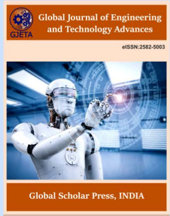
Global Journal of Engineering and Technology Advances

eISSN: 2582-5003

Cross Ref DOI: 10.30574/gjeta

Journal homepage: https://gjeta.com/



(Review Article)

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Modelling and optimization of a hybrid renewable energy systems for rural electrification in Nigeria: A review

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Global Journal of Engineering and Technology Advances, 2025, 22(01), 069-080

Publication history: Received on 06 December 2024; revised on 14 January 2025; accepted on 17 January 2025

Article DOI: https://doi.org/10.30574/gjeta.2025.22.1.0013

Abstract

The global shift towards eco-friendly energy solutions, propelled by the drive to mitigate climatic changes, has emphasized the need for innovative and sustainable approaches to rural/community electrification, particularly in regions like sub-Saharan Africa. Nigeria with over 200 million people, faces significant energy challenges, especially in rural areas where access to electricity remains a daunting challenge. Earlier in the 2020s, only 43% of this rural population had moderate electricity access, unambiguously contrasting with 90% in urban areas. This discrepancy infringes on the economic development, educational opportunities, and quality of life of the area. Nigeria's energy industry is principally reliant on conventional fuels such as natural gas, diesel, and coal which are finite and contribute to environmental degradation. In response to the inefficiencies and high costs of traditional grid extension, hybrid renewable energy systems (HRES) have appeared as a workable alternative. HRES interconnects various renewable energy sources such as solar, wind, hydro, and biomass potentially enhancing power supply stability and sustainability in rural communities. This review explores the application and optimization of HRES in Nigeria, examining the potential for integrating various renewable sources and evaluating successful case studies. An in-depth review of academic and a few physical projects spanning 10 years (2015-present) were studied using data from published articles and reports. It was observed that the Islanded HRES configuration received more attention than the grid-tied maybe as a result of the location of such communities. The review also identifies upcoming research directions to further improve the deployment and efficacy of HRES in improving community electrification in Nigeria.

Keywords: Hybrid Renewable Energy Systems; Sizing; Islanded; Grid-Tied; Economic Consideration

1. Introduction

The global energy landscape has undergone significant transformations in recent years. This shift is driven by the burning need to mitigate climatic changes by reducing greenhouse gas (GHGs) emissions and promoting the development of sustainable energy resources. In recent years, significant progress has been made towards fulfilling SDG7 (affordable and clean energy) and the UN sustainable energy mandate in achieving universal energy access by 2030 [1]. Interestingly, according to the International Energy Agency (IEA), there are about 770 million people who do not have access to electricity globally [4].

The energy access gap (EAG) in sub-saharan Africa needs a socio-eco-technical transition where on-grid and off-grid RES will play a critical role [2, 3]. Amidst many dimensions of this transformation, rural and community electrification stands out as a critical challenge and potential opportunity, particularly in a sub-Sahara region like Nigeria. It is further known that Africa's most populous nation, Nigeria still struggles with severe energy challenges, particularly in rural and

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satellite communities. Despite efforts to expand the national grid, many of these areas continue to face significant barriers to reliable electricity access. As a result, by the early 2020s, a substantial portion of these communities remain without dependable electricity, hindering economic growth, education, and overall well-being [5]. Nigeria's rural communities face significant electricity access challenges. In 2020, only 43% of these areas had access to electricity whereas 90% did in urban areas [26]. The country's electricity sector is plagued by erratic power supply, frequent outages, and limited access to reliable energy services, particularly in rural areas [6]. Giving that the International Energy Agency (IEA) report showed that approximately 80 million Nigerians, mostly in rural communities, remain without access to grid electricity, hindering economic development and quality of life [4]. Nigeria's energy sector relies heavily on finite conventional fuel resources, contributing to climate change. The country's energy mix is primarily composed of natural gas (70%), diesel (20%), and hydroelectric power (10%) [30].

Traditional grid extension methods are often inefficient and costly for rural communities. As a result, there is a growing consensus on the need for alternative solutions [6]. Hybrid renewable energy systems have emerged as a promising alternative for enhancing rural electrification [10]. By integrating multiple renewable technologies, such as solar PV, wind turbines, hydro turbines, and biomass generators, with or without storage, these systems provide a more stable and consistent power supply [20]. The benefits of hybrid renewable energy systems include enhanced reliability and stability of power supply, reduced dependence on fossil fuels, and improved sustainability of rural electrification efforts [12].

Optimal sizing of HRES involves a complex interplay of technical, economic, and social factors. Technically, integrating different renewable energy sources requires careful consideration of their variability, resource availability, and operational characteristics [7]. For instance, solar energy, which is abundant in Nigeria, has a different generation profile compared to wind or biomass. Optimizing these system components involves designing configurations that maximize energy production while minimizing costs and operational challenges. Economic optimization requires evaluating the cost-effectiveness of various HRES configurations, considering initial investment, maintenance, and operational costs. Furthermore, social factors such as community acceptance and local capacity building are essential for the effective implementation and sustainability of these hybrid renewable energy systems.

This review will delve into various aspects of HRES optimization application in Nigeria. It will explore different types of renewable energy sources, their potential for hybridization, and application types. Next, it will examine case studies of successful HRES applications, highlighting their fundamental objectives and practices. The review will also highlight technical component models and economic challenges associated with HRES, offering insights into strategies for overcoming these obstacles. Finally, it will discuss future research directions to further advance the deployment of HRES in Nigeria

2. Methods

The materials used for this study were collected relying on two major sources: the project-based data source referred to as the primary data source and the academic-published data source referred to as the secondary data source. The primary data source includes online reports on mini-grid projects by the Rural Electrification Agency (REA), World Bank-sponsored project reports and mini-grid development companies reports available online. Also, the secondary data source consists of online academic publications, and climatic data on microgrids with Nigeria as a case study.

2.1. Renewable Resources

Renewable energy is crucial for sustainable development in Nigeria, meeting the needs of both rural and urban areas [11]. Given the pressing issues associated with climatic changes and increasing carbon footprint, renewable energy system development and utilization should be a top priority. Both developed and developing countries are now embracing renewable energy to achieve energy sustainability [34]. Nigeria is endowed with vast and diverse renewable energy resources. The country's green energy potential is substantial, with estimated day-to-day energy generation of 9.34×10^5 MWh from biomass, 1.20×10^5 MWh from solar, 8.4×10^4 MWh from hydro, and 4.4×10^4 MWh from wind [31]. Regardless of the vast potential associated with RES in Nigeria, their utilization remains remarkably low. Notably, the country's renewable energy capability surpasses that of conventional energy resources by approximately 1.5 times. Numerous local researchers have led studies to evaluate the viability and availability of renewable energy resources in Nigeria, highlighting their potential for widespread adoption.

2.1.1. Solar Energy Resource

Among Nigeria's renewable energy options, solar energy stands out as the most promising due to its virtually boundless potential [9]. The nation’s geographical location within a high sunshine belt, at latitude 9.081999 and longitude

8.675277, makes it an ideal location for harnessing solar energy. The country receives well-distributed solar radiation, with varying intensities across regions, ranging from the southern to the northern parts with the south having the least [34], as illustrated in Figure 1.

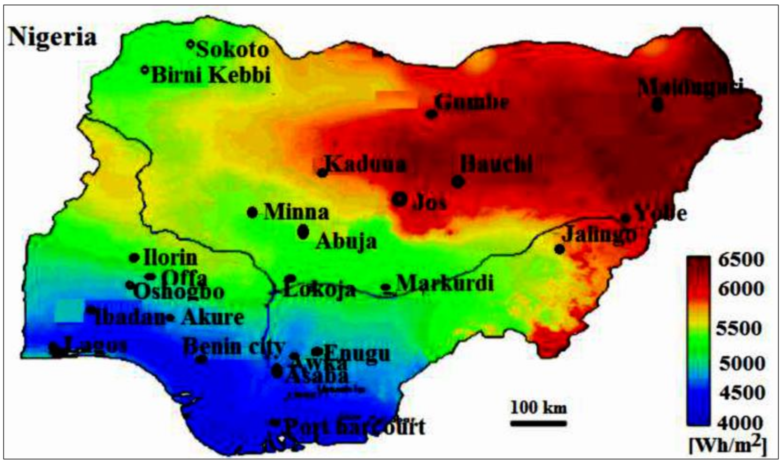

Figure 1 Solar radiation map of Nigeria. (source: NiMET, 2018)

The nation is positioned to harness significant power from limitless energy surges from the sun [14]. Figure 2 depicts the practical potential of usable energy from the PVs across the regions in the country. The solar PVs could potentially produce 3.3kWh per sqm in the coastal region to about 5.4kWh per sqm in the northern Sahel region [38]. The increase in power moving north was a result of an increased clearness index and longer sun hour.

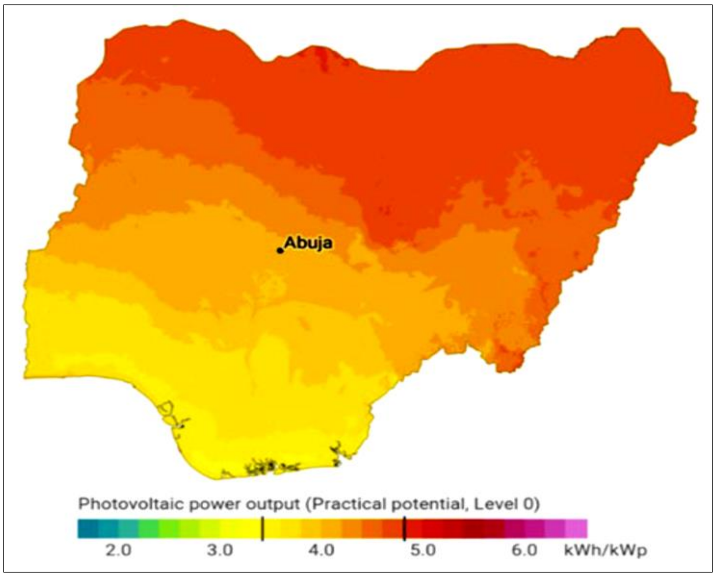

Figure 2 Solar PV power output potential across the region in Nigeria (*ESMAP* World Bank, 2020)

Nigeria receives an estimated 4.851 x 10^{12} kWh of solar energy daily, corresponding to approximately 1.082 million tons of crude oil per day [18]. In contrast, the country's daily domestic oil consumption is roughly 297,000 barrels, which translates to around 47,219 tons. This striking comparison reveals that Nigeria's solar energy potential can comfortably meet, andeven exceed, its domestic oil demand [31].

2.1.2. Biomass Resources

Another form of renewable energy source is biomass obtained from biological materials of plant and animal origin [7]. They could be used directly for heating or changed into gaseous and liquid fuels by utilizing different processes. Biomass energy originates from the sun, captured through photosynthesis, where plants transform CO_2 and water into carbohydrates. The energy stored in biomass can be harnessed through direct and indirect methods. Direct applications include burning biomass for heat or electricity generation, while indirect methods involve processing biomass into biofuels [20]. As a vital component of the Earth's carbon cycle, biomass performs a crucial part in the exchange of carbon between the atmosphere, hydrosphere, biosphere, and lithosphere. The availability of biomass in communities depends on factors such as vegetation type and parameters like tree height, stem diameter, and density.

2.1.3. Storage Technologies Used in HRES

To enhance the reliability of renewable energy (RE) systems, backup systems in the form of storage devices are integrated to mitigate the impacts of fluctuating RE sources like wind and solar [13]. This can include standby diesel generators or other energy storage devices (ESDs). These ESDs play a crucial role in HRES by storing excess energy through periods of abundance and utilizing it during peak demand [16[. Typically, off-grid systems are equipped with Energy Storage Systems (ESS) that are coupled to the main system using power electronic devices [33]. ESS play a vital role in stabilizing energy output, enhancing system flexibility, and offsetting peak demand. They can also rapidly respond to generator failures, ensuring a reliable energy supply [34]. Typically, ESS operates in three modes: charging, storage, and discharging. These systems can be categorized into various types, as illustrated in Figure 3.

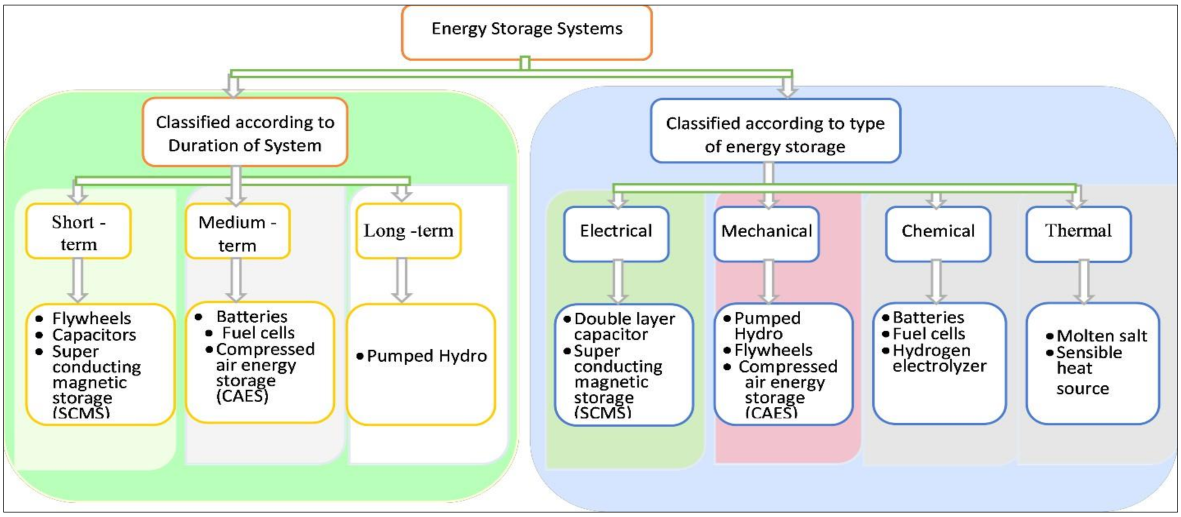

Figure 3 Classification of Energy Storage

2.2. Size Optimization Model

2.2.1. System Configuration

The configuration of HRES under consideration is depicted in Figure 4. This system integrates RESs typically: solar PV modules and a wind turbine (WT). The battery bank used as an ESS serves as a backup power source, whereas a diesel generator was positioned as a reverse power supply. A power converter was used to facilitate the conversion of direct current (DC) to alternating current (AC) and vice versa [17]. The primary load represents the energy demand of the community. Notably, the converter is assumed to incorporate an energy management system (EMS), which optimizes power flow between the load demand and the various energy sources [18].

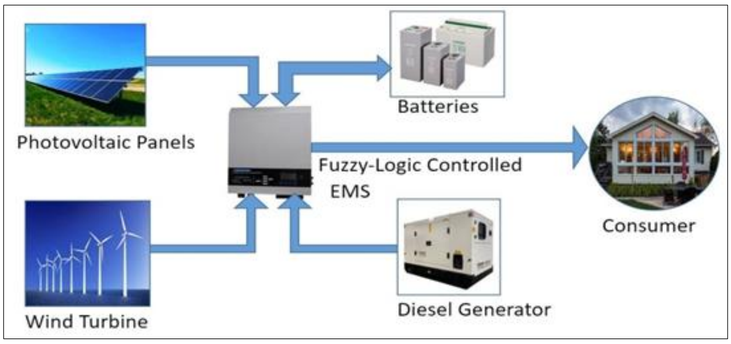

Figure 4 Used Hybrid Renewable Energy System (HRES) Configuration

The mathematical model of each component of the Hybrid Renewable Energy System (HRES) is described in detail in the subsequent section.

2.2.2. Solar Photovoltaic (PV) System Performance Model

The output power of a Solar PV system is influenced by several factors, including solar irradiance, seasonal variations, ambient temperature, PV module type, and inclination angle. According to [23], the solar panel output power (P_{PV}) can be determined using a simplified simulation model, as represented by the following equations:

$$P_{PV} = N_{PV}\eta_{PV}A_m G_t \quad \text{…………..(1)}$$

$$\eta_{PV} = \eta_{ref}\eta_{pc}\left[1-\beta\left(T_c - T_{c,ref}\right)\right] \quad \text{…………(2)}$$

$$T_c = T_a + \left(\frac{NOCT - T_{a,NOCT}}{G_{t,NOCT}}\right)G_t \quad \text{……………..(3)}$$

where $T_{a,NOCT}$= 20 and $G_{t,NOCT}$ = 800 are nominal temperatures at NOCT and Solar irradiance at NOCT (W/m^2); N_{PV} is the number of PV panels; η_{PV} is the panel conversion efficiency; A_m represent the overall surface area of the PV module in square-meter; G_t represent actual global irradiance (W/m^2); T_a represents ambient temperature; η_{pc} is the power condition efficiency (if MPPT is used) and *NOCT* represent standard PV operational temperature (°C).

2.2.3. Battery Model

Battery serves as a storage medium for electrical energy in the form of chemical energy. During periods of insufficient renewable energy, the stored energy in the battery is utilized to power the load. According to the [16], the capacity of the battery can be estimated using the following equation:

$$C_B = \frac{E_L S_D}{V_B DoD_{max} T_{cf} \mu_B} \quad \text{……….. (6)}$$

where V_B represents the battery working voltage (V); E_L represents the load demand in (kWh); T_{cf} represents the temperature correction factor; S_D represents the number of autonomy days; DOD_{max} represents the depth of discharge (%); and μ_B represents the efficiency.

Furthermore, the State of Charge (SOC) of the battery is defined as the ratio of available capacity to the rated capacity, typically measured in ampere-hours (AH) [17]. This relationship is mathematically represented as follows [19]:

$$A_{batt} = \frac{N_{batt}V_{nom}Q_{nom}\left(1-\frac{q_{min}}{100}\right)}{L_{prim,ave}} \quad \text{………(7)}$$

$$LT_{batt} = min\left(\frac{X_{batt}Y_{lifetime}FL_{batt,f}}{Z_{thrpt}}\right) \quad \text{…………(8)}$$

$$SOC = \frac{AC}{RC}100 \quad \text{……….. (9)}$$

where σ represents the self-discharge rate an hour, and E_{Gen} is the energy produced. Equation (10) is used to estimate the SOC during battery charging, while Equation (11) is used to estimate the SOC during the battery discharging. The battery optimally operates between the allowable discharge limit, denoted as SOC_{low}, and the allowable maximum charge limit, denoted as SOC_{max}.

$$SOC(t) = SOC(t-1)(1-\sigma) + \left[E_{Gen(t)} - \frac{E_L(t)}{\mu_{inv}}\right]\mu_B \quad \text{…………(10)}$$

$$SOC(t) = SOC(t-1)(1-\sigma) + \left[\frac{E_L(t)}{\mu_{inv}} - E_{Gen\,(t)}\right]\mu_B \quad \text{………(11)}$$

$$SOC = 1 - DOD \quad \text{…………..(12)}$$

2.2.4. Biomass Generator Mathematical Model

Biomass is agricultural waste material obtained from plant processing wastes and animal waste products [21]. A thermochemical or biochemical conversion system can be used to generate electricity from biomass. The thermochemical processes comprise gasification, pyrolysis, and combustion can be used to produce electricity from biomass. The most commonly known biochemical process for the conversion of organic waste to energy is the production of biogas via fermentation and subsequent conversion to electricity through the use of biomass plants (BP). In a BP, methane-rich biogas is fired inside an internal combustion (IC) engine for the production of alternating current (AC) power. The size of a BP to be installed in a given location depends on the availability of the feedstock and the volume of gas production to feed the engine. The mathematical sizing of a Biomass Power (BP) plant is determined by the equation proposed in [6]. The mathematical model for the biomass generator is represented by equation (13).

$$E_{BG} = \frac{BVA_{per\ day}CV_{BG}\eta_{BG}\Delta t}{H_{BG}} \quad \text{……………..(13)}$$

2.3. Hybrid Renewable Energy Systems Analysis

2.3.1. Islanded Hybrid Renewable Energy Systems (IHRES)

Extensive research has been conducted on the operating modes of Hybrid Renewable Energy Systems (HRES), with islanding being a crucial mode of operation, particularly for isolated or off-grid communities [22]. Also, communities with difficult terrain pose serious challenges to conventional grid infrastructure deployment, economic and environmental impact. Table 1 presents a summary of works that utilize IHRES to provide electricity for the community while reducing cost and ecological impact.

Table 1 Summary of works on IHRES

Reference & Publication Date	Location	Hybrid Proposal	Optimization Method	Project Decision Metrics	Impact Category	Challenges
Mas'ud A. A. et al (2024)	Bauchi, Yola, Minna, Jos, Anyingba, Port Harcourt	PV-WT-BESS	HOMER	LCOE	Economic	Cost of RE, Agro-Impact.
Ijeoma M. W. et al (2024)	Market Square, Port Harcourt	PV-BESS-DPG	HOMER	LCOE, Emission	Economic	Fuel Cost and Excess Energy Evacuation
Araoye T. O. et al (2024)	Nsukka Community	BPG-DPG	HOMER, GA	NPC, COE, Emission	Economic, Environment	Biomass Availability, Diesel Cost
Araoye T. O. et al (2023)	Agu-Amede Community	PV-BPG-DPG-BESS	HOMER	NPC, COE	Economic	Biomass Availability
Afolabi T. (2023)	Olooji, Ogun State	PV-WT-DPG-BESS	PSO, FLC, MATLAB	LCOE, LPSP	Economic	Low wind region
Owoeye K. SK. Et al (2022)	Edem Uruah, Akwa Ibom	PV-WT-DPG-BESS	HOMER	TCC, NPC, COE, Emission	Economic, Environment	Fuel Cost and Load Variation
Mohammed H. et al (2022)	F. M. Maitumbi, Niger State	PV-DPG-BESS	HOMER	NPC, LCOE, Emission	Economic, Environment	Fuel Cost, Quality of Simulation Load data
Kenu E. S. et al (2022)	Jakpa, Delta State	PV-WT-GPG-BESS	HOMER	LCOE, NPC	Economic	Excess Energy, Funding
Gbadamosi S. L. et al (2022)	Ilumoba, Ekiti State	PV-WT-DPG-BESS	AIMMS	LCOE, Emission	Economic, Social	Cost of Generation not clear

Osalade A. et al (2022)	Kajola Village, Ekiti State	PV-BGG-BESS	HOMER	NPC, COE	Economic	Biomass availability
Alagbu E.E. et al (2022)	Electronic Development Institute (ELDI), Awka.	PV-BESS	Technical	Component Sizing	Technical	Project Cost clearly defined
Ekpo A. A. et al (2021)	Ikot-Inyang, Akwa Ibom	PV-WT-DPG-BESS	HOMER	NPC, LCOE, Emission	Economic	ROI considered
Oladeji A. S. et al (2021)	Nigeria	PV-SHP-BESS	HOMER	LCOE, LLPI, EMR	Economic, Environment	High Project Cost and Environmental
Yimen N. et al (2020)	Kano	PV-DPG-BESS	GA, MATLAB	TAC, COE	Economic, Environment	Fuel Cost, Quality of Simulation Load data
Opedare I. et al (2020)	Abdusalam Abubakar PG Hall, University of Ibadan	PV-DPG-BESS	HOMER	NPC, COE, Emission	Economic, Environment	Fuel Cost, Excess Energy, ROI

2.3.2. Grid-Tied Hybrid Renewable Energy Systems (GHRES)

Hybrid Renewable Energy Systems (HRES) offer substantial potential in addressing the myriad challenges associated with the existing electricity delivery model and architecture. These challenges include but are not limited to, the high cost of grid extension, environmental concerns, ensuring the sustainability of energy resources, and maintaining energy security [37]. While a significant body of research has focused on the islanded mode of operating HRES, a smaller but notable subset of studies has explored the benefits of integrating HRES with the conventional grid (National Grid Supply) for communities with access to the national grid. This integrated approach aims to unlock energy affordability, particularly in areas where non-renewable resources are costly. Some of the key strategies adopted by these researchers are summarized in Table 2.

Table 2 Summary of works on GHRES

Reference & Publication Date	Location	Hybrid Proposal	Optimization Method	Project Decision Metrics	Impact Category	Challenges
Ismaila Z. et al (2023)	Saki, Oyo State & Ibeju-Lekki, Lagos State	PV-BESS	HOMER	LCOE	Economic, Environment	Initial High Cost, Unreliable grid and Technical,
Olatomiwa L. et al (2023)	Ejioku, Okuru-Ama, Damare-Polo, Agbalaenyi, Kadassaka and Doso	PV-WT-DPG-BESS	HOMER	NPC, COE	Economic, Environment	Unreliable, epileptic grid condition not considered

2.3.3. Project-based HRES

The deployed mini-grids in Nigeria served as the primary data source for this work while all consulted projects were not explicitly listed here due to want of space. With all the potential benefits accrued to distributed HRES, funding, and technical management have been the fundamental issue faced in the deployment of the system especially in rural communities. Some of the projects already in use were captured in Table 3 highlighting the basic concept, funding structure, and challenges [35].

Table 3 Few Running HRES projects across Nigeria

Project Name	Developed	Location	Hybrid System Configuration	Financing Sources	Project Action	Challenges
Nasarawa Solar Hybrid Mini grids (2021-2024)	Husk Power Systems	35 Communities in Nasarawa State	PV-DPG-BESS (Offgrid)	Equity, Debt, Grant	Electrification Intervention	Unreliable Supply, Small Storage backup, High operational cost
112.8kwp, 119.5kwp, 67.2kwp and 134.4kwp Hybrid Solar Mini grid (2024)	Darway Coast Nig. Ltd.	Agbokim, Etomi, Abia and Bendeghe in Etun LGA, Cross River	PV-DPG-BESS (Offgrid)	Debt, Grant	Electrification Intervention	Unreliable supply, Operational Cost to Demand satisfaction
Solar Hybrid Mini grids (2015-2024)	GVE Group	Over 15 Communities across Nigeria	PV-DPG-BESS (Offgrid)	Debt, Grant	Electrification Intervention	Operational performance, Small Storage unit capacity.

3. Results and discussion

3.1. Multi-Use of HRES

3.1.1. Area-Based Application

This section categorizes existing research on the diverse applications of Hybrid Renewable Energy Systems (HRES) across various sectors of society. These applications are grouped into four categories: Community, Health, Education, and Commercial. The goal is to promote eco-friendly benefits. Figure 5 illustrates that community-based HRES accounts for over half of the research, indicating that community initiatives are crucial for implementing hybrid renewable energy solutions. This emphasis on grassroots projects may aim to enhance local energy resilience and sustainability. Moreover, the commercial sector also showed a notable presence in the data indicating that businesses are increasingly adopting hybrid renewable energy strategies, likely to reduce costs, improve sustainability, and meet corporate social responsibility goals. This smaller percentage reflected in both Health and Education HRES shows a limited focus on integrating hybrid renewable energy sources specifically within health facilities.

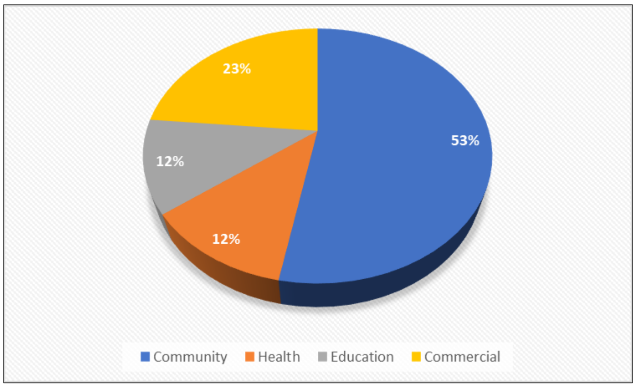

Figure 5 HRES works based on Location

3.1.2. System Configuration Application

In this paragraph, various works were done using one of the two major configuration modes in HRES application in any kind of energy source combination be it PV-WT-DGP, PV-BESS, BGG-DGP, etc. It was observed in Figure 6 that works on "Islanded HRES" (Hybrid Renewable Energy Systems) was significant with 88% and "Grid-Tied HRES" with a score of 12%. furthermore, it signifies that more works were focused on electricity provision for rural dwellers with notably no access to the National grid.

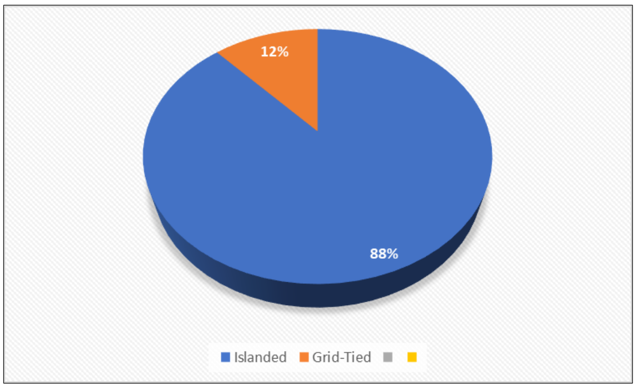

Figure 6 HRES System Configuration based Mode of Operation

3.1.3. System Optimization Methods

Optimization techniques for Hybrid Renewable Energy Systems (HRES) can be broadly categorized into two methods: deterministic and stochastic. This section analyzes and classifies the techniques used in existing works into these two groups, as illustrated in Figure 7. The figure highlights the optimization methods employed in HRES, clearly distinguishing between deterministic and stochastic approaches. Interestingly, the analysis reveals that a significant majority (75%) of HRES implementations rely on deterministic optimization techniques. This high percentage suggests a preference for approaches that offer clear, replicable solutions for planning and operating HRES, providing a sense of certainty and reliability in the decision-making process.

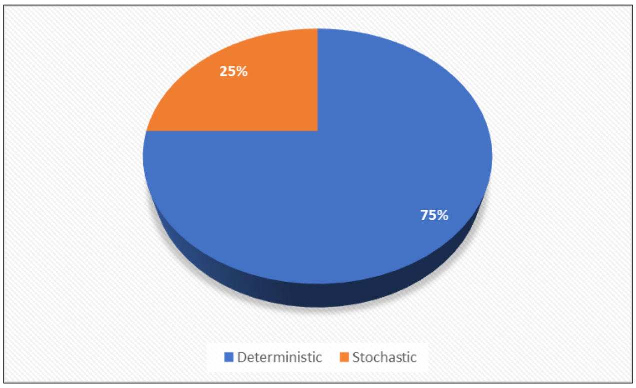

Figure 7 HRES System-based Optimization methods category used

4. Conclusion

Hybrid Renewable Energy system modeling and optimization did provide insight into the renewables integration with conventional generating sources in mitigating the existing challenges associated the conventional grid framework. Global warming, and carbon footprint reduction were some of the attractive environmental benefits of the adoption of a cleaner energy source. Optimal sizing of HRES provides energy efficiency and economic utilization of all available energy resources especially renewables as the world promotes energy sustainability and clean energy towards an improved healthy environment. Renewable energy sources are clean and abundant, but their intermittent nature and the complexity of extracting them pose significant challenges. To address this issue, Hybrid Renewable Energy Systems (HRES) combine multiple energy sources. This paper provides a comprehensive literature review on hybrid renewable energy, focusing on system configuration, economic impact, and environmental benefits. The key findings are:

- **Simulation Software**: Tools like HOMER, combined with meta-heuristic optimization algorithms, are crucial in designing and optimizing hybrid power systems, enabling tailored solutions for specific projects.
- **Economic Indicators**: The study reveals significant variations in economic indicators like NPC (Net Present Cost) and LCOE (Levelized Cost of Energy), attributed to geographical location, climate, and system configuration.

- **Community-Based Solutions**: The research strongly focuses on community-based hybrid renewable energy solutions, indicating effective grassroots movements and local engagement in sustainability efforts.
- **Commercial Sector Involvement**: The significant involvement of the commercial sector suggests a growing recognition of the benefits of renewable energy in business operations.
- **Health and Education Sectors**: In contrast, the health and education sectors show relatively low adoption rates, presenting opportunities for growth and investment in hybrid renewable energy for enhanced sustainability and resilience.
- **Islanded vs. Grid-Tied HRES**: The results indicate that islanded systems currently outperform grid-tied systems in the evaluated contexts.
- **Optimization Methods**: The study reveals a strong reliance on deterministic optimization methods in HRES, likely due to their effectiveness in stable environments and ease of implementation.

Recommendation

Future research on hybrid systems will focus on assessing their technical performance, including power losses, harmonics, and power quality, across various users and locations. This will inform policy development for energy investors. Key areas of investigation include:

- **Optimization Studies**: Rigorous optimization will be conducted to determine the impact of design and economic parameters on system performance.
- **Hybrid Solar Thermal and Biomass Systems**: Research will explore the potential of combining solar thermal energy and biomass energy in hybrid systems.
- **Grid-Tied System Integration**: Efforts will focus on understanding the challenges faced by grid-tied systems and developing innovative solutions to enhance their integration with renewable energy sources, promoting a more resilient and sustainable energy landscape.
- **Stochastic Approaches:** Further research will explore integrating stochastic approaches to enhance the resilience and adaptability of Hybrid Renewable Energy Systems (HRES), particularly in the context of variable energy sources.

Compliance with ethical standards

Acknowledgments

The authors are thankful to Nyzpat Technologies Limited for providing the funding.

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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