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Optimal Sizing Modeling of Hybrid Renewable Energy Systems for Rural Electrification in Nigeria: A Review

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ABSTRACT : *The global shift towards sustainable energy solutions, driven by the imperative to combat climate change, has underscored the need for innovative approaches to rural and community electrification, particularly in sub-Saharan Africa. Nigeria, Africa's most populous nation with over 200 million people, faces significant energy challenges, especially in rural areas where access to reliable electricity remains scarce. As of the early 2020s, only 43% of Nigeria's rural population had moderate electricity access, starkly contrasting with 90% in urban areas. This disparity hampers economic development, educational opportunities, and quality of life. Nigeria's energy sector is predominantly 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 emerged as a promising alternative. HRES integrates multiple renewable 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. The review also identifies future research directions to enhance further the deployment and efficacy of HRES in improving community electrification in Nigeria.*

KEYWORDS: *Hybrid Renewable Energy Systems, Sizing, Islanded, Grid-Tied, Economic Consideration.*

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I. INTRODUCTION

Over the years, the global energy network has witnessed profound changes, orchestrated by the ever-growing need to address climate change by reducing greenhouse gas emissions and promoting sustainable energy resource development. Amidst many dimensions of this transformation, rural and community electrification stands out as a critical challenge and potential opportunity, particularly in sub-Sahara regions like Nigeria. This Africa's most populous country with over 200 million people is faced with significant energy challenges, particularly in rural areas and satellite communities where access to national grid electricity is faced with daunting challenges. By the early 2020s, a significant portion of these communities continued to lack reliable access to electricity, which impedes economic development, educational opportunities, and overall quality of life. In 2020, only 43% of Nigeria's rural communities had access to electricity, compared to 90% in urban communities [1]. The electricity sector of the country struggles with erratic power supply, frequent outages, and a large proportion of its population, particularly in rural communities, lacking access to reliable energy services [2]. According to the International Energy Agency (IEA), nearly 80 million Nigerians, mostly in rural communities, remain off the grid, which hampers economic development and quality of life [1]. Nigeria's energy sector is heavily reliant on conventional fuel resources, which are finite and contribute to climate change. The country's energy mix is dominated by natural gas (70%), followed by diesel (20%), and hydroelectric power (10%) [3].

The conventional grid extension scheme is inefficient and costly for these types of communities. Thus, there has been a rising recognition of the need for a different solution [4]. However, hybrid renewable energy systems integrating multiple renewable technologies with or without storage, have emerged as a viable alternative for enhancing rural electrification. This system combines different sources, such as solar, wind, hydro, and biomass, to provide a more stable and reliable power supply [5]. These types of systems can enhance the reliability and stability of power supply, reduce dependence on fossil fuels, and improve the sustainability of rural electrification efforts [6].

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. 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. Additionally, social factors, including community acceptance and local capacities, play a crucial role in the successful deployment of these systems.

The pressing challenge of climate change necessitates a rapid transition from fossil fuel-based energy systems to renewable energy solutions. While significant progress has been made in the development and deployment of renewable technologies such as solar and wind energy, these standalone systems come with their own set of limitations. Solar energy generation is contingent upon daylight and clear weather conditions, whereas wind energy is unpredictable, depending on fluctuating wind speeds. The intermittency and variability of these energy sources pose a challenge to the stability of the electricity grid, thereby affecting the wider adoption of renewable energy systems. Furthermore, the current policy frameworks and economic models often do not adequately support the seamless integration of these disparate renewable resources into a unified and efficient energy system. This study is motivated by the urgent need to explore how HRES specifically those integrating solar and wind energy can address the limitations inherent in single-source systems. By delving into the technical challenges, economic considerations, and policy landscapes, this review aims to provide a comprehensive overview that can guide future research, investment, and policy-making in this domain. Moreover, the study seeks to identify the gaps in current research and policy that need to be addressed to accelerate the adoption of hybrid renewable energy systems. By synthesizing existing knowledge and providing actionable insights, this review aims to contribute to the advancement of HRES as a viable, sustainable, and efficient solution for mitigating the impacts of climate change and securing a more sustainable energy future.

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.

II. THEORY/MODELS/METHODOLOGY

I. HRES Energy Sources Technologies

Renewable energy plays a vital role, in meeting the needs of both rural and urban areas of the country in terms of sustainable development [4]. The development and proper use of renewable energy should be given high priority, especially now that issues of climate change and global warming are among the most critical issues discussed by the various governments of the world. Developed and developing countries are now adopting renewables to achieve energy sustainability [7]. The renewable energy resources in Nigeria are as enormous as they are diverse. The energy generating electricity potential from these numerous green energy resources, with a daily energy latency of 934 GWh from biomass, 120 GWh from solar, 84 GWh from hydro, and 44 GWh from wind [8]. However, the problem lies with the level of utilization which is very low. The potential of renewable energy resources in Nigeria is about 1.5 times that of conventional energy resources in terms of energy. Many indigenous researchers have investigated the availability of renewable energy resources in Nigeria to establish their viability in the country [9].

The Solar Energy Resource

Among all the renewable energy resources available, solar is the most promising of them all due to its limitless potential. Nigeria is located at latitude 9.081999 and longitude 8.675277 within a high sunshine belt and solar radiation is well distributed within the country. The intensity of solar radiation is well distributed within the country. The intensity of solar radiation exhibits remarkable variation from the northern region to the southern region [10] as shown in Fig.1.

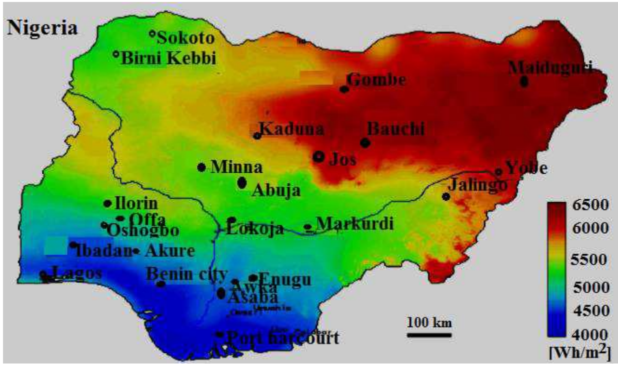

Fig.1. Solar radiation map of Nigeria. (source: NiMET, 2018)

During the day it is estimated that Nigeria receives about 4.851 x 1012 kWh of energy from the sun, which is equivalent to about 1.082 million tons of oil per day. While domestic consumption of oil is 297 thousand barrels per day. When we change barrels into tones we see a very exciting number; 297000 barrels equals 47219.2281 tons. So, it is obviously seen that domestic demand for oil can be substituted by solar energy [6].

Solar PV Model

Solar PV output power is influenced by factors such as solar irradiance, the yearly season, the surrounding temperature, the type of PV module, and the inclination angle. The solar panel output power is determined by a simplified simulation model and is given by following the equations [11]:

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

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

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

Nominal temperature Where = 20 and = 80 are nominal temperature at NOCT and Solar irradiance at NOCT (W/m2); is the number of PV panels; is the panel efficiency; is the total area of the panel module; is the incident global irradiance (W/m2); Ta is the surrounding temperature; is the power condition efficiency (if MPPT is used) and NOCT is the normal PV working temperature ().

The Wind Energy Resource

A study on the wind energy potentials for several Nigerian cities shows that the annual average speed of about 2.2 m/s in the coastal region and 4.5 m/s in the far northern region of the country. With an air density of 1.1 kg/m3, the wind energy intensity perpendicular to the wind direction ranges between 4.4 W/m2 in the coastal areas and 35.2 W/m2 at for northern region [6]. Further study on the wind resource in Nigeria revealed that the North-East and South-East of the nation possess enormous potential for harvesting wind energy, with possible wind speeds reaching as high as 8.70 m/s in the north [6] as shown in Fig.2.

Fig. 2. Wind speed map of Nigeria. (Source: NiMET, 2018)

Wind Turbine Model

The power output of a wind turbine is determined by the regional wind speed and wind turbine characteristics. This study uses the following equations to determine the output power of a wind turbine [12].

$$.P_w(t) = \begin{cases} \frac{N_{PV}(V - V_{CIN})}{V_{rat} - V_{CIN}} V_{CIN} \leq V \leq V_{rat} \\ P_R V_{rat} \leq V \leq V_{CO} \\ 0, \ \ V \leq V_{CIN} \ and \ V \geq V_{CO} \end{cases} \quad (4)$$

$$V = V_{ref}\left(\frac{H}{H_{ref}}\right)^{\alpha} \quad (5)$$

where Href (m) is the reference height; Vref (m/s) is the reference height's wind speed; α refers to the exponent; H (m) is the height of the wind turbine; V is the wind speed at H(m); Vrat (m/s) is the rated wind speed of the wind turbine; Pr (kW) is the constant power; VCIN (m/s) is the cut-in speed; and VCO (m/s) is the cut-out speed.

Biomass

Biomass is a renewable organic material that comes from plants and animals. Biomass can be burned directly for heat or converted to liquid and gaseous fuels through various processes. Biomass contains energy first derived from the sun: Plants absorb the sun's energy through photosynthesis and convert carbon dioxide and water into nutrients (carbohydrates). The energy from these organisms can be transformed into usable energy through direct and indirect means. Biomass can be burned to create heat (direct), converted into electricity (direct), or processed into biofuel (indirect). Biomass is an integral part of Earth's carbon cycle. The carbon cycle is the process by which carbon is exchanged between all layers of Earth: atmosphere, hydrosphere, biosphere, and lithosphere. The biomass availability in communities is determined by the type of vegetation and different basic parameters like tree height, stem diameter and density.

Biomass Generator Mathematical Model

Biomass is an agricultural waste material obtained from plant processing wastes and animal waste products. 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 BP is given by the equation presented by [7]. The Mathematical model of biomass generator is as in (13)

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

Storage Technologies used in HRES.

The reliability of renewable energy (RE) systems is improved by adding backup systems in the form of storage devices, especially to mitigate the impacts of constantly changing RE sources such as wind and solar. In some cases, standby diesel generators or other energy storage devices are used for this purpose. Energy storage devices are useful for HRES because they store energy in times of abundance and use up during peak load. Generally, off-grid systems are usually equipped with energy storage systems (ESS) which are coupled to the main system with the help of power electronic devices. Energy storage systems are generally smooth variations, enhance system flexibility, offset peak load, and quickly intervene when other generators, for some reason, cannot fully support the load [9]. The ESS usually has three modes of operation (charging mode, storage mode, and discharging mode) and is classified as seen in Fig.3.

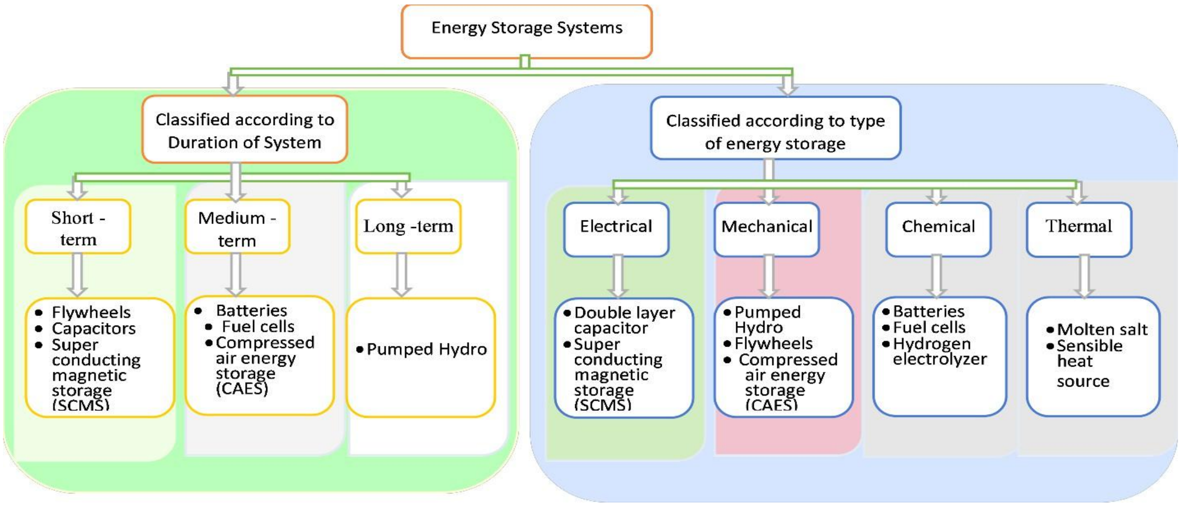

Fig. 3. Classification of Energy Storage

Battery Model

A battery stores electrical energy in chemical form. Energy stored in the battery is used to power the load when renewable energy is not sufficient. The battery capacity can be estimated by the following equation [6]:

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

Where VB is the battery working voltage; EL is the load in Wh; Tcf is the temperature correction factor; SD is the number of autonomy days; DODmax is the depth of discharge; and µB is the efficiency. Additionally, the battery SOC is defined as the available capacity divided by the rated capacity of the battery in ampere-hours (AHr). This is mathematically expressed below [13].

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

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

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

where EL is the load, σ is the self-discharge rate an hour, and EGen is the energy generated. Equation (10) is used for the battery charging, while Equation (11) is used for the battery discharging. The battery optimally operates between the allowable discharge limit, denoted as SOClow, and the allowable maximum charge limit, denoted as SOCmax.

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

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

$$SOC = 1 - DOD \quad (12)$$

II. Hybrid Renewable Energy Systems Analysis

Islanded Hybrid Renewable Energy Systems (IHRES)

The typical structure of the considered HRES is seen in Fig5. The system contains two renewable energy sources, solar photovoltaic modules, and a wind turbine. The battery is included as a backup power source, while the diesel generator serves as an emergency supply. An inverter is included that converts direct current to alternating current and vice versa. The consumer load is the energy demand of the community. The inverter is assumed to contain an energy management system that controls the power flow between the load demand and the different energy sources.

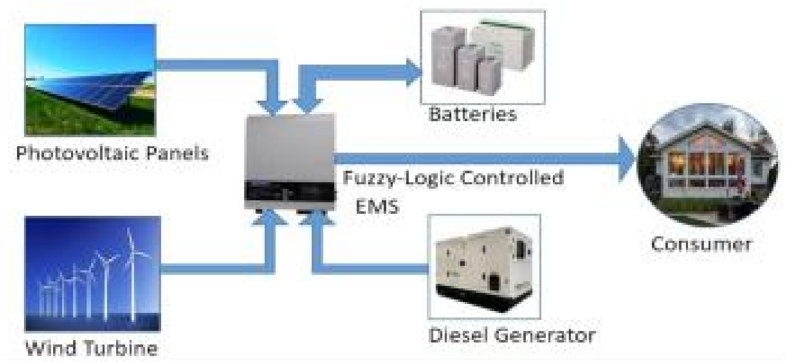

Fig 5: Hybrid renewable energy system structure.

Many studies have been carried out on modes of HRES operation and islanding is an important mode for isolated communities. Also, communities with difficult terrain pose serious challenges to conventional grid infrastructure deployment economic and the 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
[14]	Bauchi, Yola, Minna, Jos, Anyingba, Port Harcourt	PV-WT-BESS	HOMER	LCOE	Economic	Cost of RE, Agro-Impact.
[19]	Market Square, Port Harcourt	PV-BESS-DPG	HOMER	LCOE, Emission	Economic	Fuel Cost and Excess Energy Evacuation
[4]	Nsukka Community	BPG-DPG	HOMER, GA	NPC, COE, Emission	Economic, Environment	Biomass Availability, Diesel Cost
[9]	Agu-Amede Community	PV-BPG-DPG-BESS	HOMER	NPC, COE	Economic	Biomass Availability
[15]	Olooji, Ogun State	PV-WT-DPG-BESS	PSO, FLC, MATLAB	LCOE, LPSP	Economic	Low wind region
[20]	Edem Uruah,	PV-WT-	HOMER	TCC, NPC,	Economic,	Fuel Cost and

	Akwa Ibom	DPG-BESS		COE, Emission	Environment	Load Variation
[24]	F. M. Maitumbi, Niger State	PV-DPG-BESS	HOMER	NPC, LCOE, Emission	Economic, Environment	Fuel Cost, Quality of Simulation Load data
[16]	Jakpa, Delta State	PV-WT-GPG-BESS	HOMER	LCOE, NPC	Economic	Excess Energy, Funding
[13[	Ilumoba, Ekiti State	PV-WT-DPG-BESS	AIMMS	LCOE, Emission	Economic, Social	Cost of Generation is not clear
[7]	Kajola Village, Ekiti State	PV-BGG-BESS	HOMER	NPC, COE	Economic	Biomass availability
[25]	Nigeria	PV-BESS	HOMER	LCOE, NPC	Economic	Project Cost is not defined
[26]	Ikot-Inyang, Akwa Ibom	PV-WT-DPG-BESS	HOMER	NPC, LCOE, Emission	Economic	ROI considered
[2]	Nigeria	PV-SHP-BESS	HOMER	LCOE, LLPI, EMR	Economic, Environment	High Project Cost and Environmental
[17]	Kano	PV-DPG-BESS	GA, MATLAB	TAC, COE	Economic, Environment	Fuel Cost, Quality of Simulation Load data
[18]	Abdusalam Abubakar PG Hall, University of Ibadan	PV-DPG-BESS	HOMER	NPC, COE, Emission	Economic, Environment	Fuel Cost, Excess Energy, ROI

Grid-Tied Hybrid Renewable Energy Systems (GHRES)

HRES has a lot of potential in mitigating many challenges associated with the current electricity delivery model and architecture which are not limited to the cost of grid extension, environmental consideration, energy resources sustainability, energy security, etc. So many researchers have done a lot of work on the islanded mode of operating HRES, a hand few have also considered the potential locked in the integration of conventional grid (National Grid Supply) with HRES grid for communities with access to the National grid to unlock energy affordability in the high cost of non-renewable resources. Some of the highlight strategies adopted by these researches 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
[29]	Saki, Oyo State & Ibeju-Lekki, Lagos State	PV-BESS	HOMER	LCOE	Economic, Environment	Initial High Cost, Unreliable grid and Technical,
[28]	Ejioku, Okuru-Ama, Damare-Polo, Agbalaenyi, Kadassaka and Doso	PV-WT-DPG-BESS	HOMER	NPC, COE	Economic, Environment	Unreliable, epileptic grid condition not considered

III. RESULTS AND DISCUSSIONS

A. Area-Based Application

In this section, reviewed works were categorized based on the multiple applications of HRES in different areas and sectors of our society. These applications were classified under the Community, Health, Education, and Commercial sectors towards a rewarding eco-environmental benefit. As shown in Fig. 6, significant work has been done on the community-based HRES accounting for over half of the works under consideration. This suggests that community initiatives play a vital role in implementing hybrid renewable energy solutions which indicates a strong focus on grassroots projects, possibly to improve 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.

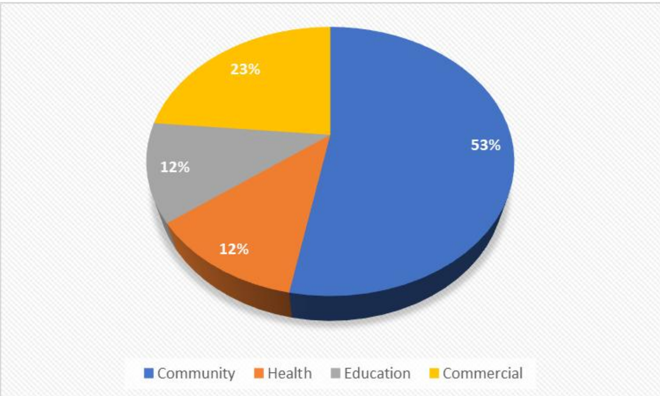

Fig. 6. HRES works based on Location

B. 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 Fig. 7 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.

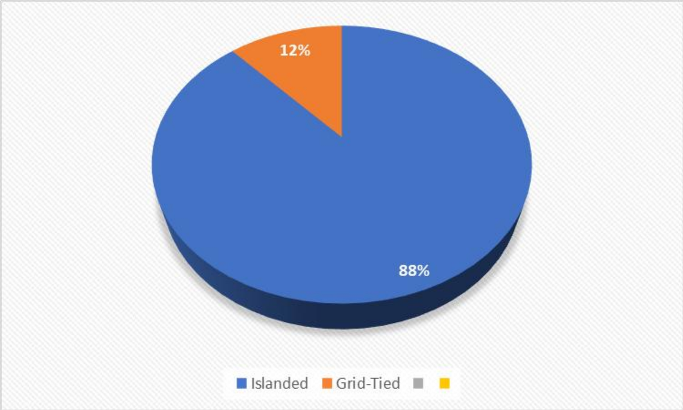

Fig. 7. HRES System Configuration-based Mode of Operation

C. System Optimization Methods

The optimization techniques are divided into two major methods: deterministic and stochastic methods. In this section, the techniques used in the works were analyzed and classified into these two major groups/methods as observed in Fig. 8. The Fig presented the use of optimization methods in Hybrid Renewable Energy Systems (HRES) with a clear distinction between deterministic and stochastic approaches. It was observed that the vast majority of HRES implementations rely on deterministic optimization techniques at 75%. The high percentage may suggest a preference for approaches that provide clarity, and replicable solutions in the planning and operation of HRES.

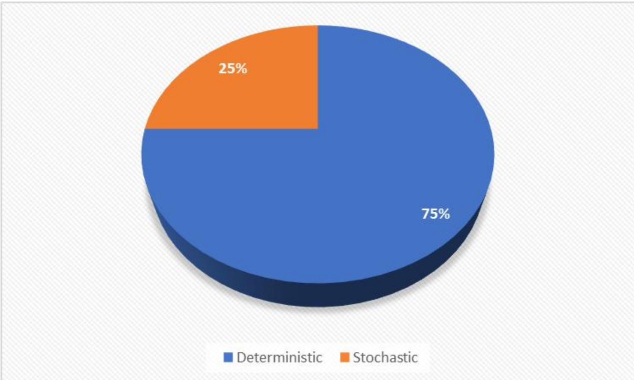

Fig. 8. HRES System-based Optimization methods category used

IV. CONCLUSION

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 limitless and clean, but the sporadic nature of most types, and processes involved in the production of their extraction medium are their biggest drawback. To solve this issue, an HRES combination of multiple energy sources was created. This paper aims to provide a literature review in the field of hybrid RE in terms of generating resource configuration, and economic and environmental impact.

The results can be summarized as follows:

- Simulation software provides valuable support in evaluating and designing hybrid power systems. It assists in assessing various design options and developing optimal operational plans tailored to specific project needs. It is noted from the studies that HOMER in combination with meta-heuristic optimization algorithms was often used in designing and optimization;

- It was noted that the economic indicators are different, whether in terms of NPC or LCOE. The significant difference is because of several factors, including geographical location, climate, system configurations, resource fractions, capacity of systems, economic factors, research period, etc.;
- The findings highlighted a strong emphasis on community-based hybrid renewable energy solutions, suggesting effective grassroots movements and local engagement in sustainability efforts;
- The commercial sector's significant involvement indicates a growing recognition of the benefits of renewable energy in business operations. In contrast, both the health and education sectors show relatively low adoption rates, pointing to potential areas for growth and increased investment to leverage hybrid renewable energy for enhanced sustainability and resilience in those fields.
- The significant difference in scores between islanded and grid-tied HRES indicates that islanded systems are currently more successful in the contexts being evaluated. The results show a strong reliance on deterministic optimization methods in Hybrid Renewable Energy Systems, which could be due to their effectiveness in stable environments and ease of implementation.

To find general conditions for the application of hybrid systems, future developments of this study will investigate the system's technical performance like power losses, harmonics, and power quality as a function of different users and locations, and enable policy formulation for energy investors. They will also need to conduct a thorough, rigorous optimization to determine the impact of the design and economic parameters on performance. In particular, carrying out studies on hybrid systems of solar thermal energy and biomass energy can be suggested.
Furthermore, efforts should be focused on understanding the barriers faced by grid-tied systems and exploring innovative solutions to enhance their integration with renewable sources, potentially leading to a more resilient and sustainable energy landscape.

More studies should be conducted on further exploration and integration of stochastic approaches to enhance the resilience and adaptability of HRES, especially in the face of variable energy sources.

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