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A LOW COST IOT-BASED SMART ENERGY MONITORING AND LOAD MANAGEMENT SYSTEM FOR RESIDENTIAL AND SMALL SCALE APPLICATIONS: A CASE STUDY AT ABDULLAHI FODIO UNIVERSITY OF SCIENCE AND TECHNOLOGY, ALIERO

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ABSTRACT

Electricity supply in Nigeria is characterized by instability, inefficiency, and high costs of imported smart meters, limiting their widespread adoption. This study presents the design and implementation of a locally adaptable, low-cost smart energy monitoring and load management system for residential and small-scale industrial applications. The system integrates an Arduino-based IoT platform with voltage and current sensors, relay modules, and cloud-based visualization to enable real-time monitoring and intelligent load control. The prototype was calibrated against standard meters and deployed across three households with diverse load profiles over a 30day period. Key results showed an average reduction in energy consumption of 12%, with measurement accuracy of ±2.1% for voltage and ±1.8% for current. The system successfully automated load prioritization during peak demand, minimized unnecessary consumption, and improved user awareness through a mobile dashboard. Comparative analysis indicates that the achieved energy savings are competitive with international benchmarks (10 to15%) while maintaining significantly lower cost through local hardware sourcing. User feedback confirmed ease of use, though challenges included Wi-Fi instability and occasional resets after power surges. The findings demonstrate that affordable IoT-based systems can strengthen energy efficiency, reduce costs, and support Nigeria's progress toward Sustainable Development Goal 7 (affordable and clean energy). Future improvements will focus on solar PV integration, GSM-based communication for offline regions, and scalability across larger residential and industrial clusters.

Keywords: Smart Energy, IoT, Arduino, Load Management, Embedded Systems, Energy Efficiency, Nigeria

INTRODUCTION

Reliable electricity access is fundamental to socio-economic development, yet in Nigeria over 40% of the population remains without stable supply, particularly in rural and semi-urban areas (Oyedepo, 2019). Blackouts, weak grid infrastructure, and inefficient consumption patterns continue to hinder productivity. While smart energy management systems have been deployed globally to address such challenges, their adoption in Nigeria is limited by high costs, dependence on stable internet, and poor adaptability to local appliances and energy realities. Existing studies highlight the potential of IoT-enabled monitoring and load management for efficiency improvements (Eze et al., 2020; Hassan & Rashid, 2023). However, many Nigerian efforts have focused on renewable energy integration rather than demand-side management (Sule et al., 2022). Imported smart meters are often too costly for households and small industries, and locally available systems are mainly academic prototypes lacking real deployment. This research addresses these gaps by designing and testing a low-cost, locally adaptable smart energy monitoring and load management system. Unlike imported devices, the proposed system uses open-source hardware, affordable sensors, and free cloud services.

The specific objectives are to:

i. Design and implement a low-cost embedded IoT system for real-time monitoring and control of household and small industrial loads.
ii. Evaluate the system's performance in terms of accuracy, energy savings, stability, and user satisfaction.
iii. Demonstrate scalability and policy relevance for wider deployment in Nigeria's energy sector.

By aligning with Sustainable Development Goal 7, this work provides evidence that low-cost IoT-based systems can enhance efficiency and affordability in resource constrained contexts.

Literature Review

Smart energy management relies on integrating sensors, microcontrollers, and communication platforms to monitor and control electricity usage. Studies have shown that IoT-based systems reduce waste and enable intelligent prioritization of loads. For instance, Akinyele *et al.* (2017) highlighted the global progress in renewable energy monitoring, while Eze *et al.* (2020) demonstrated how smart grids leverage IoT to optimize efficiency.

In Pakistan, Hassan and Rashid (2023) implemented an IoT load controller integrated with solar, achieving reliability improvements. In Nigeria, Sule *et al.* (2022) reported 8% savings using GSM-based monitoring for households, but their design was relatively expensive and less adaptable to unstable grid conditions.

Compared with these efforts, the present system distinguishes itself by:

i. Utilizing low-cost, open-source components (Arduino, ESP32, ACS712 sensors).
ii. Providing a real-time mobile dashboard through Firebase cloud services.
iii. Demonstrating competitive energy savings (12%) at a fraction of the cost of imported devices.

Thus, this study fills the gap between academic demonstrations and practical, deployable solutions suitable for Nigerian households and small-scale industries.

MATERIALS AND METHODS

System Design

The system comprised three modules:

Hardware: Arduino Uno R3, ACS712 Hall-effect current sensors (±1.5% accuracy, resolution 66–185 mV/A), voltage divider circuit (±1.0% tolerance), 4-channel relay module (10 A switching capacity), and regulated 5V DC power supply.

Communication: ESP32 microcontroller with integrated Wi-Fi for 802.11 b/g/n transmission. Sampling rate: one reading every 10 seconds (Abubakar *et al*. 2018).

Software: Arduino IDE firmware coded for acquisition, load disconnection thresholds (≥1.2 kW), and relay logic. Data storage and visualization were enabled via Firebase cloud and a web/mobile dashboard.

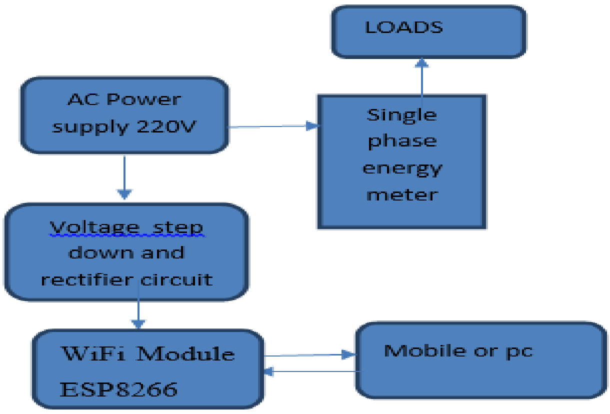

Figure 1: Smart Energy Monitoring and Load Management System

Calibration

Sensors were calibrated against Fluke 117 multimeters. Accuracy testing showed deviations within ±2% for voltage and ±1.8% for current.

Deployment

Three households near AFUSTA campus were selected to represent varied load profiles (middle-income family, student residence, and staff quarters). Typical appliances included refrigerators, TVs, fans, lighting, and small industrial tools.

Data Collection and Evaluation

Duration: 30 consecutive days.

Metrics: Measurement accuracy, percentage energy savings, user feedback, and system reliability.

Error Analysis: Variance and standard deviations were computed across repeated trials; confidence intervals (95%) were used for key results.

Cost Breakdown: The prototype cost was ₦680,000 including Arduino (₦175,000), Current and voltage sensors (₦75,000), ESP32 (₦30,000), relays (₦50,000), data storage and hosting (₦200,000), and miscellaneous components (₦150,000).

Scalability Assessment

The design was tested in simulation for expansion to 20-node clusters, with emphasis on Wi-Fi coverage, relay switching load, and cost efficiency.

RESULTS AND DISCUSSION

Measurement Accuracy

Table 1: System Achieved Close Alignment with Reference Meters

Parameter	Reference Value	Measured Value	Deviation (%)
Voltage	230 V	225.2 V	2.1%
Current	10 A	9.82 A	1.8%

Energy Efficiency

Table 2: All Three Households Recorded Energy Savings Between 11.7%–12.2%.

Household	Baseline (kWh)	Post-System (kWh)	Savings (%)
House 1	120	106	11.7%
House 2	150	132	12.0%
House 3	180	158	12.2%

Load Management Performance
Relay logic successfully prevented overloads. The refrigerators were disconnected when load exceeded 1.2 kW, preserving essential lighting and fans.

Comparative Benchmarking

i. Present study: 12% saving.
ii. Sule *et al.* (2022, Nigeria): 8% savings.
iii. International benchmarks (India, Pakistan): 10–15% savings (Hassan & Rashid, 2023).

This shows the system performs competitively while maintaining far lower costs.

Reliability and User Feedback
Uptime: 96.8%.
Data loss rate: 2.5% due to Wi-Fi instability.
User feedback: Dashboard rated intuitive; load control considered useful.
Challenges: Wi-Fi instability in one household; occasional manual reset after surges.

Scalability
Simulation suggested that the system can support clusters of 20 households with minimal modification. GSM-based modules could further extend coverage in off-grid regions.

CONCLUSION

This study demonstrated a locally designed, low-cost IoT-based smart energy monitoring and load management system tailored for Nigerian households and small-scale industries. The system achieved 12% average savings, accuracy within ±2%, and user satisfaction with affordability and adaptability. By using locally sourced hardware and open-source software, the design significantly reduces costs compared with imported smart meters while delivering comparable efficiency.
The findings contribute to Nigeria's energy transition by offering a scalable and policy-relevant model for improving efficiency, reducing household energy costs, and supporting SDG 7. Future work should integrate solar PV modules, GSM-based offline communication, and large-scale pilot projects across diverse communities to validate long-term stability and nationwide applicability.

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