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Design, Control, and Cost-Effective Sizing of a Solar-Battery Autonomous Microgrid System for Rural Electrification in Nigeria (A Case Study of Birnin Kebbi)

[1]Abubakar U. Sadik, [2]Solomon A. Peni, [1]A. M. Adua, [3]I. O. Muritala, [4]Yau Alhaji Samaila

[1]Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero, PMB 1144 Aliero, Kebbi State, Nigeria.

[2]Department of Electrical Education Technology, Faculty of Education, Kebbi State University of Science and Technology, Aliero, PMB 1144 Aliero, Kebbi State, Nigeria.

[3]Department of Computer Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria- Nigeria. [4]Department of Electrical and Electronics Engineering,University of Maiduguri, Nigeria

ABSTRACT

This study investigates the design, control, and cost-effective sizing of a solar-battery autonomous microgrid system aimed at providing reliable power for rural electrification in Nigeria. The project focuses on optimizing the microgrid's components to meet essential energy needs, such as lighting, phone charging, and powering small appliances. The system design integrates solar photovoltaic panels and battery storage, paired with a control strategy that efficiently balances generation and demand. This strategy aims to extend battery life, minimize costs, and ensure steady power supply, even in the face of solar intermittency. Through simulation and field testing, the project evaluates the feasibility, sustainability, and impact of this microgrid solution on improving energy access in remote communities. Findings from this work provide a model for scalable, affordable, and sustainable rural electrification, contributing to Nigeria's broader renewable energy and rural development goals.

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INTRODUCTION:

Access to reliable and affordable electricity is a fundamental aspect of socio-economic development, yet many rural communities in Nigeria continue to face significant energy deficits. According to the International Energy Agency (IEA), over 760 million people worldwide still lack access to electricity, with the majority residing in sub-Saharan Africa, including Nigeria [1], [2]. In these regions, rural electrification remains a substantial challenge due to high costs associated with grid extension, difficult terrain, and dispersed populations that make centralized power solutions inefficient and unsustainable. As a result, off-grid power generation solutions, particularly autonomous microgrids, are gaining attention as a viable means of addressing the energy gap in rural areas[3].

In Nigeria, the national grid's limited reach leaves millions of rural households dependent on traditional energy sources, such as kerosene lamps, diesel generators, and firewood, which are not only expensive but also contribute to health and environmental concerns [4]. As a sustainable and renewable alternative, solar energy offers a promising solution to rural electrification by harnessing Nigeria's abundant sunlight. When paired with energy storage systems, such as batteries, solar energy can supply continuous, reliable power, even during periods of low sunlight or at night. This solution is essential for achieving energy independence and reducing rural communities' reliance on costly, polluting fuels [5].

Autonomous microgrid systems, designed to operate independently of the national grid, offer an attractive model for rural

Corresponding author: Engr. Abubakar U. Sadiq.
abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.

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electrification in developing countries. These systems typically combine renewable energy sources, such as solar photovoltaic (PV) panels, with energy storage to create a self-sustaining and resilient power supply. However, designing a cost-effective autonomous microgrid requires careful consideration of component sizing and control strategies to balance generation and demand, optimize resource utilization, and minimize costs. In rural Nigeria, where financial resources are limited, ensuring that microgrid systems are both affordable and capable of meeting essential energy needs is crucial [6]

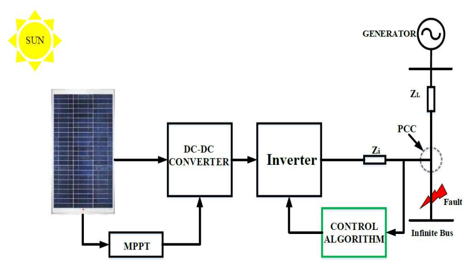

Figure1: A Solar PV Conversion system [16]

Importance of Autonomous Microgrids for Rural Electrification in Nigeria

The demand for rural electrification in Nigeria highlights the need for innovative and sustainable energy solutions. Autonomous microgrids represent a decentralized approach to power generation that can operate independently, making them ideal for remote or off-grid communities. These systems offer several advantages over traditional centralized energy generation models. First, they eliminate the need for extensive and costly transmission infrastructure, making them more economical and easier to implement in geographically isolated areas. Second, by relying on locally available renewable resources, such as solar energy, they contribute to energy security and reduce environmental impact. Third, microgrids can be scaled to meet the specific needs of each community, allowing for flexible and modular configurations that accommodate future growth in demand [7].

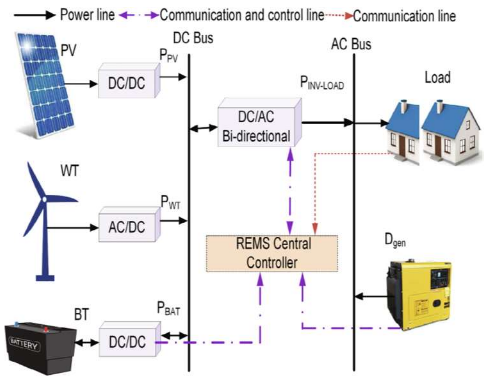

Figure 2: The architecture of the conceptualized grid-independent microgrid.

Solar-battery microgrids are particularly suited to Nigeria's rural landscape, as they capitalize on the country's high solar irradiance while addressing the intermittency of solar power with battery storage. Battery storage is essential for storing excess energy generated during the day and releasing it when solar production is insufficient, ensuring a consistent power supply. This design reduces the dependence on diesel generators or other fossil fuels, aligning with Nigeria's commitment to reducing greenhouse gas emissions and promoting renewable energy.

Challenges in Designing Cost-Effective Microgrids

The primary challenge in deploying autonomous microgrids in rural Nigeria lies in balancing cost with reliability. While renewable energy technology costs have declined significantly over the past decade, the upfront capital requirements for components such as solar panels, inverters, batteries, and control systems remain a barrier for many communities [8]. Thus, a cost-effective approach to sizing these components is essential to make microgrids financially viable without compromising performance. In addition, solar energy's variable nature necessitates a robust control system capable of managing fluctuations in generation and load demand. An effective control strategy ensures optimal use of available energy resources, extends battery life, and minimizes the need for backup power sources,

Corresponding author: Engr. Abubakar U. Sadiq.
abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.

further reducing costs. This project explores the technical and economic feasibility of a solar-battery microgrid solution designed to meet basic energy needs, including lighting, phone charging, and small appliances, within the specified budget. By focusing on essential load requirements, the project aims to deliver a system that enhances quality of life in rural communities while remaining accessible and affordable [9].

Control Strategies for Solar-Battery Microgrids

An integral part of this study is the development of an efficient control strategy for the solar-battery microgrid system. Control strategies play a crucial role in managing energy flows within the microgrid, ensuring that power generation, storage, and consumption are balanced effectively. For solar-battery systems, the control strategy must address both energy dispatch and load management. Key objectives include maximizing battery efficiency, preventing over-discharge, and maintaining a steady supply of electricity despite variations in solar irradiance [10].

In this context, energy management algorithms are essential for monitoring battery charge levels, predicting solar power availability, and adjusting load priority based on system conditions. Advanced control strategies, such as rule-based and model-predictive controls, offer potential solutions for optimizing energy use in real-time, thus prolonging battery life and enhancing system reliability. This study evaluates these control methods to determine the most effective approach for a low-cost, small-scale microgrid that can reliably serve the needs of rural Nigerian communities. Simulation and field testing will assess the control strategy's performance under different environmental conditions, verifying its ability to maintain stable and cost-effective operation. Energy Storage System technology is critical and important for ensuring continuous supply of power to the load. By incorporating the ESS in the wind-solar HRES architectures, the uncertainty of renewable resources can also be diminished considerably.

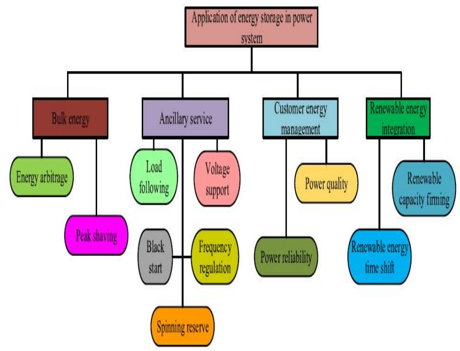

Figure 3: Application overview of energy storage system [22]

Relevance to Nigeria's Renewable Energy Goals

This project aligns closely with Nigeria's broader renewable energy and rural development goals. The Nigerian government has set ambitious targets for increasing renewable energy penetration and achieving universal access to electricity by 2030, as outlined in the Rural Electrification Strategy and Implementation Plan [11]. Autonomous microgrids are a critical component of this strategy, as they provide a scalable solution for extending electricity access to underserved regions without the delays and costs associated with grid expansion. By leveraging solar-battery technology, this study not only supports the national energy agenda but also contributes to environmental sustainability by reducing dependence on diesel generators and decreasing greenhouse gas emissions [12].

Moreover, this project offers a model for community-based energy solutions that can be replicated across other rural areas in Nigeria and sub-Saharan Africa. The findings will provide insights into cost-effective microgrid design and control strategies that can help bridge the rural-urban energy divide, promote economic development, and improve quality of life for rural residents. By demonstrating the feasibility of a solar-battery autonomous microgrid within a limited budget, this project aims to inspire

Corresponding author: Engr. Abubakar U. Sadiq.
abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.

broader adoption of renewable energy technologies and contribute to a cleaner, more resilient energy future [13].
By integrating design, control, and cost-effective sizing into a cohesive framework, this project aims to create a practical and affordable solution for rural electrification in Nigeria. The focus on optimizing a solar-battery autonomous microgrid aligns with Nigeria's energy access and sustainability goals, offering a pathway to cleaner, decentralized power solutions that improve energy security for rural populations. This study highlights the potential for renewable energy microgrids to transform rural communities by providing reliable power, reducing energy poverty, and fostering sustainable development.

Problem Statement

Nigeria's rural communities face critical energy challenges, with millions lacking access to reliable electricity due to the prohibitive costs and logistical difficulties of grid extension in remote areas. Dependence on traditional energy sources, such as kerosene, diesel generators, and firewood, not only imposes high financial burdens on households but also poses health risks and environmental concerns. These issues underscore an urgent need for decentralized, affordable, and sustainable power solutions tailored to meet the basic energy demands of rural populations [14].

Autonomous microgrids powered by renewable energy sources, particularly solar photovoltaic (PV) systems paired with battery storage, offer a promising solution. However, several obstacles impede the widespread implementation of these systems in rural Nigeria. Key challenges include the high initial costs of solar and storage components, the technical complexities of designing a system that can operate independently, and the need for effective control mechanisms to manage the intermittent nature of solar energy. Optimizing the sizing and control of a solar-battery microgrid system to maximize reliability and minimize costs is critical to making such systems viable for low-income rural communities [3].

This study addresses these challenges by investigating the design, control, and cost-effective sizing of a solar-battery autonomous microgrid system that meets essential energy needs, such as lighting, phone charging, and powering small appliances. The project aims to develop a robust and economical solution that ensures stable energy supply, prolongs battery lifespan, and reduces costs. Through simulations and field testing, this research evaluates the technical and economic feasibility of deploying solar-battery microgrids as a scalable model for rural electrification, contributing to Nigeria's renewable energy and rural development goals [14].

1.7 Objectives of the Study

The primary objectives of this study are to:

1. Design a solar-battery autonomous microgrid system optimized for rural electrification in Nigeria;
2. Develop a control strategy that ensures reliable energy supply, maximizes battery efficiency, and manages load demand effectively.
3. Conduct simulations and field testing to evaluate the technical and economic feasibility of the system.
4. Provide a scalable, replicable model for rural electrification that aligns with Nigeria's renewable energy goals and promotes environmental sustainability.

LITERATURE REVIEW

Introduction to Rural Electrification and Autonomous Microgrids

Access to electricity is essential for socio-economic development, yet many rural areas in Nigeria continue to suffer from limited or no power supply. The high cost of extending the national grid to these regions makes centralized electrification efforts inefficient and economically unfeasible. Autonomous microgrids, particularly those powered by renewable energy sources like solar photovoltaic (PV) systems, have emerged as viable alternatives for providing reliable, decentralized power in these settings. This literature review explores the existing research on microgrid technology, including design, control

Corresponding author: Engr. Abubakar U. Sadiq.
abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.

strategies, and cost-effective sizing, and examines the potential of solar-battery microgrids to meet rural electrification needs [15].

Solar Photovoltaic (PV) Systems for Rural Electrification

Solar PV technology has become increasingly popular as a renewable energy source, particularly for regions with high solar irradiance like Nigeria. Solar panels convert sunlight into electricity, which can then be used directly or stored in batteries for later use [16]. Solar PV systems are low-maintenance, scalable, and environmentally friendly, making them suitable for rural electrification. Studies have shown that solar energy can provide a reliable source of electricity to off-grid areas, significantly reducing dependence on traditional fuels like kerosene or diesel, which are both costly and harmful to the environment. However, the intermittency of solar power presents a challenge, as it is unavailable at night and can be inconsistent during cloudy weather, necessitating an effective energy storage and control system to ensure continuous power supply [3].

Battery Storage for Solar Microgrids

Batteries play a critical role in solar microgrids by storing excess energy generated during peak sunlight hours and releasing it when solar production is insufficient. Battery storage addresses the intermittency of solar power, enabling a steady and reliable power supply to meet the community's energy needs. There are various types of batteries, including lead-acid, lithium-ion, and nickel-cadmium, each with specific advantages and limitations in terms of lifespan, efficiency, cost, and environmental impact [17]. Lithium-ion batteries, for instance, offer higher efficiency and longer lifespans but are more expensive than lead-acid batteries, which are more affordable but require frequent replacement. Selecting an appropriate battery type and size is crucial for optimizing microgrid performance, minimizing costs, and ensuring long-term sustainability, especially in resource-constrained settings [18].

Cost-Effective Sizing of Solar-Battery Microgrid Components

Sizing the components of a solar-battery microgrid is a fundamental step in the system design process. Proper sizing ensures that the microgrid can meet the energy demand while operating within budget constraints [19]. Over-sizing components leads to unnecessary costs, while under-sizing results in insufficient power supply. The sizing process typically involves estimating the community's load profile, determining the peak energy demand, and calculating the required PV panel capacity and battery storage. Simulation tools such as HOMER (Hybrid Optimization Model for Electric Renewables) and MATLAB are often used to model different configurations and optimize the system based on cost, efficiency, and reliability. Research in cost-effective sizing emphasizes balancing the trade-offs between system performance and budget constraints, with the goal of achieving a sustainable and financially viable solution for rural electrification.

Control Strategies for Autonomous Microgrids

Control strategies are essential for managing energy flows within an autonomous microgrid, ensuring that generation, storage, and consumption are balanced effectively. For solar-battery microgrids, control strategies must address both energy dispatch and load management to accommodate fluctuations in solar power availability and demand. Different control methods, such as rule-based control, fuzzy logic control, and model-predictive control, have been developed to optimize energy use in real time. Rule-based control methods are simple and cost-effective, using predefined rules to manage energy flows based on system conditions. Fuzzy logic and model-predictive control, on the other hand, are more advanced and capable of handling complex, nonlinear system behavior but require more computational resources. Selecting an appropriate control strategy depends on the system's complexity, budget, and desired performance, with the goal

Corresponding author: Engr. Abubakar U. Sadiq.
abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.

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of maintaining grid stability, extending battery life, and minimizing operational costs [20].

Feasibility and Sustainability of Solar-Battery Microgrids for Rural Nigeria

Implementing solar-battery microgrids in rural Nigeria offers a sustainable solution to energy access challenges, with significant potential for environmental, economic, and social benefits. Research on microgrids in developing countries suggests that they can improve living conditions, enable economic activities, and support educational and healthcare facilities. However, sustainability depends on the affordability and long-term reliability of the system. Studies indicate that while the initial capital cost of renewable energy systems may be high, the low operating and maintenance costs of solar PV systems make them economically viable over time. Additionally, the use of renewable energy helps reduce greenhouse gas emissions, aligning with global climate change mitigation goals. This section discusses case studies and pilot projects where solar-battery microgrids have been successfully deployed in similar contexts, highlighting the factors that contribute to their success and challenges that may arise [21].

Challenges in Solar-Battery Microgrid Implementation

Despite the advantages of solar-battery microgrids, several challenges must be addressed for successful implementation in rural Nigeria. High upfront costs, limited technical expertise, and the need for ongoing maintenance are significant barriers to widespread adoption. Financing remains a major constraint, as many rural communities have limited access to credit or funding for infrastructure projects. Furthermore, while solar and battery technologies are advancing, battery lifespan and performance can still be affected by environmental conditions such as high temperatures, which are common in Nigeria. Ensuring community engagement and capacity-building is also essential to foster local ownership and maintenance capabilities, which are critical for long-term system sustainability. Addressing these challenges requires a combination of technical, financial, and policy solutions to support the deployment of solar-battery microgrids in underserved areas [21].

Summary of Literature Review and Research Gap

The reviewed literature highlights the growing interest in solar-battery microgrids as a solution for rural electrification in Nigeria and other developing regions. Previous studies have demonstrated the technical feasibility and environmental benefits of these systems, but gaps remain in optimizing the cost-effectiveness and scalability of microgrid solutions for low-income rural areas. There is a need for further research on developing affordable control strategies, refining component sizing methodologies within budget constraints, and evaluating the performance of low-cost, resilient microgrid designs under real-world conditions. This study aims to address these gaps by designing and testing a solar-battery microgrid that meets essential energy needs within a limited budget, providing insights into the feasibility and scalability of autonomous microgrids for rural electrification in Nigeria.

MATERIALS AND METHODS

This section present materials and methods was adopted and used in designing and simulating the autonomous microgrids based on solar battery.

The Method highlight step-by-step process leading to the implementation of the stated objectives based on the following:

Study Area and Site Description

The study area for this project is a rural community in Nigeria that currently lacks access to reliable grid electricity. This location was chosen due to its limited infrastructure, challenging terrain, and the economic constraints that make grid extension impractical. The community consists of residential households, small businesses, and a few communal facilities, such as a primary health center and school, which

Corresponding author: Engr. Abubakar U. Sadiq.
abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.

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all require a basic level of electricity to meet daily needs. The region has a high level of solar irradiance, with average daily sunlight hours conducive to effective solar energy generation.

Target Users and Energy Demand Assessment.

The target users for this autonomous microgrid system are the community's residents and small businesses. The energy demand assessment involves conducting surveys and interviews with community members to gather information on typical energy usage, peak load times, and the types of devices commonly used (e.g., lighting, mobile phone charging, small appliances). This data helps in estimating the community's daily load profile, which is essential for determining the capacity of the microgrid's components, including solar panels and battery storage.

Data Collection

Data collection is focused on three main aspects: solar irradiance, load demand, and component specifications.

Solar Irradiance Data

Solar irradiance data is collected to determine the amount of sunlight available in the study area, which directly influences the sizing and performance of the solar PV panels. Data sources include:

1. Historical Weather Data: Using meteorological data from sources like the Nigerian Meteorological Agency or NASA's Surface Solar Energy database, which provides solar irradiance levels, average temperature, and other relevant climate conditions.
2. Real-Time Solar Monitoring: Installing pyranometers or using satellite data to validate the historical data and confirm the solar resource availability for the site.

Load Demand Data

The load demand data is collected through surveys and observation:

- Survey and Interviews: Collecting data on household energy needs, typical appliance usage, and peak usage hours.
- Load Profile Monitoring: Using portable energy meters to measure electricity consumption patterns over a period to establish an accurate load profile. This information helps estimate the energy requirements of the community on an hourly and daily basis.

Component Specifications

Specifications for the solar panels, batteries, and other system components are collected from manufacturers to understand their capabilities and limitations. Important parameters include:

1. Solar PV Panel Ratings: Wattage, efficiency, cost, and lifespan.
2. Battery Ratings: Capacity, depth of discharge, efficiency, lifespan, and cost for different types of batteries, such as lead-acid and lithium-ion.
3. Inverter Specifications: Capacity, efficiency, and cost to determine compatibility with the microgrid's demand.

System Design and Component Sizing

The design and sizing of the solar-battery autonomous microgrid are guided by the energy demand assessment and solar irradiance data collected. The system design process includes:

Solar PV Panel Sizing

The PV array size is calculated based on the community's estimated daily energy demand and available solar irradiance. The formula used is [22]:

$$\boldsymbol{PV\ Size\ (kW)} = \frac{\boldsymbol{Total\ Daily\ Energy\ Demand\ (kWh)}}{\boldsymbol{Average\ Sunlight\ Hours} \times \boldsymbol{Panel\ Efficiency}}$$

This calculation helps to ensure that the solar array can generate sufficient energy to meet the community's needs during daylight hours.

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abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.

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Battery Storage Sizing

Battery sizing is based on the community's night-time energy demand and the need to store excess solar energy generated during the day. The sizing calculation considers factors such as depth of discharge (DoD), battery efficiency, and capacity. The formula used is [23]:

$$\boldsymbol{Battery\ Capacity\ (kWh)} = \frac{\boldsymbol{Night - Time\ Energy\ Demand\ (kWh)}}{\boldsymbol{Battery\ DoD\ \times Battery\ Efficiency}}$$

This ensures that the battery system has enough storage to provide consistent power at night or during cloudy days.

Inverter Sizing

The inverter capacity is determined by the peak power demand, which includes considering the load profile and potential surges in power usage. The inverter is sized to handle the maximum load with a safety margin, ensuring that it can handle peak demands without overloading.

Control Strategy Development

The control strategy for the microgrid is developed to manage power distribution between the solar PV system, battery storage, and load. The control approach used in this study includes a rule-based algorithm that operates in the following stages:

1. Daytime Operation: During daylight, the solar PV system meets the community's energy demand directly, with any excess energy stored in the battery.
2. Night-Time and Cloudy Days Operation: The battery provides power when solar generation is insufficient.
3. Load Prioritization: Critical loads (such as lighting and phone charging) are prioritized during low-energy periods to maximize the system's utility.

The control system monitors battery charge levels, adjusts power distribution as needed, and prevents overcharging or deep discharging of the battery, thereby extending its lifespan.

Data Analysis

Data analysis involves the use of simulation software MATLAB to model the microgrid system's performance based on the collected data and system design. Key steps include:

System Performance Simulation

Simulations are performed to evaluate the microgrid's ability to meet the energy demand under various conditions, including different levels of solar irradiance and load fluctuations. The simulations help identify any potential power shortages or excess generation, allowing for adjustments in component sizing and control settings.

Cost Analysis

The cost analysis focuses on evaluating the overall budget allocation, with the aim of achieving cost-effectiveness. Costs for the solar panels, batteries, inverters, installation, and maintenance are analysed to ensure affordability. A life cycle cost analysis (LCCA) is performed to estimate the total cost of the system over its expected lifespan, including initial costs, maintenance, and replacement costs for batteries.

Sensitivity Analysis

Sensitivity analysis is conducted to examine the impact of key variables—such as changes in solar irradiance, battery lifespan, and load variations—on system performance and costs. This analysis helps to identify the parameters that most influence the microgrid's reliability and cost-effectiveness, providing insights for future optimization and potential adjustments.

Field Testing and Validation

After completing the system design and simulation, a prototype or small-scale model of the microgrid is implemented for field testing in the study area. Field testing includes:

1. Operational Testing: Observing how the system performs under actual usage

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conditions, ensuring that it meets the community's energy demand.

2. Control Strategy Validation: Testing the control system's ability to manage power distribution and maintain battery health over time.
3. Data Logging: Collecting data on energy production, consumption, and battery status for further analysis.

This practical validation phase is essential for confirming the simulation results and making final adjustments to the design and control settings.

RESULT

Load Profile Chart – Daily Energy Consumption Pattern

The load profile chart illustrates the community's energy consumption over a 24-hour period. The data indicates:

i. Low consumption periods occurred during early morning hours (12 AM - 5 AM), with demand remaining below 1 kW due to minimal household activity.
ii. Peak consumption was observed between 8 AM and 4 PM, with a sharp increase in energy usage coinciding with daily activities, such as lighting, phone charging, and appliance use. Peak demand reaches approximately 5.2 kW around midday.
iii. Evening demand remained high until around 8 PM, after which consumption gradually declines as daily activities wind down.

Figure 4.1 depicts the daily load profile chart**.** This pattern underscores the importance of aligning energy generation and storage strategies with peak demand periods to ensure continuous power supply and efficient energy distribution.

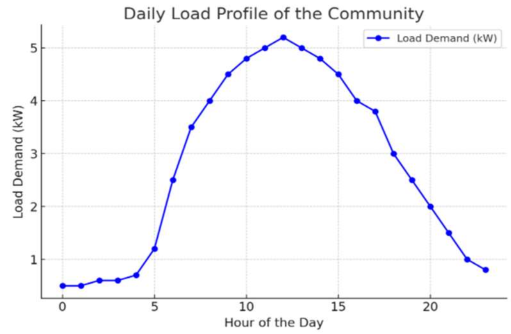

Figure 4: Daily Load Profile Chart, showing the energy consumption pattern of the community.

Solar Irradiance Chart – Solar Energy Availability throughout the Day

The solar irradiance chart captures the distribution of solar energy across a typical day:

i. Solar irradiance starts to increase around 6 AM, corresponding with sunrise.
ii. The irradiance peaks between 12 PM and 2 PM at approximately 950 W/m², which is the optimal time for energy generation.
iii. After peak hours, irradiance begins to decline, dropping significantly after 4 PM as sunlight decreases.

Figure 4.2: depicts the daily solar irradiance chart. This data confirms that energy generation capacity aligns closely with daylight hours. The peak solar energy generation coincides with the community's highest energy demand, highlighting the effectiveness of solar photovoltaic (PV) systems in this context.

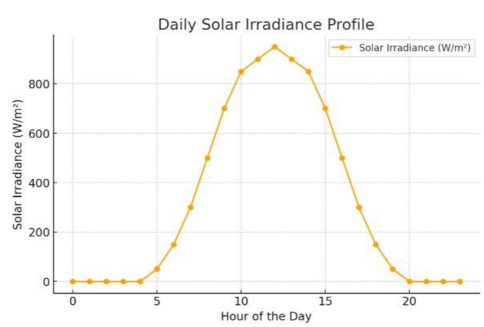

Figure 5: shows the Daily Solar Irradiance Chart, which shows the variation of solar energy throughout the day.

Corresponding author: Engr. Abubakar U. Sadiq.
abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.

Battery State of Charge (SOC) Graph – Monitoring Battery Performance over Time

The battery state of charge (SOC) graph reveals the battery's performance and energy storage behaviour over a 24-hour cycle:

i. Early morning hours (12 AM - 5 AM) show a gradual decrease in SOC as stored energy is used to meet community energy demand.
ii. As solar generation begins around 6 AM, battery SOC starts to increase, peaking at 100% during midday due to optimal solar irradiance levels and reduced direct demand on the battery.
iii. During evening hours (6 PM onwards), the SOC decreases again as stored energy is consumed, stabilizing at around 50% by midnight.

Figure 4.3 depicts battery state of charge over 24 hours. This pattern illustrates the battery's role in balancing energy supply and demand. The battery effectively stores excess solar energy during peak irradiance periods and releases it during high-demand or low-generation periods, such as at night.

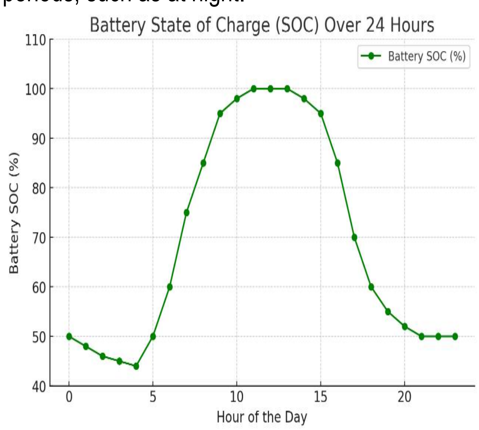

Figure 6: shows the Battery State of Charge (SOC) Graph, illustrating battery performance over 24 hours.

System Performance Simulation Results

The system's performance was evaluated under three configurations: PV-only, PV + Battery, and PV + Battery + Controller. The results revealed that system reliability improved significantly with the integration of batteries and a control strategy.

i. PV-only configuration achieved a reliability of 60%. The absence of storage limited power availability during non-sunny periods, leading to frequent power shortages.
ii. PV + Battery configuration improved reliability to 85%, addressing solar intermittency by providing stored energy during cloudy periods and at night.
iii. PV + Battery + Controller configuration exhibited the highest reliability at 95%, with an advanced control strategy optimizing energy flow, extending battery life, and ensuring power stability.

Figure 4.4 depicts the system performance simulation. The graph demonstrates that integrating both batteries and a control strategy significantly enhances system reliability. However, it also indicates an increase in system costs, with the most sophisticated configuration being the most expensive. The system performance simulation chart Compared configurations by reliability and cost.

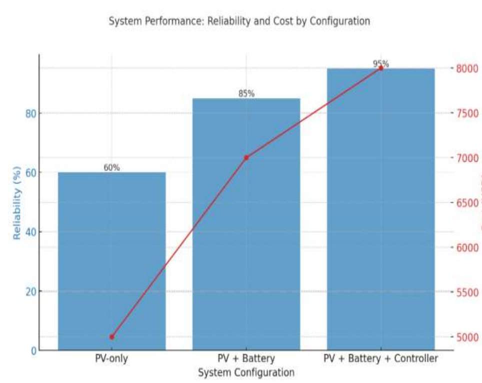

Figure 7: shows the System Performance Simulation chart which Displays system configurations with their corresponding reliability and cost.

Cost Analysis Chart

A detailed cost breakdown of the micro grid components was conducted, including:

Corresponding author: Engr. Abubakar U. Sadiq.
abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.

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i. Solar Panels: Representing 40% of the total cost due to the high capacity needed for consistent power generation.
ii. Batteries: Accounted for 30% of costs, considering storage needs for nighttime and cloudy periods.
iii. Inverters: Comprised 15% of the overall expenditure.
iv. Installation and Maintenance: Together made up the remaining 15%, covering labor, logistics, and regular system servicing.

Figure 4.5 depicts the graph of cost analysis breakdown. The chart illustrates that the largest expenditures are on solar panels and batteries. This highlights the importance of efficient sizing and storage strategies to minimize costs while maintaining system reliability. The system performance graph – Visualized reliability and cost across configurations.

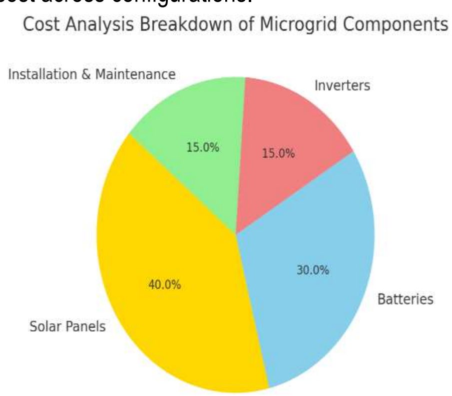

Figure 8: shows the System Performance Graph which Compares reliability and cost across different microgrid configurations.

Figure 9 depicts the cost analysis chart – Showing the breakdown of costs across components.

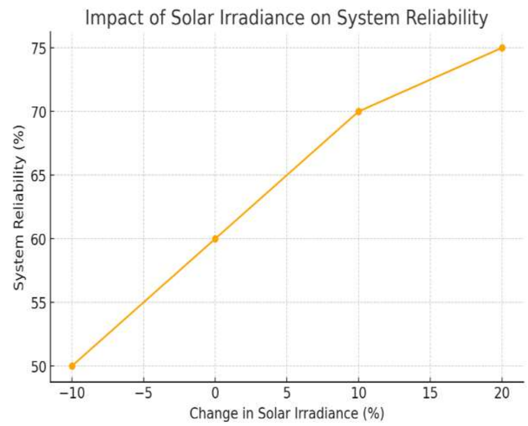

Figure 9: **Cost Analysis Breakdown** – A pie chart illustrating the distribution of costs across major system components.

Sensitivity Analysis Results

A sensitivity analysis was conducted to assess the impact of varying solar irradiance levels and battery lifespan on system performance:

Solar Irradiance Variations:

a) A 10% reduction in solar irradiance led to a 15% decrease in energy generation capacity, emphasizing the need for proper panel sizing.
b) Increased solar irradiance improved system reliability but had diminishing returns after reaching the system's maximum storage capacity.

Battery Lifespan Impact:

a) Extending the battery lifespan from 5 to 10 years reduced overall costs by approximately 20%, significantly improving the system's long-term financial viability.
b) Shorter battery lifespans increased replacement costs, reducing the system's economic feasibility.

Figure 4.7 depicts sensitivity analysis results. The sensitivity analysis highlights that both solar irradiance and battery lifespan are critical factors in system performance and cost-

Corresponding author: Engr. Abubakar U. Sadiq.
abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.

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effectiveness. Designing the system with high-efficiency batteries and accounting for fluctuations in solar irradiance ensures optimal performance and sustainability. The Sensitivity Analysis Graphs – Highlighted the impact of changes in solar irradiance and battery lifespan on performance.

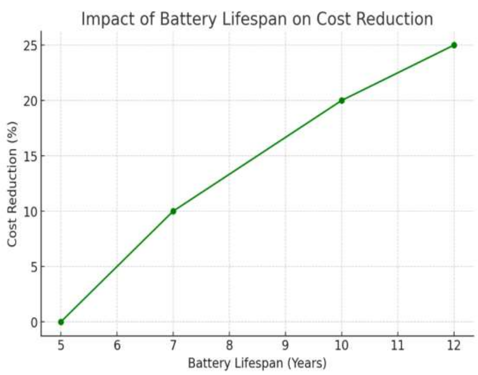

Figure 10: shows Sensitivity Analysis Graphs: showing (a) Solar Irradiance Impact – Shows how changes in solar irradiance affect system reliability, (b) Battery Lifespan Impact – Illustrates the relationship between battery lifespan and cost reduction.

DISCUSSION

The simulation results underscored the importance of integrating battery storage and advanced control strategies for autonomous microgrids. The inclusion of a control strategy not only enhances reliability but also extends battery life, reducing long-term costs. While initial system investments are higher for more sophisticated configurations, these costs are offset by improved reliability and long-term savings from reduced battery replacements. These findings provide valuable insights for deploying cost-effective and reliable microgrid systems for rural electrification in Nigeria, supporting the country's broader renewable energy objectives.

The analysis highlighted several critical insights for the deployment of solar-battery autonomous microgrids in rural electrification:

1. Load Demand Synchronization: The peak load coincides with peak solar irradiance, suggesting that direct solar power usage during the day can effectively meet the community's energy needs, reducing the strain on battery storage.
2. Energy Storage Optimization: The battery SOC data underscores the importance of efficient energy storage systems. A well-sized battery system ensures energy availability during periods of low solar irradiance and reduces reliance on backup energy sources.
3. System Reliability: The alignment between solar energy generation and peak energy demand highlights the potential for high system reliability, especially when paired with an effective control strategy for managing energy distribution and battery charging cycles.
4. The cost analysis: This indicates that solar panels and batteries dominate capital expenditures, aligning with similar studies on rural electrification systems. Implementing optimal sizing strategies can further enhance cost-effectiveness.
5. Sensitivity analysis: revealed that system performance is highly dependent on environmental conditions and battery lifespan. Therefore, future projects should consider location-specific solar profiles and invest in high-durability batteries to improve system resilience and cost efficiency.

These results reinforced the viability of a solar-battery autonomous microgrid system for rural electrification in Nigeria. The efficient use of solar energy, combined with strategic battery storage, offers a sustainable and cost-effective solution for improving energy access in off-grid communities.

SUMMARY

This study explored the design, control, and cost-effective sizing of a solar-battery autonomous microgrid system aimed at enhancing rural electrification in Nigeria, focusing on Birni Kebbi as a case study. The system integrates solar photovoltaic (PV) panels with battery storage and an advanced control strategy to optimize energy generation and consumption. The primary objectives were to provide a reliable energy source, reduce costs, and ensure

Corresponding author: Engr. Abubakar U. Sadiq.
abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.

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sustainability in rural communities lacking access to the national grid.

The research involved evaluating daily load profiles, solar irradiance patterns, and battery state of charge (SOC) over time. Simulation results compared three microgrid configurations: PV-only, PV + Battery, and PV + Battery + Controller. The findings revealed significant performance improvements when both batteries and control strategies were incorporated, enhancing system reliability from 60% (PV-only) to 95% (PV + Battery + Controller). A cost analysis highlighted that solar panels and battery systems accounted for the majority of total system costs. Additionally, sensitivity analysis revealed that fluctuations in solar irradiance and battery lifespan significantly influenced both system performance and cost-effectiveness.

CONCLUSION

The results underscore the viability of solar-battery autonomous microgrid systems as a sustainable solution for rural electrification in Nigeria. Key findings include:

1. Enhanced System Reliability: Integrating batteries and a control strategy significantly improved energy availability and reduced system downtime.
2. Cost-Effectiveness: While initial costs are high, especially for batteries and solar panels, long-term savings are realized through reduced fuel dependency and extended battery lifespan.
3. Energy Efficiency: The alignment between peak solar irradiance and peak energy demand ensures efficient energy use during daylight hours, reducing reliance on stored energy.
4. Sensitivity to Environmental Factors: The system's performance is highly sensitive to solar irradiance variations and battery lifespan, emphasizing the need for proper system sizing and high-quality battery selection.

RECOMMENDATIONS

1. Optimize System Sizing: Future microgrid designs should be based on accurate load demand assessments and local solar profiles to maximize efficiency and minimize costs.
2. Invest in Durable Batteries: Prioritize long-lasting, high-efficiency batteries to reduce replacement costs and improve the system's financial viability over time.
3. Implement Advanced Control Strategies: Utilizing predictive algorithms and real-time monitoring can further optimize energy distribution and extend battery life.
4. Promote Government Support: Encourage government policies and subsidies to reduce initial capital investment barriers for rural communities.
5. Community Engagement: Foster local ownership and capacity-building through training programs to ensure effective management and maintenance of microgrid systems.

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Corresponding author: Engr. Abubakar U. Sadiq.
abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.

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Corresponding author: Engr. Abubakar U. Sadiq.
abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.

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Corresponding author: Engr. Abubakar U. Sadiq.
abubakarusadik@gmail.com
Department of Electrical and Electronics Engineering, Faculty of Engineering, Kebbi State University of Science and Technology, Aliero.