressing Iron	~4.32A - 4.58A	~4.35A
Standing fan	~0.4A	~0.35A
Single plate electric cooker	~5.2A - ~6.52A	~5.1A
Double plate electric cooker	~13A - ~15.2A	~14.3A
Refrigerator	~ 0.65A	~0.67A
Light bulb	~0.043A	~0.038A

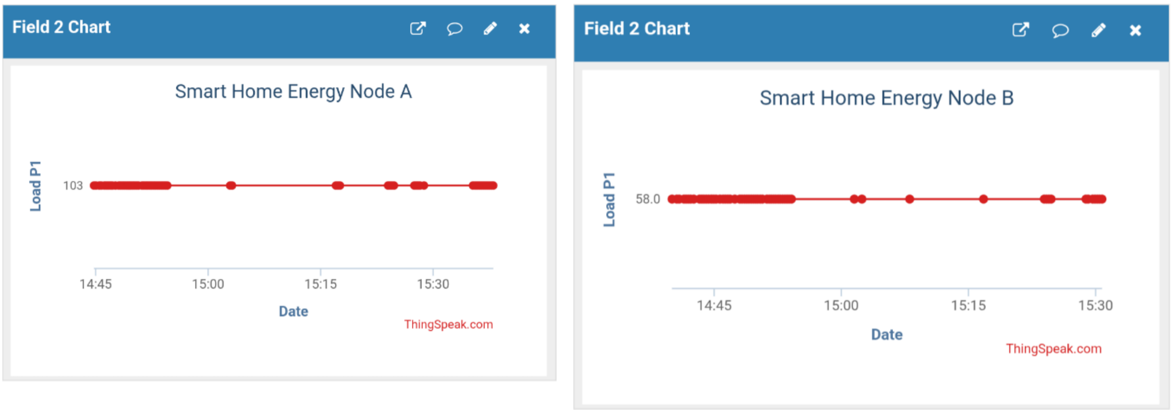

Fig. 10: Images of the load displayed on the Thingspeak IOT platform in real time

ENERGY SAVINGS

Field deployment demonstrated a 28.5% reduction in total energy consumption when the SEMS was active. Lighting loads recorded over 75% savings due to occupancy- and light-aware control. These results indicate that a substantial portion of hostel energy waste arises from appliances left on in unoccupied spaces.

By eliminating such waste and preventing excessive load usage, the system reduces reliance on backup generators, lowers fuel consumption, and extends the lifespan of electrical infrastructure.

Overall, the results confirm that the proposed system achieves both immediate operational efficiency and long-term sustainability benefits in resource-constrained residential environments.

VI. CONCLUSION AND RECOMMENDATIONS

Overall, the obtained results confirm that decentralized IoT-based energy management systems with edge intelligence represent a practical and scalable solution for demand-side energy management in resource-constrained environments, as also emphasized in recent smart grid and smart building studies (Saleem et al., 2023; Poyyamozhi et al., 2024). This paper has presented the design and implementation of a low-cost IoT-based Smart Energy Management System tailored for student hostels in Nigeria. The system integrates ESP32 microcontrollers with motion, light, current, and voltage sensors to enable autonomous, real-time control of household appliances. By adopting a decentralized edge-based architecture, each node independently manages its environment while synchronizing operational data to a cloud platform for centralized monitoring.

Experimental evaluation confirmed that the system is responsive, reliable, and effective. The average motion-to-actuation delay of approximately 140 ms demonstrates near real-time control, while Wi-Fi connectivity times of under 10 seconds ensure rapid system readiness. Load threshold enforcement protected electrical infrastructure from overload, and sensor measurements closely matched nominal appliance ratings, validating monitoring accuracy. Most importantly, field deployment achieved a 28.5% reduction in total energy consumption, with lighting loads reduced by over 75%. These results clearly show that a significant portion of hostel energy waste stems from human negligence and uncontrolled appliance use.

The proposed system offers a practical and affordable solution for energy management in shared residential environments. Its modular design allows incremental deployment across hostels, buildings, or entire campuses. By reducing waste, limiting peak demand, and lowering dependence on fuel-powered generators, the system contributes directly to cost savings, environmental sustainability, and improved power reliability.

Future work will focus on extending the rule-based control mechanism with adaptive intelligence using machine learning techniques. Predictive models could learn usage patterns and optimize control strategies dynamically. Integration with renewable energy sources such as solar photovoltaic systems and battery storage is also recommended to further enhance sustainability. Additionally, the development of a dedicated mobile application would improve user interaction and administrative control.

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