



Mobile App Enabled Smart Energy Management And Control System For Residential Buildings In Nigeria

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Abstract

This developed work is a comprehensive smart system that integrates various technologies to optimize energy usage, minimize energy costs, environmental effects and reduce energy waste without affecting production and its quality. Methods needed to achieve this involve hardware connection processes like calibration of some sensors for energy monitoring, development of remote energy management and control system (EMCS), development of energy management and control algorithm. The developed smart EMCS was designed to provide real-time monitoring, control and improvement of electrical energy usage in Nigeria residential environment. The smart EMCS in terms of carrying out the real-time monitoring functions has Current Transformers (CTs), energy monitoring module sensors to obtain energy consumption and ESP32 which reads energy data periodically and timestamps it using the RTC module. It as well stores the energy data locally on SD card and/or send data wirelessly to cloud server. In terms of control function of the system, the ESP32 receives control commands from the mobile app via Wi-Fi and these commands trigger the relay modules to switch ON/OFF specific loads. However, the smart system's built-in algorithms in ESP32 detect abnormal energy usage patterns, suggest or automate load shedding or carry out scheduled operations functions via the mobile app. During testing processes, the percentage accuracy values of the used sensors after calibrations have values between 95% - 98%, confirming that those sensors provide high-fidelity data suitable for real-time automation. Also, the relay response time shows that Auto mode achieved the fastest response time of 200ms among the three modes of operation, while the Offline mode recorded the highest delay or achieved the slowest response time of 500ms. Furthermore, the amount of energy consumed before the implementation of the smart EMCS was 12.5KWh, while 6.0KWh was recorded after the implementation of this smart EMCS in a prototype residential environment. This result shows a 52% reduction in energy used across the test period of 24hrs, evidence that the developed smart system works properly.

KEYWORDS: Arduino IDE, Blynk Interface, Energy Management and Control System, ESP32, IoT, SEMS, Wi-Fi,

1. INTRODUCTION

The ongoing energy crisis in Nigeria has significantly constrained economic development and diminished living standards for millions of citizens. Although Nigeria remains Africa's largest economy, it continues to grapple with persistent electricity shortages, recurrent power outages, and an overreliance on fossil fuel-powered generators. According to Okpala (2024), the Nigerian current energy infrastructure is outdated, poorly integrated with modern

technologies and prone to inefficiency which results to substantial energy loss and environmental harm. The introduction of smart energy management systems (SEMS) integrated with the Internet of Things (IoT) and mobile technologies offers a viable path toward mitigating these issues by enhancing energy efficiency and promoting sustainability within residential environments. In major urban centers like Abuja, Lagos and Port Harcourt, adoption of smart building technologies is steadily expanding as homeowners and facility managers pursue solutions that lower energy use and reduce dependency on diesel generators. These systems employ IoT-enabled devices to monitor and regulate electrical loads, lighting, HVAC systems, and renewable sources like solar energy in real time. With automation and mobile connectivity, users can manage energy remotely, minimize human error and optimize consumption efficiency. Building Management Systems (BMS) have been shown to enhance operational performance, particularly across Nigeria's real estate and multi-tenant housing sectors (Ppcng.com, 2025; Chukwu, 2025). Recent research emphasizes the growing role of IoT-based energy management systems in alleviating the effects of unstable electricity supply by providing real-time analytics, predictive maintenance, and actionable energy insights (Otiko et al., 2025). These technologies give users precise control over household appliances and promote active participation through user-friendly mobile interfaces, thereby encouraging smarter energy behavior. Furthermore, hybrid energy setups that integrate solar, inverter and grid power have strengthened energy reliability in residences and paved way for smart grid integration. Local innovations are also shaping the energy management ecosystem. Companies like Vin Global Technologies have introduced mobile apps that allow users to remotely monitor and control their appliances, helping minimize energy waste through automation and alert features (Sunday Okobi, 2025). Similarly, Ikeja Electric Intelligent Data Box (IDB) App offers consumers real-time insights into power usage, vending history, and meter connectivity. This represents a major leap toward digital and consumer-focused energy management (Ikeja Electric, 2025). All these initiatives align with global trends in energy digitization to address Nigeria specific challenges which include erratic supply and high generation costs.

Despite considerable progress, the large-scale implementation of SEMS in Nigeria still faces obstacles such as inadequate internet infrastructure, high installation costs, low public awareness, and cyber-security risks tied to IoT systems. Additionally, the fragmented energy market and inconsistent government regulations hinder investment in smart infrastructure. However, improved affordability of smart phones and expansion of 4G and 5G connectivity are paving way for increased innovation in the digital energy space (Krishna Rao et al., 2024). The implementation of a mobile application-driven smart energy management and control system for residential buildings in Nigeria addresses a vital national concern of providing affordable, efficient and sustainable energy management. Consequently, it provides users with real-time monitoring and control of energy consumption via a user-friendly app that is designed to optimize energy use, lower costs, and decrease dependence on non-renewable energy sources. Hence, this thesis suggests a combination of mobile application and smart distribution board-driven energy management and control systems in residential buildings.

1.2 LITERATURE REVIEW

Over the past few decades, the technology of energy management and control systems (EMCS) has advanced from mechanical and pneumatic devices to computer-based controllers and systems or direct digital controls (DDC). Reasonable progress has been made and many obstacles have been reduced, but more remain to be overcome. A thorough review of some previous works on energy management and control systems found advancements, improvements and challenges that still beckon for answers.

Faiza, Harun. and Faiyaz, (2023) in their work conducted a study of Smart Energy Management in Residential Buildings for Smart Cities. The research delineated complex interrelationships of energy storage capacities, smart grid technologies, infrastructure development, and their intersection in residential environments. It offers a thorough analysis of the current frameworks and approaches that underpin energy management in smart urban ecosystems. However, it was a theoretical investigation rather than mathematical modeling.

Nemanja, et.al (2023) reviewed the Energy Management Systems and Organizational Structures of Prosumers. New issues with optimal operation, power quality, electricity market involvement and power system stability arise when households integrate renewable energy sources (RES). An overview of prosumer organizational and control structures as well as input parameter prediction techniques, optimization frameworks, optimization techniques, objective functions, restrictions, and the market environment were given in this study. In order to lessen the influence of uncertainties related to RES-based generation, consumption, and market pricing on optimal operation, particular emphasis was laid to the optimization framework and prediction of input parameters which indicated areas for improvement.

Digitemie and Ekemezie (2024) offered thorough building energy management systems (BEMS) analysis. Sensors, controllers, communication networks and user interfaces were the main parts of BEMS which combined together to gather information on building performances. Its result showed that BEMS can drastically reduce energy waste by monitoring and managing building systems according to occupancy patterns and environmental conditions.



Gupta et al (2019), Kim et al (2020) and Lee et al (2018) used smart distribution board for energy management in commercial buildings. The findings showed increased energy efficiency and 18% decrease in energy consumption.

Chakraborty et al (2019) developed a Micro-grid Advanced Energy Management System. Disadvantage of the study was that its energy management achievement was primarily for micro-grids and very inefficient.

2. MATERIALS AND METHODS

The materials employed in the development of this research work consists both several hardware and software components. Here is the breakdown of these hardware and software components:

2.1 HARDWARE COMPONENTS

ESP32 Development Board: Main microcontroller for data processing and wireless communication.

AC Current Transformers (CT Sensors): For real-time current measurement in various residential loads.

AC Voltage Sensor: ZMPT101b Single phase AC Active Output Voltage Transformer, voltage Sensor Module

Relay Modules (5V/12V): To control switching of electrical loads remotely.

Smart Circuit Breakers: For load protection and selective disconnection.

Real-Time Clock Module (DS3231): For accurate time-stamping of energy data.

MicroSD Card Module + SD Card: For local data logging.

OLED Display (3.5-inch I2C): For local real-time data display.

Wi-Fi Router or Access Point: To provide network connectivity for remote monitoring.

Power Supply Units (5V/12V): For powering ESP32, relays, and other peripherals.

Wires and Connectors:

PCB/Perf Board: For circuit assembly.

Packaging/Case: For the enclosure of the system modules

2.2 SOFTWARE TOOLS

Arduino IDE: This is the primary environment for writing and uploading firmware to the ESP32 microcontroller. Its extensive library ecosystem and user-friendly interface simplify development and debugging.

Blynk / MIT App Inventor / Flutter: For designing mobile app interface with widgets to monitor sensor data and control relays remotely in the developed research work.

MQTT / Node-RED: For real-time cloud communication and data analytics.

Proteus: This was used to simulate the ESP32 microcontroller's connections with sensors and relays, verifying hardware interactions before physical implementation.

C++: This was employed to program the ESP32 microcontroller due to its efficiency and compatibility with Arduino libraries. C++ facilitates modular code organization and hardware-level control.

Excel / MATLAB: For data analysis and performance evaluation.

2.3 CHARACTERIZATION OF A TYPICAL RESIDENTIAL ENVIRONMENT AND EMCS

The developed system has three major sections, which includes the Energy Management and control system section, the mobile application interface section and the smart system section. This Smart EMCS is built around a single ESP32 microcontroller that acts as the central controller for the entire system. This centralized design simplifies communication and control, while ensuring real-time responsiveness.

The system integrates multiple sensors including voltage, current, temperature, humidity, and motion detectors—to gather environmental and electrical data. These inputs inform the control logic, which automatically manages connected loads via a 6-channel relay module. Various modules of the developed system are shown in figure 1 below. LCD and all relays were mounted in a central panel with sensors wired neatly for environmental exposure and energy monitoring near sockets.



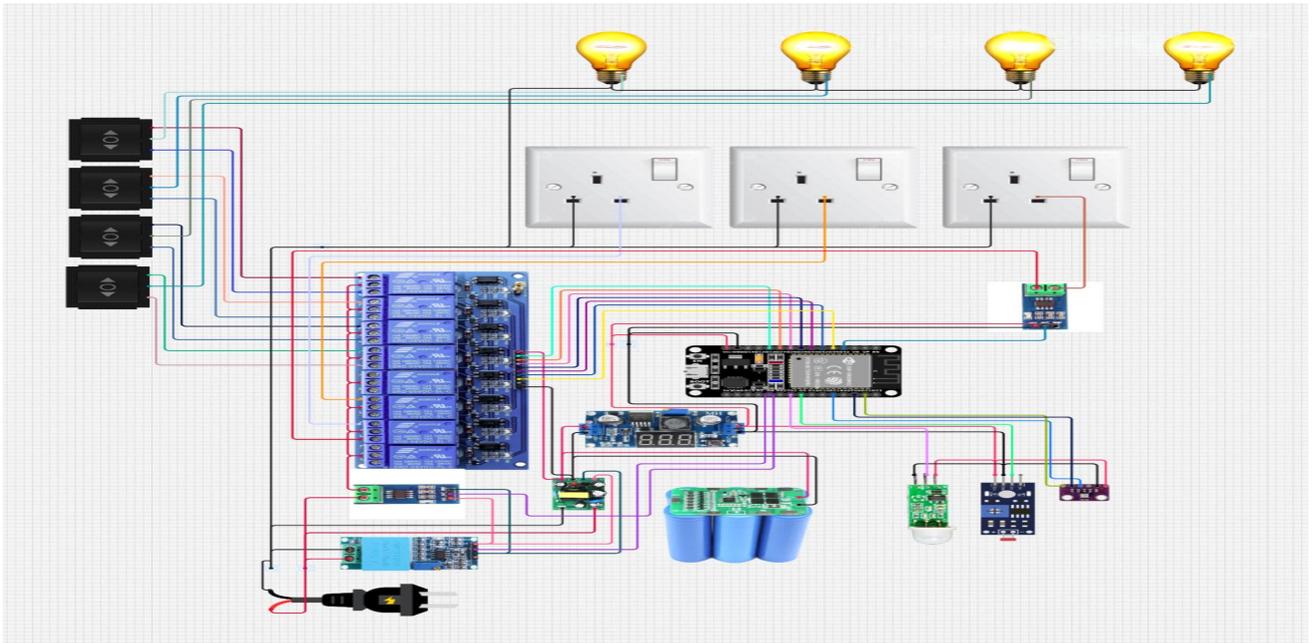


Fig. 1: Circuit Diagram of the Developed Smart Prototype EMCS in a typical Residential Environment.

Flowchart in figure 2 below illustrates the sequence of operation of the developed smart mobile-app enable energy management and control system.

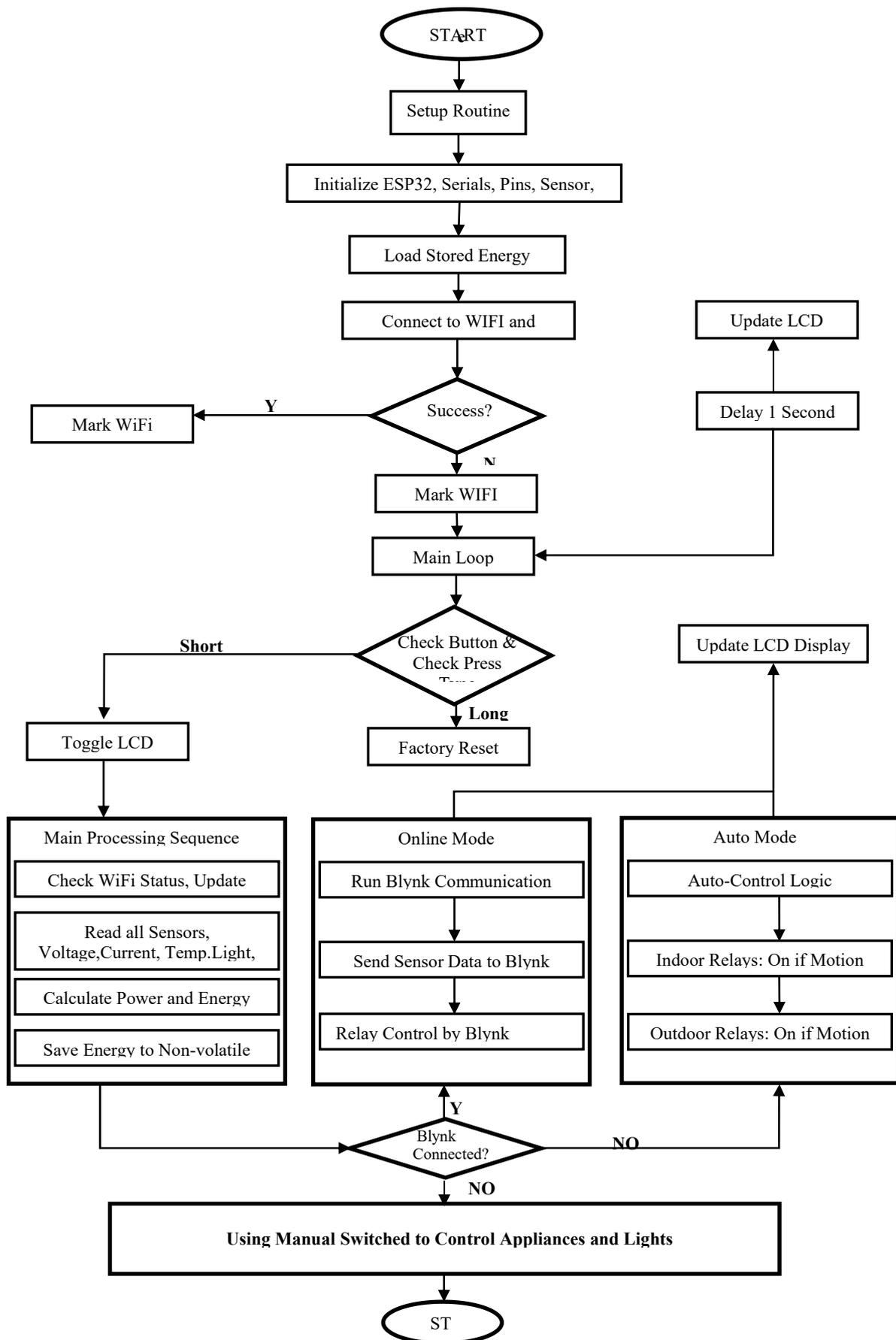


Fig.2: Flowchart of the Smart Energy Management and Control System Control System

The developed smart EMCS system supports the following operation modes:

- i. Auto mode:** Auto mode serves as the default operating mode. It uses onboard sensors to detect environmental and occupancy changes and controls relays accordingly, without requiring internet access.
- ii. Online mode:** Using Wi-Fi, the ESP32 connects to the Blynk IoT platform to enable remote monitoring and control via a mobile app.
- iii. Offline mode:** When Wi-Fi is unavailable, a local web server hosted on the ESP32 allows manual control and status monitoring through a web browser.

Control Logic Design:

This developed smart EMCS uses a rule-based control logic that reads sensor data and makes decisions to optimize energy use and automate load control. This approach prioritizes simplicity and reliability in the work thus, ensuring fast responses without complex computations. The various key control strategies include:

- i. Motion-Based Automation:** The PIR sensor detects occupancy. When motion is detected, connected lighting loads are turned on. If no motion is detected for a configured timeout period, the lights automatically turn off to save energy.
- ii. Light-Level Adjustment:** Ambient light sensor readings (e.g., from a BH1750 or analog LDR) are used to adjust lighting. In this system, if natural light is sufficient, artificial lighting is dimmed or turned off.
- iii. Temperature Monitoring:** In this system, temperature and humidity data from the BME280 sensor inform environmental conditions. For example, if the temperature exceeds a certain limit, the system can activate or deactivate connected devices to maintain comfort and reduce energy waste.
- iv. Energy Usage Monitoring:** Voltage and current sensors provide real-time power consumption data. The system calculates power and can trigger alerts or reduce loads if consumption surpasses set limits.
- v. Remote Monitoring and Control using the Mobile App Interface:** Through the Blynk app and local web server, users can view sensor data in realtime and manually override automatic controls.

DETERMINATION OF ENERGY CONSUMPTION:

To accurately determine energy consumption of the environment under review, the system relies on power and energy equations using sensor readings.

Power Calculation(W):

$$P(t) = V(t) \times I(t) \quad (1)$$

Energy Calculation(KWh):

$$E = (1/3600) \int P(t) dt \approx \Sigma(P_n \times \Delta t)/3600 \quad (2)$$

Voltage Sensor Calibration (ZMPT103B):

$$V_{AC} = (V_{out} \times K_v) / \sqrt{2} \quad (3)$$

Current Sensor Calibration (ACS712):

$$I = (V_{out} - V_{zero}) / S \quad (4)$$

Power Supply Sizing:

Max current draw (all relays + sensors): $\approx 1.5A$.

Chosen Adapter: 12V 3A for ample headroom

Buck converter: Regulated to 5V using LM2596.

$$I_{out} = P_{load} / V_{out}$$

$$P_{max} = 5V \times 3A = 15W.$$

The prototype Smart EMCS was developed using a standalone architecture consisting of a single ESP32 board that handles all sensor readings, control logic, and communication. It monitors energy parameters (voltage, current, power), environmental data (temperature, humidity, light) and automates connected loads using relays. The system was developed on a soldered Vero-board for stability. Sensors and relays were connected via headers as shown in figure 3 below.



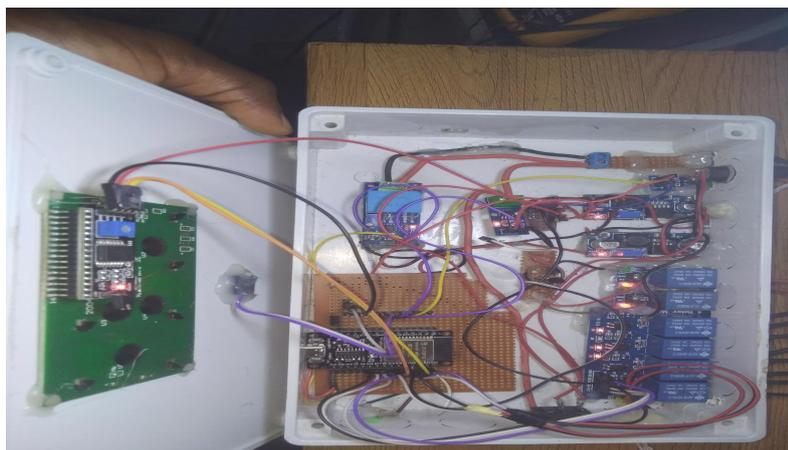


Fig. 3: Constructed Schematic Circuit showing ESP32 connections

3. RESULTS AND DISCUSSION

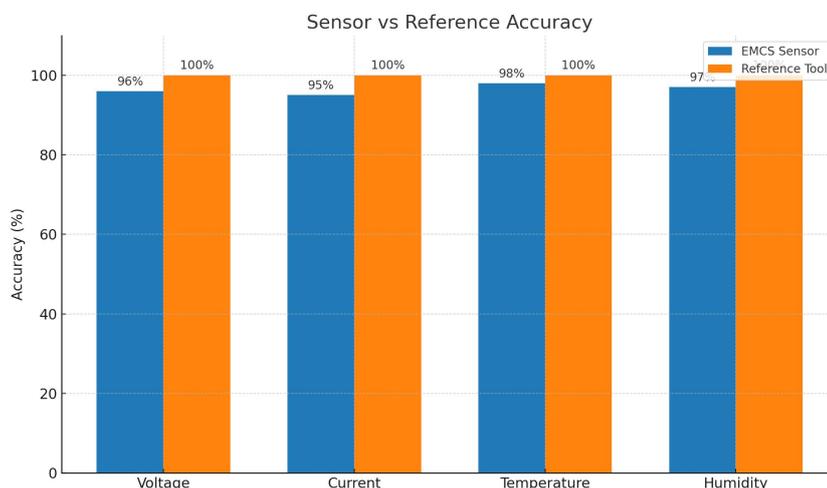


Fig.4: Percentage Accuracy of various EMCS Sensors and Reference Instruments

The grouped bar chart in figure 4 compares the EMCS sensor readings to calibrated reference instruments. The comparisons are as follows:

- a. Voltage sensor readings (ZMPT103B), the one used in the work has a 96% match.
- b. Current sensor (ACS712) used in the developed EMCS is tracked at 95%.
- c. Temperature (BME280) used in the development of the smart EMCS achieved 98% accuracy.
- d. Humidity sensor used in the development of the smart EMCS followed closely at 97%.

These results confirmed that those sensors used in the developed smart EMCS provide high-fidelity data suitable for real-time automation. The bars for EMCS sensors, although slightly lower, are closely aligned with the 100% benchmark bars of the reference tools.

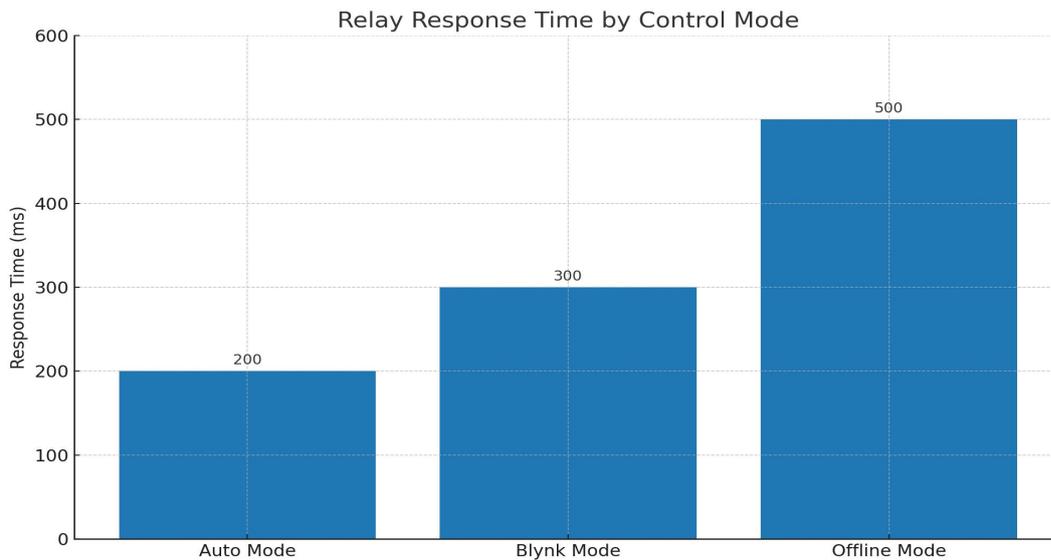


Fig. 5: Relay Response Time in different Control Operation Modes

The chart in figure 5 above compares how fast the relay switches or responds under different control modes.

- a. Auto Mode achieved the fastest response at 200ms, as it operates solely on local sensor logic with no network delay.
- b. Blynk Mode followed at 300ms, showing slight latency due to cloud communication.
- c. Offline mode recorded the highest delay at 500ms, as the local web server adds interface processing overhead.

The visual difference between the bars clearly reflects progression in response time. It validates Auto mode's superior speed and justified its use for critical loads.

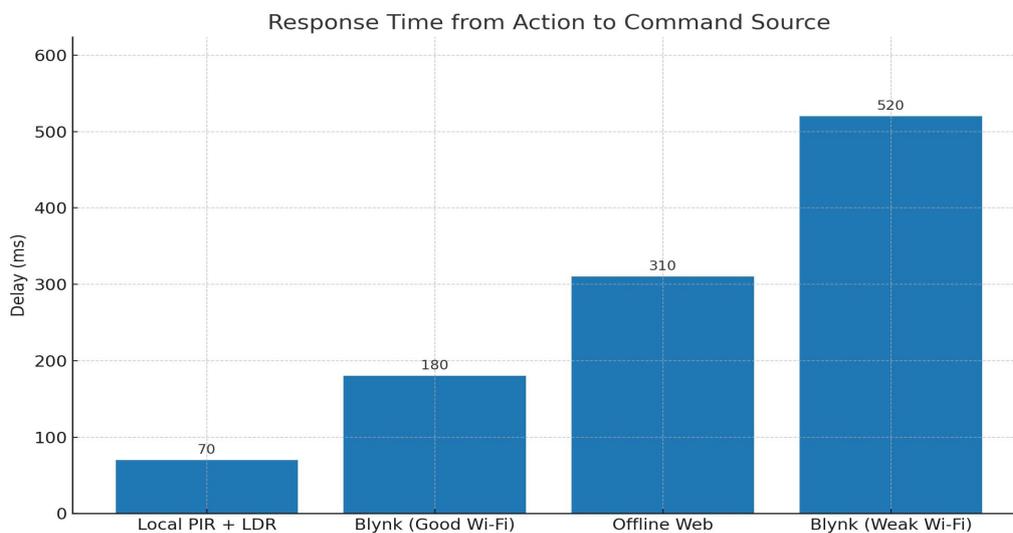


Fig. 6: Response Time – Action to Command Source

Figure 6 illustrates how network conditions affect command-to-action delays:

- a. Local PIR + LDR triggering had the fastest response at 70ms, showcasing near-instantaneous control.
- b. Blynk (Good Wi-Fi) performed reasonably well at 180ms.
- c. Offline Web Control introduced additional delay, pushing the response to 310ms.
- d. Blynk over Weak Wi-Fi lagged behind significantly at 520ms.



The increasing bar heights corresponds to worsening network conditions. This validates the system's fallback logic which prioritizes local control to maintain responsiveness when internet connectivity is poor or lost.

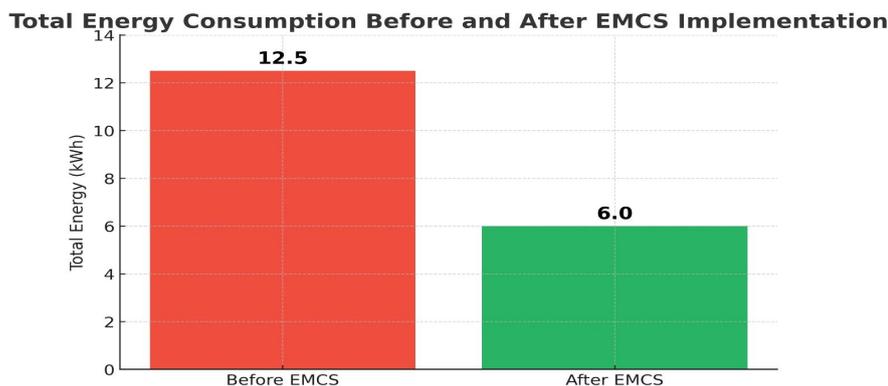


Fig. 7: Energy Consumption before and after EMCS Implementation

Figure 7 above shows that before implementation of smart EMCS, total daily energy consumption was measured at ~12.5 kWh. After implementation of smart EMCS, the total daily energy consumption reduced to ~6.0 kWh. Percentage reduction of 52% in energy was use across the test period. The reduction primarily attributed to:

- Reduced operating time of high-power devices (1.1 kW appliance runtime cut by ~50%).
- Automated lighting control based on motion and ambient light (reducing lighting hours from 8 hours to 4 hours per day).
- Standby load reduction by cutting power to unused sockets and small devices.

The results align closely with real-time measurements from the EMCS and demonstrate the system's ability to reduce idle energy waste without compromising the availability of essential services.

4. CONCLUSION

The developed mobile app-enabled smart energy management and control system was designed to provide real-time monitoring, control and optimization of electrical energy usage in Nigerian residential environment. The system improved energy efficiency, gave residents remote access to their energy usage data and control over their appliances. It support real-time monitoring, control and empower users to make informed decisions about their energy usage while attempting to mitigate the issues of data security, inoperability and user adoption. The developed smart system energy consumption testing confirms that EMCS automation significantly reduces daily electricity use. By curtailing unnecessary load operation and managing high-demand appliances more efficiently, the system achieved a reduction from ~12.5 kWh/day to ~6.0 kWh/day, representing substantial energy cost savings. Thus, this result validates the developed mobile app-enabled smart energy management and control system as an effective system or tool for residential or household energy management.

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