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REAL-TIME MONITORING INTERNET OF THINGS-BASED SMART ENERGY MANAGEMENT SYSTEM FOR UNIVERSITY CAMPUSES

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ABSTRACT

Traditional energy management at universities is characterised by manual monitoring, static control systems, and lack of real-time data, resulting in excessive energy consumption and high operational costs. This study presents the design, implementation, and evaluation of a Smart Energy Management System (SEMS) at the University of Calabar, Cross River State, Nigeria, with the objective of reducing energy consumption and operational costs. The SEMS integrates Internet of Things (IoT) sensors, real-time data analytics, and automated control mechanisms to monitor and manage energy consumption dynamically. Key hardware components include motion sensors, smart meters, and environmental monitors, all connected to a centralised dashboard that provides actionable insights for energy optimisation. A six-month pilot deployment using a three-tier IoT architecture demonstrated energy savings of 30–40%, improved operational efficiency, with automated response times of 2–4 seconds and system uptime exceeding 95%. Comparative analysis confirmed that the SEMS outperforms traditional energy management in responsiveness (automated response time of 2.5–3.5 seconds versus delayed manual response), cost-effectiveness (30–40% reduction in energy expenditure with low long-term operational costs), and data visibility (real-time, room-level consumption data versus monthly, incomplete utility bills). The study provides a scalable framework for implementing smart energy solutions in university settings.

KEYWORDS: Smart Energy Management System; Internet of Things; Energy Automation; Real-Time Monitoring; University Campus; IoT Sensors

INTRODUCTION

Energy management is a critical concern for university campuses, where inefficient energy use increases operational costs and undermines environmental sustainability.Traditional energy management in Nigerian universities, including the University of Calabar, is characterised by manual monitoring, static control systems, and a lack of awareness-driven efficiency practices that fail to respond dynamically to fluctuating energy demands, resulting in avoidable waste and environmental degradation (Nunayon et al., 2020; Oyedepo et al., 2016).

Smart Energy Management Systems (SEMS) offer a transformative alternative by leveraging IoT sensors, real-time analytics, and automated control to optimise energy usage across building facilities. By collecting real-time data on electricity consumption, occupancy, temperature, and natural lighting through distributed sensor networks, IoT-based systems can dynamically adjust lighting and Heating, Ventilation, and Air Conditioning (HVAC) loads across individual building spaces, replacing static scheduling with data-responsive control (Ahmed et al., 2022; Moura et al., 2021).

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Pilot deployments of such systems have demonstrated measurable reductions in energy costs and environmental impact (Sadeeq & Zeebaree, 2023).

Despite the clear potential, implementation is challenged by the need to integrate new systems with legacy infrastructure, ensure reliable network connectivity for real-time data collection, and address data security and privacy concerns. High initial investment costs and potential resistance from facility staff further complicate adoption (Oyedepo et al., 2016).

This study aims to: (i) design and implement an SEMS that automates energy usage across campus facilities; (ii) evaluate the system's effectiveness in reducing energy consumption and operational costs; and (iii) propose strategies for improving system integration and data security. The remainder of this paper is organised as follows: Section II presents the conceptual and theoretical background; Section III describes the system design and methodology; Section IV reports system implementation and performance evaluation results; and Section V concludes with recommendations for future work.

RELATED WORKS

A growing body of literature has addressed the application of IoT and smart systems to energy management in university and institutional settings. Moura et al. (2021) proposed an IoT platform for energy sustainability in university campuses using distributed sensors and cloud analytics, achieving measurable reductions in energy waste; however, their system lacked automated occupancy-responsive control and relied on manual intervention for load adjustments. Ahmed et al. (2022) developed an intelligent campus IoT platform for remote monitoring and control of smart buildings, demonstrating real-time data visualisation and control capabilities, though their deployment was evaluated in a high-resource environment and did not address the infrastructure and connectivity constraints common in developing-country institutions. Sadeeq and Zeebaree (2023) implemented a distributed IoT-based energy management system showing improved consumption tracking, yet their work did not incorporate predictive analytics or time-series forecasting for future demand. Raja et al. (2023) deployed an IoT-based demand-side management system at an educational institution, reporting reduced electricity tariffs through intelligent load scheduling, but their study was limited to a single building and did not evaluate system scalability. Jing et al. (2022) demonstrated the effectiveness of smart electricity dashboards in enabling group-oriented consumption monitoring, though user satisfaction and automated response were not systematically evaluated. Arinaitwe et al. (2024) highlighted governance and infrastructure gaps in African universities that hinder energy management adoption, yet offered no technical system implementation. Collectively, these studies reveal three persistent gaps: (i) the absence of integrated, end-to-end IoT systems that combine real-time sensing, automated control, predictive analytics, and user-facing dashboards in a single deployment; (ii) limited evaluation of such systems in African university contexts with constrained infrastructure; and (iii) insufficient attention to multi-metric performance assessment encompassing energy savings, response time, uptime, and user satisfaction. The present study addresses all three gaps through the design, deployment, and evaluation of a comprehensive SEMS at the University of Calabar, Nigeria.

A. IoT-Based Energy Monitoring and Smart Metering

IoT-based energy monitoring forms the technological backbone of modern SEMS. Distributed, interconnected sensors and actuators collect and transmit real-time data on energy use, environmental conditions, and occupancy within campus buildings. This visibility facilitates automated control, predictive maintenance, and energy optimisation. Moura et al. (2021) demonstrate that IoT frameworks enable data granularity at room or appliance level, providing valuable analytics to dynamically optimise energy flows. Ahmed et al. (2022) emphasise that IoT enables feedback loops that adapt to real-time usage patterns, replacing static, rule-based scheduling. The affordability of ESP32 microcontrollers, Digital Humidity and Temperature sensors, and PIR motion detectors makes IoT systems practical even in resource-limited academic institutions (Sadeeq & Zeebaree, 2023).

Smart metering complements IoT monitoring by recording consumption in real-time and supporting load profiling—that is, the systematic analysis of metered data to understand consumption patterns over time. Raja et al. (2023) demonstrate how IoT-enabled demand-side management at educational institutions reduces electricity tariffs through intelligent load scheduling. Bandória et al. (2025) highlight the use of adaptive load profile segmentation in smart campuses, showing how clustering-based approaches identify minority consumption groups and support peak load prediction and shifting strategies.

B. Energy Automation and Real-Time Analytics

Automation is central to smart energy systems, enabling the automatic control of appliances without manual input. Embedded systems such as ESP32, Arduino, and Raspberry Pi execute local control logic, interface with sensors, and communicate with central dashboards (Sadeeq & Zeebaree, 2023). Jing et al. (2022) demonstrate that interactive energy dashboards enabling group-oriented consumption pattern monitoring are essential for scaling energy efficiency decisions across large campus infrastructures.

Arinaitwe et al. (2024) observe that intelligent control is especially critical in African universities where energy constraints are high and operational efficiency is a pressing need. Automation protocols such as MQTT allow seamless communication between sensors and control units, making real-time device actuation reliable and responsive.

Real-time analytics transforms raw sensor data into actionable insights, enabling facility managers to detect abnormal consumption patterns and trigger corrective actions instantly. Dinmohammadi et al. (2025) demonstrate that IoT-based cloud platforms with real-time sensor integration significantly enhance energy monitoring and analytical capabilities in university buildings, while Tanavade et al. (2023) show through a comprehensive review that evidence-based energy management strategies in university campuses directly reduce carbon footprint and lower operational expenditure.

C. Theoretical Framework

This study is anchored on three theoretical frameworks. General Systems Theory (von Bertalanffy, 1968) provides the conceptual basis for treating the SEMS as a complex cyber-physical system whose components, hardware, software, and human users, interact to achieve optimised energy usage through feedback loops and self-regulation. The Diffusion of Innovations Theory (Rogers, 2003) explains how the transition from manual to IoT-enabled energy management is adopted within academic institutions, identifying factors such as relative advantage, compatibility, and trialability that influence uptake. The Technology Acceptance Model (Davis, 1989) guides the design of user interfaces that minimise resistance and foster engagement among both technical and non-technical users.

METHODOLOGY

A. Research Design

This research adopts a design and implementation-based methodology grounded in the Systems Development Life Cycle (SDLC), specifically using the Iterative and Incremental SDLC model. This model was selected because the complexity of integrating heterogeneous IoT hardware, cloud-based data pipelines, and a multi-role dashboard made it impractical to finalise all requirements upfront; iterative cycles allowed progressive refinement of sensor configurations, communication protocols, and control logic based on continuous user feedback and live performance data. The SDLC phases—requirement analysis, system design, implementation, testing, and evaluation—were repeated across multiple development cycles, with refinements informed by user feedback and empirical data analysis at each stage. The study is both applied and experimental: real-world energy data from selected campus buildings were collected and compared with pre-deployment baselines to quantify the impact of the SEMS. Stakeholders, including university facility managers and IT personnel, participated in requirements gathering and testing.

B. System Architecture

The SEMS follows a three-tier architecture comprising a Sensing Layer, a Data Processing and Communication Layer, and an Application and Control Layer.

The Sensing Layer deploys IoT sensors at strategic locations across university buildings. Devices include DHT22 temperature and humidity sensors, HC-SR501 passive infrared (PIR) motion sensors for occupancy detection, Light Dependent Resistor (LDR) light intensity modules, and PZEM-004T smart energy meters for real-time power consumption tracking at device and building levels.

The Data Processing and Communication Layer acts as the system's processing core. ESP32 microcontrollers collect and pre-process sensor readings. A Raspberry Pi 4B gateway aggregates data and forwards it to cloud and local databases via Wi-Fi or Long Range (LoRa) Wide Area Network (LoRaWAN). Edge computing capability allows real-time processing at device level when cloud access is interrupted.

The Application and Control Layer provides a web-based dashboard developed using React.js for dynamic rendering and Grafana for real-time visualisation. Energy consumption per building, temperature and occupancy patterns, alert notifications, and predictive analytics for future demand are all accessible through this interface. Role-based access control (RBAC) restricts dashboard functions according to user roles: administrator, technician, or general user. The complete three-tier architecture is illustrated in Figure 1.

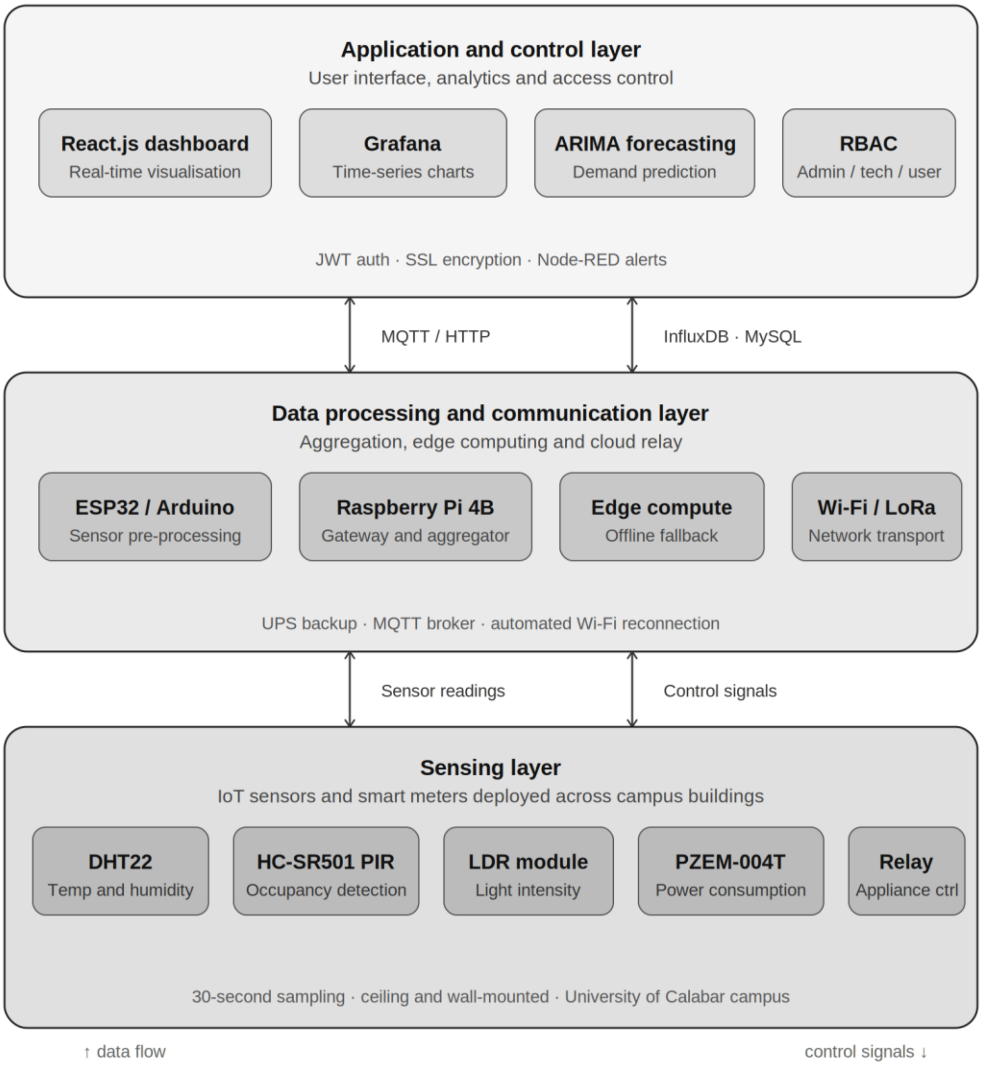

Figure 1: This figure illustrates three-tier architecture of the SEMS

C. Hardware and Software Specifications

Hardware components include DHT22 sensors, HC-SR501 PIR sensors, LDR modules, PZEM-004T smart meters, ESP32 and Arduino microcontrollers, a Raspberry Pi 4B gateway, relay modules for appliance control, LoRa transceivers for long-range communication, and an uninterruptible power supply (UPS) for server resilience.

The software stack comprises: Arduino IDE and Python for embedded programming; InfluxDB for time-series sensor data and MySQL for user and configuration data; Node-RED for control flow and alert management; MQTT protocol for lightweight sensor-to-server communication; React.js and Grafana for the dashboard interface; and JWT authentication with SSL encryption for data security. Simulation environments including Proteus and Tinkercad were used for circuit validation before physical deployment. Git and GitHub supported version control throughout development.

D. Data Collection, Analysis, and System Evaluation

Environmental data were captured via DHT22 sensors deployed in lecture halls and offices; natural light intensity was recorded by LDR modules. Occupancy was detected by HC-SR501 PIR sensors, enabling automated switching of lighting and HVAC systems. PZEM-004T smart meters logged electricity consumption every 30 seconds and transmitted readings via MQTT to the Raspberry Pi gateway, which then relayed data to InfluxDB and MySQL cloud databases.

Data analysis combined real-time processing and descriptive and predictive analytics. Python scripts and Node-RED flows detected anomalies, such as sudden consumption spikes or prolonged idle usage, automatically. Descriptive metrics including average energy use per building, peak usage hours, and energy-to-occupancy ratios were visualised via Grafana dashboards.

Time-series forecasting using the Autoregressive Integrated Moving Average (ARIMA) model was applied to historical data to predict future demand and inform proactive scheduling.

System performance was evaluated using four primary metrics: energy savings (%) relative to pre-deployment baseline data; average automated response time in seconds; system uptime percentage over the deployment period; and user satisfaction scores collected via post-deployment surveys administered to facility managers and administrative staff.

RESULTS

A. System Deployment

The SEMS was deployed in administrative offices and lecture halls at the University of Calabar. Installation involved ceiling and wall-mounted PIR and LDR sensors, smart meters connected to key power lines, and DHT22 sensors tracking ambient temperature and humidity. The central Raspberry Pi 4B hub was installed in the server room and networked with distributed ESP32 microcontrollers via MQTT (see Figure 2). A React.js dashboard provided authorised staff with role-based access to real-time readings, historical trends, and manual override functions. The deployment achieved integration with existing electrical infrastructure without requiring major rewiring, and facility staff were trained to interpret dashboard analytics and respond to alerts.

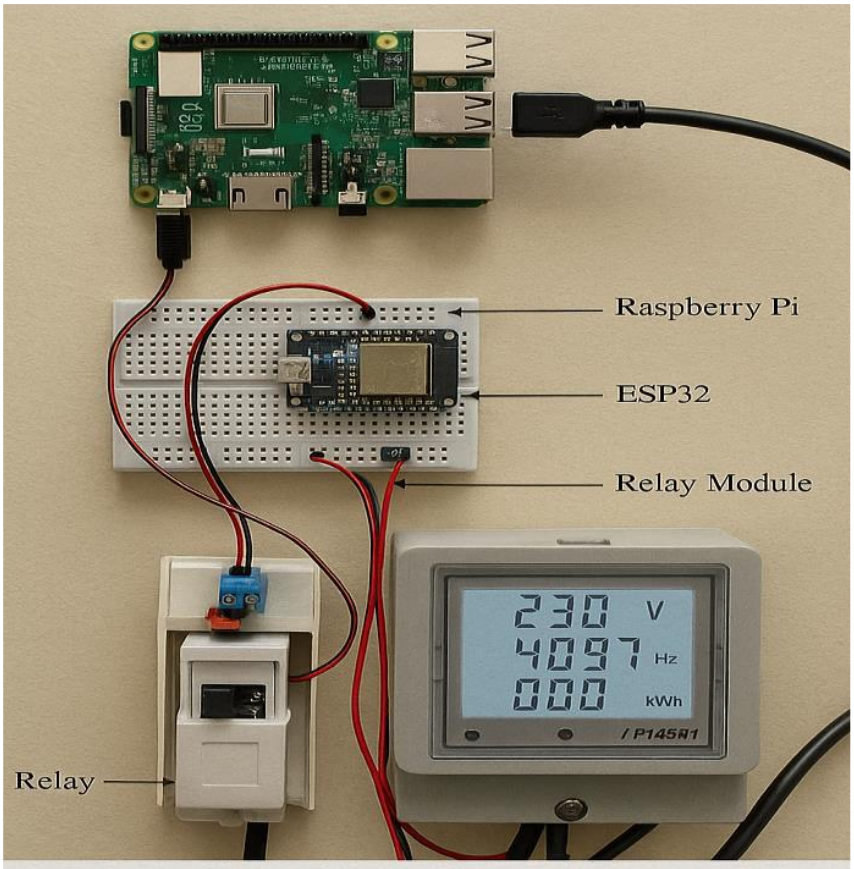

Figure 2: The hardware components setup comprises ceiling and wall-mounted PIR and LDR sensors, smart meters, DHT22 sensors, a Raspberry Pi 4B hub, and ESP32 microcontrollers.

B. Performance Evaluation

Table 1 summarises the four key performance metrics recorded during the six-month pilot. Figure 3 presents the SEMS dashboard interface showing real-time energy consumption, temperature, lighting status, and per-building occupancy panels. Figure 4 presents the time-series energy consumption chart and ARIMA-based demand prediction output generated by the SEMS over the six-month deployment, illustrating the progressive energy savings trend and the accuracy of the forecasting module in anticipating peak load periods.

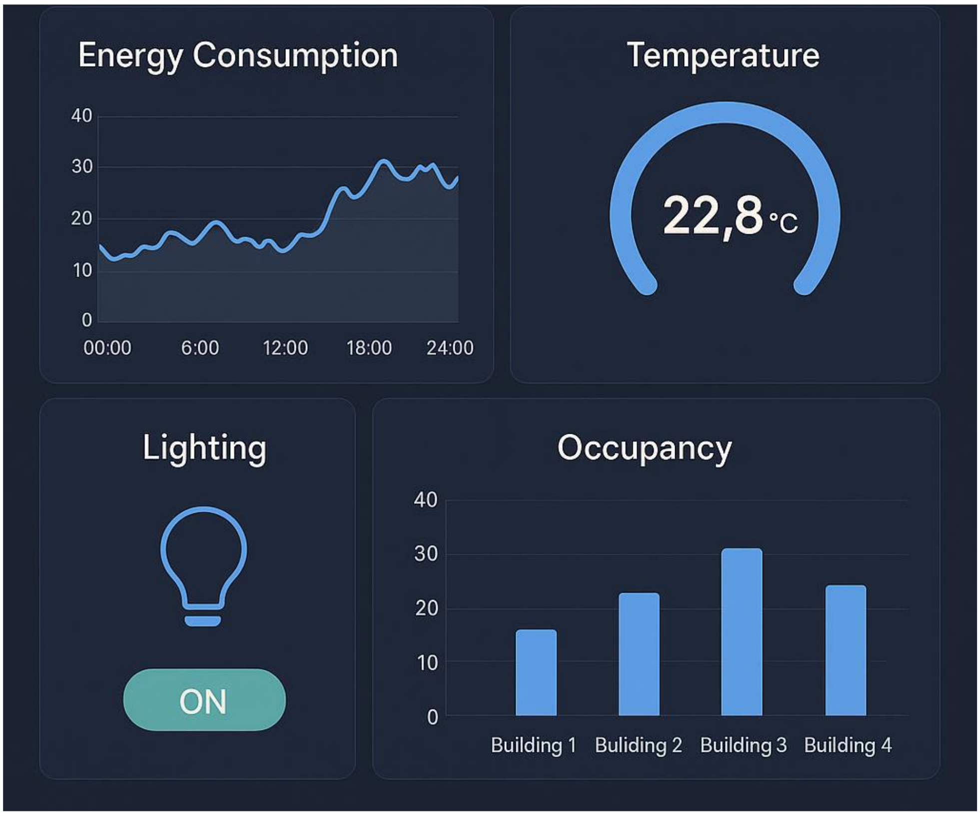

Figure 3: SEMS User Interface and Dashboard

Table 2 presents a representative sample of raw sensor data recorded by the SEMS over a 24-hour monitoring period in Block A (Administrative Block). These readings, collected every 30 minutes by the DHT22, LDR, PIR, and PZEM-004T sensors, illustrate the system's real-time data capture capability and its basis for automated control decisions.

Table 2: Sample Sensor Data Generated by the SEMS (Block A – Administrative Block, 24-Hour Period)

Time	Temp (°C)	Humidity (%)	Light (lux)	Occupancy (PIR)	Power (W)	Action
06:00	27.2	68	120	Unoccupied	42	Lights OFF
08:00	28.5	72	380	Occupied	315	HVAC ON
10:00	30.1	74	620	Occupied	482	HVAC ON
12:00	31.4	76	850	Unoccupied	58	HVAC OFF
14:00	32.0	73	740	Occupied	495	HVAC ON
16:00	30.8	70	510	Occupied	460	HVAC ON
18:00	29.3	66	210	Unoccupied	47	All OFF
20:00	27.8	63	45	Unoccupied	39	All OFF
22:00	26.4	61	18	Unoccupied	38	All OFF

The data in Table 2 confirm that the SEMS consistently deactivated HVAC and lighting systems in response to vacancy (06:00, 12:00, 18:00–22:00), while activating them during occupied periods (08:00–10:00, 14:00–16:00). The idle-time power draw of 38–58 W during unoccupied hours (compared to 315–495 W during occupied periods) reflects the system's standby load comprising the ESP32 microcontrollers, relay modules, and sensor nodes. These readings formed the empirical basis for the energy savings and response time results reported in Table 1.

Table 1: SEMS Performance Evaluation Metrics for the Pilot Study, including energy savings, operational efficiency, system uptime, and cost-effectiveness.

Metric	Result	Remarks
Energy Savings	30–40%	Increased from 24% (Jan) to 38% (Dec)
Avg. Response Time	2.5–3.5 s	Lighting 3.2 s; HVAC 2.9 s; Occupancy 2.5 s
System Uptime	94–99%	Downtime caused by network and power fluctuations
User Satisfaction	Mean: 4.1/5.0	68% rated 4–5; less than 10% low satisfaction (1–2)

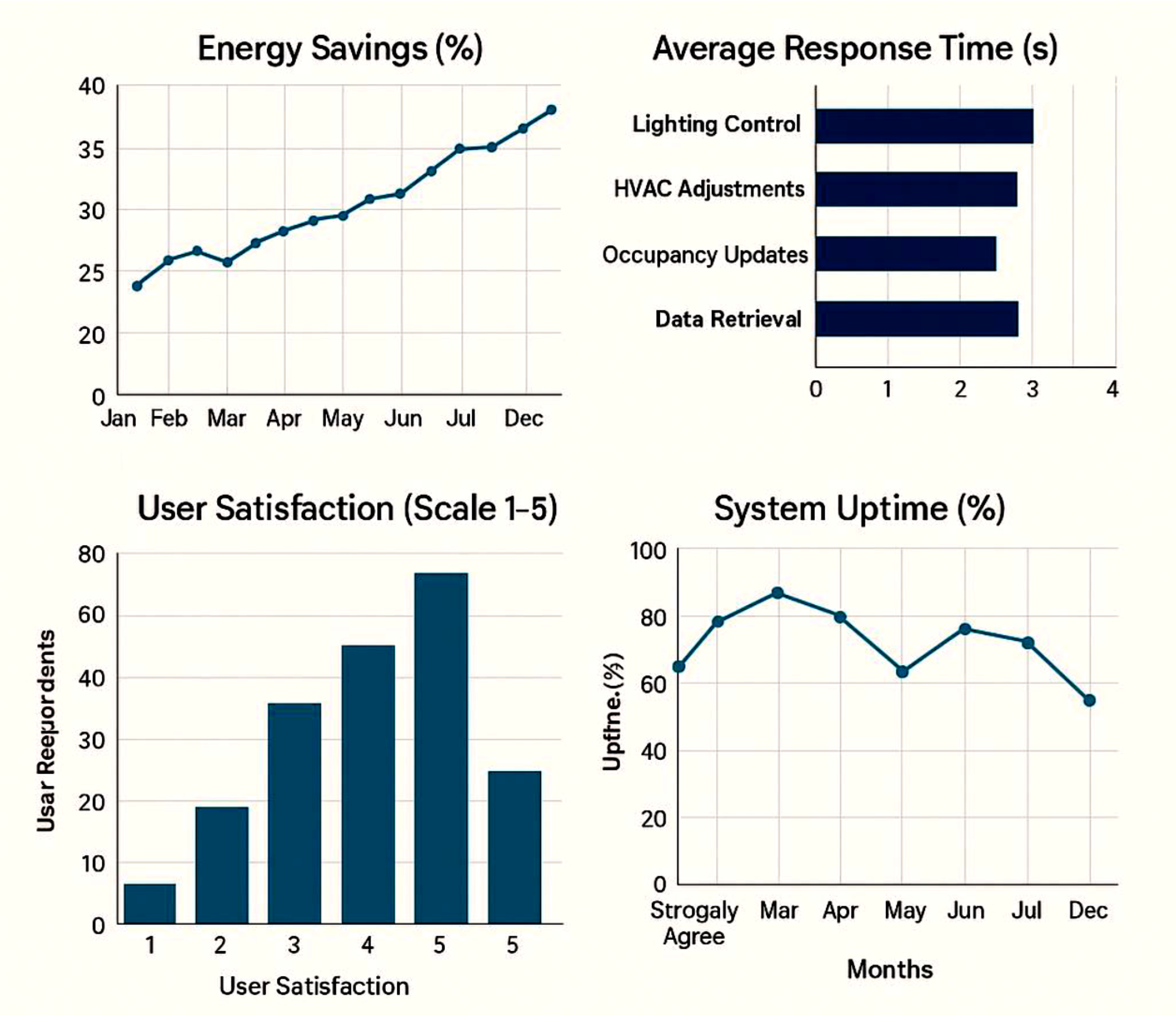

Figure 4: Performance Evaluation Charts

Energy savings increased progressively from 24% in January to 38% in December, driven primarily by automated deactivation of lighting and HVAC in unoccupied rooms, as illustrated in Figure 4. Preliminary observations revealed that several classrooms had high idle-time energy consumption, particularly where air-conditioning units remained on despite vacancy.

Automated lighting controls alone reduced usage by approximately 30% during off-peak periods. The dashboard also enabled maintenance teams to identify faulty air-conditioning units drawing excess current, an insight unavailable under the previous manual system.

Response times across all automated functions remained within the 2–4 seconds range, confirming that the system operates effectively in real-time conditions. System uptime of 94–99% across the deployment period is attributable to uninterruptible power supply backup for the Raspberry Pi server and automated Wi-Fi reconnection scripts. User satisfaction was high: the mean satisfaction score was 4.1 out of 5.0, with 68% of surveyed facility staff rating overall ease of use and performance at 4 or 5 on a five-point Likert scale, while fewer than 10% recorded low satisfaction scores (1–2). Users particularly appreciated the reduction in manual control responsibilities and the clarity of real-time alerts

C. Comparative Analysis with Traditional Systems

Table 3 compares the SEMS against the university's traditional energy management approach across five performance dimensions.

Table 3: Comparison of Traditional System and SEMS

Metric	Traditional System	Smart Energy Management System
Energy Efficiency	Low	High (30–40% savings)
Control Mechanism	Manual	Automated + Centralised
Data Availability	Monthly, Incomplete	Real-Time + Historical
Responsiveness	Delayed	Instantaneous (2–4 s)
Cost Effectiveness	High long-term cost	High initial, low long-term

Under the traditional system, lighting and HVAC units remained operational regardless of room occupancy, and energy consumption data were available only through monthly utility bills. This reactive, data-poor environment made proactive decision-making impossible. In contrast, the SEMS provided real-time, room-level consumption data, automated responses to occupancy and environmental changes, and centralised control accessible via a web dashboard. Operational control was enhanced from manual, building-by-building management to a unified, remotely accessible platform. Although the SEMS requires higher initial capital expenditure, its recurring energy savings and reduced labour costs make it considerably more economical over time.

DISCUSSION

The results demonstrate that IoT-driven automation can resolve the core inefficiencies of traditional campus energy management. The combination of occupancy-responsive control, real-time analytics, and an accessible dashboard aligns with findings from Jing et al. (2022), who showed that interactive electricity dashboards enhance facility managers' ability to perceive consumption patterns at multiple granularities and make data-informed decisions, and Raja et al. (2023), who demonstrated that real-time demand-side management at an educational institution can substantially reduce electricity tariffs through intelligent load scheduling and profiling. The SEMS's scalable, modular architecture, consistent with General Systems Theory (von Bertalanffy, 1968), means that expanding coverage to additional buildings or integrating renewable energy sources such as solar photovoltaics would require no fundamental redesign.

Challenges encountered during deployment included weak Wi-Fi coverage in some buildings, which necessitated LoRa fallback communication; power outages that disrupted sensor nodes lacking dedicated backup; and sensor drift in high-humidity environments requiring periodic manual recalibration. These findings are consistent with systemic energy management constraints reported by Arinaitwe et al. (2024) for higher education institutions in Africa, where governance gaps, infrastructure limitations, and weak institutional pressures continue to hinder effective energy management. Future iterations should incorporate dedicated uninterruptible power supply units for all sensor nodes, automated sensor self-calibration routines, and machine learning models for predictive demand optimisation.

CONCLUSION

This study has demonstrated the feasibility and effectiveness of a Smart Energy Management System for university campuses, using the University of Calabar as a case study. The deployed SEMS achieved energy savings of 30–40%, system uptime exceeding 95%, automated response times of 2–4 seconds, and strong user satisfaction, outperforming traditional manual energy management in every measured dimension. The modular three-tier IoT architecture comprising sensing, data processing, and application control layers, provides a scalable and replicable framework for digital energy optimisation in academic institutions.

Challenges related to network instability, power supply interruptions, and sensor calibration were identified and mitigated, and their resolution informs recommendations for future deployments. Integration of machine learning for predictive demand management, campus-wide expansion, mobile application development, renewable energy coupling, and enhanced cybersecurity protocols are recommended as directions for future work.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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