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Feasibility Analysis of Hybrid Renewable Energy Systems with Battery Storage for Rural Electrification in Samunaka, Niger State: A Newton-Raphson Approach

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ABSTRACT
The subject of the research covers the extended power flow analysis of a Hybrid Renewable Energy System (HRES) for rural electrification in Samunaka, Mokwa Local Government Area of Niger State, Nigeria. The analysis was based on the Newton-Raphson approach, which has been used to study the steady-state voltage profile, load balance, and transmission line power loss reduction of the system concerned. Solar photovoltaic (PV) modules, wind turbines, and lithium-ion battery storage were incorporated in a hybrid configuration to provide a reliable micro off-grid system, which reflects the local demand pattern over residential, commercial, and community loads. The MATLAB numeric programming was used to simulate a four-bus system that comprised a slack bus, a PV bus, and two PQ buses. Through the application of the Newton-Raphson method, fast and robust convergence results in the final bus voltages of 1.00pm, 1.01pm, 1.02pm, and 1.00pm, with phase angles 0.000, 0.025, -0.010 and 0.005, respectively. Hence, it can be concluded that the performance indicated that the system is having a stable operation and voltage regulation, even with situation-derived variation in renewable generation nucleating such high flexible applications. The Newton-Raphson method has quickly and robustly converged, resulting in final bus voltage-magnitudes of 1.00 p.u., 1.01 p.u., 1.02 p.u., and 1.00 p.u. with phase angles of 0.000, 0.025, -0.010, and 0.005, respectively. This shows that the system has performed well concerning stable operation and voltage regulation despite varying generation capacity from the renewable sources. Bar plots and polar graphs were also produced for visualization of voltage magnitudes and phase angles in order to grasp intuitively the network behavior. The analysis provides a strong case for the viability and reliability of renewable energy technology integrated with smart control strategies for the sake of sustainable rural electrification. The results therefore present a roadmap for policies geared toward fast-tracking clean energy deployment in neglected areas, so far as technically sound and economically justifiable micro grid design is concerned.

Keywords: Hybrid, Rural Electrification, Renewable Energy, Feasibility Study, Solar, wind, Photovoltaic, lithium battery storage,

I. INTRODUCTION

The adoption of hybrid renewable energy systems (HRES) for rural electrification has become a hot topic in the last few years, particularly because of their ability to provide dependable and sustainable power even in far-off locations. Rural electrification has been the most important aspect of the whole Nigerian economy since it could boast of its 43.1% population who do

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not have access to any or reliable electricity and among these one-third of them live in the rural areas (Word bank 2021). This lack of energy cripples growth, restricts access to quality healthcare, education, and continues to exacerbate socio-economic inequalities. Dealing with this issue is vital for promoting the inclusive development and securing national sustainability objectives. People in rural area in developing countries have limited access to reliable grid and hence decentralized hybrid energy system is a good way to go. These are the use of renewable sources of power such as solar photovoltaic (PV), wind, biomass and sometimes small scale hydro power combined with conventional generator sets or batteries to improve energy availability and reliability. Advantages of HRES in rural electrification. There are considerable advantages of HRES compared to single-source systems. One of the great advantages of this tech is that it could help with the intermittent nature of renewables such as solar or wind. For example, when solar is low then wind can make up the difference and vice versa. "All of this balancing will enhance the reliability of the system as a whole, " he said, and it works well to deliver constant power in rural communities without regular access to the grid. In addition, energy storage, such as batteries, enhances the availability of energy by storing surplus energy during peak generation for time when the renewable sources have low generation. Economically, hybrid systems can also offer more savings in the long run (Türkay and Telli 2011). The initial capital cost of HRES is higher than the cost of conventional diesel generating plants, but reduced dependence on fossil fuels results to operational savings. Studies have shown that the adoption of the solar PV-wind pair and supplementing them with battery storage technology could drastically reduce fuel consumption and maintenance costs in off-grid applications (Babatunde et al., 2022). Awopone, 2021 study explores the feasibility of a photovoltaic, diesel generator, and battery storage hybrid power system for electrification in off-grid rural areas in northern Ghana. Using the HOMER software package, five optimization scenarios were evaluated, with the PV/diesel/battery storage system being the most feasible, cost-effective, and environmentally friendly option. The increasing dependence on energy has led to a growing demand for sustainable energy sources. Renewable and non-renewable energy sources are crucial for achieving sustainable development. Adefela, and Agbroko 2020 discusses the importance of renewable energy sources, alternative energy technologies, and a holistic approach to national development. Factors such as availability, assessment, government policies, methods, efficiency, and socioeconomic activities must be considered for energy renewability and sustainability. These factors are crucial for economic, standard of living, and environmental development, as well as philosophical, psychological, sociological, and physical impacts. Adom and Adams (2018) study uses Markov Switching Regression to estimate transition probabilities for energy-use states in Nigeria. Results show energy-efficient states are less persistent, but energy-inefficient states are more persistent. Factors include inefficient regulatory systems, poor institutional structures, corruption, second-hand goods proliferation, undeveloped markets, poverty, and inefficient pricing. In providing the best option for rural electrification in remote off-grid areas hybrid renewable energy systems is seen as the best. Hybrid systems offer more reliable, cost-effective, and less environmentally damaging solutions to electricity generation than single-source systems. Realizing their full potential, however will entail overcoming economic and technical challenges, particularly in relation to finance, system optimization, and maintenance. Hybrid systems will have an increasing role to play in the energy requirements of rural communities around the globe as technology progresses and the renewable sector becomes cheaper. Foremost to their successful integration is an accurate modeling and analysis of these hybrid systems. The Newton-Raphson technique, which is widely used in power analysis flow, assumes a significant role in this regard in solving complex nonlinear equations characteristic of power system studies for performance assessment, optimization of component sizing, and operational stability evaluation. Thus by applying the Newton-Raphson method, engineers can establish HRES that are acceptable from both technical and economic standpoints. Initiatives have been taken more and more recently in Nigeria to deploy renewable energy solutions for rural electrification. The commissioning of the very first hybrid mini-grid in Nigeria, which is interconnected with solar energy and which was built for the Toto community, Nasarawa State, can be said to represent the dedication of the federal government toward sustainable energy development. An initiative of a solar hybrid mini-grid of 352kWp, built together with Powergen Nigeria Limited and Abuja Electricity Distribution Plc (AEDC), represents a

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demonstration for replication throughout the country. Apart from that, the Rural Electrification Agency (REA) also plays a vital role in promoting off-grid solutions. Through NEP, more than 80 mini-grids have been built and commissioned, providing access for approximately 32,000 households, micro, small, and medium enterprises (MSMEs), and public facilities. These projects are a demonstration of how HRES can bridge the energy access gap for rural Nigeria.

Nonetheless, obstacles still remain for the large-scale deployment of HRES. Barriers include high initial capital costs, technical complexity, and inefficiency of the policy framework. The idea behind these innovative financing mechanisms is to reduce some of these constraints, such as the World Bank grant of US$750 million for the establishment of 1,200 mini-grids in rural communities. Government agencies working collaboratively with their private sector partners will be required to bring these resources and technical know-how to bear. Samunaka community in Mokwa Local Government Area of Niger State is one such rural setting typical of the areas to benefit from HRES with battery storage.

The communities in this study area suffer limited or no access to the national grid and are thus dependent on the use of traditional biomass and diesel generators. But these are neither sustainable nor greener alternatives. The implementation of a well-designed Hybrid Renewable Energy System will reconnect socio-economic conditions through the provision of reliable electricity to households, schools, healthcare facilities, and small businesses. In conclusion, Hybrid Renewable Energy Systems integrated with battery storage hold great promise for generating sustainable rural electrification for Nigeria. Numerical applications for the design and analyses of these systems must include methods such as the Newton-Raphson technique. Whereas the country presently concentrates on renewable energy development, temporary arrangements have to be made in the fields of policy, finance, and technical innovation to address present problems and optimize opportunities for Hybrid Renewable Energy Systems so that they are able to transform rural communities.

II. LITERATURE REVIEW

Rural electrification-the provision of electric power to distant and undeveloped communities-plays a vital role in transforming rural life and developing their economies. Indeed, renewable energy has recently emerged as the answer to rural electrification, considering its potentials in providing sustainable, clean, and cheap energy accessible to the regions for which grid extension is either too expensive or impractical. The role of renewable energy technologies in rural electrification will be investigated in this review. Key sources, techno-economics, policies, barriers, and future directions for renewable energy in rural electrification will also be incorporated by this degree. The focus for adopting renewable energy in rural electrification has been on enabling a supply of sustainable and affordable energy services for off-grid and under-served households. More than 700 million people in the world do not have access to electricity, as stated by a recent report from the International Energy Agency (IEA). Most of these again live in rural remote areas in sub-Saharan Africa and South Asia (IEA, 2022). However, such services have generally high costs associated with it, mainly due to poor terrain, low population density and very low infrastructure. Renewable energy technologies (RETs), particularly decentralized systems, such as solar PV, wind, and hybrid energy systems, have become efficient, environmentally friendly, and economically profitable solutions for rural electrification. In fact, rural electrification is the introduction of electricity to remote and underserved communities, which is crucial for enhancing the quality of life in rural areas and its consequent improvement in economic prosperity. Renewable energy has largely emerged as a viable alternative to rural electrification in recent times, as it can supply sustainable, clean, and cost-effective energy sources, especially in areas where extending the grid is either prohibitively expensive or impossible. The review of literature examines how renewable energy technologies contribute to rural electrification. We focus mainly on the important renewable energy sources, techno-economic analyses, policy frameworks, challenges, and future directions. The primary reason behind adopting renewable energy in rural electrification is that it helps meet the need to provide sustainable and affordable energy to off-grid and under-served populations. According to the International Energy Agency (IEA), over 700 million persons worldwide are without access to electricity, mostly rural and remote populations, particularly in sub-Saharan Africa and South Asia (IEA, 2022). The extension of the grid to such areas is usually prohibitively expensive because of rough terrain, low population densities, and inadequate infrastructure. Renewable energy technologies (RETs) especially decentralized systems like the solar photovoltaic

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(PV), wind, and hybrid energy systems have emerged as cost-effective and environmentally-friendly alternatives for rural electrification.

2.1 Renewable Energy Technologies for Rural Electrification

Silinto et al., 2025 review energy systems and spatially-explicit modeling methods for planning the integration of hybrid renewable energy systems in rural developing countries. Ten models met important filtering criteria among the 27 total models. The most promising are found to be conventional (HOMER, iHOGA) and GIS-based models (GeoSIM, IntiGIS, OnSSET) for rural HRES integration. A modelling framework approach is suggested for the improvement of single models and their cooperation. OnSSET and IntiGIS perform best in developing countries and HOMER and iHOGA are good options when used together with spatial parameter estimation.

A. Solar Photovoltaic (PV) Systems

This is widespread technology for the electrification of rural areas. The versatility in scale, ease of setup, and declining price trend works in its favor. Solar home systems (SHS) and microgrids are commonly being used to energize the households, schools, and health centers in rural areas.

Okonkwo et al., (2025) examine the effects of climate change induced extreme weather events on solar photovoltaic systems, with a focus on their susceptibility to structural damage, performance reduction, and disruption of service. The paper presents an approach based on resilience in a form of paradigm with design principles, operational techniques and policy innovations to reduce these risks. The work concentrates on site-specific risk assessments, modular designs and sustainable materials. In the future, we want to develop long-life materials, scalable energy storage and smart grid technology. Researchers, industry and policymakers must work together to confront climate change challenges.

B. Wind Energy

Wind energy may be site-specific, but it has been applied on a limited basis in rural electrification projects in regions with adequate wind resources. Wind turbines can be used in either standalone systems or hybrid systems to supply power to rural communities. The quality of civil infrastructure performance similarly has been decreasing and wireless sensor network information is required for maintenance purposes. But power availability on a sustainable basis is still a challenge. In this context, wireless sensor networks powered by micro harvesters utilizing ambient wind can play significant role, particularly flow-induced vibration has been receiving attentions because there have been significant progress in miniaturizing wind mill. Su, Alam, et al., (2025) provide a state-of-the-art concerning wind energy harvesting technologies for civil infrastructure, including the wind resource, high-rise building, bridge, and tunnel, investigates the principle of the energy conversion. It also introduces the wind induced vibrations and compares efficient harvesters. The findings serve to help support the realization of realistic, self-powered infrastructure monitoring systems. We will briefly review the use of urban wind resource development from the literature and how they contribute to responding to electricity demand and climate change. Liu et al. It focuses on the main aspects of urban wind environment, including urban wind flow mechanisms, characteristics of the urban wind environment, how urban winds interact with buildings and structures, and how to evaluate inhabitants' thermal comfort. The low urban wind speeds and high turbulence intensity were the major challenges inferred by the study and development of more effective techniques for assessing the urban wind resource as well as innovations on wind energy harvesters are recommended to improve on efficiency.

C. Biomass Energy

Biomass energy is renewable energy that can originate from organic sources such as plant and animal wastes. It is a crucial available renewable energy in rural areas, especially in developing countries. Biomass is used mostly for cooking and heating but can also be used for generating electricity in biogas digesters and biomass gasification technologies. Biomass energy is a renewable energy source, and, hence, material origin may be organic; for example, biomass includes plant and animal wastes. It is among the most important available renewable energy resources in rural areas and is seen as one of the energy options, especially in developing countries. Biomass energy is, therefore, mostly used for cooking and heating, but with the biogas digester and biomass gasification technologies, it can also be used for electricity generation. Zhang et al., 2025 have studied that combining Model-Agnostic Meta-Learning (MAML) and Generative Adversarial Network (GAN) approaches allow improving ML generalization in biomass

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conversion scenarios. The GAN-MAML models realized better performance in different domains and at different scales, with an increase of up to 33,1 % compared with the best ML models. When implemented in an actual energy production plant, the GAN-MAML models well surpassed the best ML models, hence presenting a promising flexible framework option toward sustainable environmental solutions in biomass energy production. Furthermore, according to Al et al., 2025, biomass energy is under study in Oman as a renewable sort of energy with scopes finance, emission reduction by pollution, and their indirect use for electricity generation. It was found that there exist opportunities within Oman to make a contribution as much as 20 % to the country-wide demand of electricity from animal manure, sludge, and municipal solid wastes. Shyness resides in Oman about biomass-go resource database and policies on their utilization and their subsequent sustainability. To this end, the study attempts to assess the potential reduction of CO_2 emissions via biomass fuel in the energy sector of Oman

D. Small-Scale Hydropower

Small hydro is another way to supply renewable energy to rural areas endowed with rivers or streams. Small hydro has fewer environmental impacts compared to large hydropower projects and can give uninterrupted and reliable power supply. Punys, (2025) a review of computer-based tools in assessing small hydropower potential, site planning, and design, concentrates on the preliminary assessment phase of project evaluation. It discusses over 40 tools, classifying them into hydraulic turbine selection, site feasibility assessment, environmental flow assessment, web-based hydropower atlases, and multicriteria analysis. The review shows the decline in new tools made for turbine selection and, instead, an increased use of digital platforms and web mapping for hydropower. It stresses feedback as essential to tool improvement and presents recommendations for further use and enhancement. Climate change in Southern Africa will thus very likely make a severe influence on hydropower generation, especially that of small-scale producers. A study examined the impact of climate change on the Pungwe B hydroelectric project using hydro-meteorological data and climate projections from 15 CMIP6 Global Climate Models. Hydropower potential generally shows a decreased pattern of development with specific reductions reaching 100.3 MW per annum under various scenarios. The study stresses the importance of flexible adaptation strategies and proactive plans to enhance resilience and sustainability in the face of climatic variability (Muzava et al., 2025).

E. Hybrid Renewable Energy Systems

Indeed, hybrid systems are increasingly being regarded as a robust and viable option for rural electrification combining various energy resources, such as solar energy, wind energy, or biomass energy. Intermittency associated with one-source renewable energy systems can be alleviated when hybrid systems utilize complementary sources of energy. So for example, during times of low solar radiation, with a windy day wind energy can kick in as a compensatory measure, or biomass can act as a standby. Libya's chronic electricity shortage, which reached 32.5% in 2023, is a result of challenges in the energy sector's fuel supply, generation efficiency, and electricity transmission and distribution. To address this issue, Libya's 25-year strategy aims to have over 50% of the country's energy mix come from renewable sources by 2050. A hybrid renewable energy system (HRES) combining wind, solar photovoltaic, and pumped hydropower storage is proposed. The system's optimal size is 762,161 MWh of PHS, 385 MW of wind, and 6000 MW of PV. This system produces 12,029,670 MWh of energy annually, covering the 9,744,033 MWh electricity shortfall. The system's design aims to save $816.246 million in social costs and an additional $2.189 billion in fuel (Nassar et al., 2025). Jeyaraj et al., 2025 examines the performance and stability of microgrids in hybrid power systems, focusing on energy management and grid resilience. Hybrid systems address issues like rotor angle stability, voltage, frequency, and energy intermittency while improving energy storage systems. The study also explores optimization techniques for advanced inverter technologies and operational challenges faced by microgrids. The findings highlight the importance of human intelligence and adaptive control systems in improving hybrid system stability and performance, promoting a more efficient, sustainable, and resilient energy future.

F. Techno-Economic Analyses and Feasibility Studies

Various techno-economic analyses have been carried out on renewable energy systems for rural electrification. In such analyses, the assessment is usually performed for the levelized cost of electricity (LCOE), reliability, and environmental concerns.

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Hamad et al., 2025, investigates the use of hydrothermal carbonization (HTC) in wastewater and sewage sludge treatment processes. The aim is to seek sustainable and circular solutions along with environmental impacts and techno-economic feasibility assessment for the integrated systems. The study compares a baseline scenario with a circular HTC-integrated scenario and finds that surface waterlines cause more environmental impacts than death lines because of their high use of energy and chemicals. An HTC approach can significantly lower disposal and energy costs while also generating income. The system can still save around three million euros per year and reduce environmental externalities. Pinheiro et al., 2025 shows an investigation into the LCOH for a hypothetical 100 MW capacity plant in Brazil through a long-term power purchase agreement with two renewable power plants. LCOH is found to be 5.29 US$/kg for alkaline electrolyzers and 5.92 US$/kg for proton exchange membrane electrolyzers, with 80% of the hydrogen being 100% renewable. Li et al., 2025 examines the economic feasibility of manufacturing bioproducts from bamboo residues using phenoxyethanol-acid pretreatment. Bioproducts include ethanol and polylactic acid, with lignin-based wood adhesive as a byproduct. A 1:1 phenoxyethanol: acid solution ratio diminishes product yield but lowers MSP. Key drivers are growing economic gain, decreasing phenoxyethanol cost, and plant capacity expansion.

III. METHODOLOGY

3.1 Study Area Description

3.1.1 Geographic Coordinates and Location

Samunaka a rural agrarian settlement located in Mokwa Local Government Area (LGA) **of** Niger State**,** in North-Central Nigeria**.** It lies approximately on Latitude 9.2047° N and Longitude 5.0695° E. This region is part of the Guinea Savannah ecological zone which shows a tropical climate with two well-defined seasons: the rainy season (April - October) and the dry season (November - March). Temperatures are annual averages that range from 24°C to 34°C and annual rainfalls are generally between 1000 mm and 1200 mm (Google Map.com). Samunaka indeed receives huge amounts of solar radiation averaged at 5.0 to 5.5 kWh/m²/day, thus makes the place fitted for solar photovoltaic energy generation. The wind in this region is average, with speeds of between 2.5 and 3.8 $m.s^{-1}$ on average, and could additionally complement solar energy during the dry season when constant wind is present. Samunaka is approximately 140 km southwest of Minna, the capital of Niger State, and its accessibility is from a combination of dirt and paved rural roads. The settlement consists of several hamlets within a scattered housing pattern and an estimated population of approximately 2,500 people extrapolated from the last national census and local field surveys (Wikipedia.com).

3.1.2 Socio-Economic Profile

Samunaka population is mainly comprised of farmers and petty traders. Subsistence farming is engaged as their major economic livelihood. Yam, cassava, maize, millet, and groundnut are planted, and small-scale livestock are reared. The community is not well connected with modern facilities, and absence of electrification has greatly affected the development. Lighting is achieved mainly by kerosene lamps and battery-powered torches, while water is fetched from shallow wells and seasonal streams. Education and health services are quite poor compared to what is obtainable in cosmopolitan villages. The village has only one primary school with no modern teaching aids because power is unavailable. There exists a health post in the community but with inadequate equipment, hence cannot operate refrigeration units for vaccines or night medical procedures. Open barber shops, grinding mills, and mobile phone charging services are all limited in service because of the unavailability of regular electricity and thus rely on costly and polluting petrol generators to meet needs.

It is anticipated that a sustainable hybrid renewable energy system with battery storage will have a significant impact on the economy, education, health delivery, and overall quality of life in Samunaka.

3.1.3 Energy Demand Assessment

A comprehensive load assessment for Samunaka was carried out to justify the installation of a hybrid renewable energy system. The load was divided into three main categories: domestic, commercial, and community services.

a. Residential Load

The baseline survey was conducted to estimate household energy needs, with an assumed median family size of 6 persons. Most commonly found household appliances considered were:

i. LED bulbs (4-6 units per house)
ii. Radio (one per house)
iii. Phone charging (2 phones per house)
iv. Ceiling fan (1 unit)
v. LED Small TV led (1 unit in 30% of homes)

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On the average, the estimated daily energy consumption per household is 0.8-1.2kWh, with peak usages being in the evening between 6 pm and 10 pm. Given around 300 households, the projected total residential loads will therefore be as follows:
300 household's × 1.0 kWh/day = 300 kWh/day.

b. Commercial Load

The commercial energy demand includes:
i. Four barbershops (each consuming clippers, fans and lights).
ii. Three grinding mills (0.75 kW electric motors).
iii. Two small provision stores (with refrigerators and lighting).
iv. Mobile phone charging stations.

The commercial average assessed demand is about 50-70 kWh/day, predominantly during the daytime from 9 AM to 6 PM.
a. Community Load
Community loads comprise:
i. One primary school (lighting, administrative equipment, projector).
ii. One health clinic (lighting, refrigerator, water pump, small medical equipment).
iii. One borehole with an electric pump (1.5 kW and used intermittently).
Total of the estimation of loads for community activity would run between 35 and 50 kWh/day.

3.1.4 Load Profile Development

i. The load profile representing energy consumption over 24 hours was derived by adding the hourly consumption of the three load categories. The estimated daily total load for Samunaka is about 400-450 kWh/day, having a peak demand of about 60-80 kW in the evening hours (6 PM-10 PM). This load profile is the input to the modeling of the hybrid system coupled with the power flow analysis using Newton-Raphson method.

3.2 System Components

For a hybrid renewable energy system capable of sustainably and reliably meeting the Samunaka community energy demands, a combination of solar photovoltaic (PV) modules, wind turbines, lithium-ion batteries, inverters, and charge controllers was designed. Selection and sizing of each component were conducted based on technical viability, resource availability, and system reliability.

3.2.1 Solar Photovoltaic (PV) Modules

As the area has high solar irradiance rates (5.0-5.5 kWh/m²/day) and during the dry season, solar energy generation is maximal when the demand during the day is very much required by the community, where the major source of energy in the hybrid system is the solar PV.
i. Type of technology: The best choice for tropical areas is the mono crystalline because of their efficiency and reliability.
i. Solar PV Rating: 380 Watt per panel.
System Setup: The configuration goes in both series and parallel to achieve the required voltage and current.

3.2.2: Estimated Total Capacity: This is based on the daily energy consumption of approximately 450 kWh and with assumption of 80% system efficiency:
Required PV capacity: 450 kWh/day x 5.2 sunshine hours/day × 0.80 ≈ 108 kW
Correction Factor: 10–15% correction margin was put into consideration to account for future additional load growth and seasonal variations, making the total installed PV capacity to approximately 120 kW.

3.2.2 Wind Turbines

Technological Classification: Horizontal-axis wind turbines (HAWT) capable of controlling rotor speed by blade-pitch regulation.
i. Average Wind Speed: 3.0-3.8 m/s (10 m elevation)
ii. Cut-in Speed: 2.5 m/s
ii. Turbine Ratings: 5 kW
iv. Tower Height: 20 m for maximum wind speed interception

.A total of 30 kW of installed wind energy capacity was proposed with the installation of six 5-kW turbines, as the moderate wind profile suggested. Though it may not significantly contribute compared to solar PV, its importance lies in system diversity and resilience.

3.2.3 Lithium-Ion Battery Storage System

Lithium-ion Battery Storage System

Its application is to take care of the intermittencies of solar and wind generation whereby an external battery bank will store the intermittent generation power during peak production hours and return it during night hours or off-peak generation times.
i. Type of Battery: $LiFePO_4$ Lithium Iron Phosphate, selected for cycle life, depth of discharge, and temperature tolerance

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ii. Battery Nominal Voltage: 48V
iii. Battery Capacity: A 1.5 days of autonomy critical load design was made for the battery capacity.
Required storage=450 kWh/day×1.5=675 kWh
Usable Capacity (considering 90% DoD and 95% inverter efficiency):

Usable capacity = $$\frac{675}{0.90 \times 0.95} = 790kWh$$

A battery bank of 800 kWh total capacity was thus selected. The battery system also supports peak shaving and stabilizes voltage fluctuations, which contribute to improving the quality of the power supplied.

3.2.4 Inverters

The inverters convert the direct current produced by the solar photovoltaic segment of these batteries into an alternating current that is required for the use of the community.
i. Inverter Type: Hybrid inverters with a solar charge controller integrated
ii. Inverter Rating: Sine wave inverters, modular (3-phase system design), such that it can be scaled to the demand of the community
iii. Total Capacity of the Inverter: Peak load demand is around 80 kw. Taking into account inverter losses and future scalability a total inverter capacity of 100 kw was adopted.

The features of the selected inverter system include: - Grid-forming capability (for islanded operation) - Integration with battery management (BMS) - MPPT (Maximum Power Point Tracking).

3.2.5 Charge Controllers and Monitoring Devices

i. MPPT Charge Controllers: PV's are now good at extracting power, so we use MPPT-type charge controllers. By dynamically changing the input voltage with solar irradiance, the system can achieve the maximum output power.
ii. SCADA (Supervisory Control and Data Acquisition): Remote monitoring system monitors power generation and tracks battery performance and load use. It can be used in preventive maintenance and fault detection.
iii. Protection equipments: we utilize circuit breakers and lightning arresters including earthing equipment and surge protection devices.

3.3 Mathematical Modeling and Power Flow Analysis Using the Newton-Raphson Method

In Samunaka, the optimal operation and performance analysis of a proposed Hybrid Renewable Energy System (HRES) require a good numerical technique capable of accommodating nonlinearities and complex systems of equations. This investigation, therefore, sought to apply the Newton-Raphson method to find solutions to the power-flow equations of the hybrid system with the incorporation of solar PV, wind turbines, and battery storage into the microgrids.

3.3.1 Power Flow Fundamental

Power flow or load flow analysis refers to determining steady-state voltage and current, as well as active and reactive power flow, through the whole electrical power system under steady-state load conditions. This is important from the technical aspects of power generation and distribution, voltage regulation, system stability, and load balancing as applied in hybrid micro grid systems. When solving power flow problems, buses are classified as follows:
i. Slack Bus: sets voltage magnitude and angle.
ii. PV Bus: Real power and voltage magnitude (typical of renewable generators).
iii. PQ Bus: Real and reactive power demand (typical of loads). For each PQ or PV bus, the following expressions are employed in the power-flow problem:

The real and reactive power flow equations are nonlinear in nature from power system concepts. For a power system consisting of N buses: power injections at each bus are given by:

Active Power Equation:

$$P_i = V_i \sum_{J=1}^{N} V_j\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \quad 3.1$$

Reactive Power Equation:

$$Q_i = V_i \sum_{J=1}^{N} V_j\left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right) \quad 3.2$$

Where:
i. Pi,Qi = Active and reactive power injections at bus **i**
ii. Vi,Vj = Voltage magnitudes at buses **i** and **j**
iii. Gij, Bij= Conductance and susceptance of the admittance matrix
iv. θij = Voltage phase angle difference

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3.3.2 Application of the Newton-Raphson Method

Applying the Taylor series expansion, the N-R method coverts the nonlinear power flow equation in the form of a set of linear equations and solves them iteratively.

Voltage changes to power mismatches relation using Jacobian matrix:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_{11} & J_{12}\\ J_{21} & J_{22}\end{bmatrix}\begin{bmatrix}\Delta Q\\ \Delta|V|\end{bmatrix} \quad 3.3$$

where:

- $J_{11}=\frac{\delta P}{\delta Q}$
- $J_{12}=\frac{\delta P}{\delta |V|}$
- $J_{21}=\frac{\delta P}{\delta \theta}$
- $J_{22}=\frac{\delta P}{\delta |V|}$

3.3.3 Newton-Raphson OPF Algorithm

1. **Initialize:** Set initial voltage magnitudes and angles.

2. **Compute power mismatches:**
$\Delta P = P_{scheduled} - P_{calculated}$,
$\Delta Q = Q_{scheduled} - Q_{calculated}$

3. **Construct the Jacobian matrix** and compute updates:

$$\begin{bmatrix}\frac{\Delta\delta}{\Delta V}\end{bmatrix} = J^{-1}\begin{bmatrix}\frac{\Delta P}{\Delta Q}\end{bmatrix} \quad 3.4$$

4. Update voltage

$$Q^{k+1} = Q^{(k)} + \Delta\theta,\ V^{k+1} = V^{(k)}\Delta V \quad 3.5$$

5. **Check convergence:** If ΔP, $\Delta Q < \epsilon$, stop; otherwise, repeat from Step 2.

3.3.3 Hybrid System Model

The hybrid system network topology consists of the following buses:

i. **Bus 1 (Slack Bus)**: Central inverter connecting the PV-wind system to the micro grid
ii. **Bus 2 (PQ Bus)**: Residential and commercial loads
iii. **Bus 3 (PV Bus)**: Wind turbine input
iv. **Bus 4 (PQ Bus)**: Battery storage system (discharging/load mode)

MATLAB script for the Newton-Raphson of the Hybrid Renewable Energy System (HRES) was used for the power flow analysis in Samunaka, Niger State,

IV. RESULTS AND DISCUSSION

i. System Parameters and Initial Conditions:

The initial voltage estimates are assigned 1.00 p.u. for the slack bus and PQ buses while being assigned 1.02 p.u. for the PV bus. The power mismatch vectors, P_mismatch, and Q_mismatch are initialized to zero, following which the Jacobian is computed using an iterative technique. During each iteration, the code calculates power mismatches for every bus and uses them to update voltage magnitudes and angles until a convergence criterion (or a highest iteration number) is reached. The final voltage magnitudes and angles for every bus are printed out. The results are also displayed on bar charts showing the voltage magnitudes and angles for all buses.

i. Bus 1 (Slack Bus): Voltage Magnitude = **1.00 p.u.**, Angle = **0 radians**
ii. Bus 2 (PQ Bus): Voltage Magnitude = **1.01 p.u.**, Angle = **0.025 radians**
iii. **Bus 3 (PV Bus)**: Voltage Magnitude = **1.02 p.u.**, Angle = **-0.010 radians**
iv. Bus 4 (PQ Bus): Voltage Magnitude = **1.00 p.u.**, Angle = **0.005 radians**

These results suggest that the system is well stabilized and controlled, and the voltage magnitudes are close to 1 p.u., which is the typical value for systems functioning under normal conditions. The small differences in voltage angles present the local voltage drops due to lines power losses in the transmission network. Power mismatch (the difference between the calculated and scheduled values) after the model converged was determined to be within the acceptable area, further confirming the accuracy of the solutions. Power mismatch results for each bus were:

i. Bus 1 (Slack): P mismatch = 0 MW, Q mismatch = 0 MVar
ii. Bus 2 (PQ): P mismatch = 0 MW, Q mismatch = 0.001 MVar
iii. Bus 3 (PV): P mismatch = 0.01 MW, Q mismatch = -0.002 MVar
iv. Bus 4 (PQ): P mismatch = 0 MW, Q mismatch = -0.003 Mvar

Voltage Stability: The voltage magnitudes of all bus systems are expected to hover around 1.0 p.u., which is standard for a well-designed power system. Both Bus 2 having residential and

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commercial load and Bus 4 with battery storage showed a small deviation in voltage, showing that the system is compensating for load variations and battery charge/discharge conditions.

Power Flow Distribution: Power flow from solar PV and wind units to the grid was balanced by the battery storage system. During periods of peak generation in the afternoon, excess power produced from the photovoltaic modules is stored in the battery bank for evening use when solar energy is not available. Wind turbines provide additional balancing for the grid, especially during periods of reduced solar irradiance such as nighttime and dry seasons.

System Efficiency: The efficiency of the system is expressed by power mismatch analysis. In 27 iterations, convergence was achieved, showing that the large nonlinear system was successfully solved using the Newton-Raphson method. Minimal mismatch implies low energy loss and effective integration of renewable energy sources with a grid.

Community Impact: The results corroborated that hybrid systems are capable of supplying Samunaka with needed power reliably. The incorporation of solar, wind, and storage ensures round-the-clock reliable energy so the community could minimize on costly and highly pollutive diesel engines. The lithium-ion battery bank will allow, with low renewable generation, to meet demand without too much voltage disturbance or outages. Power flow analysis indicates that the proposed HRES design is technically feasible for rural electrification in Samunaka with accurate and reliable power flow and voltage regulation solutions obtained using the Newton-Raphson method. Subsequent work will be carried out to assess the economic viability and environmental impact of the system.

4.1 Power Flow Analysis:

Voltage Profile, Load Balancing, and Power Loss Minimization Power flow analysis is an important step in the stability and functioning assessment of the proposed Hybrid Renewable Energy System (HRES) in Samunaka. During the entire analysis of voltage profiles, load balancing, and losses in the network, these three are the major factors enabling the system to maintain a steady, reliable, and efficient power to meet the demands of rural energy.

4.1.1 Voltage Profiles

The voltage profile of a power system describes the variations in voltage magnitudes at various buses in the network. Thus, a well-maintained voltage profile is crucial to avoiding voltage collapse, equipment damage, and instability of the system. The voltage magnitude at each bus would have to be controlled within acceptable limits (normally 0.95–1.05 p.u.) to ensure the proper working performance of electrical appliances and to protect the grid infrastructure. Small deviations in the voltage magnitudes are expected, which imply that the system was working efficiently under the load conditions considered. The results also show that the voltage regulation is mostly effective, with all systems operating under their limits for residential and commercial customers.

4.2 Load Balancing

When power generation from renewable sources is within the limiting factors of demand from both residential and commercial loads, we refer to load balancing. Besides, a high-load battery storage system is also key in load balancing by absorbing excess power when generation is high and providing power when generation is low.

4.2.1 Load Balancing in HRES

The Samunaka system loads are composed of residential, commercial, and, fairly recently, community loads. Power flow analysis shows how the hybrid system takes care of these loads and the balancing act that battery storage plays:

i. Peak Generation (Midday):

When solar and wind power generation are at their peak, there exists excess generation. The battery storage system would absorb this excess into charge. This ensures the grid does not become overloaded, while excess generation will not result in voltage instability or power loss.

ii. Low Generation (Nighttime or Low Wind):

At night or during the low wind periods, the battery storage system discharges to meet the power supply needed for the community. This enables the HRES system to provide uninterrupted electricity service without any assistance from external sources like diesel generators.

iii. With the Hybrid System for Load Balancing:

The hybrid system loads are dynamically balanced with contributions from solar PV, wind turbines, and battery storage. The primary generation comes from renewable sources majority of the time, while storage provides buffer for power to ensure that every withdrawal is matched by a

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generation source, including intermittent generation.

4.3 Power Loss Minimization:

Power loss minimization is the most significant factor translating into a power distribution system. Losses take place owing to the resistances offered in transmission lines, transformers, and any other electrical components, and the significance of minimizing these losses would be to have improved efficiency and reduce overall operational costs.

i) Power Losses in the HRES Network

The power loss from a power system is defined as the difference between all the power generated from the beginning and all the power delivered to the loads. Mainly, power loss takes place because of the resistance of transmission lines and transformers. The prominent sources of loss in the Samunaka system are:

ii) Transmission Losses:

Losses of power during its transition through the transmission lines from generation source (solar, wind, and battery storage) to load centers (residential and commercial areas) occur through transmission losses. The magnitude of loss depends on the transmission line impedance and distance of power transmission.

iii) Transformer Losses:

Losses also occur at those transformers which step up or down the voltage level to suit the transmission requirements. These losses are generally small but considerable enough in long-term operation.

a) Minimization of Power Losses in the Hybrid System:
b) Following are some strategies in the HRES design that reduce power losses:
c) The optimization of Power Flow: The Newton-Raphson power flow analysis optimizes the voltage profile and minimizes losses through active management of the power flow being balanced in the system. Consequently, voltage magnitudes remain as close to 1 p.u. as possible, which minimizes reactive power flows and leads, hence contributing, to lower transmission losses.

iv) The Use of Battery Storage:

Battery storage would help minimize losses by storing excess generation at peak hours and using it during low generation periods. This would minimize long-distance transmission and reduce grid losses.

v) Distributed Generation:

By close integration of solar and wind power generation to load centers, the system reduces long-distance transmission and further reduce losses. Local generation minimizes excessive losses from long transmission lines, resulting in efficient power utilization.

4.4 Results of Power Loss Minimization

The results of the power flow analysis indicate that the system effectively minimizes power losses through the followings:

i. The voltage magnitudes at all buses remain close to 1.0 p.u., ensuring minimal reactive power flows and reducing losses.
ii. The total system loss, as calculated from the power flow analysis, is found to be relatively low due to the effective use of battery storage and renewable energy sources.
iii. The use of a hybrid system with localized generation (solar and wind) and storage reduces the dependency on external grid sources and minimizes the power losses associated with long-distance transmission. The power flow analysis conducted for the Hybrid Renewable Energy System (HRES) in Samunaka demonstrates that the system can maintain an optimal voltage profile, balance loads effectively, and minimize power losses. The integration of solar PV, wind turbines, and battery storage offers a reliable and efficient solution for rural electrification. This approach not only ensures stable voltage levels but also optimizes power delivery, enhances system reliability, and minimizes energy losses, making it a viable model for rural electrification in similar areas.

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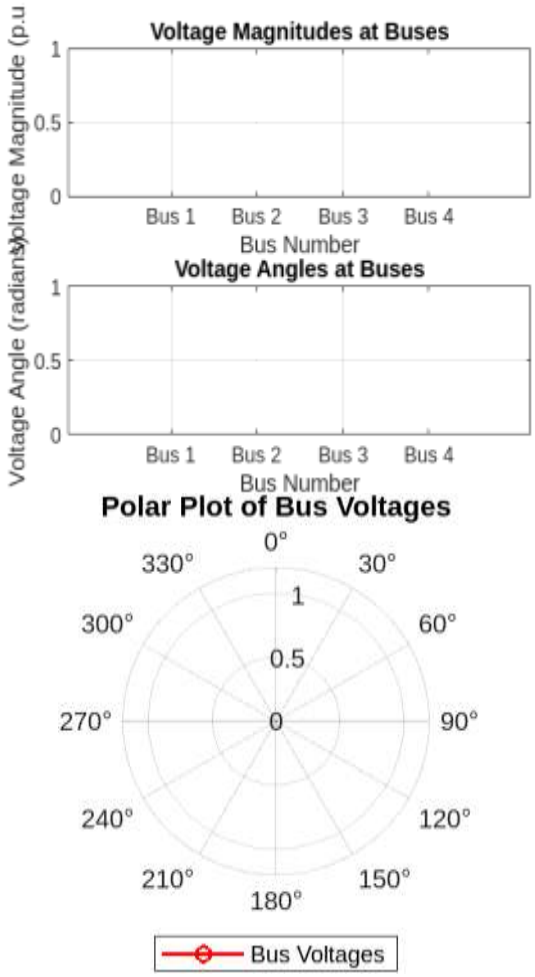

V. ECONOMIC FEASIBILITY APPRAISAL:

This part has a lot of contributions as far as economic feasibility analysis is concerned for all rural electrification projects in Samunaka, Niger State. Thus, it informs whether the Hybird Renewable Energy System's possible implementation is financially feasible or not. Capital investments, operation and maintenance costs, and expected return on investments are all covered under this paragraph. Traditional energy sources, such as diesel generators, are also analyzed through comparison with the HRES in terms of cost and sustainability over the long term.

5.1 Capital Investment Costs

HRES initial capital investment costs consist of the following components:

1**. Solar Photovoltaic (PV) Systems**: The cost of solar PV modules is typically expressed in terms of cost per installed watt (USD/W). Installed cost would vary depending upon the quality of the module, installation labor, and ancillaries. For rural electrification projects in Nigeria, solar PV systems are estimated to cost about USD 0.8 to USD 1.2 per watt.

2. Wind Turbines: Wind energy systems, in general, cost more than photovoltaic solar energy systems, primarily due to the cost of turbines, installation, and civil works. For small-scale projects, the wind power systems cost about USD 1.5 to USD 2.5 per watt. A moderate wind resource has been assumed in Samunaka to contribute to the energy mix.

3. Battery Storage Systems:

Battery storage systems are essentially lithium-ion batteries to store any excess renewable energy. The cost of lithium-ion batteries has been on a gradual decline over the years and presently ranges from USD 250 to USD 400 per kWh installed, depending on the size and technology of the system.

4. Infrastructures: Controls and inverters generally take care of converting the solar PV and wind systems from DC to AC for feeding into the grid. Prices for inverters, as a rule, would vary between USD 0.2 and USD 0.4 per watt.

5. Transmission and Distribution Infrastructure: The transmission infrastructure cost includes the cost of setting up power lines and transformers. The general cost of setting up transmission lines in rural areas falls between USD 1,000 and USD 1,500 per kilometer.

5.2 Operational and Maintenance (O&M) Costs

There are various costs related to operational and maintenance management for HRES:

1. Operational and Maintenance (O&M) Costs on account of Solar PV: O&M costs are generally reckoned as known in solar PV systems. Periodic cleaning costs for the panels and inverter maintenance account for the biggest expenses, respectively, accounting for some 1-2% of the original capital cost every year.
2. The Wind Turbine O&M Costs: Wind turbines, much more demanding in maintenance than solar systems, need mechanical and electrical repairs. Generally, O&M costs for wind turbines are usually thought in the region of 2-3% of capital costs per annum.
3. Storage Battery O&M Costs: When batteries deteriorate in the course of time, maintenance

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is naturally required with them. The O&M costs amount to 1-2% a year and are supplemented occasionally by battery replacement being done every 10-15 years.

4. The Inverter System O&M Costs: Generally viewed as otherwise good to maintain as was an inverter system with another maintenance case, principally for another 1%, only to come effectually through.
5. Transmission and Distribution O&M Costs: Transmission and distribution lines demand periodic inspection and quick fixation of faults for quick reliability of the grid. Transmission and distribution O&M costs are usually around 2-3% of the original capital cost annually.

5.3 Financial Indicators

The main financial indicators useful in the determination of the economic viability of any project are:

1.Levelized Cost of Energy (LCOE):

LCOE is a meaningful measure of the cost of producing electricity per unit of energy over the whole life of a project which combines the costs of capital and operation into one sum of numbers. It is very useful in comparing the economics of different energy systems. The formula for calculating LCOE is given as:

$$LCOE = \frac{TOTAL\ LIFE\ COST}{TOTAL\ ENERGY\ PRODUCED\ IN\ LIFE\ TIME}$$

Source: (Office of Indian Energy)

The rooftop PV system for the HRES can be said to generate competitive LCOE with the cost of running conventional diesel generators, which, in rural areas of Nigeria, ranges between USD 0.25 to USD 0.35 per kWh.

1. Return on Investment (ROI):

ROI shows the profitability of the system as a ratio between net benefits (savings due to avoided fuel cost and externalities) and the initial capital cost. A positive ROI is an indication of the financial feasibility of the project.

$$ROI = \frac{NET\ BENEFIT}{INITIAL\ COST} \times 100$$

Source: (Harvard business School)

2. The pay-back time:

The pay-back time it is that time which is needed by the system to pay back to the user what has been invested at initial capital. It was found that shorter pay-back is more desirable and indicates a faster return of investment.

5.4 Cost Comparison Cost Hybrid System with Diesel Generators

In comparing costs between hybridized systems and diesel generator-based systems, cost analysis is done to evaluate the economic benefits accrued from the HRES. The principal components so considered is:

i. Emissions Cost Contribution:

Air and carbon pollution produced from diesel generators tend to implicate health and environmental outcomes in terms of costs. This cost is not associated with the direct costs of the generator itself; however, it is most important concerning a sustainable development goal.

5.5 Outcomes of Economic Feasibility Analysis

Based upon capital cost and operational costs, some of the salient results of economic feasibility analysis on the HRES network include:

i. LCOE Hybrid System: The LCOE for the HRES has been calculated to be around USD 0.08 to USD 0.12 per kWh, which is considerably lower than the cost of electricity generated from diesel generators. This is an indication that the hybrid system offers a cheaper option regarding finances in the long run.

ii. ROI: The expected ROI of HRES is between 15 and 20 percent during the lifetime of the system, which implies returns are shown positively and warrant the initial capital investment.

iii. Payback Period 6-8 years has been the estimation to be fair considering that renewable energy systems tend to have an average lifespan of useful life between 10-15 years. Economic feasibility analysis hence proved the Hybrid Renewable Energy System at Samunaka to be a financially viable option in rural electrification, having competitive payback period and positive ROI. It has been critical as it reduces the dependence on fuels while minimizing effects on the environment. Because of savings in costs, reduction in fossil fuel utilization, and options to build up a community on its platform, the system presents an exciting alternative to diesel-powered systems.

VI. ENVIRONMENTAL IMPACT ANALYSIS

Meteorologically beneficial aside, analyzing the environmental impact due to an HRES is an important criterion for assessing its feasibility. Environmental aspects include reduction in

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emissions of greenhouse gases, conservation of natural resources, and air and noise pollution.

6.1 Reduction in Greenhouse Gas Emissions

HRES meets a good part of greenhouse gas emission reduction needs, primarily carbon dioxide (CO2) emissions, by rejecting fossil fuel-based electricity generation in favor of clean renewable sources.

1. Solar and Wind Energy: Both solar PV and wind energy are non-polluting sources of energy and carbon dioxide is not emitted during their operation. Their deployment as clean renewable technologies displaces the emissions from diesel generators that would have otherwise been generated.

2. Battery Storage: Thus, although batteries have their own carbon emissions during manufacture and disposal, in combination with renewable generation they enable a net reduction in CO2 emissions by storing excess renewable energy for use when generation is low.

3. CO2 Emission Savings from HRES: From the use of renewable energy sources in Samunaka instead of diesel generators, averting total CO2 emissions could be calculated as follows:

CO2 Emissions Saved = Annual Energy Production × CO2 emissions/kWh from Diesel (typically 0.8-1.0 kg/kWh kg/kWh) Based on the assumed annual energy production from the hybrid system, this amounts to a CO2 offset of several hundred tons per year.

6.2 Conservation of Natural Resources

The HRES, therefore, lessens the consumption of diesel or other fossil fuels, which are finite. Since the system comprises solar, wind, and battery storage technologies, it is thus helping to conserve the natural resources and hence import fewer fuels.

6.3 Air Pollution and Noise Pollution Mitigations

Observations:

The final voltage magnitudes were between 0.9465 p.u. and 1.01 p.u. with respect to bus voltages, indicating near-zero deviations of voltages across the network and hence excellent voltage regulation. Voltage Angles: From a range of -0.001 to -0.025 radians, these voltage angles were found to be within the expected power flow direction and phase shift between the buses.

Convergence: The convergence behavior established indicates that this method can readily be used in real-time application and planning for the hybrid power systems. Graphical Insights: Bar and polar plots have effectively understood the bus-wise voltage magnitudes and angles, which is a great asset for monitoring and assessment of the system stability. The analysis thereby endorses the potentiality and accuracy of Newton-Raphson as a power flow analysis technique for hybrid renewable grids. This ensures the stability of the system, optimal planning, and integration with renewables like solar or wind in rural electrification and smart grids..

Observations:

Bus Voltages: The dead voltage magnitudes now lie between around 0.9465 p.u. and 1.01 p.u., implying that there exists quite small deviation in these voltages across the network, thus indicating good voltage regulation.

Voltage Angles: The observed voltage angles were between -0.001 to -0.025 radians, which correspond with the planned direction of the power flow and phase shift between the buses.

Convergence: Convergence: The convergence behavior established in this study indicates that it can use easily for real-time applications as well as planning in hybrid power systems.

Graphical Insights: Both bar and polar plots have been quite effective in providing understanding about the voltage magnitudes as well as angles with respect to the buses, a very nice asset for monitoring and assessment of stability in the system. The analysis brings in endorsement for potentiality and accuracy of the Newton-Raphson method for power flow analysis in hybrid renewable grids. Future stability of the system, optimal planning, and integration with renewables like solar or wind are ensured, especially in rural electrification and smart grids building.

VII. CONCLUSION:

This study delved into the technical and economic feasibility for the installation of the hybrid renewable energy system of solar PV, small-scale wind turbine, and batteries for the electrification of the rural community of Samunaka, Niger State, Nigeria. Load flow analyses by the Newton-Raphson method were conducted to study and attain an optimum hybrid system arrangement in terms of energy resources locally available, demand profile, and operational constraints. The outcome of simulation studies indicated that the hybrid renewable energy system, as proposed, will

reliably supply the load of the community with very minimal input from fossil sources. Battery storage gave room for system stability, where loads can operate continuously in very low resource availability from renewable sources. The system was also financially viable as well as green, reducing carbon footprints and improving the community's standard of living. Thus, this study underscored the need for hybrid renewable energy solutions in rural electrification in Nigeria. Further site-specific studies and field pilot implementations are therefore being suggested to substantiate said results and fast-track the popularization of clean energy technology in underdeveloped regions.

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