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Hybrid Renewable Energy Systems for Rural Electrification in Nigeria: A Critical Review of Renewable Energy Resources and Challenges

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Abstract- Nigeria continues to face inadequate and unreliable electricity supply, particularly in rural communities where grid extension is often technically and economically challenging. Although the country has substantial solar, hydropower, biomass, and wind resources, their spatial and seasonal variability limits the suitability of uniform renewable-energy solutions. This review critically synthesizes evidence on renewable-resource characteristics, HRES suitability, and deployment challenges for rural electrification in Nigeria using a structured literature-review approach. The analysis indicates that resource abundance alone is insufficient for HRES selection; system suitability depends on local resource quality, temporal complementarity, electricity demand, storage requirements, technology costs, infrastructure, and socioeconomic conditions. Solar PV offers the broadest geographical applicability, while hydropower and biomass can provide more controllable generation where suitable water resources and sustainable feedstock are available. Wind energy is more location-dependent and should be incorporated only where adequate wind regimes are demonstrated. The review further shows that adding technologies does not necessarily improve system performance because increased component numbers and storage capacity can raise capital, maintenance, and replacement costs. Major deployment barriers include financing constraints, battery degradation, biomass supply-chain limitations, inadequate infrastructure, limited technical capacity, operation and maintenance challenges, policy constraints, and insufficient field validation. The review identifies methodological inconsistencies in resource datasets, load profiles, economic assumptions, and performance indicators that limit cross-study comparison and generalization. Future research should therefore prioritize standardized, site-specific and time-resolved datasets, lifecycle and degradation modelling, integrated technical-economic-environmental and socioeconomic assessment, and long-term field validation. Overall, reliable and affordable rural HRES deployment in Nigeria requires location-specific configuration based on resource complementarity and local demand rather than resource potential alone.

Index Terms: Hybrid renewable energy systems; rural electrification; Nigeria; solar energy; hydropower; biomass; wind energy; renewable energy resources; rural communities.

I. INTRODUCTION

Reliable electricity supply is fundamental to economic development, healthcare, education, productive activities, and improved living standards. However, Nigeria continues to face significant electricity supply challenges, with electricity demand exceeding available supply and electricity access and reliability remaining inadequate, particularly in rural and underserved communities (Sambo, 2008; Olufemi, 2023). These challenges have increased the need for decentralized electricity solutions that can provide reliable power to communities where conventional grid extension is technically or economically difficult. Although fossil fuels have historically played an important role in Nigeria's electricity generation, their continued use is associated with fuel-price volatility, greenhouse-gas emissions, and environmental degradation. Consequently, increasing attention has been directed towards renewable energy resources, particularly solar, hydropower, biomass, and wind, as potential resources for expanding sustainable electricity supply in rural areas (Ibrahim et al., 2021; Cheng et al., 2010; Haiges et al., 2019). Nigeria possesses considerable renewable energy resources with potential for rural electrification. Solar energy is widely available across the country, while hydropower resources are particularly important in areas with suitable rivers and water resources. Biomass resources are available from agricultural residues, animal waste, and municipal solid waste, whereas wind resources are more geographically concentrated. Despite this resource diversity, their availability varies considerably with location, season, and weather conditions. Solar generation, for example, is influenced by solar radiation and cloud cover, hydropower depends on water availability and seasonal hydrological conditions, biomass depends on the availability and accessibility of feedstock, and wind generation varies with local wind characteristics. These spatial and temporal variations can constrain the reliability of electricity generation when individual renewable resources are used independently. HRES therefore provide an important approach for combining complementary renewable resources, with battery storage and/or dispatchable backup generation where necessary, to improve the reliability and continuity of rural electricity supply (Dutta et al., 2018; Dawoud et al., 2018; Oliveros-Cano et al., 2020). The potential benefits of HRES for rural electrification are closely related to the characteristics and complementarity of the renewable resources available at a particular location. Combining resources with different temporal availability can reduce dependence on a single energy source and improve renewable-energy utilization. However, the effectiveness and sustainability of HRES can be affected by resource variability, geographical conditions, electricity demand, technology availability, storage requirements, and the availability of conventional backup resources. In particular, battery degradation and replacement can increase lifecycle costs, while biomass-based systems may face challenges associated with feedstock availability, transportation, storage, and seasonal supply. The suitability of an HRES for a rural community therefore depends on the characteristics of the local renewable resources and the ability of the selected resources to complement one another (Lian et al., 2019). Although considerable research has examined renewable energy resources and HRES applications in Nigeria, important gaps remain in understanding their suitability for rural electrification across different geographical and resource conditions. Existing studies are frequently location-specific and employ different resource datasets, making it difficult to establish how the characteristics of solar, hydropower, biomass, and wind resources influence HRES suitability across Nigerian regions. Furthermore, differences in resource availability, seasonal variability, local energy demand, technology costs, and operating conditions can result in substantially different system outcomes. Consequently, findings from one location cannot necessarily be generalized to other rural communities without considering their specific resource and socioeconomic conditions. Several challenges also constrain the wider deployment of HRES in rural Nigeria. These include high initial investment requirements, limited access to affordable financing, battery degradation and replacement costs, inadequate infrastructure, unreliable supply chains, biomass-feedstock collection and transportation difficulties, operation and maintenance constraints, shortages of local technical expertise, and limited long-term field validation of proposed systems. Rural-community affordability and participation are also important because technically feasible systems may not be sustainable where electricity tariffs, maintenance costs, or ownership arrangements are inconsistent with local economic conditions. Addressing these challenges requires greater integration of resource assessment with technical, economic, environmental, and socioeconomic considerations in HRES planning. Against this background, this review critically examines the renewable energy resources and challenges associated with hybrid renewable energy systems for rural electrification in Nigeria. The review evaluates the availability and characteristics of major renewable resources, including solar, hydropower, biomass, and wind, and considers their spatial and temporal variability and potential complementarity in HRES applications. It further examines the major technical, economic, environmental, infrastructural, operational, policy, and socioeconomic challenges affecting HRES deployment in rural communities. By synthesizing existing evidence across different Nigerian locations and resource conditions, the review identifies key limitations in current research and highlights priorities for the development and sustainable deployment of HRES for rural electrification in Nigeria.

II. REVIEW METHODOLOGY

A structured literature review methodology was adopted to identify, evaluate, and synthesize published research on hybrid renewable energy systems (HRES) for rural electrification in Nigeria. The review primarily focused on renewable energy resources, their availability and characteristics, HRES applications, and the technical, economic, environmental, infrastructural, operational, policy, and socioeconomic challenges affecting their deployment in rural communities. The review process comprised four main stages: identification of relevant literature from selected academic databases, development and application of a structured search strategy, application of predefined inclusion and exclusion criteria, and screening and selection of eligible studies. The overall approach was guided by the principles of transparency and reproducibility recommended by the PRISMA 2020 framework (Page et al., 2021). Previous reviews of HRES have similarly employed structured approaches to classify renewable resources, system applications, configurations, and associated deployment considerations (Sawle et al., 2018).

2.1 Literature Databases

The literature search was conducted using major academic databases covering renewable energy, electrical engineering, energy systems, rural electrification, and related areas. The principal databases were Scopus, Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar. Scopus and Web of Science were used primarily to identify peer-reviewed and indexed scientific publications, while ScienceDirect and IEEE Explore provided access to research on renewable energy systems, power engineering, energy storage, and hybrid-system applications. Google Scholar was additionally used to broaden the literature search and identify relevant publications that may not have been retrieved from the other databases, as well as to trace citations from key studies. The search primarily targeted peer-reviewed journal articles and relevant conference proceedings. Authoritative reports from recognized energy institutions were also considered where they provided relevant information on Nigeria's renewable energy resources, electricity access, energy policies, or rural electrification. The use of multiple information sources supports broader identification of relevant evidence and is consistent with the reporting principles of PRISMA 2020, which require reviews to clearly identify the information sources used in the search process (Page et al., 2021). Previous HRES reviews have similarly considered a broad range of literature in examining renewable resources, system configurations, and associated methodological approaches (Sawle et al., 2018).

2.2 Search Strategy

A structured keyword-based search strategy was developed to identify studies relevant to renewable energy resources and HRES applications for rural electrification in Nigeria. The search terms were organized around four principal concepts: hybrid renewable energy systems, renewable energy resources, rural electrification, and Nigeria. Boolean operators AND and OR were used to combine related terms and refine the search. The principal search expressions included combinations such as “hybrid renewable energy system” AND Nigeria, “hybrid energy system” AND “rural electrification” AND Nigeria, “renewable energy” AND “rural electrification” AND Nigeria, “solar PV” AND battery AND Nigeria, “PV” AND biomass AND Nigeria, “PV” AND hydro AND Nigeria, “PV” AND wind AND battery AND Nigeria, and “hybrid renewable energy” AND Nigeria. Additional searches incorporated terms associated with renewable-resource assessment, energy storage, mini-grids, reliability, techno-economic assessment, emissions, and deployment challenges. The search strategy was designed to identify both studies directly undertaken in Nigeria and methodological studies providing relevant evidence for understanding HRES applications and rural renewable-energy deployment. The reference lists of key publications were also examined to identify additional relevant studies through backward citation searching. This approach helped broaden the evidence base beyond the results obtained through database keyword searches. In accordance with PRISMA 2020 principles, the

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information sources, search strategy, and eligibility criteria were defined as part of the study-selection process (Page et al., 2021).

2.3 Inclusion and Exclusion Criteria

Predefined inclusion and exclusion criteria were applied to ensure that the selected literature was relevant to the objectives of the review. Studies were included when they examined renewable energy resources relevant to Nigeria; HRES applications; rural, off-grid, isolated, or mini-grid electricity supply; or the technical, economic, environmental, reliability, and operational aspects of renewable and hybrid electricity systems. Studies addressing solar PV, hydropower, biomass, wind energy, battery storage, and conventional backup generation were considered where they contributed to understanding HRES applications or rural electrification. Peer-reviewed journal articles and relevant conference proceedings were given priority. Authoritative institutional reports were also considered where they provided reliable information on national renewable energy resources, electricity access, energy policies, or rural electrification. Studies were excluded when they were unrelated to renewable or hybrid electricity generation, did not provide information relevant to rural or decentralized electricity supply, duplicated another publication, or lacked sufficient methodological or technical information for meaningful synthesis. Studies focusing entirely on applications outside Nigeria were excluded from the Nigeria-specific synthesis unless they provided methodological evidence directly relevant to understanding HRES applications, resource complementarity, or rural renewable-energy deployment. General websites, commercial webpages, news articles, and other non-scholarly materials were excluded as primary scientific evidence. These criteria were applied to maintain consistency in the selection process and ensure that the final evidence base addressed the scope of the review. The explicit definition of eligibility criteria also supports transparency and reproducibility in accordance with PRISMA 2020 recommendations (Page et al., 2021).

2.4 Study Screening and Selection

The study-selection process comprised identification, removal of duplicate records, title and abstract screening, full-text assessment, and final inclusion of eligible studies. Records retrieved from the selected databases using the defined search terms were first compiled, after which duplicate records were removed. The titles and abstracts of the remaining records were screened to assess their relevance to renewable energy resources, HRES, rural electrification, and associated deployment issues. Studies considered potentially relevant during the initial screening were subsequently subjected to full-text assessment against the predefined inclusion and exclusion criteria. Particular attention was given to the geographical context of the study, renewable resources considered, HRES application, rural electrification relevance, methodological approach, and reported technical, economic, environmental, reliability, infrastructural, operational, policy, or socioeconomic findings. Studies that did not satisfy the eligibility criteria were excluded, with the principal reason for exclusion recorded to improve transparency. The final body of literature was organized according to the major themes of the review: renewable energy resources in Nigeria, HRES applications and configurations, resource complementarity, and challenges affecting rural deployment. The selected studies were then critically synthesized by comparing their geographical context, renewable resources considered, methodological approaches, major findings, limitations, and implications for rural electrification in Nigeria. Where quantitative performance information was reported, indicators such as levelized cost of energy (LCOE), net present cost (NPC), loss of power supply probability (LPSP), renewable fraction, energy production, emissions, and reliability were considered. These indicators provide useful measures of the technical, economic, environmental, and reliability implications of HRES deployment.

III. RENEWABLE ENERGY RESOURCES FOR RURAL ELECTRIFICATION IN NIGERIA

Nigeria's rural electricity challenge is closely associated with the geographical distribution of settlements, the cost of extending centralized

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electricity infrastructure, and the availability of locally exploitable energy resources. Geospatial electrification studies indicate that population density, proximity to existing transmission infrastructure, technology costs, and local resource availability significantly influence the least-cost choice among grid extension, mini-grid, and standalone electricity systems (Mentis et al., 2015). Similarly, Oparaku (2003) demonstrated that grid-extension distance is an important determinant of rural electricity-supply costs, while Ohiare (2015) highlighted the substantial investment requirements associated with extending electricity access across Nigeria's geographically dispersed communities. More recent studies have shown that solar, wind, hydropower, and other decentralized renewable-energy options can become economically attractive in remote and low-density settlements where conventional grid extension is technically or economically unsuitable (Olatomiwa et al., 2016; Rahman et al., 2020). Consequently, decentralized renewable-energy systems, particularly mini-grids and standalone systems, have become important options for improving electricity access in underserved and remote communities. The International Renewable Energy Agency (IRENA, 2023) identifies renewable mini-grids and standalone systems as important approaches for extending electricity services to remote and last-mile communities. This potential is also demonstrated by Nigerian studies reporting the technical and economic feasibility of decentralized hybrid configurations, including PV–diesel–battery and other renewable-based systems for rural applications (Adefarati et al., 2024; Seidu et al., 2026). Nigeria possesses substantial renewable-energy resources, but their magnitude, geographical distribution, and temporal characteristics vary considerably among locations. Kenneth et al. (2024), using a GIS-based approach, demonstrated significant geographical variations in solar, wind, biomass, and small-hydropower resources across Nigeria. Solar energy is broadly available, hydropower is concentrated in areas with suitable water resources and hydraulic conditions, biomass potential is associated with agricultural and organic waste streams, and wind resources exhibit considerable spatial variation. Therefore, national-level resource abundance should not be interpreted as evidence of uniform technical or economic suitability at individual rural sites. The suitability of a renewable resource for rural electrification depends on resource quality, seasonal and temporal variability, local electricity demand, geographical conditions, infrastructure availability, technology costs, and operating requirements. These factors are particularly important for HRES because combining resources does not automatically result in better system performance. The benefits of hybridization depend on whether the selected resources exhibit useful temporal and seasonal complementarity relative to the electricity-demand profile. Olatomiwa et al. (2015) demonstrated this location dependence by evaluating hybrid energy systems across Nigeria's six geopolitical zones and showing that the economically preferred configuration varied according to geographical location and associated techno-economic conditions. The Nigerian evidence therefore indicates that the challenge is not simply to identify areas with renewable-energy potential but to determine which resources and combinations are technically suitable, economically viable, and sustainable for particular rural communities. Resource assessment should consequently be undertaken at an appropriate spatial and temporal resolution and should consider both resource availability and electricity-demand characteristics. This provides the basis for examining the major renewable-energy resources that can contribute to rural HRES development in Nigeria.

3.1 Solar Photovoltaic Energy

Nigeria has substantial potential for decentralized solar electricity because solar resources are available across the country and many rural communities remain underserved by conventional electricity infrastructure. However, the relevance of solar energy to rural electrification depends not only on national solar-resource abundance but also on geographical variation, local electricity demand, infrastructure conditions, and the economics of alternative electricity-supply options. This distinction is important because considerable technical solar potential at the national level does not imply that identical PV systems will be economically optimal across different rural communities. The development of solar-based mini-grids also involves

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socioeconomic considerations. Sesan et al. (2024), using evidence from Nigeria and Kenya, showed that greater inclusiveness in mini-grid deployment can strengthen commercial viability. This highlights the importance of affordability, community participation, and electricity-user characteristics alongside technical resource assessment. Consequently, the sustainability of decentralized solar systems should be evaluated within the technical, economic, and socioeconomic context of the target community. Nigeria's solar resource exhibits a geographical gradient. Bawonda and Adefarati (2023) assessed solar-energy potential in representative locations across the country's six geopolitical zones using analytical and HOMER-based simulation approaches. Their estimated average daily global solar radiation was 5.86 kWh/m²/day in Sokoto, 5.71 kWh/m²/day in Maiduguri, 4.84 kWh/m²/day in Jos, 4.67 kWh/m²/day in Ado-Ekiti, 4.69 kWh/m²/day in Abakaliki, and 4.44 kWh/m²/day in Asaba. These values indicate generally stronger solar conditions in the northern regions than in the selected southern locations, although substantial PV potential exists across all six geopolitical zones. Table 1 summarizes the representative solar-resource estimates.

Table 1: Representative solar-resource potential across Nigeria's six geopolitical zones

	Representative location	Estimated average daily solar radiation (kWh/m²/day)	Relative solar potential
North-West	Sokoto	5.86	Very high
North-East	Maiduguri	5.71	Very high
North-Central	Jos	4.84	High
South-East	Abakaliki	4.69	High
South-West	Ado-Ekiti	4.67	High
South-South	Asaba	4.44	Moderate–high

Source: Adapted from Bawonda and Adefarati (2023).

The representative values show the highest estimated solar radiation in Sokoto (5.86 kWh/m²/day) and Maiduguri (5.71 kWh/m²/day), while the lowest among the selected locations occurs in Asaba (4.44 kWh/m²/day). Jos, Ado-Ekiti, and Abakaliki occupy intermediate positions. These differences have direct implications for PV-based HRES because solar-resource availability influences potential energy yield, PV capacity requirements, storage needs, and overall system economics. Nevertheless, the values should be interpreted as representative-location estimates rather than averages for entire geopolitical zones because considerable intra-regional variation may occur. A higher solar resource does not necessarily guarantee the lowest-cost HRES. Electricity demand, battery requirements, component costs, reliability constraints, and the availability of complementary renewable resources can alter the preferred configuration. Solar-resource assessment should therefore be regarded as an essential input to HRES planning rather than a sufficient basis for technology selection. PV technology is particularly attractive for rural electrification because of its modularity, allowing systems to range from individual standalone installations to community-scale mini-grids. PV systems also have no direct fuel requirement during electricity generation, thereby reducing dependence on diesel supply and exposure to fuel-price fluctuations. However, PV generation is inherently variable because its output depends on solar irradiance, cloud cover, seasonal conditions, and time of day. No electricity is generated by the PV array during nighttime, creating a temporal mismatch between generation and demand. This variability creates a strong rationale for combining PV with battery storage and complementary generation technologies. Emezirinwune et al. (2024) examined the integration of HRES with sustainable agricultural activities and demonstrated their potential to support rural development while addressing local energy requirements. Lewis et al. (2024) assessed hybrid microgrid systems for rural electrification in northeastern Nigeria and demonstrated the importance of combining renewable generation with storage and backup generation to satisfy electricity demand under variable resource conditions. Ukoima et al. (2024) similarly evaluated alternative PV–wind HRES configurations for rural electrification and showed that system performance depended on the selected architecture and local resource conditions. These studies demonstrate that the contribution of PV to rural electrification is determined not merely by solar-resource availability but by how effectively solar generation is integrated with demand, storage, and complementary resources. Resource complementarity, however, should be demonstrated from temporal resource and load data rather than assumed simply because different technologies are combined. PV sizing also illustrates the importance of site-specific system design. Increasing PV capacity can increase renewable-energy utilization and reduce dependence on fuel-based generation, but excessive capacity may increase capital expenditure and generate surplus electricity during periods of low demand. Conversely, insufficient PV capacity can increase reliance on storage or dispatchable generation. Onochojah and Onoriode (2025) demonstrated the importance of appropriate component sizing through their design of a solar–wind–battery system for rural electrification in Awgu, Enugu State. Okelola et al. (2025) similarly investigated a PV–wind–biomass configuration for rural electrification in Kwara State and demonstrated the potential benefits of combining complementary renewable resources. Ozue et al. (2025), in their review of HRES modelling and optimization for rural electrification in Nigeria, further emphasized the importance of appropriate modelling and optimization approaches in identifying technically and economically feasible system configurations. These findings reinforce the need to move beyond general assessments of solar-resource abundance toward integrated assessment of resource characteristics, electricity demand, storage requirements, and complementary generation. Solar energy provides one of the most geographically accessible renewable resources for rural electrification in Nigeria. Nevertheless, the appropriate PV capacity and HRES configuration are location-dependent. A system suitable for Sokoto may not be optimal for Asaba, Ado-Ekiti, or Abakaliki because differences in solar radiation, electricity demand, battery requirements, land availability, infrastructure, and technology costs can substantially influence system design. Consequently, solar-resource assessment should form a foundation for HRES planning, but configuration selection should be based on site-specific resource and demand conditions.

3.2 Hydropower

Hydropower is an important renewable-energy resource for rural electrification in Nigeria because of the country's rivers, streams, and reservoirs. It converts the potential and kinetic energy of water into mechanical energy through turbines and subsequently into electrical energy through generators. For rural electricity supply, its potential advantages include renewable energy availability, relatively low operational emissions, long infrastructure life, and the ability to provide electricity for extended periods where adequate water flow is available. However, substantial national hydropower potential does not necessarily translate into economically exploitable capacity at individual rural sites. Hydropower development requires assessment of local flow characteristics, hydraulic head, seasonal water availability, civil infrastructure, accessibility, and economic feasibility. Consequently, national resource estimates should be distinguished from technically and economically exploitable small- and micro-hydropower potential. Site-specific investigations demonstrate the potential of hydropower for decentralized electricity supply. Otun et al. (2012) assessed the Kangimi Reservoir in Kaduna State and estimated potential generation of approximately 1.109 MW and 0.692 MW under different dam-axis elevations. The estimated hydroelectric potential was sufficient to meet the calculated 872.566 kW energy demand of surrounding communities, demonstrating the potential relevance of small hydropower to rural development. Similarly, Oladeji et al. (2020) investigated River Oshin in Kwara State and identified three off-grid rural communities as potential beneficiaries of small-hydropower development. Their findings demonstrate the importance of proximity between suitable water resources and unserved communities in determining the feasibility of decentralized hydropower. Muteba et al. (2023) assessed a proposed micro-hydropower system for smallholder farmers in Wurno-Gassol, Taraba State. Using hydrological data, hydraulic-loss analysis, and hydropower design tools, the study obtained a maximum discharge of 1.21 m^3/s and a net head of 5.2 m, resulting in a proposed system comprising two Kaplan turbines with a combined peak capacity of 106 kW. The study reported simulated system efficiencies of up to 86.1%, indicating that relatively low-head water resources can support technically feasible micro-hydropower systems when appropriate site conditions and turbine technologies are available. Hydropower development also has an important socioeconomic dimension. Agwu et al. (2023) examined socioeconomic needs and perceptions associated with micro-hydropower development among rural communities in Taraba State. Their findings emphasize the importance of community participation and appropriate management arrangements in determining the sustainability of rural hydropower projects. Thus, the availability of water resources should be considered alongside community needs, institutional capacity, local management arrangements, and socioeconomic conditions. Seasonal hydrological variability represents a major consideration for HRES applications. Hydropower output depends on river discharge and hydraulic head, both of which can change substantially between wet and dry seasons. Representing hydropower as a constant renewable source in HRES models can therefore produce unrealistic estimates of energy availability. Models based only on average annual flow may overestimate generation during dry periods and consequently underestimate storage or backup-generation requirements. Hydropower can nevertheless complement PV generation because the two resources have different generation characteristics. PV is constrained by daylight and solar-weather conditions, whereas hydropower can potentially provide electricity during periods of low solar generation where sufficient water flow exists. This complementarity may reduce dependence on battery storage and conventional backup generation. However, the extent of the benefit depends on the seasonal relationship between solar availability, river discharge, and electricity demand. The geographical distribution of suitable hydropower resources is another important consideration. GIS-based investigations have identified potential small-hydropower sites across different Nigerian states, including Borno, Niger, Edo, Anambra, and Jigawa. However, differences in water bodies, waterlines, inundation areas, and site characteristics mean that hydropower suitability cannot be assumed to be uniform across the country. The distinction between theoretical, technical, and economically exploitable hydropower potential is therefore critical. Reported national estimates may differ because of variations in definitions, datasets, and assessment assumptions. In addition, rural hydropower projects can face high initial costs, difficult terrain, inadequate hydrological data, equipment limitations, maintenance requirements, and financing constraints. A technically suitable site may consequently remain economically unattractive where expected electricity demand is low. Oyinna et al. (2023) provide recent evidence that small-hydropower resources are geographically distributed across all six geopolitical zones of Nigeria. Their assessment used GIS-based indicators, including waterlines, inland waters, inundated areas, and potential site locations, rather than establishing a comparable MW total for every geopolitical zone. The study identified particularly strong prospects in the North-East and North-West and comparatively lower prospects in the southern zones, as shown in Figure 1.

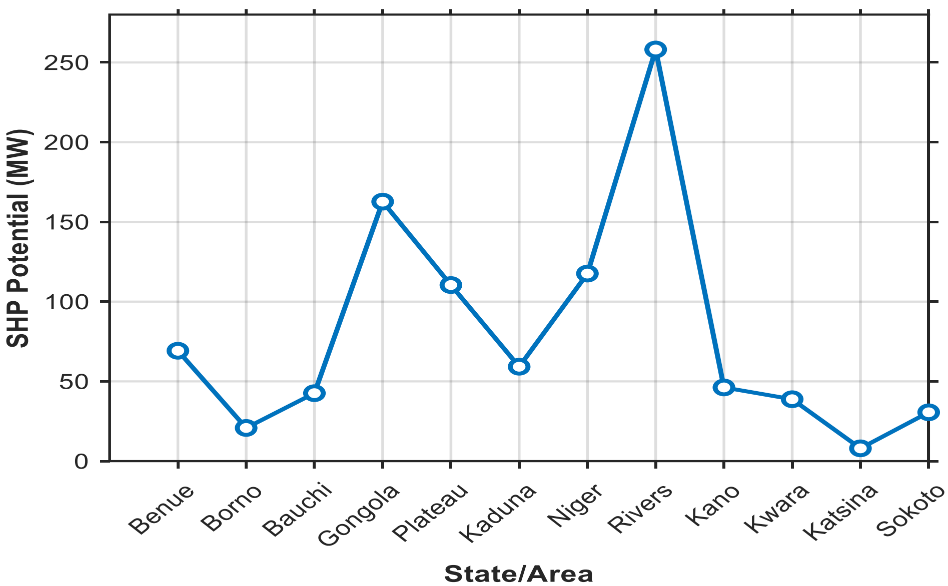

Figure 1: Small Hydropower Potentials in Selected States in Nigeria
Source: Data used are from Oyinna et al. (2023).

Hydropower can make an important contribution to rural HRES where sufficient and economically exploitable water resources are available. Its value is greatest where hydrological conditions provide reliable generation and where its temporal characteristics complement other renewable resources. Conversely, strong seasonal variability or high civil-infrastructure costs may reduce its suitability. Hydropower should therefore be incorporated into rural HRES planning only after site-specific hydraulic, environmental, socioeconomic, and economic assessments.

3.3 Biomass Energy

Biomass is particularly relevant to Nigeria because agricultural, forestry, livestock, and municipal activities generate substantial quantities of organic residues. Important biomass resources include agricultural residues, wood and forestry residues, animal and human wastes, municipal organic wastes, and aquatic biomass. These resources can be converted into useful energy through thermochemical processes such as combustion, gasification, and pyrolysis, or biochemical processes such as anaerobic digestion. The appropriate conversion pathway depends on feedstock characteristics, including moisture content, chemical composition, availability, and quantity. Tursi (2019) emphasized that biomass is a heterogeneous renewable resource whose conversion characteristics and energy performance depend strongly on feedstock properties and the selected conversion technology. The magnitude of Nigeria's agricultural biomass resource is substantial, but the theoretical resource should not be interpreted as fully exploitable energy. Iye and Bilsborrow (2013) estimated 55.9 Tg/year of agricultural residues, corresponding to 657.01 PJ/year of theoretical energy potential. Field residues accounted for 38.4 Tg/year, while processing residues contributed 17.4 Tg/year. Approximately 85% of field-residue availability occurred in the three northern zones. When competing uses were considered, available field residues declined to 21.2 Tg/year, equivalent to 248.78 PJ/year. At a 50% collection-efficiency assumption, the quantity available for medium- to large-scale bioenergy production declined further to 10.6 Tg/year, equivalent to 124.39 PJ/year.

Table 2: Agricultural-residue availability and energy potential in Nigeria

Resource category/scenario	Residue availability (Tg/year)	Energy potential (PJ/year)
Total agricultural residues	55.9	657.01
Field residues	38.4	452.33
Processing residues	17.4	204.68
Field residues after competing uses	21.2	248.78
Field residues at 50% collection efficiency	10.6	124.39

Source: Iye and Bilsborrow (2013).

The substantial difference between theoretical and practically recoverable biomass demonstrates why resource availability should be treated critically in HRES planning. Agricultural residues may have competing uses as domestic fuel, animal feed, soil amendment, or inputs to other productive activities. Collection efficiency, transportation distance, seasonal availability, storage losses, and local markets can further constrain the quantity available for electricity generation. The geographical concentration of agricultural residues has important implications for rural HRES. Biomass systems located close to agricultural production and processing centres may benefit from reduced feedstock transportation and storage requirements. Conversely, systems located far from reliable feedstock sources may face higher operating costs and greater risk of supply interruptions. Biomass availability should therefore be represented as a location-specific constraint rather than as an unlimited fuel resource. Biomass conversion technologies also influence the suitability of biomass-based HRES. Gasification can convert solid biomass into combustible syngas and provide a pathway for electricity generation and other energy applications. Detchusananard et al. (2020) demonstrated the potential of biomass gasification for hydrogen-rich gas production and showed that operating conditions influence energy and exergy performance. These findings emphasize that biomass-resource assessment should be accompanied by assessment of conversion efficiency, technology suitability, feedstock quality, and operating requirements. Municipal organic waste represents another potential biomass pathway. Nigerian municipal solid-waste streams contain combustible organic fractions that may support waste-to-energy applications while contributing to waste-management objectives. However, practical utilization depends on waste collection, segregation, transportation, feedstock consistency, and the availability of suitable conversion technologies. Municipal waste should therefore be treated as a location-dependent supplementary resource rather than as a uniformly available fuel across rural Nigeria. Biomass provides an important opportunity for rural HRES because it can provide relatively controllable renewable generation and utilize locally available agricultural and organic residues. However, its sustainability depends on the quantity of recoverable feedstock, competing uses, collection efficiency, logistics, conversion technology, and local socioeconomic conditions. These factors distinguish biomass from resources such as solar and wind and should be explicitly considered when assessing its suitability for rural electrification.

3.4 Wind Energy

Wind energy can contribute to rural HRES in Nigeria, but its suitability is strongly location-dependent. Okeniyi et al. (2015) assessed wind resources in Katsina, Warri, and Calabar, representing northern, southwestern, and southeastern Nigeria, respectively. Katsina exhibited substantially stronger wind conditions, with observed wind speeds ranging from approximately 6.44 to 10.65 m/s, whereas Warri and Calabar recorded ranges of approximately 3.18–4.54 m/s and 3.97–4.88 m/s, respectively. The results therefore demonstrate considerable geographical differences in wind-resource conditions.

Table 3: Representative wind-resource characteristics in selected Nigerian locations

Region	Location	Wind-speed range (m/s)	General implication
Northern Nigeria	Katsina	6.44–10.65	Favourable wind-resource conditions
South-West	Warri	3.18–4.54	Relatively low wind-resource conditions
South-East	Calabar	3.97–4.88	Relatively low wind-resource conditions

These differences demonstrate that wind turbines should not be incorporated into rural HRES solely because national wind-potential estimates indicate resource availability. Site-specific wind assessment is necessary because turbine output depends strongly on wind speed, hub height, turbine characteristics, and local terrain. In northern communities with favourable wind conditions, wind generation may contribute significantly to renewable electricity supply. In locations with weak wind conditions, however, turbine installation may increase capital expenditure without providing sufficient energy output. The value of wind energy also depends on its temporal relationship with other renewable resources and the electricity-demand profile. Where wind generation occurs during periods of low solar or hydropower availability, it can potentially reduce battery-storage and backup-generation requirements. However, such complementarity must be established from time-resolved resource data rather than inferred from resource availability alone. The geographical distribution of biomass and wind resources further illustrates the need for location-specific HRES planning. Iye and Bilsborrow (2013) reported that approximately 85% of field-residue availability occurred in the three northern zones, while Okeniyi et al. (2015) identified substantially more favourable wind conditions in Katsina than in the selected southern locations. These findings suggest that northern rural communities may have stronger justification for considering biomass–wind combinations where both resources are locally available, whereas communities with weaker wind or biomass resources may require greater reliance on solar, hydropower, storage, or other complementary resources. Thus, wind energy represents a potentially useful component of rural HRES in selected Nigerian locations, but its inclusion should be justified through site-specific assessment of wind characteristics, electricity demand, technology costs, and resource complementarity.

3.5 Renewable Resource Complementarity for HRES

The principal advantage of hybridization is the ability to combine renewable resources with complementary temporal and seasonal characteristics. In Nigeria, solar, hydropower, biomass, and wind vary considerably in their geographical distribution and availability, creating opportunities to improve supply continuity when appropriately combined. Solar and wind are variable, while hydropower and biomass can provide comparatively controllable generation under suitable conditions; battery storage complements these resources by shifting surplus electricity to periods of deficit. However, hybridization does not automatically improve system performance. Additional technologies and larger storage capacities can increase capital, operating, maintenance, and replacement costs. Resource complementarity should therefore be quantitatively assessed using site-specific resource and load profiles rather than assumed from resource abundance alone. CNG may provide useful backup for reliability but is a conventional fuel and should not be classified as renewable. The optimal HRES configuration depends on local resource availability, temporal variability, electricity demand, infrastructure, and socioeconomic conditions. Rural communities with strong solar, hydro, biomass, or wind resources may therefore require different configurations, reinforcing the need for location-specific HRES planning focused on resource complementarity, reliability, and affordability rather than simply maximizing the number of technologies.

IV. CHALLENGES TO HRES DEPLOYMENT IN RURAL NIGERIA

Despite the considerable renewable-energy resources available in Nigeria, several barriers constrain the large-scale deployment and long-term sustainability of HRES in rural communities. These challenges are interconnected and extend beyond the technical design of energy systems.

4.1 Technical and Resource Challenges

Renewable resources vary spatially and temporally across Nigeria. Solar irradiation, wind speed, hydrological conditions, and biomass availability differ among communities and between seasons. Consequently, systems designed using generalized or average resource data may not accurately represent actual operating conditions. The absence of reliable long-term site-specific resource and electricity-demand data can therefore affect system sizing and performance assessment. Storage presents another technical challenge, particularly for PV- and wind-dominated systems. Battery degradation, limited storage capacity, efficiency losses, and replacement requirements can affect long-term system performance. Hydropower systems face seasonal variations in river discharge, while biomass systems depend on the availability, quality, collection, and transportation of feedstock.

4.2 Economic and Financing Challenges

High initial capital costs remain an important barrier to rural HRES deployment. PV modules, batteries, inverters, turbines, biomass-conversion equipment, distribution networks, and civil infrastructure can require substantial upfront investment. Although renewable systems may reduce fuel expenditure over their operating lifetime, rural households and communities may have limited access to affordable financing. The economic feasibility of HRES also depends on assumptions regarding component costs, replacement periods, discount rates, fuel prices, system lifetime, and electricity demand. Differences in these assumptions among studies make direct comparison of reported economic outcomes difficult. Financial models should therefore incorporate realistic local costs and appropriate lifecycle assumptions.

4.3 Biomass-Fuel and Supply-Chain Challenges

Although Nigeria has substantial biomass resources, theoretical resource potential does not represent guaranteed feedstock availability. Competing uses, collection efficiency, transportation, storage, seasonal availability, and changes in agricultural production can affect the reliability of biomass supply. Rural biomass systems may therefore face interruptions or increased operating costs when feedstock cannot be obtained locally at an acceptable cost.

4.4 Infrastructure, Operation and Maintenance Challenges

Many rural communities have limited access to technical infrastructure, spare parts, maintenance services, and trained personnel. This can increase system downtime and reduce the expected lifetime of equipment. HRES projects should therefore consider local operation and maintenance capacity during system planning rather than focusing solely on initial technical feasibility.

4.5 Policy, Institutional and Socioeconomic Challenges

The long-term sustainability of rural HRES is also influenced by policy stability, financing mechanisms, electricity tariffs, regulatory arrangements, ownership structures, and institutional capacity. Community participation is particularly important because local acceptance can influence project management, tariff collection, maintenance, and system protection. Sesan et al. (2024) demonstrated the importance of inclusiveness in mini-grid deployment, highlighting the connection between social considerations and commercial viability. Affordability is another important consideration. A technically reliable system may not be sustainable if electricity tariffs are beyond the ability of rural users to pay. Conversely, tariffs that are too low to recover operating and maintenance costs can undermine the financial sustainability of the system. Rural HRES planning should therefore integrate technical design with community affordability, financing arrangements, ownership models, and local economic conditions. The challenges facing HRES deployment in rural Nigeria demonstrate that renewable-resource availability alone is insufficient to guarantee successful electrification. Sustainable deployment requires an integrated approach that combines accurate resource assessment, appropriate system design, realistic economic analysis, reliable supply chains, effective operation and maintenance, supportive policies, financing, and community participation. Table 4 synthesizes the major technical, economic, resource, operational, and institutional challenges affecting HRES deployment for rural

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electrification in Nigeria, based on evidence reported in the reviewed literature. The severity ratings and identified research gaps represent the authors' critical synthesis of the available evidence rather than classifications reported directly by individual studies.

Table 4: Critical synthesis of major challenges, evidence, consequences, and research gaps affecting HRES deployment in rural Nigeria

Challenge	Evidence in Nigeria	Affected technology	Consequence	Severity	Research gap
Battery replacement	Simulation studies	PV/Battery	Higher lifecycle cost	High	Limited field data
Biomass logistics	Agricultural studies	Biomass	Fuel insecurity	High	Poor local supply-chain data
Technical skills	Rural deployment evidence	All HRES	Downtime	High	Limited O&M datasets
Financing	Mini-grid studies	All	Low adoption	High	Need innovative financing
Seasonal hydro	Hydrological studies	Hydro	Reliability reduction	Medium–High	Long-term datasets

Source: Authors' synthesis based on the reviewed literature

V. RESEARCH GAPS AND FUTURE RESEARCH

Despite growing research on renewable resources and HRES for rural electrification in Nigeria, significant gaps remain. Existing studies differ in locations, resource datasets, load profiles, economic assumptions, and performance criteria, limiting direct comparison and generalization. Future research should adopt standardized assessment frameworks using site-specific, hourly or sub-hourly resource and load data to account for spatial and seasonal variability. Limited attention has also been given to long-term system behaviour, including battery degradation, component replacement, maintenance, and changing resource conditions. HRES assessment should therefore integrate technical, economic, environmental, reliability, and socioeconomic criteria, including LCOE, NPC, LPSP, emissions, affordability, community acceptance, and local technical capacity. Greater field validation is also needed to compare simulation results with actual system performance. Given Nigeria's geographical diversity, future studies should evaluate location-specific resource combinations rather than assume a uniform national configuration. Overall, research should move toward integrated frameworks combining accurate resource and load assessment, lifecycle modelling, socioeconomic factors, and field validation to support reliable, affordable, and sustainable HRES deployment in rural Nigeria.

VI. CONCLUSION

Nigeria has substantial solar, hydropower, biomass, and wind resources for rural electrification, but their availability varies spatially and seasonally. Therefore, HRES configuration should be selected based on local resource quality, demand, storage needs, costs, infrastructure, and socioeconomic conditions rather than national resource potential alone. The evidence shows that resource complementarity is more important than simply adding more technologies, which can increase cost and maintenance complexity. Key barriers include financing, resource variability, battery replacement, biomass logistics, inadequate infrastructure, technical capacity, and policy constraints. Future research should focus on site-specific time-resolved data, lifecycle and degradation modelling, integrated technical-economic-environmental assessment, socioeconomic factors, and field validation. A location-specific approach is essential for reliable, affordable, and sustainable HRES deployment in rural Nigeria.

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