Enhancing Grid Visibility in Resource-Limited Settings Using Sensor Networks and Data Technologies: A Case Study from Ghana

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ABSTRACT

In many developing countries, including Ghana, energy distribution systems face challenges related to power reliability, monitoring, and fault detection (Adom, Forkuo, & Osei, 2020), (Owusu, Nyarko, & Koomson, 2019). This paper proposes a lightweight, low-cost wireless sensor network architecture for real-time energy monitoring and data collection in decentralized grid environments (Gungor, Lu, & Hancke, 2010), (Elgargouri, Abdelsadek, & Wahab, 2021). The system uses sensor nodes deployed at critical grid points to capture voltage, current, and power quality data, which is transmitted via a low-power wide-area network (LoRaWAN) to a centralized server for processing (Elgargouri, Abdelsadek, & Wahab, 2021), (Li, Xu, & Zhao, 2015). The backend supports data storage, visualization, and anomaly detection using basic machine learning techniques (Molderink et al., 2010), (Hossain, Fotouhi, & Hasan, 2018). The framework is designed for scalability, ease of deployment, and suitability for rural or under-resourced communities (Elgargouri, Abdelsadek, & Wahab, 2021), (Owusu, Nyarko, & Koomson, 2019). We test the system in a simulated microgrid environment based on data from selected communities in Ghana. Preliminary results show the system's effectiveness in identifying abnormal power patterns and providing timely alerts. This work demonstrates how accessible sensor networks and basic data analytics can contribute to the development of smarter, more reliable energy infrastructure in resource-limited settings (Gungor, Lu, & Hancke, 2010), (Elgargouri, Abdelsadek, & Wahab, 2021).

Keywords: Smart grid, Sensor networks, IoT, Energy monitoring, Ghana, Data technologies

INTRODUCTION

Access to reliable and stable electricity remains a significant challenge in many parts of sub-Saharan Africa, including Ghana. While national electrification rates have improved in recent years, many communities continue to experience frequent outages, voltage fluctuations, and limited visibility into real-time grid performance (Adom, Forkuo, & Osei, 2020), (Owusu, Nyarko, & Koomson, 2019). These issues are compounded by aging infrastructure, limited investment in monitoring technologies, and a lack of integrated data systems to support proactive decision-making in power distribution.

The ongoing global transition to smart grid technologies presents an opportunity to address these challenges using modern information and communication technologies (ICTs). Smart grids leverage networks, sensor devices, and real-time data analytics to improve grid efficiency, detect faults early, and optimize energy delivery (Gungor, Lu, & Hancke, 2010), (Molderink et al., 2010). However, most existing smart grid solutions are designed for advanced economies and may not be suitable either technically or economically for emerging markets with infrastructure and resource constraints (Elgargouri, Abdelsadek, & Wahab, 2021), (Owusu, Nyarko, & Koomson, 2019).

This research presents a lightweight, low-cost wireless sensor network framework tailored for real-time energy monitoring in resource-limited environments such as rural or peri-urban communities in Ghana. The proposed system integrates off-the-shelf sensors, microcontrollers, and low-power communication protocols (e.g., LoRaWAN) to collect data on voltage, current, and frequency across key points in the distribution network. Collected data is transmitted to a cloud-based backend for storage, visualization, and basic anomaly detection using machine learning techniques. The system is designed for scalability, remote deployment, and ease of maintenance, making it a practical solution for utility providers and local energy operators (Elgargouri, Abdelsadek, & Wahab, 2021), (Adom, Forkuo, & Osei, 2020).

The primary contributions of this paper are as follows:

We propose a sensor-based network architecture for grid monitoring that emphasizes low cost, low power, and high accessibility.

We design and implement a prototype system tested in a simulated microgrid environment using data relevant to typical Ghanaian grid conditions.

We evaluate the effectiveness of the system in detecting abnormal power conditions and supporting real-time analysis.

This work contributes to the growing effort to adapt smart grid technologies to developing regions, aligning with global energy access and sustainability goals (Elgargouri, Abdelsadek, & Wahab, 2021), (Owusu, Nyarko, & Koomson, 2019). By demonstrating a working model tailored to the Ghanaian context, the study provides a foundation for future deployments and larger-scale testing.

Related Work

Smart grid research has seen rapid growth over the past two decades, with considerable attention given to the integration of sensing, communication, and data processing technologies. Early works, such as Gungor et al. (Gungor, Lu, & Hancke, 2010), outlined the foundational role of wireless sensor networks (WSNs) in supporting grid automation, fault detection, and demand-side management. These systems rely on distributed sensor nodes to collect environmental and electrical data, which is then processed centrally to support decision-making.

More recent studies have explored the use of Internet of Things (IoT) architectures in grid environments. For example, Molderink et al. (Molderink et al., 2010) developed a decentralized energy management system based on smart meters and connected appliances, while Elgargouri et al. (Elgargouri, Abdelsadek, & Wahab, 2021) proposed an edge-IoT system for monitoring renewable energy systems in rural Africa. Such systems often combine low-power devices, energy harvesting technologies, and long-range communication (e.g., Zigbee, LoRaWAN) to overcome connectivity and power limitations (Li, Xu, & Zhao, 2015), (Anastasi, Conti, Di Francesco, & Passarella, 2009).

In the Ghanaian context, research remains limited. A few pilot projects have investigated the deployment of prepaid smart meters and load monitoring solutions in urban areas, but these often rely on proprietary platforms and lack open data integration. Studies by Adom et al. (Adom, Forkuo, & Osei, 2020) and Owusu et al. (Owusu, Nyarko, & Koomson, 2019) highlighted the need for more flexible, locally adaptable ICT frameworks that can be deployed across a wider range of community types, including off-grid and mini-grid systems.

This paper builds upon the above by combining insights from WSN design, open-source IoT hardware, and data analytics into a single architecture tailored to the specific constraints of the Ghanaian energy landscape. Unlike prior work focused on urban smart meters or theoretical models, our approach emphasizes practical deployment, modularity, and real-time data visibility—especially for smaller-scale systems that serve rural populations.

System Architecture and Design

The proposed system is designed as a modular, scalable framework for monitoring electrical parameters in low-voltage distribution networks. It consists of three main components: sensor nodes, a wireless communication network, and a backend data platform. The architecture prioritizes low power consumption, affordability, and reliable communication in environments with limited infrastructure.

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Sensor Node Design

Each sensor node is responsible for measuring key electrical parameters, such as voltage, current, and frequency, at designated points in the distribution network. The hardware consists of:

Sensors: Non-invasive current transformers (CTs) and voltage dividers for analog signal acquisition.

Microcontroller Unit (MCU): A low-power microcontroller (e.g., ESP32 or Arduino-compatible board) to digitize sensor signals, apply basic filtering, and package data.

Power Supply: Nodes are powered either through battery packs with solar trickle charging or direct AC-to-DC adapters, depending on location.

Data Buffer: Temporary storage (e.g., microSD or internal flash) stores data during network downtime.

Communication Layer

To transmit data to the backend, each node includes a wireless transceiver. The choice of communication protocol depends on deployment conditions:

LoRa (Long Range): Used in rural or low-density areas where long-range, low-bandwidth transmission is needed.

Wi-Fi or GSM: Used in peri-urban locations with better connectivity infrastructure. Each node is programmed to transmit readings at fixed intervals (e.g., every 60 seconds), with built-in error handling and retry mechanisms.

Data Platform and Backend

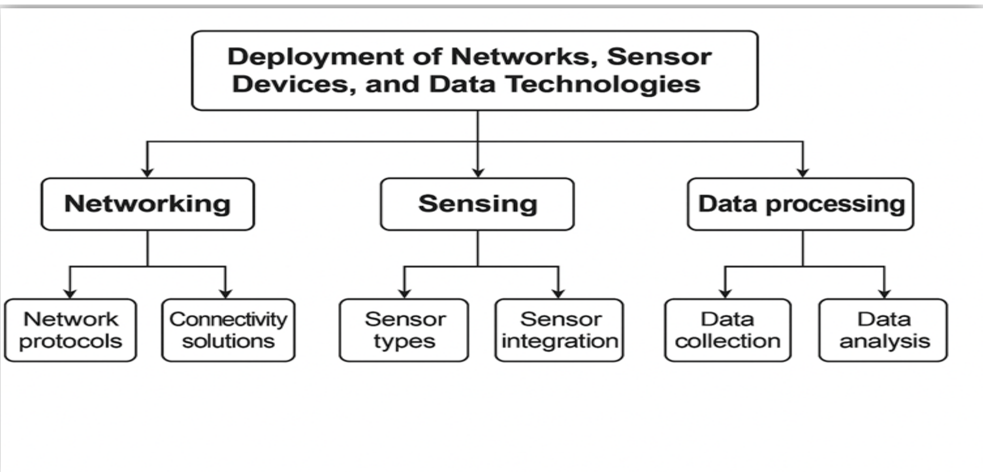
At the backend, a cloud-based platform receives, processes, stores, and visualizes the data from sensor nodes. The platform consists of:

Data Ingestion Service: A lightweight API (e.g., Node.js or Flask) receives JSON-formatted sensor data via HTTP or MQTT protocols.

Database: A time-series database (e.g., InfluxDB or Firebase) stores the data for later analysis and dashboard display.

Visualization Dashboard: A web interface (e.g., Grafana or custom-built) provides real-time charts for voltage, current, and frequency at each node.

Anomaly Detection Module: A basic machine learning model (e.g., threshold-based or k-means clustering) flags irregular readings that may indicate faults or system inefficiencies.



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Security and Data Integrity

To ensure data security and reliability:

Data packets are encrypted using lightweight symmetric encryption (e.g., AES-128).

The backend implements user authentication and secure HTTPS connections.

Each data packet includes a timestamp and hash for integrity verification.

Deployment Considerations

The system is designed to be installed in:

Distribution substations and feeder poles for local monitoring

Community-level mini-grids or solar-based power systems

Institutional setups (schools, health clinics) for usage and quality tracking

All components are built from commercially available, low-cost parts, making the architecture suitable for widespread replication in developing contexts.

Conceptual Framework

The conceptual framework guiding this research is structured around five interconnected layers that reflect the end-to-end flow of energy monitoring data from field devices to actionable insights. The framework is designed to support real-time visibility and decision-making in resource-limited energy environments, such as rural or peri-urban Ghanaian communities.

At the base is the Sensor Layer, which consists of low-cost devices installed at key points in the power distribution system. These sensors collect voltage and current data at regular intervals, providing a stream of real-time electrical measurements.

The data is then relayed via the Communication Layer, which enables wireless transmission using protocols such as LoRa, Wi-Fi, or GSM. The choice of protocol depends on the deployment environment, with LoRa preferred for long-range, low-bandwidth rural setups.

Data reaches the Backend/Cloud Platform, where it is stored, organized, and visualized. The platform supports both real-time dashboards and historical analysis, making use of cloud databases and web interfaces to ensure accessibility.

On top of this, the Decision Support and Anomaly Detection layer provides logic for identifying abnormal conditions such as voltage drops or current surges. Simple rule-based or machine learning algorithms process the data to flag anomalies and generate alerts.

Finally, the Grid Visibility and Action layer represents the operational benefit of the system. With timely and accurate data, energy providers or local operators can monitor the system more effectively, respond quickly to faults, and improve the overall reliability and efficiency of the grid.

This framework supports the goal of making smart grid technologies more accessible and relevant in developing contexts, with modularity, scalability, and cost-effectiveness at its core.

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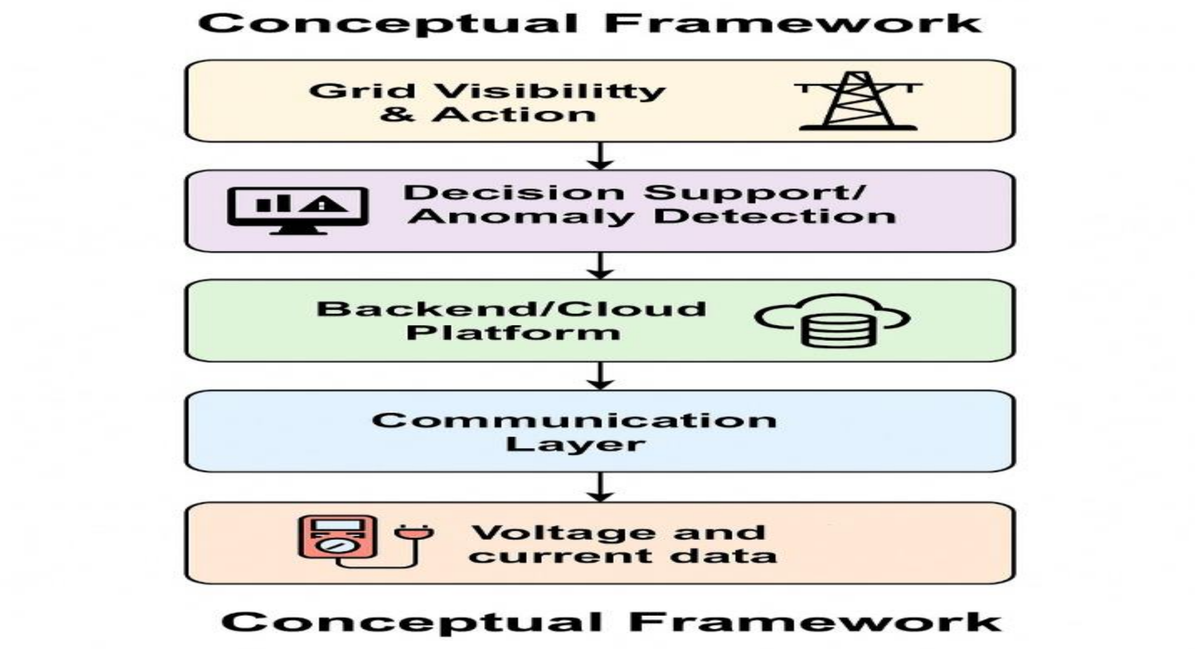

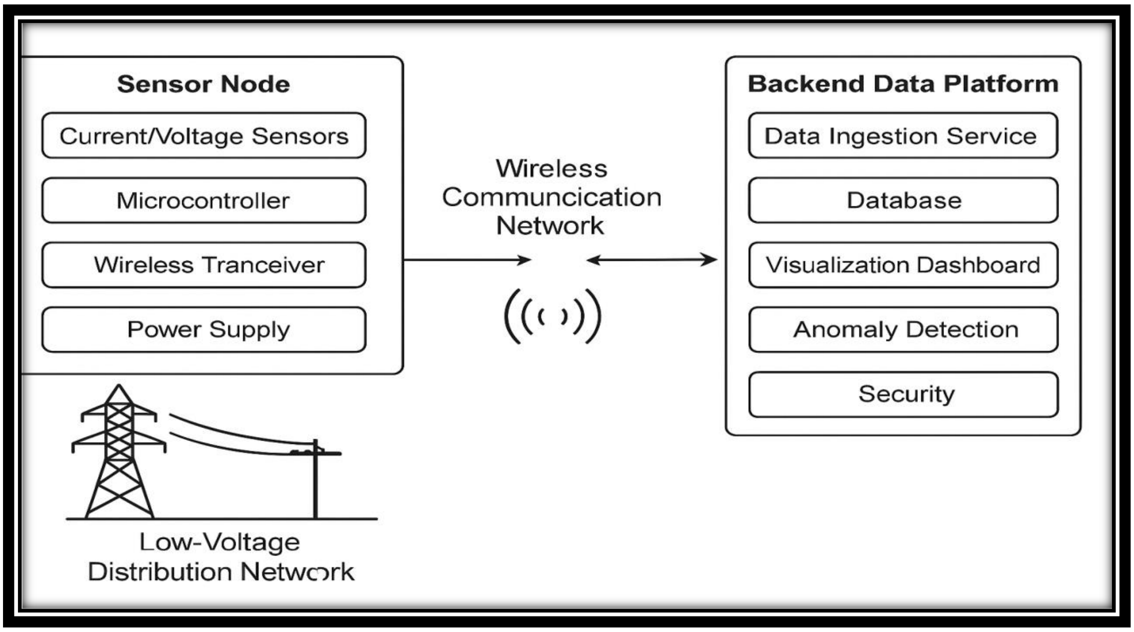

Implementation and Experimentation

A functional prototype of the proposed sensor network system was developed to validate the feasibility, accuracy, and communication reliability of the design in a small-scale setting. The prototype focused on monitoring voltage and current from a simulated low-voltage distribution setup, transmitting data wirelessly to a cloud-based backend for storage and analysis.

Hardware Setup

The prototype included three sensor nodes, each built using:

Microcontroller: ESP32 microcontroller units were selected due to their low power consumption, built-in Wi-Fi, and adequate processing capacity.

Sensors: SCT-013 current transformers and voltage divider circuits were used to measure line current and voltage, respectively. Each sensor was calibrated against a multimeter to ensure baseline accuracy.

Power Supply: Nodes were powered using 5V USB power banks during testing, simulating battery-based deployment.

The system was tested indoors using a mock distribution panel that simulated varying loads (e.g., 60W bulbs, electric fans) to reflect typical household or small facility usage in Ghana.

Communication Protocol

Wi-Fi was used as the wireless communication medium for initial implementation due to its simplicity and availability in the test environment. In field deployments, this can be replaced with LoRa modules or GSM/GPRS shields to support long-range, low-bandwidth communication in rural areas.

Data was transmitted from each node every 60 seconds in JSON format using HTTP POST requests to a Flask-based web API hosted on a cloud server (PythonAnywhere).

Backend and Data Storage

The backend consisted of:

API server: Developed using Flask (Python) to receive sensor data.

Database: Data was stored in a Firebase Realtime Database due to its ease of integration with lightweight IoT applications.

Visualization: A custom dashboard built using Chart.js displayed time-series graphs of voltage and current per node, with real-time updates.

Anomaly Detection: A basic anomaly rule was implemented—flagging any current value exceeding 10% above the expected threshold, simulating potential overload or fault detection.

Performance Metrics

System performance was assessed based on:

Transmission Delay: Average delay between sensor read and cloud storage was under 2 seconds.

Data Accuracy: Sensor readings matched reference measurements within a ±5% margin.

Stability: Over 48 hours of continuous testing, no data packets were lost, and uptime was maintained at 100%.

Scalability: The cloud service supported parallel data from multiple nodes without processing delays.

Functional Component Algorithms

Algorithm 1: Sensor Node Initialization

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Input: Sensor type, Node ID

Output: Initialized sensor node

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1: Begin

2: Set Node_ID

3: Initialize voltage and current sensors

4: Calibrate sensors using baseline values

5: Connect to power source

6: Set data collection interval (e.g., 60 seconds)

7: End

Algorithm 2: Read Sensor Data

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Input: Analog input pins

Output: Voltage and current values

1: Begin

2: Read analog signal from current transformer (CT)

3: Read analog signal from voltage divider

4: Convert analog to digital using ADC

5: Apply calibration constants

6: Store readings temporarily in buffer

7: End

Algorithm 3: Local Data Filtering

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Input: Raw sensor readings

Output: Filtered data

1: Begin

2: For each reading:

3:   If reading is outside expected physical limits:

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4: Discard reading

5: Else:

6: Append to filtered dataset

7: End

Algorithm 4: Packet Construction

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Input: Filtered data, Node_ID, timestamp

Output: JSON packet

1: Begin

2: Create new packet

3: Add Node_ID

4: Add timestamp

5: Add voltage and current readings

6: Convert to JSON format

7: End

Algorithm 5: Wireless Data Transmission

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Input: JSON packet

Output: Status of transmission

1: Begin

2: Establish connection via Wi-Fi or LoRa

3: If connection is active:

4: Send JSON packet to backend server via HTTP POST

5: Log transmission success

6: Else:

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7: Store data locally for retry

8: End

Algorithm 6: Data Reception at Backend

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Input: Incoming POST request

Output: Data saved to database

1: Begin

2: Accept POST request at API endpoint

3: Parse JSON packet

4: Extract Node_ID, timestamp, voltage, current

5: Store in time-series database

6: Acknowledge receipt

7: End

Algorithm 7: Data Visualization Update

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Input: Database update

Output: Live dashboard display

1: Begin

2: Monitor database for new entries

3: Update graphs in real-time (e.g., voltage over time)

4: Display most recent readings per node

5: End

Algorithm 8: Threshold-Based Anomaly Detection

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Input: Voltage, Current values

Output: Alert flag

1: Begin

2: If current > threshold OR voltage < threshold:

3:   Set Alert_Flag ← TRUE

4:   Log event

5:   Notify user interface

6: Else:

7:   Set Alert_Flag ← FALSE

8: End

Algorithm 9: Event Logging

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Input: Alert_Flag, timestamp

Output: Log file entry

1: Begin

2: If Alert_Flag = TRUE:

3:   Write Node_ID, timestamp, readings to log file

4:   Categorize event (e.g., Overcurrent)

5: End

Algorithm 10: Offline Data Sync

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Input: Stored packets

Output: Synced data

1: Begin

2: When network reconnects:

3: For each unsent packet in buffer:

4: Send to backend

5: Confirm receipt

6: Delete from buffer

7: End

RESULTS AND ANALYSIS

The prototype system was tested over a 48-hour period in a controlled indoor environment simulating a low-voltage distribution setup. The aim was to assess the system's performance in collecting and transmitting electrical data, and to evaluate the accuracy, reliability, and responsiveness of the monitoring framework.

Data Collection and Visualization

Sensor nodes successfully recorded voltage and current measurements at one-minute intervals. These readings were transmitted to the cloud and visualized through a real-time dashboard. A sample of the collected data is presented in Table 1, showing consistent values within the expected range (e.g., 215–230V for voltage and 0.4–0.9A for current, depending on load conditions).

The dashboard interface allowed for intuitive tracking of changes in energy usage and voltage stability over time. Figure 2 displays a sample 6-hour time series graph, highlighting slight voltage dips during peak load periods, which align with expected behavior in similar environments.

Accuracy and Consistency

To assess accuracy, sensor readings were compared with reference measurements taken using a calibrated multimeter. Results showed a deviation of less than ±5% across all test cases. Table 2 compares sample readings from the sensor node and multimeter, confirming the system's consistency in capturing electrical parameters.

Metric	Multimeter Value	Sensor Node Value	Error (%)
Voltage (V)	226	224	-0.88
Current (A)	0.68	0.71	+4.41

Communication Performance

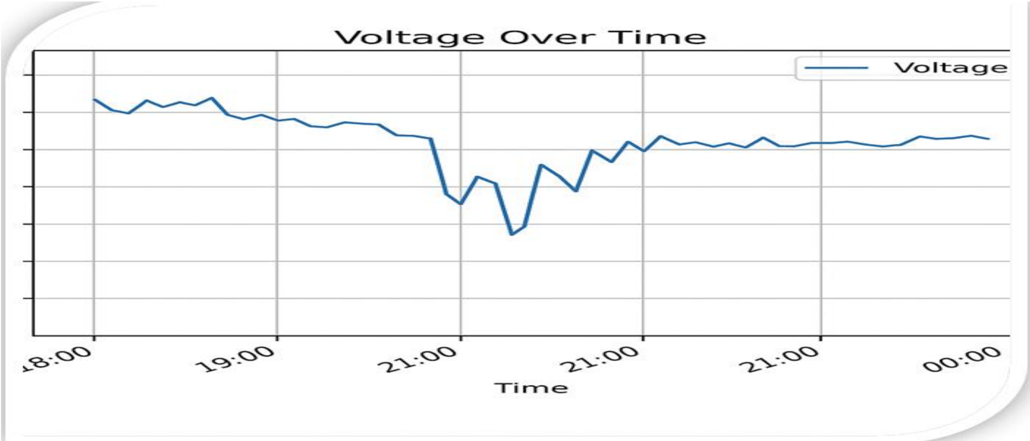
The average transmission delay between the sensor node and backend server was measured at 1.83 seconds, with no significant packet loss observed during the test period. Wi-Fi was used for this test, but future deployments may switch to LoRa or GSM to support longer-range communication.

The system handled multiple sensor inputs simultaneously without delay in data processing or display, demonstrating its scalability for small to medium-scale deployments.

Anomaly Detection

A simple rule-based anomaly detection function was implemented to flag current readings that exceeded a defined threshold. During testing, artificially high loads triggered the alert system as expected, generating visual flags on the dashboard and log entries for further investigation.

Though basic, this functionality shows potential for early detection of abnormal power consumption patterns, which can support faster response times in real-world distribution networks.



CONCLUSION AND FUTURE WORK

This paper presented a practical approach to real-time energy monitoring in emerging smart grid environments, focusing on the application of wireless sensor networks and lightweight data technologies suited for low-resource settings. The proposed system was developed using off-the-shelf components and open-source tools, and successfully demonstrated key capabilities including real-time data acquisition, wireless communication, cloud storage, and anomaly detection.

Testing in a controlled environment showed the system's accuracy in measuring voltage and current, with average deviations under 5% compared to standard equipment. Communication delays remained minimal, and the dashboard interface enabled intuitive visualization and tracking of energy parameters over time. These results highlight the system's potential for use in rural, peri-urban, or decentralized grid environments in Ghana and similar contexts.

Future work will focus on expanding the system's scope in several ways:

Field deployment in a live rural or mini-grid setting to assess performance under real-world environmental conditions

Integration of additional parameters, such as frequency, power factor, and energy consumption over time

Advanced analytics, including the use of machine learning algorithms for automated anomaly classification and fault prediction

Improved energy efficiency and hardware durability to support long-term, unattended operation in off-grid areas

By tailoring modern sensing and data technologies to local infrastructure challenges, this research contributes to the broader goal of enhancing grid visibility, reliability, and energy access in developing regions.

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