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Real Time Implementation of Iot Enabled Solar Energy Load Management System for Rural Community (Usaka Umuofor)

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Abstract
This study presents the real-time implementation of an IoT-enabled solar energy load management system tailored for off-grid rural electrification in Usaka Umuofor Village, Abia State, Nigeria. Motivated by persistent challenges such as load imbalance, inefficient energy usage, and inadequate power prioritization in rural solar deployments, the research introduces an intelligent framework that dynamically manages energy loads based on real-time voltage thresholds. The system classifies loads into three tiers: priority, essential, and non-essential and intelligently disconnects or reconnects them based on battery voltage thresholds: low (<12.5 V), medium (12.6–12.9 V), and peak (≥13 V). Leveraging ESP32 microcontrollers, ACS712 current sensors, and SIM800L GSM modules, the system integrates with the ThingSpeak IoT platform for remote monitoring, alerting, and data analytics. Real-time load control is executed through embedded C++ logic, supporting autonomous decision making and efficient power distribution.
Performance evaluation over a 14-day period demonstrated 100% uptime for critical medical loads, 89.86% overall system efficiency, and sub-500 ms switching latency. The system also showed robustness under adverse weather and communication disruptions. Comparative analysis with existing systems highlights its novelty in combining real-time control, fault recovery, and energy scheduling tailored for rural constraints. This work contributes a scalable, low-cost model that integrates embedded systems and cloud-based IoT services for sustainable energy access.
Keywords: IoT-based load management, Solar energy systems, ESP32, Voltage threshold, Thing Speak, Energy optimization, Embedded systems

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I. INTRODUCTION

Access to reliable and sustainable electricity remains a pressing challenge for rural communities in sub-Saharan Africa, where grid infrastructure is either non-existent or highly unreliable. In Nigeria alone, over 85 million people lack access to electricity, with many rural dwellers depending on costly and environmentally harmful fossil-fueled generators [1]. Solar photovoltaic (PV) systems offer a promising alternative for these off-grid settings due to their modularity, low maintenance, and scalability [2]. However, the effectiveness of solar energy systems is often compromised by the absence of intelligent load management strategies, leading to inefficient energy utilization and frequent outages.

Traditional solar installations in rural areas typically rely on manual switching or fixed control mechanisms that do not adapt to varying energy supply or consumption profiles. This limitation results in power wastage during periods of excess generation and system shutdowns during low voltage conditions. Moreover, the lack of real-time monitoring and control makes these systems difficult to maintain and scale [3], [4].

Recent advancements in the Internet of Things (IoT), embedded microcontrollers, and wireless sensor networks have opened new opportunities for dynamic, real-time energy management. Through integration of microcontrollers such as the ESP32, cloud-based analytics platforms like ThingSpeak, and communication modules including GSM or LoRa, it is now feasible to create intelligent systems that prioritize loads, monitor system performance, and issue alerts in real-time [5],[7].

This research presents the development and implementation of a real-time IoT-enabled solar energy load management system tailored for a rural Nigerian village Usaka Umuofor in Abia State. The system aims to dynamically isolate, reconnect, and prioritize power distribution among three load categories: priority (e.g., medical devices), essential (e.g., lighting and refrigeration), and non-essential (e.g., fans, classroom devices), based on pre-defined voltage thresholds.

Unlike existing systems that either focus on monitoring without control [8], or simulations without field validation [9], the proposed solution is fully deployed, scalable, and tested under real environmental conditions. It includes embedded logic for load control, GSM based notification systems, and a human friendly interface for rural end users. Key performance metrics such as load uptime, system responsiveness, and energy efficiency were evaluated over a two-week period.

This study contributes to bridging the energy access gap in rural areas by offering a low cost, scalable framework that merges solar PV technology with intelligent embedded systems and cloud-based IoT platforms. It is envisioned as a replicable template for community energy systems in developing countries.

II. RELATED WORKS

Numerous researchers have explored the integration of IoT in renewable energy systems to enhance load management and system monitoring. In [4], Yahya et al. implemented a solar panel monitoring platform using ThingSpeak, which provided robust visualization but lacked real-time control capabilities. Their system focused on system diagnostics rather than active management. By contrast, the proposed system in this study integrates both control and monitoring in real time.

Behera et al. [5] proposed a wireless sensor network (WSN) for load prediction in smart homes, focusing primarily on simulated data. While insightful, their work did not explore real-world conditions or embedded control strategies, which our system addresses. In the context of Nigeria, Akinyele et al. [6] proposed a theoretical model for solar energy deployment in rural communities, emphasizing policy and reliability analysis. However, the work stopped short of presenting an implementable or testable prototype. Our work extends theirs by developing and testing a deployable model.

Ali et al. [7] demonstrated IoT-based energy meters to monitor consumption patterns in real-time, yet did not address load prioritization or scalability. Our system advances these features through an intelligent prioritization algorithm embedded in microcontrollers. Recent works such as [8] and [9] have started exploring hybrid IoT-PV systems, yet many still rely on Wi-Fi or require stable broadband infrastructure. In contrast, this paper's implementation leverages GSM-based communication, ensuring operability in remote, low-infrastructure regions.

The combination of autonomous switching, GSM-based alerts, priority load protection, and low-cost implementation in this study offers a unique contribution. It meets the practical demands of rural electrification and improves on gaps identified in previous literature by combining real-time action with data analytics, cost efficiency, and community relevance.

III. METHODOLOGY

3.1 System Overview

The proposed system consists of a 6.8 kW solar photovoltaic (PV) array, a deep-cycle battery bank of 880 Ah at 48 V (totaling 42.24 kWh of theoretical storage), and an IoT-integrated embedded control mechanism. The system components include:

20 × 340 W monocrystalline solar panels (total: 6,800 W)
880 Ah battery bank at 48 V
ESP32 microcontroller for control operations
ACS712 current sensors and voltage dividers for data acquisition
SIM800L GSM module for SMS alerts and communication
ThingSpeak IoT platform for cloud-based monitoring and analysis
Electromechanical relays for load switching
Three load categories were defined and prioritized:
Priority Load: Medical equipment (200 W)
Essential Load: School and clinic devices (800 – 1000 W)
Non-Essential Load: 3HP Water Pump (≈2200 W)

3.2 Load Management Logic and Algorithm
The control logic is based on real-time monitoring of the battery voltage and solar generation status. Three voltage thresholds guide load switching:

i. Low (<12.5 V): Only priority loads are maintained.
ii. Medium (12.6–12.9 V): Essential loads are re-enabled.
iii. Peak (≥13.0 V): All loads, including the pump, are activated.

The control algorithm is implemented in Embedded C++ and deployed on the ESP32. It includes a rolling average filter (to suppress transients) and a 10-second hysteresis window to prevent rapid load toggling.

3.3 Energy Balance and Battery Autonomy Calculation

3.3.1 Daily Solar Energy Generation Potential:
Total Installed PV Power: 20 × 340 W = 6,800 W
Assumed Peak Sun Hours (PSH): 4.5 hours
Energy Generation = 6,800 W × 4.5 h = 30,600 Wh/day (30.6 kWh)
System Efficiency (approx. 75%) → Usable energy is approximately 22.95 kWh/day

3.3.2

3.3.3 Battery Storage Analysis:
Battery Capacity = 880 Ah × 48 V = 42.24 kWh
Usable energy with 80% Depth of Discharge (DoD): 0.8 × 42.24 = 33.79 kWh

3.3.4 Total Daily Load Demand:

Load Category	Power (W)	Runtime (hr)	Daily Energy (Wh)
Priority Loads	200	24	4,800
Essential Loads	800	12	9,600
Non-Essential (Pump)	2,200	2	4,400
Total Demand			**18,800**

This analysis confirms that both the PV array and battery bank are adequately sized for the load profile, with margins for scalability and buffer for adverse conditions.

3.4 Communication and IoT Integration
The ESP32 transmits sensor data via GSM (fallback mode) or Wi-Fi to the ThingSpeak platform every 15 seconds. ThingSpeak channels plot solar voltage, battery voltage, solar current, and solar power across four dedicated fields. Threshold crossings trigger SMS notifications using SIM800L, sent to designated stakeholders.

3.5 System Architecture and Workflow
The architecture comprises five main blocks: sensing, control logic, switching relays, GSM transmission, and cloud logging. All load decisions are made locally in real time, while remote monitoring via ThingSpeak enables data logging, diagnostics, and trend visualization.
This structured methodology enhances energy efficiency, ensures uninterrupted critical service, and provides transparency through real-time data access.

IV. RESULT AND DISCUSSION

4.1 Prototype Deployment and Test Environment
The IoT-enabled solar load management prototype was physically deployed in Usaka Umuofor village, Nigeria, over a two-week real-time testing period. The system was installed on a modular test rig comprising the ESP32 controller, 20 × 340 W monocrystalline panels, and an 880 Ah deep-cycle battery system at 48 VDC. Loads simulated include a 200 W medical refrigerator, school lighting and computing equipment (800 W), and a 3 HP submersible DC water pump.

The sensors (ACS712 current sensors and voltage dividers) were connected to the ESP32 analog pins. Voltage and current readings were taken every 15 seconds and sent via SIM800L GSM module to ThingSpeak IoT dashboards. Threshold decision logic ran locally on the ESP32 and executed load switching via high-current relays.

4.2 Voltage Threshold Performance
The core logic categorized load operation under three voltage thresholds:

i. <12.5 V: Non-priority and essential loads disconnected.
ii. 12.6–12.9 V: Essential loads activated.
iii. ≥13 V: All loads enabled including the water pump.

Table 4.1 shows sampled data points over a 24-hour period. Load switching behavior confirmed real-time reactivity to battery status.

Table 4.1: Load Response to Voltage Thresholds

Time	Battery Voltage	Priority Load	Essential Load	Pump Load
06:00	12.3 V	ON	OFF	OFF
10:00	12.7 V	ON	ON	OFF
14:00	13.2 V	ON	ON	ON
20:00	12.6 V	ON	ON	OFF
00:00	12.1 V	ON	OFF	OFF

This behavior was consistent across testing days and proved the robustness of the control logic in prioritizing loads intelligently based on real-time battery conditions.

4.3 Load Uptime Reliability

Load uptime was tracked for each category using ThingSpeak logs. Over the 14-day test period, the system recorded:

i. Priority Load (200 W Clinic Device)**:** 100% uptime
ii. Essential Load (School/Clinic)**:** 86.3% uptime
iii. Non-Essential Load (Pump)**:** 58.4% uptime

These figures align with the system's design goals: ensuring uninterrupted service to critical loads while rationing non-essential loads intelligently. Unlike static load-shedding systems, this adaptive method improved energy efficiency and demand matching.

4.4 System Latency and Responsiveness

Latency was measured from threshold crossing to load actuation. Table 3.2 shows average response times:

Table 4.2: Switching Delay Metrics

Load Category	Average Delay (ms)
Priority Load	420
Essential Load	375
Non-Essential Load	460

All switching events occurred in less than 500 ms, indicating near instantaneous reaction crucial for sensitive devices like medical coolers. This outperformed related works such as [5] and [12], which reported latencies above 1 second.

4.5 Comparative Evaluation with Related Work

A comparison with existing literature (Table 3.3) confirms superior real-time control, autonomous switching, and robust communication integration.

Table 4.3: Comparative Analysis with Prior Systems

Feature	Behera et al. [5]	Yahya et al. [12]	This Study
Real-time load control	n/a	n/a	✓
Voltage threshold decision	Simulated only	n/a	✓
GSM alert + cloud monitoring	n/a	✓	✓
Rural field deployment	n/a	✓	✓
Latency < 500ms	n/a	n/a	✓

This validation suggests the proposed system not only bridges the energy gap in rural contexts but also advances prior research by combining control and visibility in a single framework.

4.6 Energy Utilization Efficiency

As shown in Section II, daily solar generation is estimated at 30.6 kWh with a usable average of ~22.95 kWh/day after efficiency losses. Total demand from priority and essential loads is ~18.8 kWh/day. Load logs and ThingSpeak graphs confirmed that peak-time generation matched or exceeded demand.

Solar power output, voltage, and current charts further validated panel health, while night drops in battery levels and switching logs confirmed dynamic control based on solar input.

4. Fault Detection and Remote Monitoring

System anomalies such as a zero-current state or low voltage sustained over time triggered SMS alerts to administrators. These features enabled proactive maintenance—key in remote regions lacking skilled technical personnel. The ThingSpeak dashboards allowed remote diagnosis, log review, and historical trend analysis.

V. DISCUSSION

5.1 Performance of Voltage Threshold Load Control

The intelligent load management system demonstrated real-time responsiveness to changing solar energy and battery conditions using a three-tier voltage threshold scheme. Unlike conventional systems that rely on static timers or manual switching, the proposed model autonomously maintained 100% uptime for critical priority loads such as clinic equipment, ensuring uninterrupted health service delivery a crucial advantage in rural contexts [4], [13].

The system's decision-making logic successfully transitioned between operational states (low, medium, peak) with negligible delay (average < 500 ms), validating its readiness for real-world deployment. The integration of rolling averages and hysteresis logic minimized false triggers, thus stabilizing load behavior under fluctuating solar input—a feature lacking in systems reported in [5], [12], and [15].

5.2. Solar Power Utilization and Battery Management

The 6.8 kW solar array combined with an 880 Ah battery bank provided theoretical energy reserves that comfortably exceeded the daily energy demand of 18.8 kWh. Recorded data showed that even on days with below-average solar irradiance, the system managed to prioritize and sustain essential services through intelligent load rationing.

The calculated energy utilization efficiency approached ~89.86%, factoring losses from conversion, cable resistance, and panel misalignment. This figure outperforms similar works like [11] and [17], which reported 70–80% utilization under ideal lab conditions but without real-world dynamics such as dust, load surges, or fluctuating irradiance.

5.3. IoT Integration and Remote Visibility

ThingSpeak dashboards provided intuitive visualization of solar voltage, battery charge levels, load states, and current flows. Unlike systems in [6] and [10] that lack user-friendly feedback mechanisms, the use of GSM-triggered SMS notifications alongside real-time IoT dashboards improved system transparency and user engagement.

Additionally, the platform enabled stakeholders (e.g., community leaders) to monitor energy availability and take informed decisions without technical expertise. This human-centric feedback loop is critical for sustainability and was notably absent in earlier rural implementations [9].

5.4. Fault Tolerance and System Scalability

The architecture maintained data upload consistency across the 14-day test period, with less than 2% downtime due to signal interference. The modular structure allows replication in similar rural communities with minimal reconfiguration. With communication upgrades such as LoRaWAN, the system's reach can be extended to more remote locations without GSM infrastructure [14].

Moreover, additional sensor nodes can be introduced to monitor ambient temperature, panel soiling, or inverter performance, further enhancing the system's predictive maintenance capabilities. Compared to previous literature, which often ended at simulation or single-load trials [3], [7], this work validates multi-load real-time deployment with low-latency switching and robust communication.

5.5 Contribution to Research and Practice

This project bridges the gap between theoretical load scheduling models and practical field deployment. Unlike prior research focusing only on demand forecasting or energy optimization in isolation [1], [8], this study presents a fully functional, low-cost template applicable to rural healthcare, education, and agricultural sectors. The system aligns with Sustainable Development Goal 7 (affordable and clean energy) and offers a scalable blueprint for off-grid electrification in developing countries.

5.6 Limitations and Future Work

While the system performed efficiently, areas for improvement include:

i. Communication Resilience**:** GSM connectivity, while cost-effective, was affected by network drops. Integration of LPWAN (e.g., LoRa) would improve reliability in remote settings [14].

ii. Energy Forecasting**:** While real-time control was achieved, future upgrades could incorporate machine learning models to forecast solar availability and adjust load schedules accordingly [16].

iii. User Training**:** As with most IoT systems, user adoption is enhanced by training and interface localization, especially in rural settings with limited digital literacy.

VI. CONCLUSION

This research successfully designed and implemented a real-time IoT-enabled solar energy load management system tailored for off-grid rural communities, with Usaka Umuofor in Abia State, Nigeria serving as the case study. The system addressed a critical challenge in rural energy management: how to reliably distribute limited solar energy across multiple loads with varying priority, under fluctuating solar and battery conditions.

By incorporating a microcontroller-based control unit (ESP32), voltage and current sensors, and GSM-IoT communication, the system dynamically prioritized and shed loads based on real-time battery voltage thresholds. Critical medical loads were maintained with 100% uptime throughout the 14-day test period, while non-essential loads were intelligently rationed without compromising system integrity or stability. The embedded C++ algorithm implemented hysteresis and filtering techniques to reduce false switching, and the ThingSpeak platform offered continuous monitoring, analytics, and remote visibility.

Comparative analysis with related literature confirmed the novelty and technical edge of this solution. While previous studies either relied on simulation [3], [11] or lacked real-time control logic [4], [6], this system combined low-cost hardware, robust decision algorithms, and field deployment to demonstrate practical viability.

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