Optimum hybrid configuration for rural and remote power generation in different geopolitical zones of Nigeria.

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2023

Optimum hybrid configurations for rural and remote power generation in different geopolitical zones of Nigeria

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Abstract

This study uses Hybrid Optimization Model for Electric Renewables (HOMER) software to conduct techno-economic analysis and identify optimum hybrid system for power generation in rural (remote) areas across six geopolitical zones of Nigeria, ranging from arid to tropical vegetation. The study uses a typical village or remote community of 50 households, comprising 400-500 people with a community clinic, school, hall, and commercial centres alongside small-scale agro-processing units. Energy sources considered include small hydro (SHP), solar photovoltaic (PV), wind, and diesel genset. Three core system performance indicators, namely, net present cost (NPC), levelized cost of energy (LCOE), and renewable fraction (RF) are utilized to assess project feasibility. Sensitivity analysis of key parameters is also carried out to unravel the impact of their changes on overall system performance. The results suggest SHP-PV-generator set-up as the optimal design (best hybrid system) for delivering the most affordable (cost-effective), accessible (off-grid) and acceptable (environmentally friendly) electricity supply to rural communities in the six zones. Furthermore, the PV-wind-SHP-generator, SHP-generator, wind-SHP-generator, PV-generator, PV-wind-generator (in that order) are also feasible solutions for implementation at the selected sites. Nonetheless, the last two options would require government incentives and support mechanisms to attract investors. The findings of this study provide feasible pathways on how governments in developing countries such as Nigeria can deploy cost-efficient energy technologies as part of their Renewable Energy Master Plans (REMPs) to provide rural electrification while reducing GHG emissions.

Keywords: Hybrid System, HOMER Software, SHP, Solar PV, Techno-economic Analysis, SDG 7

Highlights

- Explored techno-economic assessment of hybrid power in remote locations across Nigeria with HOMER software package.
- Developed a typical village load profile to estimate annual average power requirement
- Superior performance of various hybrid configurations over the conventional diesel genset system.
- Observed notable variation in the environmental emissions of hybrid design across fuel and zones.

1 Introduction

Lack of electricity is amongst the most significant challenges facing many developing countries today, especially in Asia and Africa. In Nigeria, Africa's most populous country with approximately 220 million people, only about 60% of the populace had access to electric power as of 2022 [1,2]. National grid coverage extends to just 30% of rural communities; thus, about 70% of the rural population in Nigeria still has difficulty accessing modern energy services. Remote rural areas in Nigeria require access to affordable and reliable electricity to foster inclusive development.

Moreover, as previous studies [3, 4, 5] found that on-grid solutions are not economically favourable for rural electrification in Nigeria, the alternative solution to extend electricity supply to remote areas will be through Autonomous decentralized (off-grid) generation. Aside from being eco-friendly with no long distribution infrastructure requirement, off-grid solutions deliver high-quality and reliable electricity for lighting, cooking, water supply, and agro-allied purposes, among others [6]. These advantages are also coupled with the possibility of being connected to the national grid in the future [7]. This thus highlights the need to examine off-grid and stand-alone hybrid power generation to supply electric power to most remote areas of Nigeria.

A hybrid system comprises of one or several renewable energy sources working alongside standby secondary non-renewable modules and storage units to meet a given electricity demand load. The rationale for developing a Hybrid Energy System (HES) is to curb energy supply disruption alongside intermittency in power delivery associated with renewable technologies [8, 9]. As it uses complementary energy supply sources, HES boosts reliability and efficiency and balances the power supply [7]. Technically, HES can be stand-alone or grid-connected and serve alternating current (AC) and direct current (DC) electric and thermal loads. Several studies considered HES an excellent solution for electrification in remote rural areas with no grid access [5, 7, 10, 11, 12].

With the aid of a Hybrid Optimization Model for Electric Renewables (HOMER), this paper develops hybrid energy systems (comprising of hydro, solar, wind, and diesel genset) to boost rural electricity access across the six geopolitical zones of Nigeria using three core system performance indicators: Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and Renewable Fraction (RF). A sensitivity analysis of critical parameters is also carried out to unravel the impact of their changes on overall system performance.

The rest of the paper is structured as follows: Section 2 describes the HOMER Microgrid Modeling Software and its applications. While the HOMER software has been applied in the Nigerian context, they often deployed a limited set of technologies, or the load profiles utilized were inconsistent with the country's prevailing climatic seasons. This paper addresses these issues, thus filling a critical knowledge gap. Section 3 deals with the materials and methods, including itemizing all the underlying data and assumptions in our model. We present and discuss our results in Section 4 and then conclude in Section 5 with some policy recommendations.

2 Synopsis of HOMER Microgrid Modeling Software

HOMER is a robust microgrid modeling software developed in 1992 at the National Renewable Energy Laboratory (NREL), USA, for designing reliable and cost-effective distributed generation systems [13, 14]. Currently available in over 42 versions with more than 250,000 users from 193 countries [13], HOMER simulates and optimizes stand-alone and grid-connected micropower systems with any combination of wind turbines, PV arrays, run-of-river hydropower, biomass power, microturbines, internal combustion engine generators, fuel cells, batteries, and hydrogen storage, serving both electric and thermal loads, amongst others [15, 16]. In addition to modeling the physical behaviour of the power system, HOMER optimising tool captures the total cost of installing and operating the system over its life span [15,16,17].

Structurally, HOMER contains various energy system components that assist in arriving at suitable technology options based on cost and available resources [13, 14]. Thus, HOMER's utilization requires information on key components (including their types, numbers, costs, efficiency, and lifespan, among others), resources, economic constraints, and control methods [16]. Aside from simulating and optimising micropower systems, HOMER performs sensitivity analysis and compares power generation technologies across various applications.

2.1 Previous HOMER Applications

Researchers have extensively used HOMER to perform off-grid electrification analyses in developed and developing countries. To mention a few, HOMER was adopted to investigate the feasibility of zero-energy homes [17], simulate stand-alone systems with hydrogen fuel in Newfoundland, Canada [18], explore the role of Gen-sets in small solar power systems in Sri Lanka [19], to examine the feasibility of a stand-alone wind-diesel and PV-diesel hybrid in Saudi Arabia [20,21,22], investigate the economic feasibility of off-grid electricity generation with hybrid systems in India [6, 23, 24], access Performance of hybrid photovoltaic/ diesel energy system in Malaysia [25,26], determine the prospect of wind-PV-battery hybrid system in Bangladesh [23] and evaluate the feasibility of renewable energy systems in Iran [28].

In Nigeria, related studies using HOMER tools have been presented. For instance, Ajao et al. [29] conducted a cost-benefit analysis of a wind turbine-solar hybrid system in Nigeria using HOMER software. They reported a pay-back period of approximately thirty-three years for the designed hybrid system. They found grid power connection to be the least expensive option, but it may not be accessible to most rural households as they were far from the grid. The study then recommends off-grid power supply for those areas. Nwosu et al. [30] investigated the possibility of combining wind and solar resources for electricity generation (either grid-connected or stand-alone hybrid system) in the southern eastern states of Nigeria. With Nsukka as a case study, the study combined a variable speed wind turbine with a 6 by 2 solar PV array to satisfy the load requirement of a 3-bedroom flat apartment and discovered that low wind resources could be hybridized with the high solar profile to power stand-alone or grid-connected systems.

In North-Central Nigeria, Adaramola et al. [31] utilized HOMER to examine wind energy potentials alongside economic analysis in six selected locations using wind speed data spanning 19 to 37 years (measured at 10 m height). The results indicated that the LCOE for the chosen sites ranged between ¢4.02 and ¢166.79, with Minna and Bida being the most and least viable sites, respectively. Relatedly, Adaramola et al. [32] conducted a techno-economic evaluation of wind energy systems in the South-Western region of Nigeria. Their result revealed that electricity cost varied from 0.06997$/kWh and 0.11195 $/kWh to 2.86611 and 4.58578 $(kWh at limit values of turbine-specific cost band intervals of 1000 and 1600 $/kW.

Adaramola et al. [33] adopted HOMER to examine the possibility of using hybrid PV solar-diesel power systems for electricity generation in rural and semi-urban areas of Northern Nigeria. The optimal simulation outcomes revealed that the system LCOE ranges between $0.348/ kWh and $0.378/kWh, depending on the interest rate. Further, Okundamiya & Omorogiuwa [34] used HOMER to investigate the economic, technical, and environmental viability of adopting a photovoltaic-diesel-battery hybrid system in Nigeria. The analysis results indicated that the PV-diesel-battery system utilization in Nigeria could have cost-saving and emission-reduction benefits for the country without compromising reliability.

Olatomiwa et al. [35] employed HOMER simulation software to examine the economic feasibility of different power generation configurations comprising solar arrays, wind turbines, and diesel generators in different locations across the six geopolitical zones of Nigeria. The work reveals PV/diesel/battery hybrid renewable system configuration as the optimum combination for both sensitivity cases of 1.1 and $US1.3/l of diesel. Similarly, Oyedepo et al. [36] performed a techno-economic appraisal of using HES for electricity generation in rural neighborhoods across the six geopolitical zones of Nigeria. The study found the highest optimum results in Warri ($2,441,222 and $0.721/kWh of NPC and COE, respectively) and the lowest in Maiduguri ($2,225,387 and $0.658/kWh).

Overall, the literature showed that all previous studies using HOMER in Nigeria, except Olatomiwa et al. [35] and Oyedepo et al. [36], focused mainly on states or specific localities or climatic regions of the country and, therefore, did not adequately capture the landscape in all the country's six geopolitical zones. In addition, the hybrid options presented by Olatomiwa et al. [35] and Oyedepo et al. [36] have a limited set of technologies (PV/wind/diesel generators), thus ignoring hydropower (SHP) turbines, which the country has a huge potential [37,38]. Moreover, the load profiles stipulated were not in tandem with the prevailing climatic seasons in the country. This paper addresses these issues, thus filling a critical knowledge gap.

3 Material and Methods

3.1 Study Area and Layout

The study was conducted for six remote areas/villages, one in each geopolitical zone of Nigeria (Figure 1), reported in the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) [39] to possess significant SHP and other RE potentials to boost electricity access in ECOWAS region.

Figure 1: Selected Location in each of the six Geopolitical Zones of Nigeria

Geo-Political Zone	State	Site Location	Geographic Coordinate Latitude (N)	Longitude (E)
North East (NE)	Gombe	Balanga	9°55'20"	11°35'58"
North West (NW)	Kastina	Kabomo	11°32'33"	7°28'43"
North Central (NC)	Kwara	Asa Dam	8°24'50"	4°26'28"
South East (SE)	Ebonyi	Edukwu	6°43'15"	8°10'31"
South West (SW)	Ekiti	Elemi	7°54'19"	5°16'20"
South South (SS)	Delta	Ibrede	5°32'60"	6°23'60"

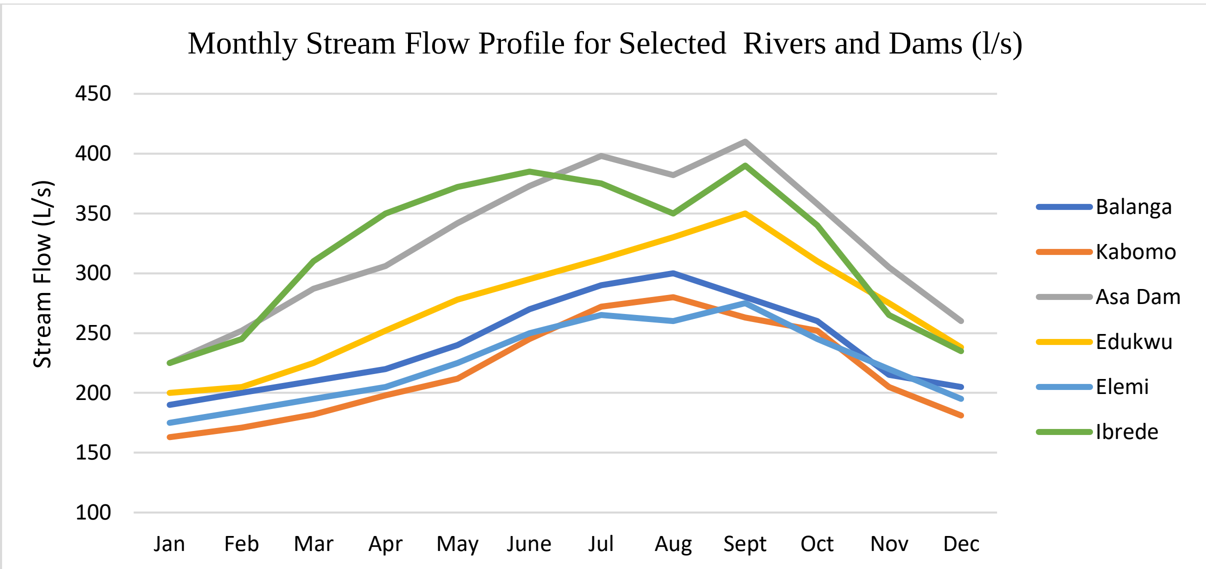
Source: Authors' construct, based on ECREEE [39], GoogleMaps and FollowThePin plots

3.2 Renewable Energy Potentials at Selected Locations

3.2.1 Hydro Resource

Figure 2 shows the locations' hydro potential. In line with the country's prevailing (wet and dry) seasons, the flow of these rivers drops during the dry season (November to February), but rapidly increases from March to October (wet season) with heavy rainfall.

Figure 2: Calibrated Flow Rate for Selected Sites



Source: Authors' Estimation

Following the standard SHP guide and previous works [6, 40], the turbine efficiency was selected to be 75%. The HOMER calculated nominal power for selected sites based on available head, design flow rate, and efficiency, which are reported in Table 2.

Table 2: hydropower Potential Capacity at Selected Locations

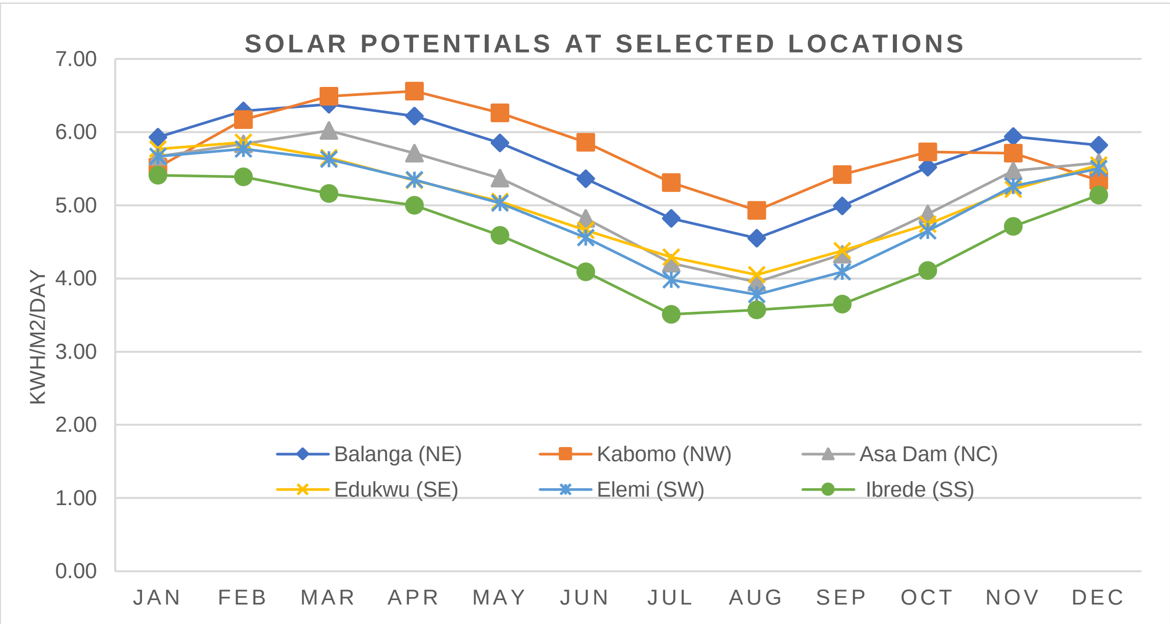
River/Dam[1]	Assumed Flow rate (l/s)	Estimated Head (m)	Nominal Power (kW)
Balanga	250	18.0	33.1
Kabomo	250	20.0	36.8
Asa Dam	380	12.5	34.9
Edukwu	350	15.0	38.6
Elemi	250	15.0	27.6
Ibrede	380	10.0	28.0

Source: ECREEE [39]; FAO [41]; HOMER's Estimation

3.2.2 Solar Resource

Figure 3 presents the solar resource potentials of selected locations sourced through their geographical coordinates from the National Aeronautics and Space Administration (NASA) database [42]. The scaled annual average solar radiation ranges from 4.53 – 5.78kWh/m^2/day for almost the whole period of the year, although during the rainy season, March and October the potential falls between 6.5 and 3.5 kWh/m^2. In sum, the locations have promising solar resource potential.

Figure 3: Solar Radiation profile at Selected Locations



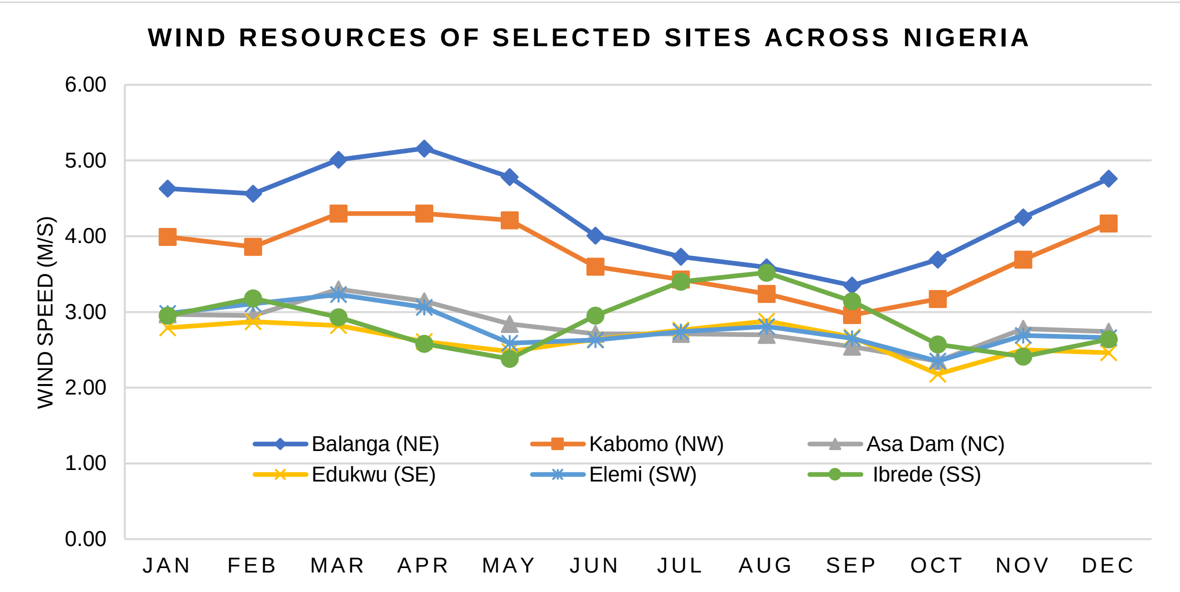
Source: NASA [42]

[1] Pre-feasibility studies on hydropower potential of these locations have been previously conducted by ECREEE [39], see details of the potential capacity therein

3.2.3 Wind resource

Figure 4 shows the monthly average wind speed for the selected sites, covering ten years as obtained from the NASA database [32]. The highest wind speed values occur in March (for NC and SW), April (NE, and NW) and August (SE and SS), whereas the least is observed in May (for SS), September (NE and NW) and October (NC, SE and SW). In sum, the locations possessed moderately good average annual wind speeds ranging from 2.64 m/s in Edukwu to 4.29 m/s in Balanga, which thus makes the utilization of wind power modestly feasible.

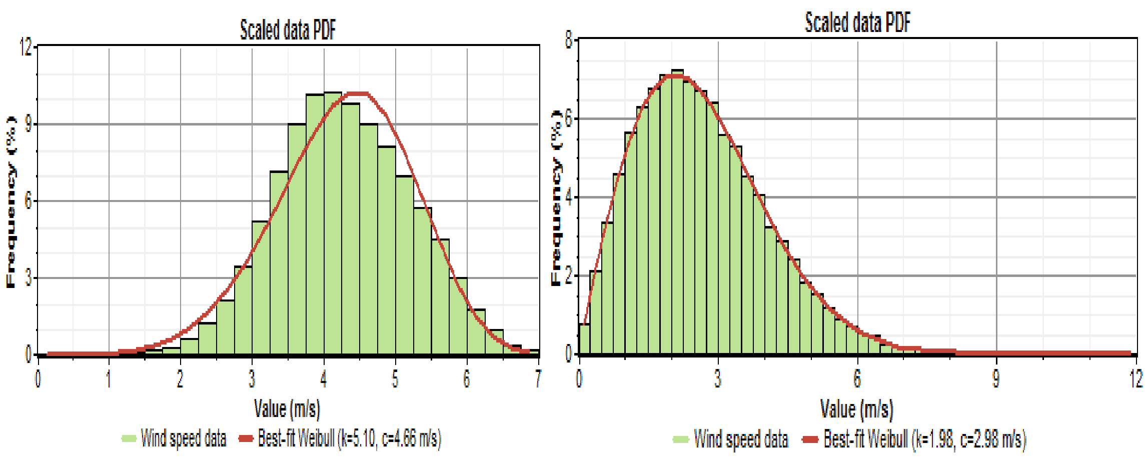
Figure 4: Wind Speed Profile of Selected Sites



Source: NASA [42]

Moreover, the Weibull parameters, often referred to as Weibull shape factor (k), alongside the scale parameter (c), are estimated by HOMER software to be 4.66 and 5.10 m/s and 1.98 and 2.98 m/s, respectively, for the site with the highest, Balanga (NE) and least, Edukwu (SE) wind speed. Figure 5 (a) and (b) respectively demonstrate the wind speed probability density function of these two sites.

Figure 5: Wind Speed Probability Distribution Function for Balanga (a) and Edukwu (b



Source: Generated by HOMER

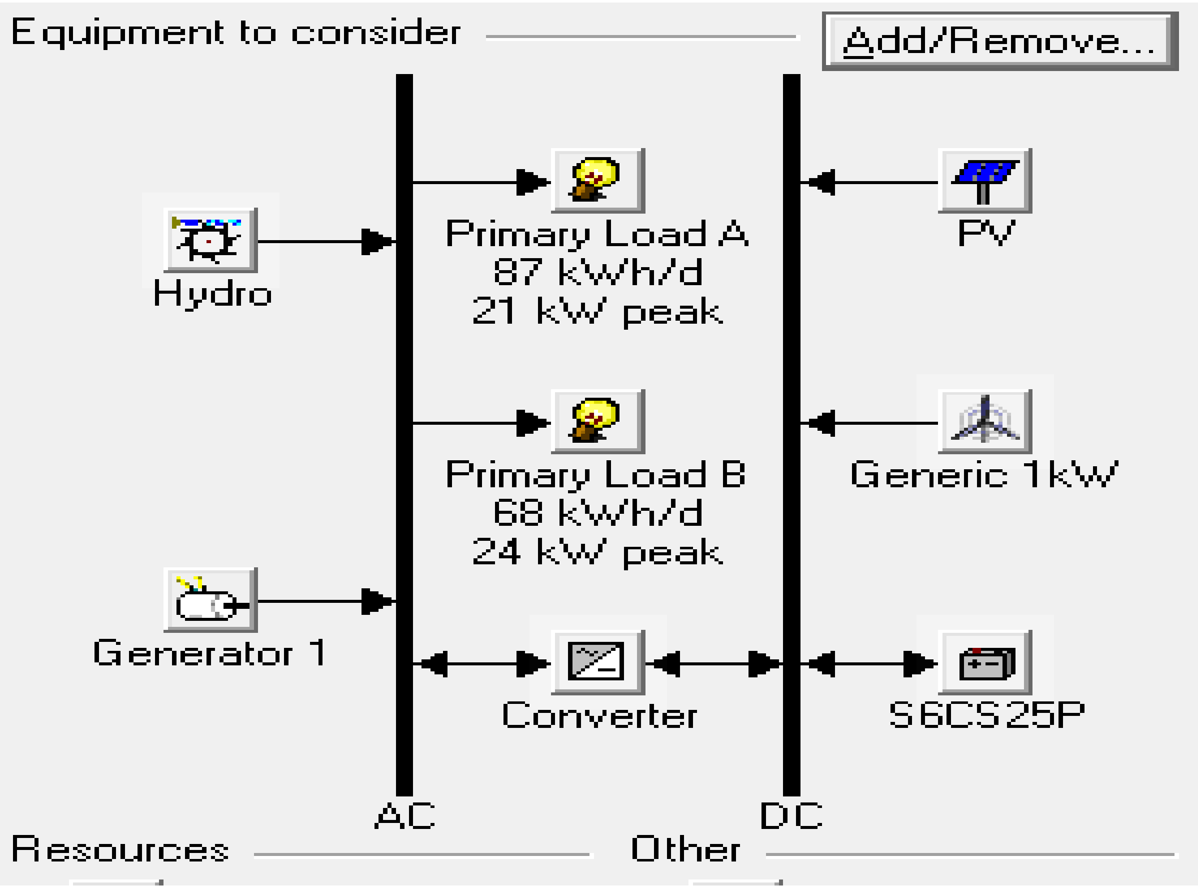
3.2.4 Diesel Price

The market price of diesel in Nigeria in 2018 was about $0.64 per litre (L) [43], but the recent subsidy removal increased the market value to approximately $0.75/L. This value is accordingly assumed in this study. However, with the global oil price fluctuations, the diesel pump price is considered to vary from 0.60 to $8.10/L to capture the effect of price fluctuations on the overall hybrid system cost and ascertain the environmental implications.

3.3 Technical & Economics Assumptions of Hybrid System Components

The proposed system is made up of hydropower (SHP) turbines, solar PV, wind turbines, diesel genset (for back-up), batteries and converters, as schematically depicted in Figure 6 below.

Figure 6: Schematic Depiction of Hybrid SHP/PV/wind/diesel/battery Structure.



Source: Developed by Authors from HOMER

Furthermore, the key information regarding the characteristics, sizing and pricing of these components is presented in Table 3 below and in the appendices (Table A-1 and A-2).

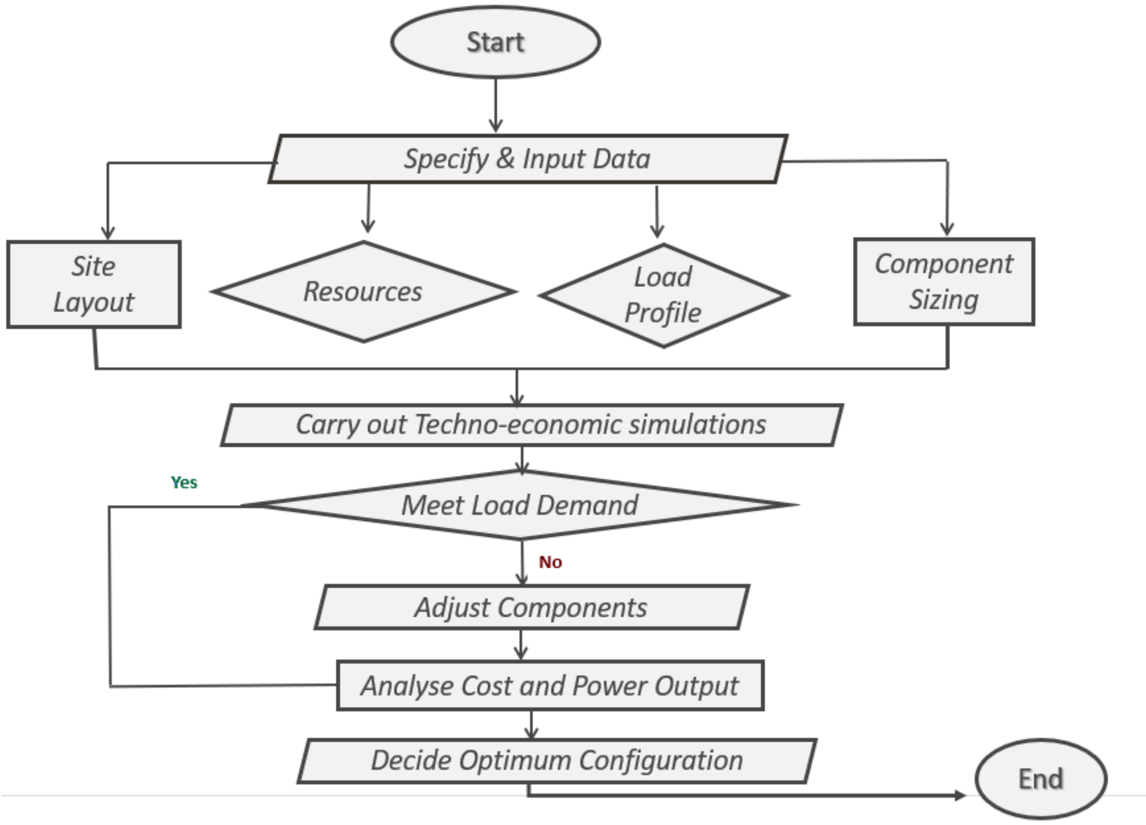
Table 3: Hybrid Components: Characteristics and Technical Data

Hydro Turbine	**Value**
Nominal Power (kW)	27-40
Quantity Considered	1
Lifetime (years)	25
Hydro Turbine Control	
Minimum flow ratio	25%
Maximum flow ratio	100%
Turbine efficiency	75%
Pipe head loss	9.50%
Wind Turbine Model: Generic 1kW	**Value**
Sizes Considered (kW)	0-10
Wind Turbine Control	
Hub Height (m)	25
Lifetime (years)	15
PV Module type: 1kW PV Array	**Value**
Module Size Considered (kW)	0-18
Lifetime (years)	20
PV Control	
Derating factor	90%
Tracking system	No Tracking
Azimuth	9.916˚
Ground reflectance	20%
AC Generator Brand: IkW DG	**Value**
Size Considered (kW)	15
Quantity Considered	1
Lifetime	15,000 hrs
Diesel Generator Control Min.	30%
Fuel used Diesel Fuel curve int.	0.08 L/hr/kW
Fuel curve slope	0.25 L/hr/kW
Fuel: Diesel Price	$0.75/L
Lower heating value	43.2 MJ/kg
Density	820 kg/m3
Carbon content	88.00%
Sulphur content	0.33%
Battery type: Surrette 6CS25P	**Value**
Quantity Considered	10
Lifetime throughput	9,645 kWh
Battery: Surrette 6CS25P Control	
Nominal capacity	1,156 Ah
Voltage	6 V
Batteries per string	8
Converter type:	**Value**
Converter Sizes to Consider (kW)	20

Lifetime (years)	15
Converter Control	
Inverter efficiency (%)	90%
Inverter can parallel with AC generator	Yes
Rectifier relative capacity (%)	100
Rectifier efficiency (%)	85

Figure 7 also shows the flowchart we followed for conducting the techno-economic evaluation.

Figure 7: Flowchart of techno-economic Evaluation



Source: Authors' construct

3.4 Synopsis Estimated Electrical Load

Sambo [44] pointed out that electric power in Nigerian rural communities is needed for domestic purposes (lighting, cooking, heating, and powering of household appliances like television, radio, fan, among others), agricultural purposes (for irrigation and crop processing like drying, grinding, threshing and oil extraction), community infrastructural purposes (schools, clinics, and halls) and to support agro-allied activities. Importantly, this goes beyond the simple binary measure of whether a community is connected or not to highlight more productive uses of energy within the Multi-Tier Energy Access Framework (MTF) [45]. In essence, most of the anticipated activities means that households and communities operate at Tier 5 (the highest scale on the MTF). Based on this, the study estimates the electrical load demand for a typical rural/remote community (during wet and dry seasons) as shown in Table 4 follows:

Table 4: Electricity Load Requirement for hypothetical village in Nigeria

S/N	Load Description	Amount in use	Power (Watts)	Wet Season (March–October) Hours/day	Wet Season (March–October) Watt-hrs/day	Dry Season (November-February) Hours/day	Dry Season (November-February) Watt-hrs/day
LOAD TYPE A							
	a. Domestic Load						
	Lighting (CFL)	4	20	12	960	10	800
	Radio	1	10	8	80	7	70
	Television	1	80	4	320	4	320
	Ceiling Fan	2	30	2	120	6	360
	Mobile Phone	2	5	5	50	4	40
	Total				***1,530***		***1,590***
	Total No. of Houses in the Community	**50**			**76,500**		**79,500**
	b. School						
	Lighting (CFL)	4	20	2	160	2	160
	Ceiling Fan	2	30	0	0	2	120
	Computer	1	300	4	1200	4	1200
	Total				***1,360***		***1,480***
	c. Clinic						
	Lighting (CFL)	6	20	12	1440	10	1200
	Television	1	80	8	640	8	640
	Ceiling Fan	4	30	2	240	6	720
	Vaccine Refrigerator	1	600	8	4800	12	7200
	Total				***7,120***		***9,760***
LOAD TYPE B							
	a. Community Hall/ Infrastructure						
	Lighting (CFL)	6	20	6	720	5	600
	Ceiling Fan	4	30	3	360	6	720
	Television	1	80	5	400	6	480
	Community Street Lights (CFL)	5	30	12	1800	10	1500
	Total				***3,280***		***3,300***
	b. Industrial, Agriculture & Commercial Load						
	Shops	5	500	5	12500	6	15000
	Small Industry & Agro-processing Units	2	3000	5	30000	6	36000
	Water (Well) Pump	3	745.6	2	4474	6	13421
	Irrigation Pump	2	1491.2	0	0	4	11930
	Total				***46,974***		***76,351***
	c. Miscellaneous Load		**100**	**6**	***600***	**6**	***600***
OVERALL LOAD REQUIREMENT					**135,834**		**170,991**

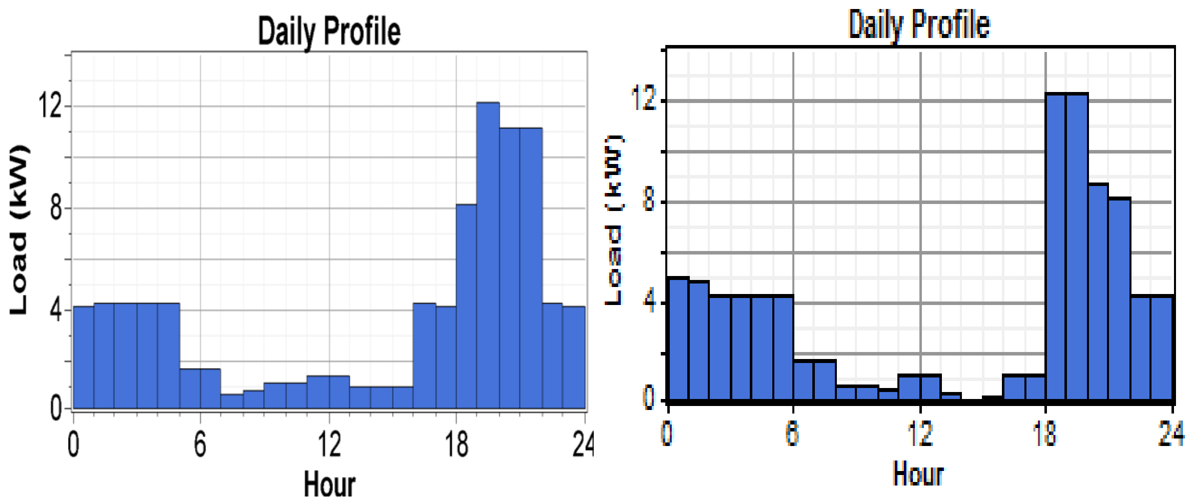
It can be noticed from Table 4 that the load demand estimates for dry (November to February) is higher than that of wet (March to October) season. This is principally due to extreme dryness with high temperature reaching 40˚C (104.0 ˚F) during this season, which consequently increases the utilization rate of basic appliances (fans and refrigerators), and domestic/agricultural facilities, like water and irrigation pumps to ensure water availability and enhance overall economic productivity. Whereas in the wet season, the reverse is the case. It is characterized by cold weather conditions, abundant rainfall, and increased cloud cover, which considerably reduces the need for appliances.

3.4.1 Primary Load A

This load is designed to cater to the village's domestic, health, and education power requirements. With an estimated scaled annual average of 87.1kWh/day alongside a load factor of 0.167, the peak power demand is expected to happen between 19:00 and 22:00. This is the period in which rural dwellers customarily require electric power for lighting and powering of household appliances. Figure 8 (a) and (b) respectively represent the outlook of this load during the dry and wet seasons. In general, the load is higher in the latter than the former owing to the high energy-consuming peculiarities of the dry season earlier mentioned.

Figure 8: Load sketch for Primary Load A during the Dry (a) and Wet (b) Seasons

(a) **(b)**



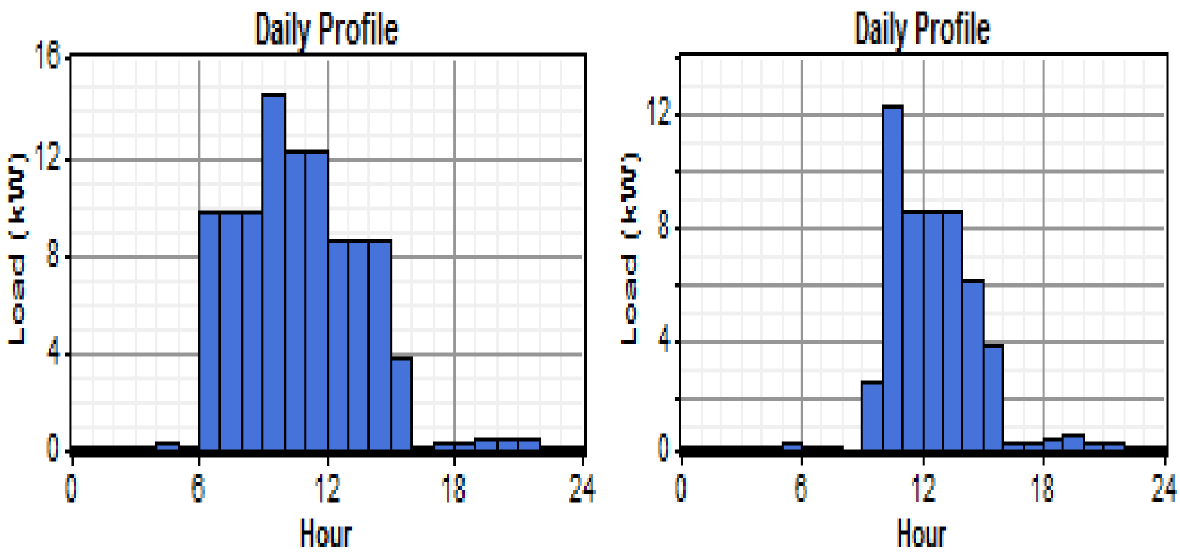
Source: Author's Computation with HOMER

3.4.2 Primary Load B

This consists of electric load to supply the community hall, local business, micro industries and agro-allied units in the community. The scaled annual average value is estimated at 68.4kWh/day with a load factor of 0.128. This load during the dry season, as depicted by Figure 9 (a) increases from about 9.8 kW between 6:00 and 9:00am to peak a period of 14.6kW the following hour, which subsequently decline step wise to reach 3.7 kW by 4:00pm. Contrarily in the wet season, the load increases sharply from 2.5kw at 9:00am to reach 12.3 kW in the next hour (10:00am) and thereafter remains uniform for three hours before nosediving to reach 3.7kW by 4:00pm. In sum, the primary operational period of this load is between 06:00am - 4:00pm, which represents the period of high electricity demand for community's industrial, agricultural, and commercial activities.

Figure 9: Load sketch for Primary Load B Dry (a) and Wet (b) Seasons

(a) **(b)**

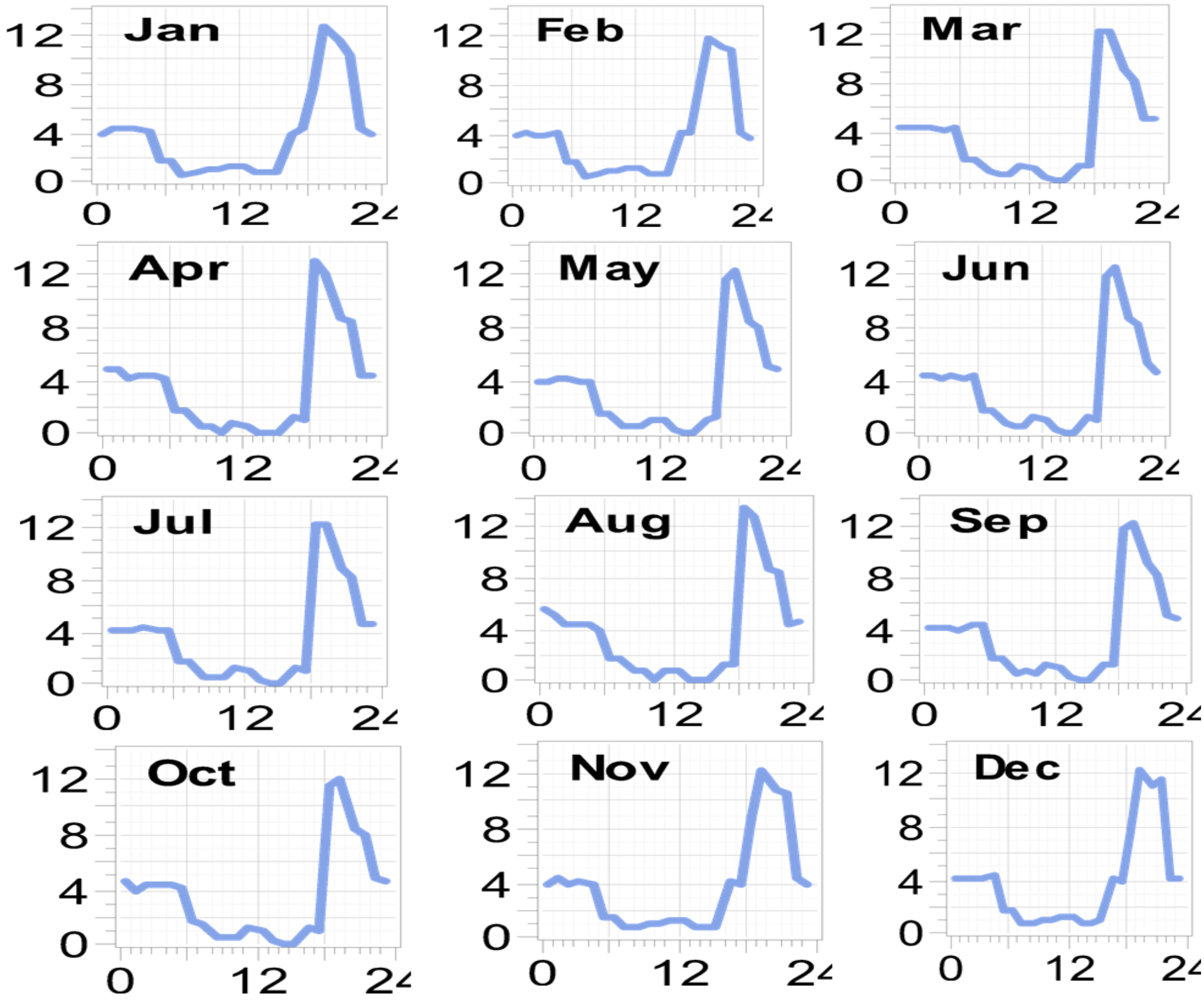


Source: Author's Computation with HOMER

In addition, the daily electric load distribution profile of the village on monthly basis is as shown in Figure 10. While the hourly load curves may appear similar for some months, especially those in the same season, a closer look at the tails, the lower crests and plateaux of the curves will unravel the major differences in the hourly load configuration of each month. For instance, during the wet season (March- October), the load demand is slightly different in April, August and September because these three months represent the vacation periods in the Nigerian primary and secondary schools' academic calendar and as such, no school load would be required.

Generally, it can be observed that the load requirements are lowest during day times, from 8:00am to 4:00pm, as these constitute the significant working hours for rural dwellers, who are predominantly farmers and spend such periods on farms. The highest demand, on the other hand, is seen to occur during the night-time from 6:00 p.m. to 10:00 p.m. as this denotes the recreational cum resting period. Having developed the hourly data, data relating to the proposed hybrid system's economic feasibility and technical performance has been fed into the HOMER software for simulation and optimization purposes.

Figure 10: Village hourly load requirement by months (January and December)



Source: Author's construct

4 Results and Discussion

4.1 Optimal Hybrid Configuration for Six Geopolitical Zones of Nigeria

The overall top five optimal hybrid architectures for the six geopolitical zones in Nigeria is presented in Table 5 below. The most cost-effective configuration in all cases falls within the PV/hydro/generator/battery design. The first row in each location denotes the most optimal system configuration, based on lowest NPC value. For instance, in Balanga, the optimal configuration contains 9kW solar PV, 33.1kW hydro, the 12.5kW generator, 16 batteries and 10kW converter. The second rank is like the first rank except that it contains 12kW PV instead of 9kW PV. All the top 5th ranked system contains no wind, except for Elemi and Ibrede, with the 5th rank containing 2kW wind turbine

Table 5: Extract from HOMER's Overall Simulation result: Top Five for each site

	PV	Wind	Hydro	Gen.	Battery	Converter	Total Capital Cost	Total NPC	Tot. Ann. Cap. Cost	Tot. Ann. Repl. Cost	Total O&M Cost	Total Fuel Cost	Total Ann. Cost	Operating Cost	COE
	kW	kW	kW	kW	no.	kW	$	$	$/yr	$/yr	$/yr	$/yr	$/yr	$/yr	$/kWh
Balanga (NE)	9	0	33.1	12.5	16	10	9,1345	**317,077**	7,838	1,123	11,408	6,839	27,209	19.370	**0.479**
	12	0	33.1	12.5	16	10	9,8845	**318,088**	8,482	1,178	11,294	6,341	27,295	18,813	**0.481**
	12	0	33.1	12.5	16	15	10,2345	**318,669**	8,782	1,217	11,194	6,152	27,345	18,563	**0.482**
	15	0	33.1	12.5	16	15	10,9845	**319,266**	9,426	1,267	11,006	5,698	27,396	17,970	**0.483**
	15	0	33.1	12.5	16	10	10,6345	**319,869**	9,126	1,231	11,156	5,936	27,448	18,323	**0.484**
Kabomo (NW)	12	0	36.8	12.5	16	10	103,845	**326,567**	8,911	1,183	11,398	6,531	28,023	19,112	**0.494**
	15	0	36.8	12.5	16	10	111,345	**329,446**	9,555	1,237	11,281	6,197	28,270	18,715	**0.498**
	15	0	36.8	12.5	32	10	130,065	**330,386**	11,161	1,661	10,143	5,387	28,351	17,190	**0.500**
	12	0	36.8	12.5	16	15	107,345	**331,294**	9,211	1,237	11,566	6,414	28,428	19,217	**0.501**
	12	0	36.8	12.5	32	10	122,565	**332,305**	10,517	1,614	10,431	5,952	28,515	17,998	**0.502**
Asa Dam (NC)	9	0	34.9	12.5	16	10	91,345	**260,534**	7,838	990	8,889	4,639	22,357	14,518	**0.394**
	12	0	34.9	12.5	16	10	98,845	**264,134**	8,482	1,045	8,794	4,344	22,665	14,184	**0.399**
	0	0	34.9	15	16	10	69,470	**265,026**	5,961	844	9,938	6,000	22,742	16,781	**0.401**
	3	0	34.9	15	16	10	76,970	**266,408**	6,605	896	9,788	5,572	22,861	16,256	**0.403**
	15	0	34.9	12.5	16	10	106,345	**269,737**	9,126	1,104	8,774	4,142	23,146	14,021	**0.408**
Edukwu (SE)	3	0	38.6	12.5	16	10	76,345	**251,877**	6,551	881	9,114	5,068	21,614	15,062	**0.381**
	9	0	38.6	12.5	16	10	91,345	**255,005**	7,838	982	8,746	4,316	21,882	14,044	**0.386**
	12	0	38.6	12.5	16	10	98,845	**258,266**	8,482	1,035	8,616	4,028	22,162	13,680	**0.39**
	0	0	38.6	15	16	5	65,970	**259,545**	5,661	793	9,843	5,975	22,272	16,611	**0.392**
	3	0	38.6	15	16	10	76,970	**261,733**	6,605	891	9,698	5,266	22,459	15,855	**0.396**
Elemi (SW)	9	0	27.6	12.5	16	10	91,345	**297,360**	7,838	1,075	10,493	6,111	25,517	17,678	**0.450**
	12	0	27.6	12.5	16	10	98,845	**299,069**	8,482	1,126	10,335	5,720	25,663	17,181	**0.452**
	15	0	27.6	12.5	16	10	106,345	**303,300**	9,126	1,182	10,268	5,450	26,026	16,901	**0.459**
	9	0	27.6	12.5	16	15	94,845	**305,287**	8,139	1,139	10,874	6,045	26,197	18,058	**0.462**
	9	2	27.6	12.5	16	10	98,345	**307,009**	8,439	1,217	10,649	6,040	26,345	17,906	**0.464**
Ibr ede	3	0	28	15	16	10	76,970	**237,362**	6,605	831	8,618	4,315	20,368	13,763	**0.359**
	0	0	28	15	16	10	69,470	**241,383**	5,961	797	9,079	4,876	20,713	14,752	**0.365**

	9	0	28	15	16	10	91,970	**241,572**	7,892	936	8,239	3,663	20,729	12,837	**0.365**
	12	0	28	15	16	10	99,470	**247,091**	8,536	995	8,209	3,464	21,203	12,667	**0.374**
	3	2	28	15	16	10	83,970	**248,087**	7,206	976	8,818	4,290	21,288	14,083	**0.375**

Source: Authors' construct

In sum, the optimal design is similar for all regions (although with significantly different NPC and COE), and it is composed of different combinations of PV/SHP/generator/batteries configuration. Wind turbine is not chosen by HOMER for any of the sites owing to the weak average wind speed and high capital outlay, which may not make it yields lowest NPC for the proposed system. However, few instances wind integration and feasibility are observed in categorized optimization discussed below.

In Table 6, the first six rows reveal the matching hybrid components sizes that signifies the least-cost hybrid solution for each of the six locations. Of course, the contribution of wind turbine in all cases is zero; the average wind speed in 4 of the 6 locations is low, as earlier depicted in Figure 4, thus making it an unattractive component for hybrid applications in majority of the locations. The proposed system configuration gives the highest and lowest capital cost of $103,845 and $76,970 respectively in Kabomo (NW) and Ibrede (SS). These locations from the NPC perspective equally give the highest ($326,567) and lowest ($ 237,362) NPC respectively.

Moreover, the cost of electricity (COE) follows similar pattern with total NPC as it increases from $0.359/kWh in Ibrede, $0.450/kWh in Elemi to reach $0.494/kWh in Kabomo. Generally, the capital cost, NPC and COE is highest in the northern part of the country because of the huge solar potential that require high investment cost to develop and high reliance on diesel generation to supplement production especially during the dry-season months with low flow rate.

Table 6: Best Hybrid System Configuration for Six Geopolitical Zones in Nigeria

		Balanga (NE)	**Kabomo (NW)**	**Asa Dam (NC)**	**Edukwu (SE)**	**Elemi (SW)**	**Ibrede (SS)**
PV	kW	9	**12**	9	3	9	**3**
Wind	kW	0	**0**	0	0	0	**0**
Hydro	kW	33.1	**36.8**	34.9	38.6	27.6	**28.0**
Generator	kW	12.5	**12.5**	12.5	12.5	12.5	**15.0**
Battery	no.	16	**16**	16	16	16	**16**
Converter	kW	10	**10**	10	10	10	**10**
Total Capital Cost	$	91,345	**103,845**	91,345	76,345	91,345	**76,970**
Total NPC	**$**	**317,077**	**326,567**	**260,534**	**251,877**	**297,360**	**237,362**
Tot. Ann. Cap. Cost	$/yr	7,838	**8,911**	7,838	6,551	7,838	**6,605**
Tot. Ann. Repl. Cost	$/yr	1,123	**1,183**	990	881	1,075	**831**
Total O&M Cost	$/yr	11.408	**11,398**	8,889	9,114	10,493	**8,618**
Total Fuel Cost	$/yr	6,839	**6,531**	4,639	5,068	6,111	**4,315**
Total Ann. Cost	$/yr	27,209	**28,023**	22,357	21,614	25,517	**20,368**
Operating Cost	$/yr	19,370	**19,112**	14,518	15,062	17,678	**13,763**
COE	**$/kWh**	**0.479**	**0.494**	**0.394**	**0.381**	**0.450**	**0.359**

Source: Authors' construct

4.2 Net Present Cost of Feasible System Architects

In Table 8 above, the least NPC ($237,362) is obtained in Ibrede (SS) whereas Kabomo (NW) yields the highest NPC of $326,567. The result shows the existence of direct relationship between NPC and the designed flow rate. The lower the water flow in a site, the higher the NPC value will be. This is because lower flow rate will make the hydro system to supply the load for a shorter period, thus increasing the need for, and operating hours of the diesel generator; this will give rise to diesel consumption and (O&M) cost associated with diesel, which thus culminating in an increased NPC.

Likewise, Table 8 displays the threshold of total annual costs ($20,368-$27,209) required to implement the proposed hybrid system in each region. Overall, the total annual cost ($20,368-$27,209) is higher than the operating cost ($13,763-$19,370). Nevertheless, both costs have significant impacts on the NPC and COE.

4.3 Annual Average Electricity Production by Optimal Configuration

According to Table 9, the annual average electrical output, which ranges from 129,283 kW/yr (Asa Dam) to 94,230 kW/yr (Elemi), is predominantly supplied by PV, SHP and generator. The highest production occurs in the former owing to its high flow rate with sizeable solar radiation compared to other sites. SHP dominates the generation mix in all cases, as it is seen to account for 84.3%, 76.9% and 63.2% of the total electrical production in Ibrede (SS), Asa Dam (NC) and Balanga (NE) respectively. Next to SHP is PV, whose contribution ranges from 3.9%, in region with least solar potential Ibrede (SS) to 19.4% in Kabomo (NW) with the maximum solar radiation as earlier revealed in Figure 2. Additionally, the generator constitutes another significant component (for supplementing renewable power and meeting the load demand) as it is seen to be responsible for 12-20% of the overall system output.

Table 9: Annual Average Electricity Production by Optimal Configuration

		Balanga (NE)	Kabomo (NW)	Asa Dam (NC)	Edukwu (SE)	Elemi (SW)	Ibrede (SS)
Total Elec. Prod	**kWh/yr**	**103,727**	**115,657**	**129,283**	**115,750**	**94,230**	**114,017**
PV Production	kWh/yr	16,992	22,456	15,152	4,947	14,570	4,424
Wind Production	kWh/yr	0	0	0	0	0	0
Hydro Production	**kWh/yr**	**65,528**	**73,309**	**99,477**	**94,607**	**60,515**	**96,109**
Gen. Production	kWh/yr	21,207	19,892	14,654	16,196	19,145	13,484
AC Primary Load Served	kWh/yr	56,749	56,736	56,746	56,733	56,745	56,750
Renewable Fraction		**0.80**	**0.83**	**0.89**	**0.86**	**0.80**	**0.88**
Cap. Shortage	kWh/yr	27	53	37	48	35	19
Cap. Shortage Frac.		0	0	0	0	0	0

Unmet Load	kWh/yr	9	21	12	24	13	7
Unmet Load Frac.		0	0	0	0	0	0
Excess Electricity	**kWh/yr**	**43,470**	**55,477**	**70,399**	**56,559**	**33,995**	**54,854**

Source: Authors' construct

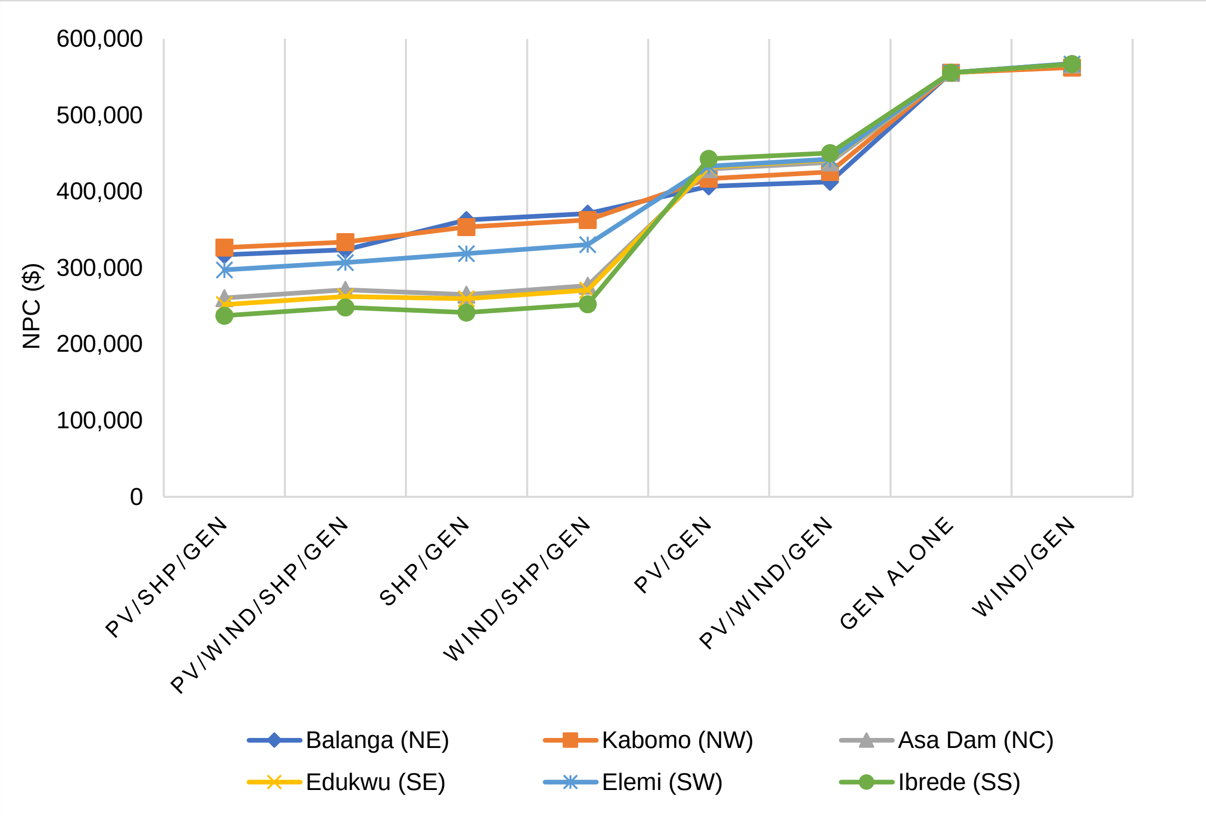
As for the renewable fraction (RF), Bekele and Palm [39] noted that a system can only be classified as renewable system if the contribution of its renewable component is 27% or more. Far beyond this value, the least contribution of renewables is 80%, achieved by the optimum set-up obtained for Balanga (NE) and Elemi (SW) as shown in Table 6. Whereas Asa Dam (NC) gives the highest RF proportion of 89%, followed by Ibrede (SS), 88%, and Edukwu (SE), 86%.

In sum, the PV/SHP/diesel system enables renewable technologies to supply about 80-90% of the average annual electricity production. As a result, the capacity shortage and unmet load turns out to be very small, 7-24 and 19-48 kW/yr respectively, which accordingly makes their overall impact to be insignificant (0%). Likewise, the excess electricity produced constitutes about 36-54% of the total production because of moderately low power requirement especially during the wet season (March-October) when water flow is high and hydro plant operates at full capacity. This substantial unused electricity reveals the system's capability to meet extra load or future increase, and as well supply electricity to neighbouring communities.

4.4 Categorized/ Other Promising Hybrid Designs for Nigeria's Geopolitical Zones

As illustrated below, the use of PV/SHP/Gen gives the least cost (and most viable) hybrid power supply option, followed by PV/wind/SHP/generator, while SHP/generator and wind/SHP/generator set-up respectively gives the third and fourth best optimal solution. The NPC of stand-alone diesel generator that is slightly higher than that of wind/generator makes them the seventh and eighth options respectively. However, these last two combinations can be regarded as infeasible options owing to their high NPC, low wind speed in majority of the sites alongside associated huge pollutant emission that will adversely affect the environment

Figure 10: Possible System Configuration for six geopolitical zones in Nigeria



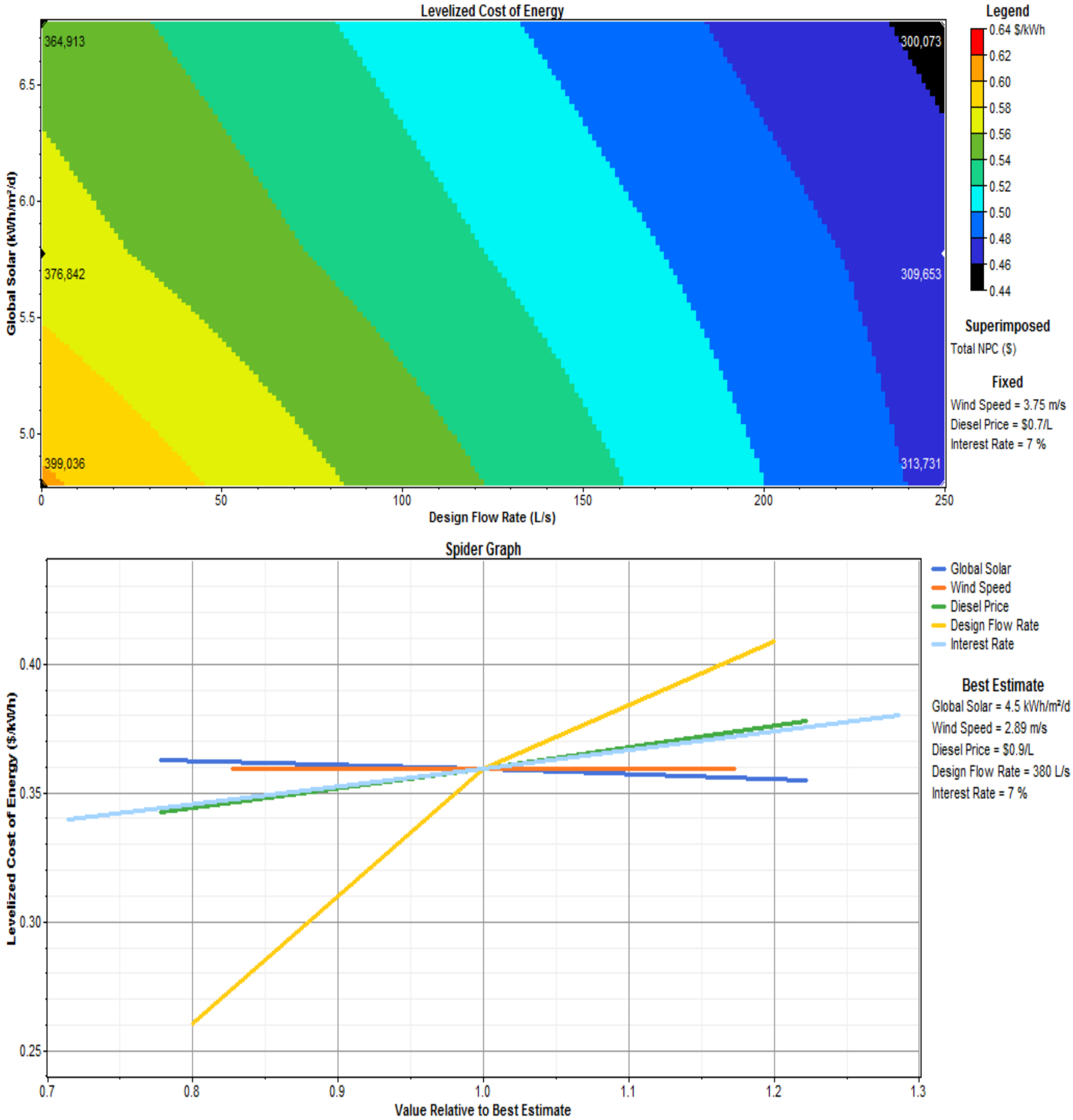
Source: Authors' construct

From the above, it can thus be deduced that system configuration with SHP is more cost-effective than other renewable power combinations. As such, the COE values of optimal feasible systems without SHP can be relatively high compared to Nigeria's current electricity tariff. Nonetheless, given the country's low electrification rate, especially in rural areas, this cost needs to be considered as a decisive factor. Additionally, the impressively high RF penetration coupled with reduced diesel fuel consumption supports clean energy development in rural areas, lessens environmental pollutant emission into the atmosphere, and improves the living standard of people in remote areas.

4.5 Sensitivity Analysis

Figure 11 (a) showcases the surface plot of levelized COE superimposed with the total NPC for Kabomo (NW) with the highest electricity cost. Power generation from SHP increases with increasing design flow rate, thus causing a reduction in the system's overall NPC. Similarly, the LCOE decreases (from $0.62 to 0.44 kW/h (see the legend) with decreasing NPC (from $399,036 to $313,731). Furthermore, Figure 11 (b) summarises the impact of variation in five considered variables, including design flow rate, wind speed, solar radiation, diesel price and interest rate on the hybrid system's economic effectiveness, in terms of NPC and LCOE values

Figure 11: Surface Plot on Sensitivity of Flow Rate and Impact of Variation in other Parameters



Source: Authors' construct

It suggests that variation in the design flow rate significantly impacts the hybrid system's output alongside its economic effectiveness in terms of NPC and LCOE values. As such, if SHP option is not available, the cost of electricity will be very high in all the locations. As illustrated in Fig. 11 (b), the designed flow rate is the most sensitive parameter as its variation primarily affects the system's LCOE, followed by interest rate and diesel price. In contrast, the effect of solar radiation on LCOE is found to be small yet slightly more pronounced than that of wind speed.

4.6 Environmental Emissions of Selected Hybrid Configurations

As per the magnitude of pollutant emissions from the developed hybrid configurations, Table 10 suggests that the hybrid combination PV/Wind/SHP/Gen provides the least pollutant emission against the optimum configuration (PV/SHP/Gen). This is due to higher number of renewable components (three - PV, wind, and SHP) as against (two – PV and SHP) in the selected optimum configuration. Nonetheless, stand-alone diesel generator stimulates the highest emission volume.

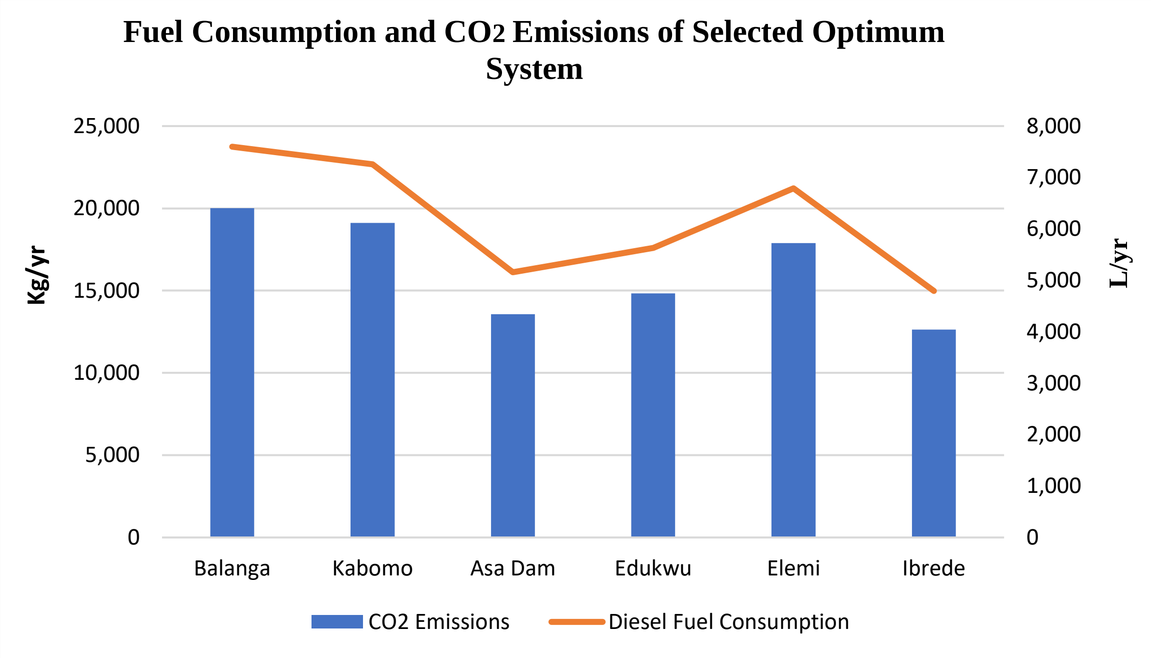
Table 10: Comparison of Environmental Emissions from Hybrid Configurations

Hybrid Configuration	**Emission Kg/yr**											
	CO_2	**CO**	**UHC**	**PM**	**SO_2**	**No_x**	**CO2**	**CO**	**UHC**	**PM**	**SO2**	**NOx**
	Balanga (NE)						**Kabomo (NW)**					
PV/SHP/Gen	20,010	49	5	4	40	441	19,110	47	5	4	38	421
SHP/Gen	27,088	67	7	5	54	597	27,410	68	7	5	55	604
PV/Wind/SHP/ Gen	**14,211**	**35**	**4**	**3**	**29**	**313**	**31,659**	**78**	**9**	**6**	**64**	**697**
Wind/SHP/Gen	26,828	66	7	5	54	591	28,688	71	8	5	58	632
PV/Gen	30,740	76	8	6	62	677	31,659	78	9	6	64	697
PV/Wind/Gen	30,023	74	8	6	60	661	28,688	71	8	5	58	632
Gen Alone	**59,130**	**146**	**16**	**11**	**119**	**1,302**	**59,130**	**146**	**16**	**11**	**119**	**1,302**
Wind/Gen	58,474	144	16	11	117	1,288	58,031	143	16	11	117	1,278
	Asa Dam (NC)						**Edukwu (SE)**					
PV/SHP/Gen	13,574	34	4	3	27	299	14,829	37	4	3	30	327
SHP/Gen	17,555	43	5	3	35	387	17,483	43	5	3	35	385
PV/Wind/SHP/ Gen	**13,483**	**33**	**4**	**3**	**27**	**297**	**14,739**	**36**	**4**	**3**	**30**	**325**
Wind/SHP/Gen	17,480	43	5	3	35	385	17,397	43	5	3	35	383
PV/Gen	33,779	83	9	6	68	744	34,157	84	9	6	69	752
PV/Wind/Gen	33,468	83	9	6	67	737	33,924	84	9	6	68	747
Gen Alone	**59,130**	**146**	**16**	**11**	**119**	**1,302**	**59,103**	**146**	**16**	**11**	**119**	**1,302**
Wind/Gen	58,813	145	16	11	118	1,295	58,871	145	16	11	118	1,297
	Elemi (SW)						**Ibrede (SS)**					
PV/SHP/Gen	17,881	44	5	3	36	394	**12,625**	**31**	**3**	**2**	**25**	**278**
SHP/Gen	23,808	59	7	4	48	524	14,268	35	4	3	29	314
PV/Wind/SHP/ Gen	**17,673**	**44**	**5**	**3**	**35**	**389**	**12,552**	**31**	**3**	**2**	**25**	**276**
Wind/SHP/Gen	23,662	58	6	4	48	521	14,138	35	4	3	28	311
PV/Gen	34,477	85	9	6	69	759	36,148	89	10	7	73	796
PV/Wind/Gen	34,215	84	9	6	69	754	35,730	88	10	7	72	787
Gen Alone	**59,130**	**146**	**16**	**11**	**119**	**1,302**	**59,130**	**146**	**16**	**11**	**119**	**1,302**
Wind/Gen	58,876	145	16	11	118	1,297	58,803	145	16	11	118	1,295

Source: Authors' construct

Finally, with CO_2 as the principal GHG accounting for the largest percentage of all emissions whenever fuel is burnt, Figure 12 demonstrates the relationship between fuel consumption (in L/yr) and the total volume of CO2 (in Kg) produced by the selected optimum hybrid configuration per year. The Figure reveals that the higher the fuel consumption, the higher the CO_2 emission volume. Balanga (NE) consumes the most fuel, whereas Ibrede (SS) consumes the least.

Figure 12: Fuel Consumption and CO_2 Emissions Nexus



Source: Authors' construct

With the above analysis, it can be concluded that a hybrid configuration system comprising of SHP, PV and generator constitutes the most cost-effective option for off-grid rural electricity supply across the six geopolitical zones of Nigeria. The presence of SHP in the system in the mix makes it the highest RF but least NPC and COE values, thus economically viable for power supply. Without SHP however, the RF reduces while the value of NPC and COE increases, which may thus require government interventions to make such arrangements very attractive to prospective investors.

5 Conclusion and policy recommendations

The key findings of the study can be summarised as follows:

- The most cost-effective configuration falls within the PV/hydro/generator/battery design. This in Balanga (NE), with the highest NPC and COE, contains 9kW solar PV, 33.1kW hydro, 12.5kW generator, 16 batteries, and a 10kW converter
- HOMER does not choose wind turbines for any of the sites owing to the averagely weak wind speed and high capital outlay, which may not make it yield the lowest NPC for the proposed system. However, simulation results from other wind-related configurations yet prove wind system to be cost-effective in sites with good wind speed with regards to NPC analysis
- The proposed system configuration gives the highest and lowest capital costs of $103,845 and $76,970, respectively, in Kabomo (NW) and Ibrede (SS). From the NPC perspective, these locations equally give the highest ($326,567) and lowest ($ 237,362) NPC, respectively.
- Moreover, the cost of electricity (COE) follows a similar pattern to total NPC, ranging from $0.359/kWh in Ibrede (SS) to $0.494/kWh in Kabomo (NW). Hence, it constitutes the cheapest and most expensive electricity generation cost among the selected sites.

- The annual average electrical output, which ranges from 129,283 (in Asa Dam) to 94,230 kW/yr (Elemi), is predominantly supplied by SHP (63-85%), followed by diesel generator (12-20%) and solar PV (4-19%).
- As for renewable fraction (RF), the least RF value of 80% is obtained in Balanga (NE) and while the highest value of 89% is observed in Asa Dam (NC). As such, the proposed PV/SHP/diesel system will enable renewable technologies to supply about 80-90% of the average annual electricity production
- In terms of the concern for capacity shortage and unmet load, the value obtained is very small, 7-24 and 19-48 kW/yr respectively, thus making the overall impact to be insignificant (0%)
- The excess electricity production (of about 36-54%) reveals the capability of the proposed configuration to meet extra load, future demand increase, and as well supply electricity to neighbouring communities
- Apart from PV/SHP/generator being the optimal design, PV/wind/SHP/generator, SHP/generator, wind/SHP/generator, PV/generator, PV/Wind/generator constitute other feasible solution for implementation in the selected sites. Although the last two might require government incentive and support mechanisms to be attractive to investors
- As generator only and wind/gen systems provide the highest NPC (of over $555,627) and emit around 58,870 kg of CO_2 per year. They are considered to be economically infeasible owning to associate the high NPV and also GHGs cum pollutant emissions from the system
- Also, the emission from the optimum configuration system in this least-cost region Ibrede (SS) is estimated to contain 12,625 kg/yr of CO_2, 25.0 kg/yr for SO_2 and 278 kg/yr of NOx.
- Finally, the sensitivity analysis unravels variation in designed hydro flow rate as the most significant determinant of LCOE and NPC, followed by interest rate, diesel price and solar radiation. However, the effect of wind speed variation is observed to be trivial in all the considered sites.

From the foregoing therefore, this study concludes that the proposed best hybrid system, Hydro/PV/generator, has the potential of delivering the most affordable (cost-effective), accessible (off-grid) and acceptable (environmentally friendly) electricity supply to rural communities in the six geopolitical zones of Nigeria. More so, the suggested hybrid option can significantly improve rural dwellers' socio-economic growth and standard of living, thereby reducing the growing rate of rural-urban migration in the country. Finally, the emission result reveals that the suggested hybrid system significantly reduces the GHGs and particulate matter emissions compared to diesel power generation, thereby making it a superior option for curbing the rising concern of global warming stemming principally from high CO_2 emission into the atmosphere.

The findings of this study provide possible pathways for Nigeria to implement the laudable Renewable Energy Master Plan (REMP) of rural electrification and reach 36% renewable electricity generation by 2030 [47]**.** RE policies need to combine distinct (fiscal and market) support mechanisms with an enabling environment (both regulatory and institutional) and huge upfront costs and long-term financial investments to accelerate the pace of decentralized solution deployment for rural electrification across the country's six geopolitical zones.

Policy Recommendations

- The creation of an enabling environment and measures (both regulatory and institutional) for rapid uptake of decentralized power generation in rural areas to foster energy access, agricultural productivity, and rural economy is needed.

- Provision of fiscal and market supportive mechanisms/incentives (such as subsidies, grants, tax breaks, tax reductions, rebates, and specific funding) to attract investors to rural electrification projects and recoup their capital outlays is essential to improving project profitability.

- Finally, significant upfront costs and long-term financial investments are required to accelerate the pace of off-grid hybrid solutions for the electrification of remote rural areas across the country's six geopolitical regions. The government could attained this by setting up public-private partnerships (PPPs) with investors, including national and global pension funds, to source cheaper long-term capital.

CRediT authorship contribution statement

Nathaniel Babajide: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Theophilus Acheampong:** Conceptualization, Formal analysis, Writing – review & editing. **Bridget Menyeh:** Conceptualization, Review & Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A-1: Hybrid System Component: Sizing Details

Hydro Turbine (kW)	PV Array (kW)	Wind Turbine (Quantity)	Diesel Generator (kW)	Battery (string)	Converter (kW)
20	0	0	0	0	0
30	3	2	5	2	5
40	9	4	10	4	10
	12	6	7.5	6	15
	15	8	10	8	20
	18		12.5	10	
			15		

Source: the study

Table A-2: Cost of the Hybrid System Components

Components	Capital Cost (US$/kW)	Replacement Cost (US$/kW)	O&M Cost (US$/kW-yr)
Hydro Turbine	30,000	25,000	2,000
Wind Turbine (Generic 1kW)	3,500	2,800	100
Solar PV (1kW)	2,500	2,000	10
Generator (1kW)	250	200	0.25/hr
Battery	1,170	800	50
Converter	700	550	100