Contents list available at IJRED website

International Journal of Renewable Energy Development

Journal homepage: https://ijred.undip.ac.id

Research Article

Comparison of the Grid and Off-Grid Hybrid Power Systems for Application in University Buildings in Nigeria

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Abstract. The Nigerian Universities rely on weak and unreliable fossil-based electric grids with diesel engine generators (DEG) as a backup. However, there is a potential to light up the campuses using power systems derived from primary renewable power systems (RPS) like wind turbine (WT) and solar photovoltaic (PV), that can be on or off-grid to improve the energy mix and duration reliably. This study presents the comparative analysis of the optimal hybrid grid and off-grid systems (OGS & OOGS) for serving the demand load of university buildings in four climatic regions of Nigeria. HOMER Pro is used to design and select the systems based on minimal net present cost (NPC) and cost of electricity (COE). The impact of a minimal renewable fraction of 95% on the optimal system architecture (OSA) and COE is studied for both grid and off-grid modes. Also, sensitivity analysis of the impact of key variables on performance for the sites is carried out. It is found that the OGS in the four regions is PV/Converter (Conv), while for the OOGS, it is PV/WT/DEG/battery (BB)/Conv except in Port Harcourt (PH), where it is PV/DEG/BB/Conv. The COE for the OGS in the Savana and monsoon climes of Enugu and PH are 10 and 19% more than that in the warm-semi arid climate zones of Maiduguri and Kano, which is approximately 0.09 $/kWh. The COE ($/kWh) for the OOGS is 0.21 in Maiduguri, 0.245 in Kano, 0.275 in Enugu and 0.338 in PH. An obligatory 95% RF changes the architecture and increases COE in all the locations except Maiduguri, with a slightly improved COE but higher NPC like other locations. It is established that the suggested hybrid system is beneficial and feasible for supplying more reliable and clean energy to educational buildings in different Nigerian locations.

Keywords: Renewable energy; Electric load; Nigeria energy resources; Techno-economic analysis; Hybrid system

Received: 26th Oct 2022; Revised: 28th Dec 2022; Accepted: 28th January 2023; Available online: 10th Feb 2023

1. Introduction

Energy is the driving force for economic progress and improvement in the living standards in a nation, particularly the developing ones. It can likewise be used to increase a country's productivity indicators, including education and research output. Thus, a steady and quality electricity supply is necessary to aid sustainable development. Nigeria suffers from severe electricity poverty, with a significant gap between demand and supply. Whereas the highest demand is projected to be 24 GW, the capacity of installed generators stands at about 12 GW while the electric grid is only able to dispatch about 5 GW daily, which is insufficient for a country of over about 200 million people (USAID 2022). Thus most of the homes, industries, businesses and universities in Nigeria receive an electricity supply of about 50%, far less than their demand (Diyoke, Ngwaka, & Onah, 2021).

Quality education is key to a country's national development and modernization, and every nation can only develop within the quality of its educational system. Thus Nigerian Academies and other research establishments deserve special consideration in terms of access to quality and reliable electricity, among others. It is miserable to note that although the management of Nigerian universities expends a huge chunk of their annual budget on monthly energy bill payments, accessibility to a steady electricity supply in educational establishments in Nigeria which is an essential commodity for effective learning, research, institutional operation and student residency has continued to be irregular and erratic (REA undated). When obtainable, the electric supply is usually of low voltage, thus threatening some extremely delicate teaching and research equipment produced in accordance with the contemporary microelectronic age (Vanguard, 2018). Consequently, various departments in Nigerian universities resort to using ineffective, costly, polluting and very noisy petrol and diesel generating sets to supply their energy requirements.

The energy demand in Nigeria, including its university sector, will continue to grow due to increasing urbanisation, development and population explosion (Adewuyi *et al.*, 2020). It is projected that the electricity demand will surge 16.8 times by 2030. There are other estimates that put the predictions for 2025 and 2030 at 77.5 GW and 119.2 GW, respectively (Netherlands Enterprise Agency, 2021).

Power supply availability and reliability in the country and the nation's institutions of learning can be improved by deploying microgrid power systems (MPS). An MPS is a self-sufficient energy system that uses distributed generation (DG) energy sources to supply electricity to a distinct geographical footprint like a college campus, hospital complex, business

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https://doi.org/10.14710/ijred.2023.49814

centre, or neighbourhood. The MPS can be operated in two modes: grid-tied (on-grid) or stand-alone (off-grid).

Nigeria possesses abundant conventional energy sources such as natural gas, crude oil, coal, and lignite, as well as renewable energy sources like biomass, wind, solar, and hydropower. In the future, wind and solar power are expected to play a major role in driving global power generation growth among these energy sources.. This is because of the substantial decline in the cost of RE technologies over the past few years, especially for solar and wind power. Thus, the country's huge exploitable solar or wind energy resources can be tapped into a domestic mix of wind and solar PV to address the major problem of the lingering power crisis in the nation's educational institutions. This has the potential to help in decreasing the Nigerian carbon footprint related to electricity generation. Also, it will help meet the current and future electrification needs of the nation's institutions of learning in an economically feasible way. Although power derived from RE is progressively becoming key for governments across the globe, its sporadic nature and low power density are challenges that must be addressed. Systems incorporating different RE power sources with or without fossil-based power systems in an optimised combination in the so-called hybrid renewable power systems (HRPS) have been suggested to solve these problems (Bani Hani *et al*., 2022). These systems leverage the benefits of the complementary characteristics of the diverse RE sources making up the system to maximise system efficiency, resource utilisation, and system reliability. Accordingly, optimised hybrid power systems (HPS) have been tipped as the key to unlocking maximum efficiency and cost savings in using solar and wind power systems in future power systems.

Given that HRPS can be on-grid or off-grid, comparative information is required about the cost and performance of the two configurations at different demand loads and operating conditions. Such information is critical for decision-making regarding which HRPS to deploy for switching from the traditional fossil-based grid power to HRPS. Thus many researchers in Nigeria and across the globe have focused on the modelling and optimisation of HRPS for both on-grid and off-grid applications. Their findings conclude that HRPS are a sustainable, reliable and cost-effective route for powering communities and institutional buildings with substantial environmental benefits. The authors (Oladigbolu, Al-Turki, & Olatomiwa, 2021) carried out a comparison of standalone hybrid power systems (HPS) for powering rural healthcare facilities in Nigeria. Another study (Esan *et al*., 2019) evaluated the reliability of an HRPS mini-grid for powering a rural community in Kwara State, Nigeria. Also, (Babatunde *et al*., 2021) assessed the usage of HRPS with battery storage for powering a building at the University of Lagos, Nigeria. Their results suggest that the optimal configuration for the site is a diesel engine of 20 kW, 70 kW PV, 40 kW converter and 70, 3000 Ah batteries. A comparison of two different configurations of an HPS for multi-generation in Nigeria was reported by (Diyoke, Ngwaka, & Onah, 2021). Another related study (Diyoke & Ngwaka, 2021) reported on the thermodynamic assessment of an HPS consisting of wind and biomass for a rural off-grid community in Nigeria. There is also a substantial amount of research on HRPS for both grid and off-grid applications outside Nigeria. A comparison of the different grid and off-grid hybrid renewable energy systems was reported by (Jahangir *et al*., 2020). Their results indicate that the COE of the on-grid systems, which ranges from 0.093–0.139 $/kWh, is less than that for the off-grid systems, which lie in the range of 0.136–0.182 $/kWh for large-scale demand. A related study (Das, Hasan, & Rashid, 2021) presented a techno-economic viability analysis on off and on-grid PV/Wind/Diesel/Battery HPS and showed that the grid-tied HPS with a sell-back option has substantial cost benefits. The optimal design optimisation of off-grid solar PV/fuel cell HPS for powering a university building in the desert region was reported by (Ghenai & Bettayeb, 2019). In another similar study, (Nesamalar *et al*., 2021) studied the feasibility of an HRPS under two dispatch strategies (Cycle Charging (CC) and Load Following (LF)) for both standalone and grid-tied application in an educational institution in India. Studies have been conducted to optimize off-grid energy systems for rural electrification. One such study, performed by (Li, Liu, & Li, 2020)., looked at a solar, wind, and biomass system in western China. Another study, by (Tawfik *et al*., 2018), used iHOGA software to size a hybrid power system (HPS) based on two renewable energy generators (PV/WT) and two conventional generators (diesel engine/battery) for a rural village in Malaysia. An investigation of the techno-economic comparison of ten hybrid energy storage systems for off-grid RE applications based on a novel probabilistic reliability index was presented by (He *et al*., 2022). A study of the technical, economic and emission performance of HPS consisting of two or more hydro/solar/wind/diesel/batteries for energy supply in Gilgit-Baltistan, Pakistan was studied by (Ali *et al.,* 2021). Several other studies on the techno-economic analysis of HRPS using HOMER Pro have been conducted globally to address electricity demand and rural electrification. Table 1 summarizes some of these studies.

Based on the literature reviewed above, it can be noted that various optimized HRPS for meeting demand have been proposed for both grid and off-grid use in Nigeria and globally. It is also apparent that there is no one optimal HPS structure. However, the optimal configuration depends on the weather data, resource availability and potentials, electric load patterns, and economic and environmental policies. Despite many studies on hybrid systems in Nigeria, a comparison of the optimal grid and off-grid HRPS for university buildings is lacking. Therefore, it is vital to carry out a techno-environmental performance assessment of HRPS under specific Nigerian climatological conditions to advise their optimal combination and operating mode (grid or off-grid); to ensure their sustainability. Thus, the aim of the research is to find the best grid and off-grid HRPS for a Nigerian educational building, compare the options based on techno-environmental and economic factors, and determine if the grid or off-grid solution is a cost-effective alternative to the current weak fossil-based grid. The analysis will also be applied to three other Nigerian locations to examine differences in optimal systems for grid and off-grid use.

Although many studies have been carried out for specific Nigerian meteorological zones, the contribution of this research to the prevailing body of literature in the HRPS field includes the following:

i. First-of-its-kind comprehensive comparison of an on and off-grid optimal HRPS for meeting the electric load of typical Nigerian university buildings in four different temperate-based climate zones of Nigeria
ii. Unlike most of the published work for Nigeria, this work uses a combination of HOMER Pro and RETScreen Expert to measure the number of trees and waste recycling required to offset all the CO_2 emissions from the HRPS and achieve a completely green building.
iii. Real Nigeria market-based economic and micro-economic parameters have been used, except default values in HOMER Pro.

This study is crucial in supplying data to support decision-making by policymakers, stakeholders, and the government in RE development and integration. It also serves as input for designing and selecting a hybrid renewable energy electrification system configuration for use in Nigerian university buildings.

2. Methodology

The modelling of an HRPS system requires accurate load, metrological and other fuel resource data for the location of interest to obtain a proper operative performance in different situations. In this research, the methodology adopted to propose and model the HRPS for educational buildings consists of the following steps:

- Selection of study location
- Energy audit to determine load
- Resource assessment
- Hybrid system configuration
- Design, optimisation and environmental analysis using a combination of HOMER Pro and RETScreen Expert
- Sensitivity analysis

The techno-economics of the project is analysed using HOMER Pro, including the greenhouse gas emissions, while RETScreen Expert accounts for the trees and waste recycling needed to offset the emissions.

2.1 Study location

Nigeria is characterised by four distinct temperature-based climate zones such as warm desert climate (Zone A), warm semi-arid climate (zone B), tropical savanna climate (Zone C), and monsoon climate (Zone D), as can be seen from Figure 1 (Hamisu Umar *et al.*, 2021). The Warm desert climate (BWh) is a scorching and dry climate with low rainfall in the farthest north-eastern part of Nigeria (Maiduguri and Yobe). The temperature in this area is very high, exceeding 40 ℃ sometimes (Hamisu Umar *et al.*, 2021). Warm semi-arid climate (BSh) is the main climate type in the northern part of Nigeria (Kano, katsina, Sokoto, and Gombe). This zone is hot and dry, with annual rainfall lower than that of the southern part of the country. The rainy season in this climate zone is about four months (June-September), with the remainder of the year being hot and dry, with temperatures nearing a high of almost 40 ℃ in some locations.

The most common climate in Nigeria is the tropical Savanna climate (Aw). It occurs in most of the central and southern regions of the country. This region experiences a distinct rainy season (April-September) and Dry season (December – March) (World Bank, 2021), with a mean monthly maximum and minimum temperature of 33 and 20 ℃ at Port Harcourt during the year. Typically, the north has higher average maximum temperatures and lower average minimum temperatures. The annual rainfall is heavy and abundant in the savanna climate and generally above 2000 mm (Hamisu Umar *et al.*, 2021). This study considered one representative institutional building location in each of the four climate zones. Table 2 displays the chosen locations with their geographic coordinates.

Table 1
Some previous research works, the system architecture and summary of findings

Reference	Hybrid architecture	Mode	Location	Application	Summary of findings.
(Gabbar & Siddique, 2023)	PV/wind/nuclear	Off-grid	Durham, Ontario	Transportation electrification	COE of 0.26 USD/kWh.
(Al Afif, Ayed, & Maaitah, 2023)	PV/wind	Grid and off-grid	Al-karak, Jordan,	Residential	On-grid PV/Wind system with battery storage is the optimal system with COE of 0.024 USD$/kWh
(Mulenga *et al.*, 2023)	PV/Diesel	Off-grid	Chilubi island, Zambia	Rural electrification	PV/Diesel/Battery with COE of $0.182/kWh is the lowest cost option
(Amole *et al.*, 2023)	Grid only, PV only and the PV-Grid	Grid	Oyo State, Nigeria	Village energy supply	PV-Grid system is the best system with COE of 0.1904 $/kWh
(Benti, Mekonnen, & Asfaw, 2023)	PV/wind	Off-grid	Western Ethiopia	Rural electrification of households	PV/battery/converter combination is the most cost-effective, with lowest COE of $0.173/kWh
(Kumar & Channi, 2022)	PV/biomass	Off-grid	Punjab, India.	Rural electrification of households	The CO_2/year emission of the optimal HRPS is much better than Grid-only and PV-diesel generators
(Al-Najjar *et al.*, 2022)	PV/Biomass/diesel	Grid	Gaza city	Residential	COE of $0.438/kWh is the lowest energy cost
(Asamoah *et al.*, 2022)	PV/grid, PV/Genset	Grid and off-grid	Nankese, Ghana	Residential	PV-Grid is the best option with a COE of $0.0824/kWh while off-grid standalone PV-Genset has $0.309/kWh.
(See *et al.*, 2022)	PV/WT/Battery/DG	Off-grid	Malaysia	Remote island	PV/Battery/DG is best system with COE of 0.198$/kWh
(Ali *et al.*, 2021)	Hydro/Wind/PV with DG or Battery Storage	Off-grid	14 sites across Gilgit-Baltistan	Remote Residential	WT/Hydro/Battery has the least COE ranging from 0.0470–0.0968 $/kWh
(Çetinbaş, Tamyürek, & Demirtaş, 2019)	Solar only and Solar/wind/diesel	Grid	Eskişehir, Turkey	Hospital complex	COE ranging from 0.052-0.055 $/kWh

2.2 The load profile

The electrical demand load of the Mechanical and Electrical Engineering building of Enugu State University of Science and Technology (ESUT) was considered a typical load for all the locations considered in this analysis. This building is located in Agbani Town, Enugu (6° 18.3' N, 7° 33.8' E) in Nkanu west local government area of Enugu State in the Southeastern region of Nigeria, as shown in Figure 1. It comprises two floors, with a hip roof area of over 700 m^2, perfect for installing the roof-top PV modules. The hourly electrical load of the building was calculated using the HOMER Pro software, based on a survey of the power consumption of appliances in the building. The survey determined the ratings of all equipment in the building and their daily usage duration. Table 3 shows the ratings and length of service of all appliances in the building. A 30% load safety factor is imposed on the total building load to cover any future expansion. Also, The hourly and day-to-day variations that may accompany the estimated electric load demand of the building are incorporated by allowing a day-to-day and time step-to-time step random variability of 15 and 20 in HOMER Pro, respectively. The annual average energy consumption of 254 kWh per day and a peak load consumption of 32.04 kW was determined. Figure 2 (a) depicts the minimum, maximum and mean of the monthly electrical load demand for the building whereas Figure 2 (b) shows the yearly 24-hourly demand profile. These figures indicate that the peak demand in the building occurs between the hours of 10 am and 3 pm when office and teaching activities are at their peak.

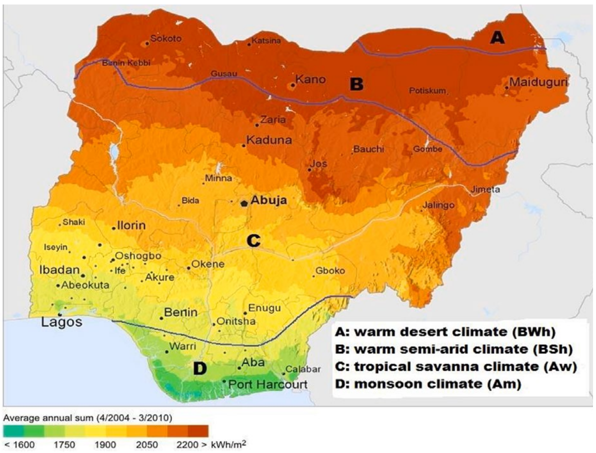
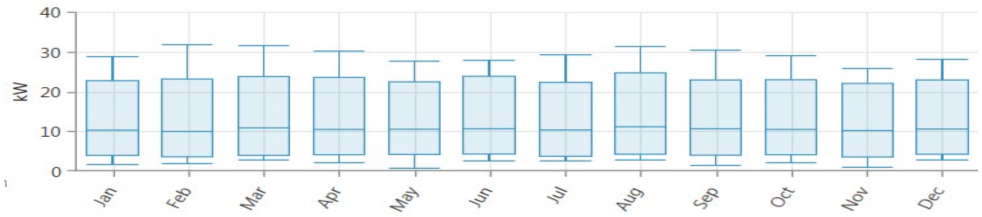


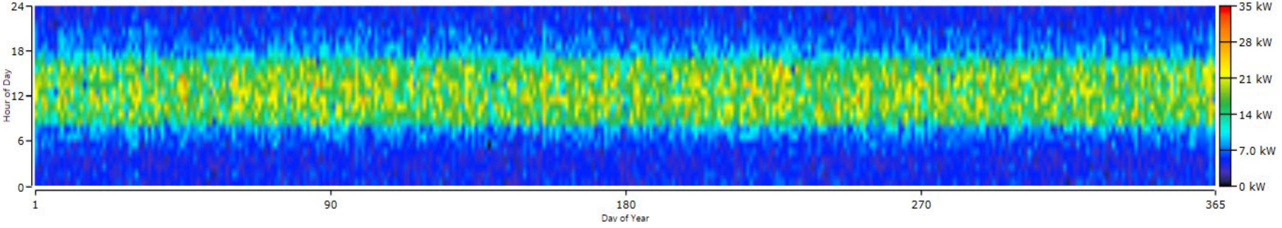
Fig. 1 Solar radiation distribution map of Nigeria with marked climate zones © 2020 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis (World Bank 2020).

Table 2
The Geographical coordinates of the analysed sites

S/N	Climate Zone	Sites	Lat (^{o}N)	Long (^{o}E)	Elevation (m)
1	Warm desert (Zone A)	Maiduguri	11.49	13.91	383.80
2	Warm semi-arid (Zone B)	Kano	12.1	8.35	472.14
3	Tropical savanna (Zone C)	Enugu	9.27	7.03	305.00
4	Monsoon (Zone D)	Port Harcourt	4.50	6.56	6.1



(a) Average monthly load



(b) Yearly load profile

Fig. 2 Building load profile (a) average monthly load; (b) yearly load

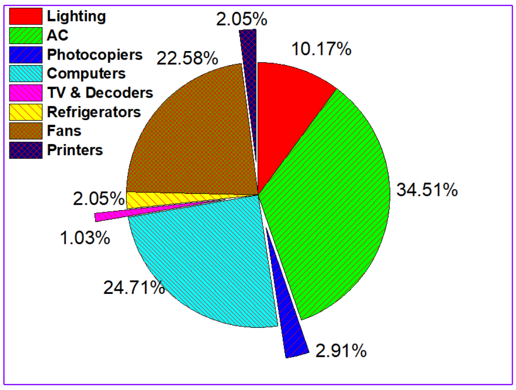


Fig. 3. Energy consumption of appliances

The building has an average demand of about 11 kW throughout the year, but it can experience demand beyond 31 kW from February to march. The breakdown of energy consumption by appliances in the building was also determined. As shown in Figure 3, electricity demand from cooling appliances (air conditioners and fans) plays a major role in the electric load of the building. This represents about 60% of the daily electric load, of which the air conditioner accounts for 35%, and the fans account for about 23% of daily electricity consumption respectively. Computers account for 25%, while lighting (internal and external) represents only 10% of the overall load. The other loads comprise TVs and decoders, refrigerators and printers.

2.3 The resource potential

Nigeria has plentiful reserves of RE resources like biomass, hydro, solar and wind .These resources vary across the four climate zones (see Figure 1) in Nigeria. The mean wind speed in Nigeria ranges from more than 7 m/s in the warm desert climate (Zone A) to about 5.11 - 6.0 m/s in the warm semi-arid climate (zone B). The tropical savannah climate (Zone C) has a wind speed that is less than 4 m/s (Ayodele, Ogunjuyigbe, & Amusan, 2018), while the monsoon climate (Zone D) has a wind speed that ranges from about 2 to 2.3 m/s at 10 m meteorological height. Also, the daily solar radiation potential in kWh/m^2 for the warm desert climate (Zone A) ranges from 6.11 for Nguru in Yobe to 6.34 in Borno; for Zone B, it ranges from 5.62 in Sokoto to 6.01 in Gusau. The tropical savanna climate (Zone C), and the monsoon climate (Zone D) have radiation potential (kWh/m^2) that varies from 4.35 in Benin to 5.77 in Zaria and 3.96 in Port-Harcourt to 4.22 in Akwa-Ibom respectively. Like the wind and solar resources, the temperature in the various zones also fluctuates. The temperature is highest in the core north and reduces towards the south. For each city, the air temperature, wind speed and solar radiation at their respective latitude and longitude were obtained from the NASA database in HOMER Pro software (HOMER. 2022). The mean monthly daily temperature and wind speed at 10 m height based on 30-years (1984-2013) data and solar radiation based on 22-years (1983 to 2005) data for each study location are shown in Figure 4 (a-d).

The mean values of temperature (°C) /wind speed (m/s)/solar radiation (kWh/m^2/day) for the locations are 25.21/4.09/4.93 for Enugu, 26.4/4.5/6.04 for Kano, 28/5.5/5.9 for Maiduguri and 25.6/3.15/4.13 for Port Harcourt. Once more, it can be noted that the potential of solar radiation is more uniformly distributed throughout the year in the warm semi-arid climate zones – Kano and Maiduguri. Also, observe that declining wind speed coincides with rising solar radiation in the Tropical Savana and Monsoon climate –Enugu and Port-Harcourt, depicting a complementary relationship between the two sources in the climate zone.

3. Modelling of the Hybrid Renewable Power System (HRPS)

3.1 The proposed system description

The grid-connected hybrid renewable power system (HRPS) considered in this analysis is shown in Figure 5 (a). It comprises a wind turbine (WT) system, a solar photovoltaic (PV) system, a converter (Conv) and the grid. The grid serves as a backup power component to supplement any insufficient output from the HRPS. There is no feedback tariff regime in the Nigerian power sector, so any surplus power generated by the HRPS is used solely to charge the battery bank (BB). In the off-grid system shown in Figure 5 (b), the grid is replaced with a diesel engine generator (DEG) connected to the AC bus. DEG acts as a backup system to deliver any shortfall arising from the variable nature of RE power, and the BB system is employed to supply even demand and improve the stability and reliability of the network in both operating modes. Hybrid systems containing one or more generators with a BB require a dispatch strategy (DS); a set of regulations controlling how the generators operate to charge the BB anytime there is insufficient generation. In this work, the Combined Dispatch (CD) strategy is applied in the grid mode while the load following (LF) strategy is used in the off-grid mode, as these strategies result in the most cost-effective systems among the modes considered.

3.2 Modelling of the system architectures

The HRPS for the grid and off-grid mode were designed and optimised in HOMER Pro using the inbuilt modules of the electric load, power components and resources. Firstly, the monthly demand load of the building is imported into the load module of the HOMER Pro software. Then the configuration of the HRPS, as shown in Figure 5 (a & b), is configured in HOMER Pro using the appropriate in-built power generating components and ancillaries such as PV, WT, battery bank (BB), Converter (Conv) and grid**.** The energy resources required by the power-generating components, such as ambient temperature, solar irradiation and wind speed of the study areas, are downloaded from the inbuilt library of NASA metrological data in HOMER Pro for the study site**.** Then the technical specifications of the different components of the HRPS, including costs and dispatch strategy (CD for the grid system and LF for the off-grid system), are inputted into the HOMER Pro software.

HOMER Pro is then used to optimise and rank the optimal HRPS for the site based on minimal net present cost (NPC). Detailed mathematical modelling of the various components of the HRPS can be found in the HOMER Pro user manual (HOMER, 2022). A brief account of the main constituents will be presented in the following sections.

3.2.1. Solar PV

The generated power by the PV modules depends on solar radiation and ambient temperature. In HOMER Pro, the following equation is used to calculate the PV output power (Alsafasfeh, 2015; HOMER, 2022):

$$\mathrm{P} = P_{PV} f_{PV} \times \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right)\left[1 + \alpha_P\left(T_c - T_{C\,STC}\right)\right] \tag{1}$$

Where P is the output power generated from the PV panel, Ppv denote the optimized PV panel size, f_{PV} is the PV derating factor [%], $\bar{G}_T$ is the solar radiation on the inclined surface (W/m^2), $\bar{G}_{T,STC}$ represent the solar radiation at the standard test conditions (W/m^2), $T_{C,STC}$ is the cell temperature at standard test conditions and α_P is the power temperature coefficient (%/°C). The cell temperature (T_C) is calculated from the ambient temperature (T_a) and the incident irradiation as follows :

$$\mathrm{T}_C = T_a + .\, \bar{G}_T\left(\frac{T_{c,NOCT} - 20}{0.8}\right)\left[1 - \frac{\eta_{mp}}{0.9}\right] \tag{2}$$

Where = $T_{c,NOCT,}$ *and* η_{mp} denote the nominal operating cell temperature (°C) and the efficiency of the PV array at its maximum power point (%). The efficiency of the PV array at its maximum power point (%) varies directly with temperature based on the subsequent equation (HOMER, 2022):

$$\eta_{mp} = \eta_{mp,STC} \cdot \left[1 + \alpha_P\left(\mathrm{T}_C - \mathrm{T}_{C,STC}\right)\right] \tag{3}$$

Where $\eta_{mp,STC}$ is the max power point efficiency at standard test condition.

3.2.2. Wind Turbine (WT)

Taking the wind speed variability into account, HOMER Pro computes the output power of the WT in every time step by means of the power curve of the selected wind turbine in a three-step process. Firstly the wind speed (v_{anem}) at anemometer height (h_{anem}) is converted to the appropriate hub height (h_{hub}) wind speed ($\mathrm{v_{hub}}$) using either the power or logarithmic law. Then the power output of the WT at $\mathrm{v_{hub}}$ is calculated and then adjusted for the actual density of air at the site as follows:

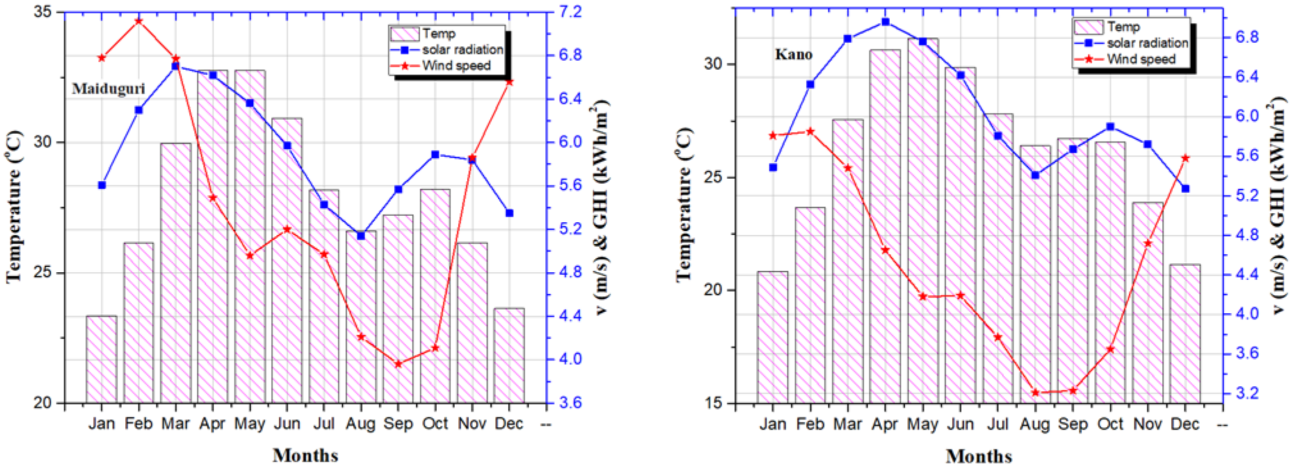
$$P_{WT} = \mathrm{N}_W \times \sum_i f_i(v) P_{WT,i}(v_{hub}) \quad \times \frac{\rho}{\rho_0} \tag{4}$$

$$v_{hub} = v_{anem}\left(\frac{h_{hub}}{h_{nem}}\right)^{\alpha} \; or \; v_{anem}\frac{\ln\left({h_{hub}}/{h_0}\right)}{\ln\left({h_{anem}}/{h_0}\right)} \tag{5}$$

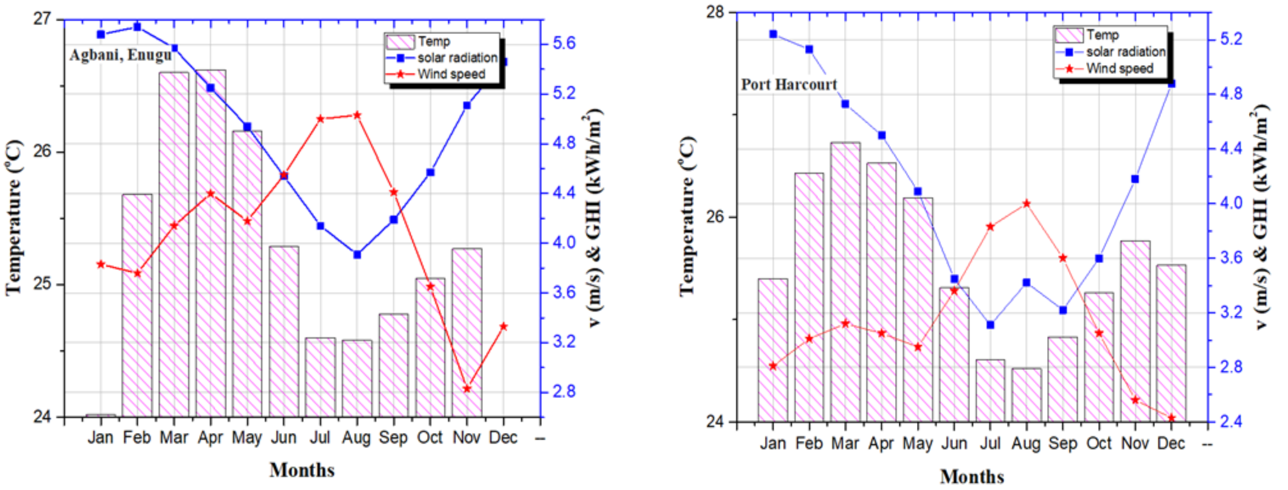
Where N_W is the number of WT; $f_i(v)$is the probability of duration at site wind speed v; $P_{WT,i}(v_{hub})$ is the hub height power production from the turbine from its power curve at the time i (kW), ρ is the actual air density (kg/m^3); ρ_0 *is* the air density at standard temperature and pressure (1.225 kg/m^3); α is the wind shear coefficient for the site and h_0 is the surface roughness length (m).

Table 3
Load estimation for building

S/N	Section	Appliances	Qty	Rating (W)	Use (hr/d)	AC load (Wh/d)
1	2 Unit Head Offices	Bulbs.	4	20	8	640
		Ceiling fan.	2	120	8	1920
		Laptop.	2	65	4	520
		AC.	2	750	5	7500
		Printer.	2	500	4	4000
		Desktop	2	250	4	2000
		Photocopier	2	950	3	5700
		TV set.	2	80	8	1280
		TV decoder.	2	18	8	288
		Refrigerator	2	250	8	4000
		Projector	3	282	2	1692
2	15 Offices	Bulbs.	30	20	8	4800
		Ceiling fan.	15	120	8	14400
		Laptop.	30	65	4	7800
		AC	15	750	5	56250
3	5 Lecture halls	Ceiling fan.	20	120	8	19200
		Bulbs	30	20	8	4800
4	Computer Lab	Bulbs.	6	20	8	960
		Ceiling fan.	9	120	8	8640
		AC	1	750	5	3750
		Interactive board	1	220	2	440
		Desktop computer.	38	250	4	38000
5	2 Stairways	Bulbs	12	20	9	2160
6	12 toilets	Bulbs	12	20	4	960
7	6 Pathways	Bulbs	20	20	9	3600
8	Outside lights	Bulbs	7	20	14	1960
				Total appliance load (kWh/day)		197.3



(a) Maiduguri (b) Kano



(c) Enugu (d) Porthacourt (PH)

Fig. 4. Mean monthly solar radiation, wind speed and temperature

Apart from the use of a power curve, the power output of a WT can also be calculated using (Diyoke, 2019):

$$P_{WT}(v_{hub}) = N_W \times \frac{1}{2}\rho A {v_{hub}}^3 Cp(\lambda, \beta)\, \eta_m \eta_G \qquad (6)$$

Where; η_m *and* η_G is the mechanical and generator efficiency of the WT; $C_p(\lambda, \beta)$ is the power coefficient which is determined by the WT blade angel (β) and the tip speed ratio (λ) and A is the swept area of the WT blades (m^2).

3.2.3. Battery system

The battery ensures that the HRPS serves the load uninterruptedly at times of shortfall in generated power. The battery bank (BB) is charged during excess power production and discharged during a shortfall. The BB capacity mainly depends on the daily demand load (E_{load}) shortfall and the time (t) needed for the BB to serve this load. The attainable BB size at a time (t) in the charging and discharging cycles can be described as follows (Das, Hasan, & Rashid, 2021):

$$E_{BB}(t) = E_{BB}(t-1) \times (1-\varphi) + \left(E_{HRPS}(t) - \frac{E_{load}(t)}{\eta_{inv}}\right) \times \eta_{BB} \qquad (7)$$

$$E_{BB}(t) = E_{BB}(t-1) \times (1-\varphi) - \left(\frac{E_{load}(t)}{\eta_{inv}} - E_{HRPS}(t)\right) \qquad (8)$$

Where $E_{BB}(t)$ and $E_{BB}(t-1)$ is the available BB capacity (kWh) at periods t and t-1, respectively, $E_{HRPS}(t)$ is the total power output by the HRPS at time t, φ is the self-discharge rate of the battery, η_{BB} *and* η_{inv} are the efficiency of BB and the inverter respectively.

3.3. Economic assessment

The main economic output in HOMER Pro is the total net present cost (NPC). It is the value that determines the ranking of all the HRPS architectures in the optimisation results and the basis from which the total annualised cost (TAC) and the levelised cost of energy (COE) are calculated. The total NPC) is the sum of the discounted cash flow (costs – revenues) every year of the project duration. as follows (Hassane et al., 2022; HOMER, 2022):

$$NPC = \frac{C_A}{CRF(i,t)} \tag{9}$$

$$CRF(\$) = \frac{i \times (1+i)^N}{(1+i)^N - 1} \tag{10}$$

$$i = \frac{r-e}{r+e} \tag{11}$$

Where; C_A is the total annual cost (\$); CRF is the capital recovery factor; t is the annual project lifetime; N is the number of years; i is the annual real interest rate (%); r, *is* the nominal interest rate; e is the annual inflation rate. The average cost of useful energy generated by the system in \$ per kWh is termed COE. It can be expressed as the ratio of total annualised cost (TAC) in \$ to the annual electricity served (AES) in kWh as follows:

$$COE\ (\frac{\$}{kWh}) = \frac{TAC}{AES} \tag{12}$$

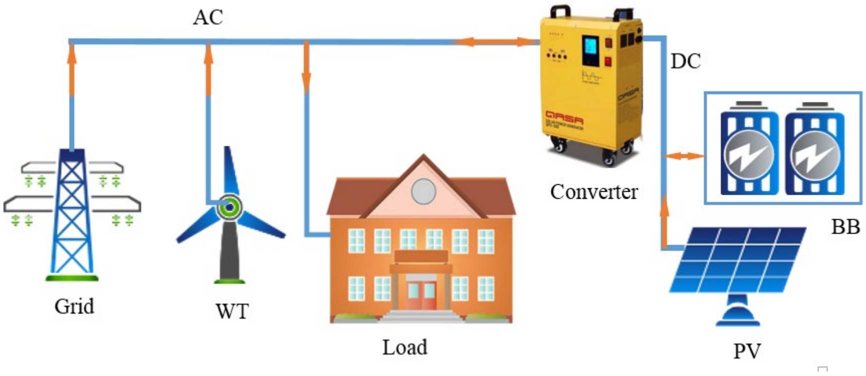
Tables 4 and 5 show the technical and cost parameters of the components of the HRPS architectures. The lifetime of the project is assumed to be 25 years at a nominal (real) discount rate of 25% (8.7%) and an inflation rate of 10% (Udeani, Jaramillo, & Williams, 2021). The local capital cost of the components in Naira (₦) was obtained from Jumia online retail shop for Nigeria (JUMIA, 2022) and converted to equivalent US dollars using 1 ₦ to \$ 417.47 (Xe, 2022).

A 10 % of the capital cost of each component is allowed for shipment from Lagos to the study site. Enugu Electricity Distribution Company (EEDC) per kWh tariff in Enugu for Jan – Dec 2022 ranges from a maximum of ₦59.02 (0.14 \$) for band A customers with a daily min of 20 hours of electricity to a minimum of ₦35.4 (\$0.085) for band E customers with a minimum of 4 hours of electricity per day (EEDC, 2022). The value of 0.14 per kWh has been used.

3.4 Environmental assessment

The environmental performance of the HRPS is assessed by estimating the amount of emission in the grid and off- grid mode. In HOMER Pro, the quantity of pollutants released by the generator of HRPS in off-grid mode is determined by multiplying the emissions factors of the concerned pollutants (in g/kWh) by the annual fuel consumption of the generator. In the grid mode, the amount of pollutants is calculated by multiplying each pollutant's emission factor (in g/kWh) by the net grid purchases (in kWh). The emissions factors for important pollutants presented in Table 6 have been used in the model.

(a) Grid system (GS)



(b) Stand-alone or off-grid system (OGS)

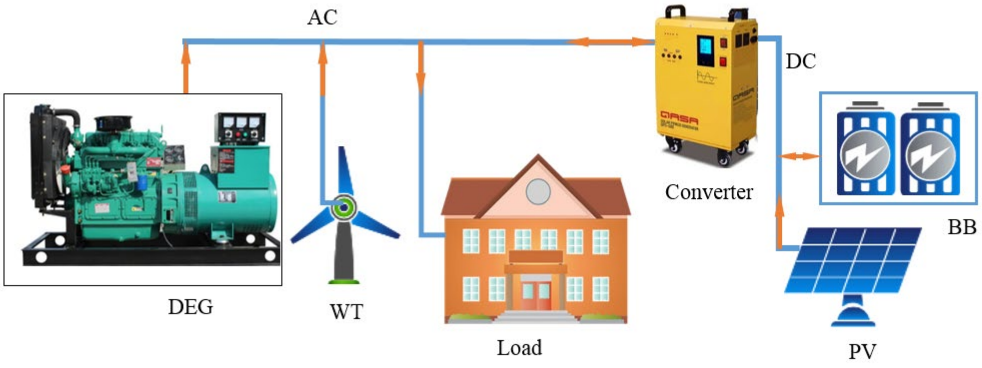


Fig. 5. Schematic diagram of the grid (top) and off-grid (bottom) hybrid system

Table 4
Technical specifications of the HRPS components

Components	Parameter	Rating
Converter: Generic converter	Generic capacity (kW)	33
	Efficiency (%)	97.6
PV: Huawei SUN2000 30kW with Generic PV	Rated capacity (kW)	30
	Operating Temperature (°C)	45
	Efficiency (%)	17.3
WT: Eocycle EO25 Class IIA	Rated capacity (kW)	25
	Cut in/cutout speed (m/s)	3.5/25
	Hub height (m)	30
Battery: 1kWh Lead Acid	Nominal capacity (kWh)	1
	Nominal voltage (V)	12
	Round trip efficiency (%)	80
Diesel generator	Capacity (kW)	30
	Fuel curve intercept (L/hr)	1.15
	Fuel curve slope (L/hr/kW)	0.297

Table 5
Cost parameters of the system

Components	parameter	Specification
PV Huawei SUN2000 with Generic PV(JUMIA, 2022)	Capital cost ($/kW)	600
	Replacement cost ($/kW)	500
	O&M ($/kW/yr)	10
	Lifetime (yrs)	25
WT (JUMIA, 2022)	Capital cost ($/kW)	2000
	Replacement cost ($/kW)	1750
	O&M ($/kW/yr)	10
	Lifetime	20
Battery (Udeani, Jaramillo, & Williams, 2021)	Capital cost ($/unit)	265
	Replacement cost ($/unit)	265
	O&M ($/kW/yr)	10
	Lifetime (yrs)	10
Converter- Generic Converter (Oladigbolu, Ramli, & Al-Turki, 2020)	Capital cost ($/kW)	300
	Replacement cost ($/kW)	300
	Lifetime (yrs)	15
Diesel generator (JUMIA, 2022)	Capital cost ($/kW)	250
	Replacement cost ($/kW)	200
	O&M ($/hr/yr)	0.05
	Fuel price ($/L)	0.693
	Lifetime (hrs)	15000
Grid (Odou, Bhandari, & Adamou, 2020)	Capital cost ($/Km)	15500
	O&M ($/yr/Km)	310
	Tariff ($/kWh)	0.14

Table 6
Emissions factors for DEG and the grid (Udeani, Jaramillo, & Williams, 2021)

Pollutant	DEG Emmision factor (g/L)	Grid Emissions factor (g/kWh)
Life Cycle GHG Emissions ($CO_{2\text{-}e}$)	2617	440
Carbon Monoxide (CO)	16.5	0.32
Particulate Matter ($PM_{2.5}$)	0.1	0.01
Nitrogen Oxide (NO_X)	15.5	0.80

3.5 Sensitivity analysis

The project and resource parameters are subject to variability with time. Also, these parameters can vary with location. To account for these uncertainties and to enable the applicability of the study to different locations, a sensitivity analysis is implemented to assess the impact of varying key project and resource parameters on the NPC and COE. The key variables analysed are the capital cost of solar PV (C_{PV}), wind turbine (C_{WT}) and battery (C_{BB}), solar global horizontal irradiation (GHI), wind speed (v), discount rate (d), inflation rate (e), and the educational building load demand. This analysis will further assist in identifying the performance response of the system to the variation of these input parameters. The values of the sensitivity parameters were varied from their base values by a factor of ±50%.

4. Result and Discussion

4.1 Technical performance

The results obtained from modelling using HOMER Pro software are presented and discussed for each of the 4 sites in the 4 geographical locations considered. The optimal HRPS architecture and ratings for the four sites are summarised in Table 7. In the grid mode, the AC load of 92,798 kWh/year is served by the same optimal system architecture (OSA) consisting of one solar PV power generating component with a dedicated converter (PV/Conv) in the LF dispatch strategy whereas in the off-grid mode, the load is served by two or more power generation sources (PV/WT/DEG or PV/DEG) of different ratings, with dedicated converters (Conv). It is observed that the capacity of the PV module in grid mode is lower than its off-grid counterparts in all locations. However, it is lowest in the warm-semi climate zone of Maiduguri with very high solar radiation potential and highest in PH's monsoon climate with very low GHI potentials. This means that the capacity of PV modules installed in a given location for the grid and off-grid applications varies inversely with the location's solar resource potential. In addition, it is observable from Table 7 that the size of the BB storage capacity required to meet the electrical demand load in the off-grid systems varies from site to site. This is due to the variable climate conditions at the different sites and the failure of the systems to meet the demand load. Consequently, the annual energy production (AEP) is higher in the off-grid mode than in the grid mode for all sites. The AEP of the optimal grid-connected PV systems in the four locations is 70, 73, 63 and 54 MWh for Maiduguri, Kano, Enugu and PH, respectively. The corresponding excess energy is about 6.58, 7.36, 7.26 and 6.19 % of the AEP. Based on these, the total annual electricity exported to the grid comes to 7,919, 8,066, 5,892, and 4,097 kWh/yr, while that bought from the grid is about 39,834, 38,768, 44,936 and 50,672 kWh/yr respectively. These results indicate that implementing a grid-connected solar PV system at the universities is worthwhile. Besides providing electricity for the building load, the system can also feed electricity back to the grid, which is even more than what is bought from the grid. This is exemplified in Figure 6 for the Enugu location.

When the optimal off-grid systems were deployed in the sites, the AEP for the sites increased by 130% for Maiduguri; 100% for Kano, 110% for Enugu and 111% for PH, with the DEG supplying 5.03, 4.92, 7.92 and 17.7 % of the AEP respectively. Because of the inclusion of additional power source components (WT, DEG and BB) in the optimal off-grid systems architecture, the annual energy production by these systems is far more than their respective grid counterparts. This consequently leads to excess energy of about 39.5, 30.7, 23.7 and 8.49 % of the AEP in these locations. This extra energy is used for charging the BB, which will be discharged to supply power during insufficient power output. Figures 7 (a) show the average monthly contribution of the power source components of the optimal on-grid system in serving the electrical demand load in Enugu. In this system, the PV contributes about 58.3% (62,771 kWh) of the total output at a capacity factor of 17.8%, while grid purchases make up the remaining 41.7%.

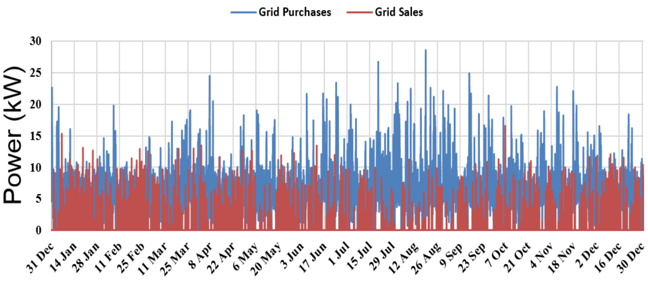


Fig.6. Energy sold and purchased from the grid at Enugu

The mean and maximum output of this PV panel is 7.17 kW (172 kWh/day) and 30 kW, respectively, with a penetration rate of 67.6% and 4,488 hours of operation per year, giving an LCOE of 0.0448 $/kWh. The energy bought from the grid to satisfy the load demand in this location and the energy sold to the grid when the generated electricity surpassed the demand is depicted in Figure 6. It is noted that the monthly electricity purchased varies inversely to the occurring solar resource on the site. It rises from April until August when it reaches its maximum, and then steadily declines until December. Meanwhile, the monthly energy sold to the grid steadily increases from August to January, when solar radiation is high. Figure 7 (b) shows the average monthly contribution of the off-grid power sources to serving the electrical demand load in Enugu; 82,141 kWh of the AEP are supplied by solar PV, 39,352 kWh by wind turbines, and 10, 453 kWh by the DEG. The electricity generated hourly by each component (solar PV, WT and DEG) is represented in Figure 8 (a-c).

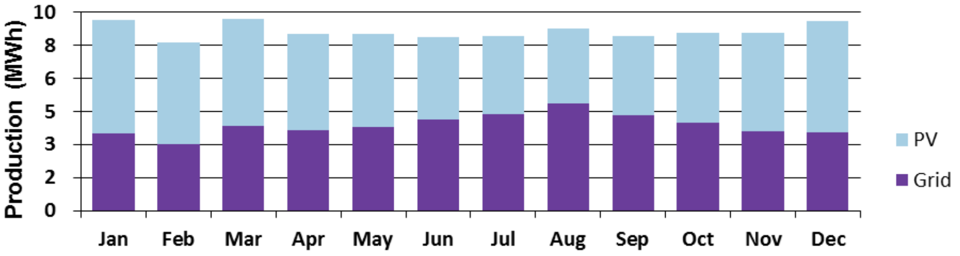
a) The PV panel has a mean output of 9.38 kW (225 kWh/day), maximum output of 30 kW and a penetration rate of 88.5%. This PV module's total annual operating hours are 4,488 hrs/year, mostly between 8h and 15h when solar radiation is high, giving an LCOE of 0.0539 $/kWh. Because of the persistent rain in the rainy season that brings cloud cover, PV module production is lower in the rainy season (April - September) than in the dry season (December - March).
b) The WT contributes 29.8% of annual electricity production. Its annual operating hours are 5,689 per year, a mean output of 4.5 kW and a capacity factor of 18% at an LCOE of 0.133 $/kWh. The annual maximum output of this component is about 25 kW recorded in the Months of June to September, as shown in Figure 8 (b), because of the high wind speed during the months.
c) The 36 kW generator (Gen) produces 7.92% of the AEP at an electrical efficiency of 28.3 %. It operates for about 638 hours per year and consumes about 3,751 litres of fuel. This power component is active throughout the months (Figure 7 (b)) because the combined outputs from the PV and WT are not enough to meet the load during these periods. Its maximum output during the year is 35 kW and occurs in November when the combined output from the other power sources (PV and WT) is lowest.

Unlike the grid systems, the optimal off-grid systems generate a significant amount of surplus energy that could meet potential future increases in demand in the building (like more appliances and longer usage times). However, utilizing this excess energy would come with added expenses, raising the overall cost of the energy supplied by the system further

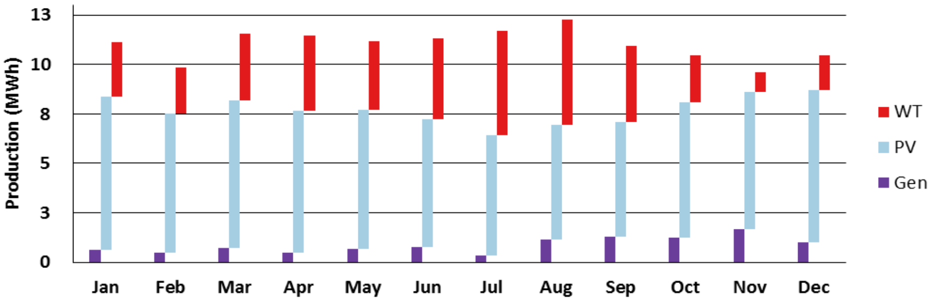
Table 7
Optimal configurations and ratings for each location

Geographical Location	Grid		Off-Grid	
	Optimal Architecture	**Ratings (kW)**	**Optimal Architecture**	**Ratings* (kW)**
Maiduguri	PV/Conv	37.5/21.7	PV/WT/DEG/BB/Conv	45.8/25/36/88/26.7
Kano	PV/Conv	37.6/21.7	PV/WT/DEG/ BB/Conv	51.9/25/36/133/26.6
Enugu	PVConv	40.4/21.2	PV/WT/DEG/ BB/Conv	63.6/25/36/129/26.4
Port-Harcourt	PV/Conv	41.2/20.7	PV/ DEG/ BB/Conv	122/36/153/27.6

** Battery bank rating is in kWh*

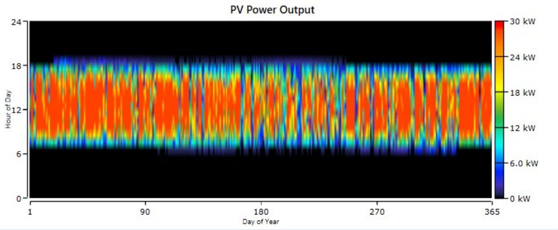


(a) Optimal grid system for Enugu

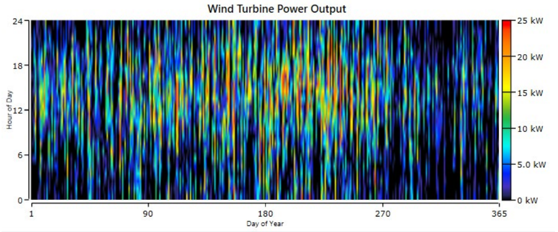


(b) Optimal off-grid system

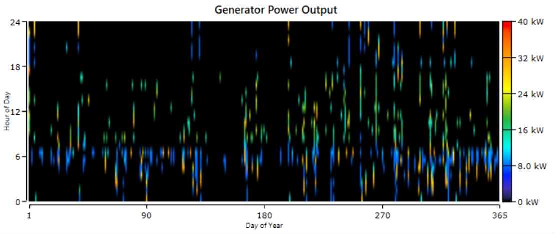
Fig.7. Contribution of power sources to total power output in OOGS



(a) Solar PV



(b) Wind turbine (WT)



(c) Generator

Fig. 8. The hourly production by (a) PV (b) WT, (c) Gen

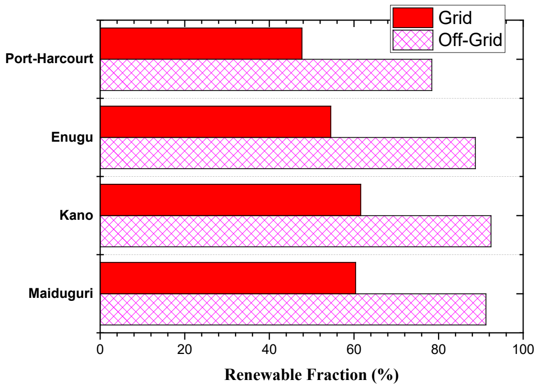


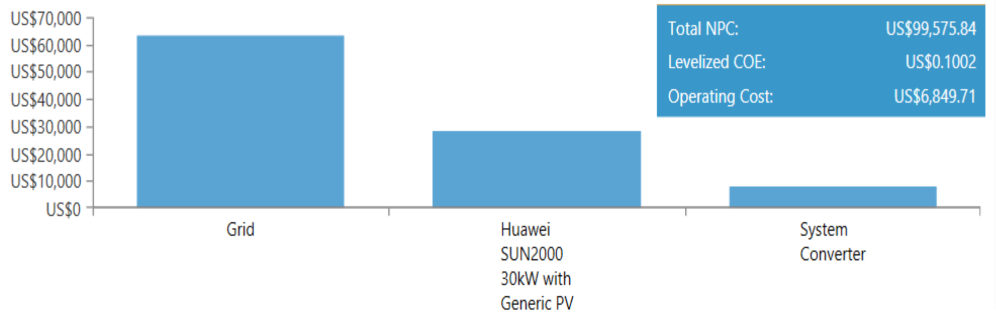
Fig. 9. Renewable fraction (RF) of the optimal systems

Figure 9 compares the renewable fraction (RF) of the optimal grid and off-grid systems (OGS and OOGS) for the four sites. RF is higher in the off-grid mode than in the grid mode in the four locations because the PV capacity in the off-grid mode is higher than in the grid mode in the four locations. Also, the highest percentage contribution of non-renewable power sources to annual energy output comes from grid-connected systems. In the off-grid mode, RF varies between 92.4 in Kano's warm climate zone and about 78.4 in PH's monsoon climate zone. In the grid mode, the RF varies from a high of 61.6% in Kano to a low of 47.7% in Port-Harcourt. Similarly, the highest percentage contribution of renewable power sources in the AEP is highest in the optimal off-grid system for Kano (84.1%) making the role of DEG negligible. Thus, renewable PV/WT power sources dominate the demand load, so the RF reaches the highest value of 92.4% at the location.

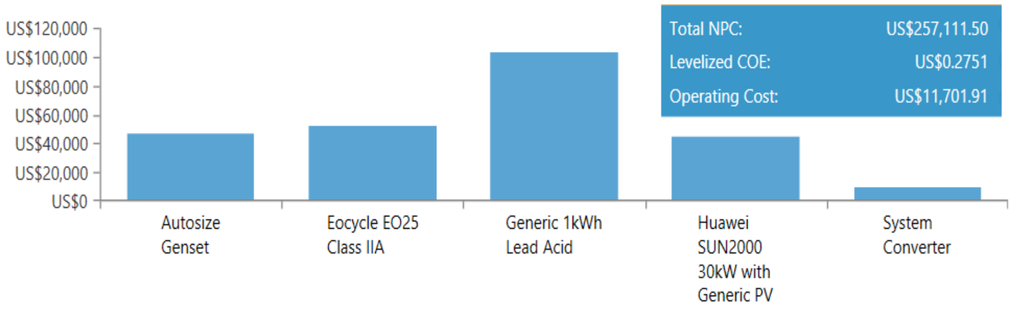
4.2 Economic Performance

To evaluate the profitability and cost-effectiveness of deploying optimal HRPS for meeting the electric demand of University buildings in the four locations, the net present cost (NPC) and cost of electricity (COE) were determined. Also, using the grid with a COE of 0.14 $/kWh and a 36 kW diesel engine Genset (DEG) with a COE of 0.544 $/kWh as base cases for the grid and off-grid systems, the return on investment (ROI), and discounted payback period (DPB) were evaluated. The results are presented in Table 8. In the grid mode, since the annual operation and maintenance costs (O&M) and total initial costs (TIC) are minimum for PV/Grid in Maiduguri and Kano (see Table 8), the COE is lowest at 0.09 $/kWh in these locations. Similarly, the COE for the off-grid PV/WT/DEG/Battery in these locations is more than the on-grid systems but comparable with an average difference of about 10%. This is because these two sites' wind and solar potentials are almost the same distribution and potential, (see Figure 4 (a & b)). However, the COE of standalone PV/WT/DEG/Battery and PV/DEG/Battery in Enugu and PH is higher at COE of 0.275 and 0.338 $/kWh, respectively. It is noted that the PV/Grid systems have a lower COE and NPC than the off grid systems in the four locations. This is because of the inclusion of extra expensive power components (WT, DEG and BB) that are only optimally used sometimes in the off-grid systems due to the low potential of other renewable sources. Besides, a high wastage of unused energy generated by these off-grid system components plays a huge role in their higher costs than optimal grid systems. Nevertheless, a benefit of having the DEG or battery bank in the off-grid optimal systems is they serve as a backup to guarantee the reliability of the system.

In terms of how long it will take for the initial investment costs to be repaired and the return on investment, it can be seen that the initial capital cost of the best off-grid systems will be paid off much faster than their respective equivalent optimal grid system for each location. Also, the ROI of optimal off-grid systems is better. This is because of their high energy tariffs. From these results, it is established that the COE from the optimal PV/Grid hybrid systems (0.09-0.11 $/kWh) is cheaper than the electricity supplied by the optimal off-grid system (0.22-0.34 $/kWh) in all the sites depending on the solar and wind resources. Compared with the grid tariff of 0.14 $/kWh, installing the PV/Grid system in the locations will lead to COE savings ranging from 21 to 35%. However, the optimal off-grid systems (PV/WT/DEG/BB or PV/DEG/BB) are more expensive than the COE of grid-only electricity and the PV/Grid systems by over minimal 55 and 143 percentage points, respectively.



(a) Optimal grid system



(b).Optimal off-grid system

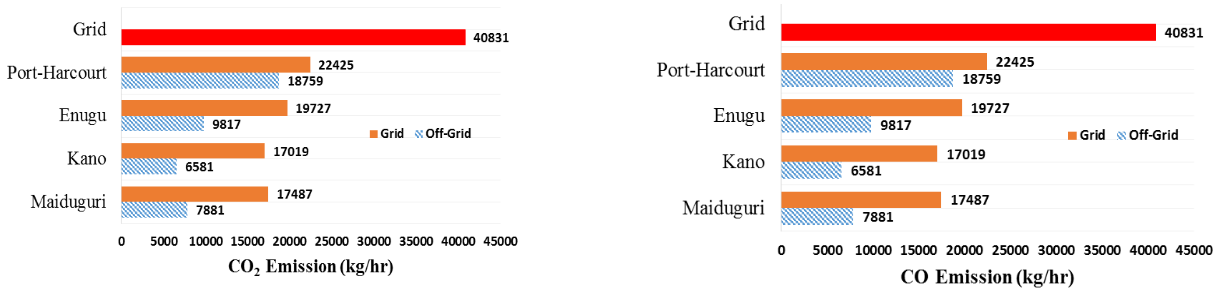
Fig. 10. Contribution of components to total NPC

Table 8
Summary of optimal systems economic assessment results for the locations

	Maiduguri		Kano		Enugu		Port-Harcourt	
Economic parameter	Optimal Grid system	Optimal off-grid system	Optimal Grid system	Optimal off-grid system	Optimal Grid system	Optimal off-grid system	Optimal Grid system	Optimal off-grid system
NPC -$	90,556	202,596	89,166	229,125	99,576	257,111	108,029	315,507
COE- $/kWh	0.0893	0.217	0.0878	0.245	0.100	0.275	0.111	0.338
TIC-$	29,026	117,857	29,123	133,375	30,601	139,275	30,925	131,246
O&M - $/yr	6,110	8,416	5,963	9,509	6,850	11,702	7,657	18,298
DPB -yrs.	5.23	2.95	5.22	3.40	6.60	3.68	8.08	3.81
ROI -%	19.7	33.7	20.1	28.1	16.0	24.9	13.22	21.4

Table 9
Results of inclusion of WT in the OGS

	Maiduguri	Kano	Port-Harcourt
Parameter	**PV/grid/WT/BB/Conv**		
PV capacity (kW)	26.5	26.5	32.9
WT capacity (kW)	25	25	25
Converter capacity (kW)	18.5	18.5	19.0
NPC ($)	110,103	118,548	147,861
COE ($/kWh)	0.0784	0.0960	0.146
Grid purchases (kWh/yr)	19,810	25,800	43,286
Excess energy (kWh/yr)	1,705	1,954	3,090
Renewable fraction (%)	85.8	79.0	56.9



(a) CO_2 (b) CO

Fig. 11. Comparison of emission of CO_2 and CO by the optimal systems

Considering the variations in local resources and factors like wind velocity, solar irradiance and economic factors, the COE ranges obtained in this study are as expected and could be considered to be within realistic boundaries when compared with similar studies in the open literature for Nigeria and other African regions. For instance, the authors (Amole et al., 2023) found a COE of 0.19 $/kWh for a PV-Grid system intended for application in Oyo state, Nigeria. In another study for a location in Ghana, the authors (Asamoah et al., 2022) reported the COE of a grid-connected PV system as $0.0824/kWh while that for the standalone (PV-DEG) system was $0.309/kWh. In other locations, such as Ethiopia, a COE of 0.326 was reported by (Benti, Mekonnen, & Asfaw, 2023) for an off-grid hybrid PV/WT/DEG/BB system. Outside Africa, a COE of the grid and off-grid systems ranging from 0.093–0.139 $/kWh and 0.136–0.182 $/kWh, respectively, were reported by (Jahangir et al., 2020) for large-scale demand. In the future, the expected technological advancement will drive down the COE of HRPS systems further. Figure 10 (a & b) present the contribution of components to the total NPC of the best grid and off-grid systems for Enugu. In the grid system, the cost breakdown reveals that over half (about 64%) of the total system cost (NPC) of about $ 99,575.84 (See Table 8) is consumed by the operations and maintenance of the grid ($63,349), followed by the solar PV ($28,297$) and the converter ($7,929.73). Thus, reducing the grid tariff will lessen the NPC and hence make the COE from the system even cheaper. In the off-grid mode, the WT, BB and DEG components make up over 78% of the total system cost, with the BB being the costliest system component, accounting for about 40% ($103,246) of the total system cost ($, 257, 111.45). The WT accounted for the second highest cost, accounting for about 20% of the NPC, followed by the BB (18%), PV (17%) and converter (4%). Thus the high energy cost of the off-grid systems is caused by the cost of the WT, BB and DEG components and a reduction in the cost of all or any of these components will reduce the energy cost of the system. Also, as suggested by the authors (Muh & Tabet, 2019), if the system is designed so that both DC and AC appliances can be connected to the load, the cost of inverters will be avoided, which will cause a reduction in the system cost. The high cost of the batteries is due to their low expected life of about 4.84 years, which leads to a very high replacement interval and hence cost over the system's life.

We explored the impact of including a second renewable energy component in the optimal PV/grid system. When a WT generator is included in the system, the RF increases. This reduces the need to purchase energy from the grid and reduces the excess energy produced. However, this is at the expense of increasing NPC and COE. For example, the modification of the optimal grid system for the Savana climate of Enugu (PV/Conv/Grid) to (PV/WT/Conv/Grid) consisting of 27.4 kW rated solar PV, 25 kW WT and 21.2 kW converter leads to a decrease in grid purchases by about 26% to 3212 kWh per year; a decrease in excess energy by 36.8% to 4,937 kWh/yr and an increase in the RF by about 27.9% to 0.70. However, the NPC and COE increased by about 28.8 and 16.0 % to $128,267 and 0.116 $/kWh, respectively. Table 9 shows the results for other locations. Adding WT to the optimal PV/grid systems in the educational buildings in the considered locations provides no economic benefit. However, it escalates the cost and complexity of the HRPS architecture probably because of the higher cost of WT compared to solar PV.

4.3 Environmental performance

The comparison of the concentration of major emission species of CO_2 and CO from the optimal grid and off-grid hybrid system configurations in the four geographical locations against that from the existing grid-only electricity in the university buildings is displayed in Figure 11 (a & b).

It is apparent that installing the optimal systems in the educational buildings will considerably decrease CO_2 emissions throughout the project. According to the findings, using optimal PV-grid systems in educational buildings will deliver CO_2

emissions reductions of 57.2, 58.3, 51.7 and 45.1 % in Maiduguri, Kano, Enugu and Port-Harcourt, respectively, when compared to the grid emissions. In the optimal off-grid systems, more GHG (CO_2) emissions reductions of 80.7, 83.9, 76 and 54.1% is observed for the respective locations. The observed trend of more CO_2 emission reduction in off-grid systems agrees with results from previous studies. The authors (Al Afif, Ayed, & Maaitah, 2023) found that the emissions of CO_2 by a Wind/Grid/Battery/Converter system are cut by 58% in comparison to Grid only system. The emissions of CO_2, the chief pollutant responsible for global warming, are more in the best grid systems when compared to the best off-grid systems in all four locations. This is because the proportion of power production contribution from fossil fuel sources is more in the optimal grid systems in the four locations than in the optimal off-grid systems (see Table 7). The diesel generator (DEG) of the determined optimal off-grid systems for Maiduguri, Kano, Enugu and Port-Harcourt runs at 538, 421, 638 and 1,207 hours per year and consumes a total of 3,011, 2,514, 3,751 and 7,167 litres of diesel per year respectively to produce their respective yearly CO_2 emissions. To compensate for the CO_2 emissions by the grid systems and achieve a net zero carbon in all the educational buildings, about 1.61, 1.57, 1.81, and 2.06 hectares of forest absorbing carbon are needed to be planted in Maiduguri, Kano, Enugu and Port-Harcourt respectively. This is equivalent to planting about 804, 783, 907, and 1031 trees in the respective locations based on an average of 500 trees per hectare. Using off-grid systems will require fewer trees/hectares to offset all the CO_2 emitted. About 362 trees will need to be planted in Maiduguri, 303 in Kano, 452 in Enugu and 863 in PH. Waste recycling can also be employed to offset CO_2 emissions from the systems. It is estimated that the quantity of required waste recycling in the grid/off-grid systems is 6.03/2.72, 5.87/2.27, 6.80/3.38 and 7.73/6.47 tonnes at the respective locations.

Finally, a scenario whereby the various institutions decide to install an HRPS that will guarantee a minimal RF of 95% to minimize grid purchases (GP) or diesel engine pollution is considered. Results show that the optimal grid system in this scenario for the four sites is the same and equals a combination of a PV/WT/Grid/Conv in different capacities, while in the off-grid mode; it is a combination of PV/WT/DEG/BB/Conv in various capacities for the locations. Table 10 summarises the results of the optimal systems architecture for this scenario. The results show that the RF show a proportional relationship with NPC in the four locations for both the grid and off-grid systems. COE increases in all locations except Maiduguri, with a slightly improved COE but higher NPC like other locations. Also, it is deduced that the high capacity of renewable power resources results in lesser emissions in both modes, while the application of DEG as a backup power component of an HRPS leads to a rise in energy costs (Das *et al.,* 2021). Thus, this shows that HRPS does not best serve the delivery of significant electric loads with high levels of RE penetration.

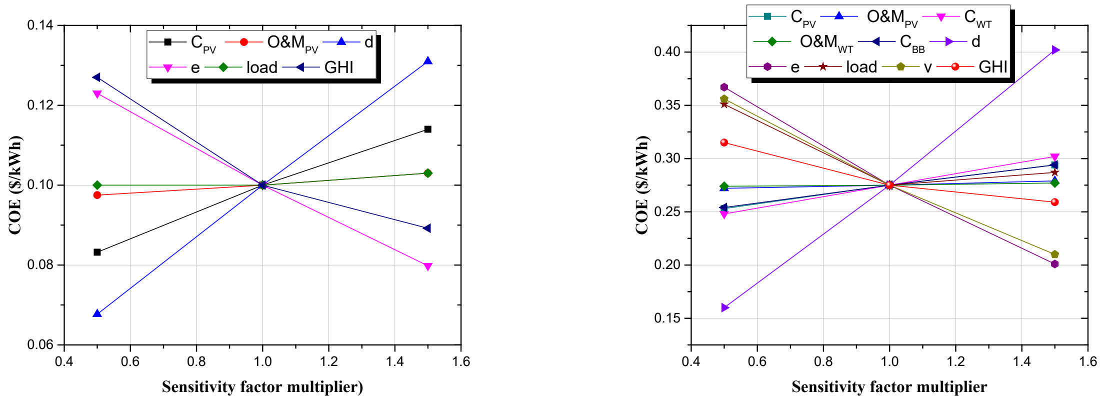
4.4. Sensitivity analysis

In the sensitivity analysis, the OGS and OOGS for the Enugu site are used for the sensitivity analysis since the representative load for the study is from the site. Figures 12 (a & b) display the impact of the variation of the sensitivity parameters on the COE for the OGS (PV/Conv/Grid) and OOGS (PV/WT/DEG/BB/Converter) for the site. It can be deduced that the discount rate (d) has the highest impact on the COE of the OGS, followed by the inflation rate (e) and solar PV capital cost (C_{PV}) in that order. For the OOGS, the discount rate (d) has the highest impact on COE, followed by the inflation rate (e) and the wind turbine capital cost (C_{WT}) in that order. For example, a rise in the cost of capital or the discount rate by about 50% from their base values leads to a reduction in the NPC by about 38 and 36 % in the best grid and off-grid systems, respectively. Their corresponding COE is increased by about 31% in both systems. On the other hand, a 50% reduction of the discount rate from its base value leads to an increase in the NPC by about 150 and 94 % in the grid and off-grid systems, respectively. Their respective COE reduces by about 32 and 42 % in the best grid and off-grid systems, respectively, with respect to their base case values.

Table 10
Results of optimal systems to guarantee RF of 95% in the locations

Parameter*	Maiduguri		Kano		Enugu		Port-Harcourt	
	Grid	Off-grid	Grid	Off-grid	Grid	Off-grid	Grid	Off-grid
PV size (kW)	49.1	51.8	43.3	65.3	90.1	89.6	166	204
WT size (kW)	50	25	100	25	125	25	350	25
BB size (kWh)	-	141	-	151	-	171	-	185
DEG size (kW)	-	36	-	36	-	36	-	36
Conv size (kW)	33.0	26.8	27.3	26.7	31.9	28.4	38.3	27.6
NPC ($) 000	176.9	208.5	287.5	233.5	379.7	266.5	950.5	364.7
COE ($/kWh)	0.0737	0.223	0.0996	0.250	0.125	0.285	0.254	0.390
AEP (MWh/yr)	242.5	164.2	292.0	149.9	305.4	137.4	376.6	129.6
GP (MWh/yr)	11.9	-	14.3	-	15.0	-	18.5	-
DEGP (MWh/yr)	-	4.6	-	4.5	-	4.6	-	4.6
EE (%)	3.9	39.9	2.1	33.3	16.4	26.5	31.9	20.8
RF (%)	95	95	95	95.1	95	95	95	95
CO_2 (kg/yr)	5,223	4,118	6,283	4,097	6,596	4,196	8,141	4,216

* EE: Excess energy; GP: grid purchases; DEGP: diesel engine production



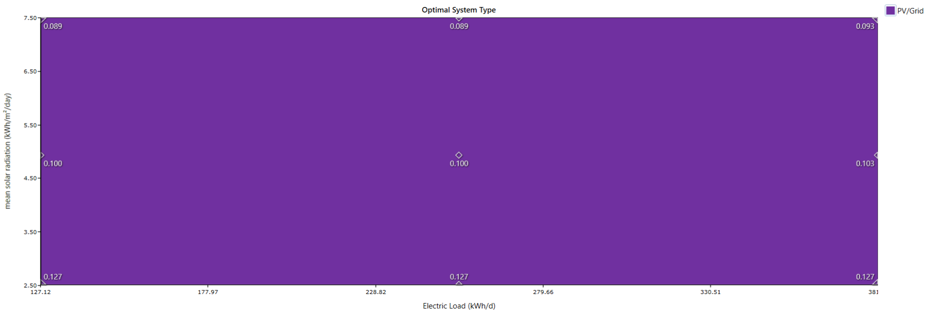
(a) Grid system

(b) Off-grid system

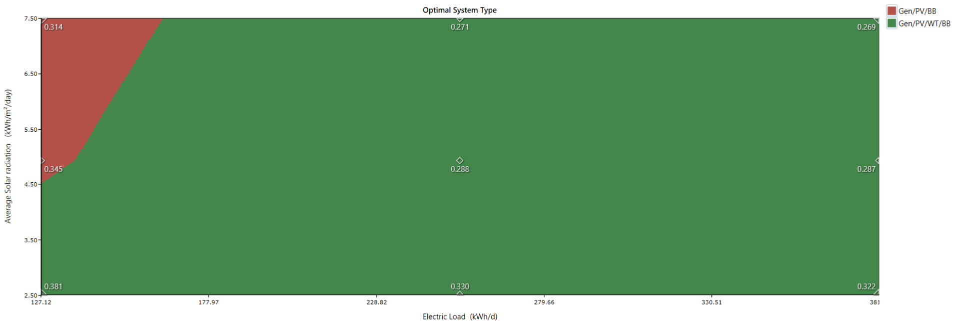
Fig. 12. Sensitivity analysis results for (a) OGs (b) OOGS

We also evaluated the impact of simultaneous variation of demand load, with RE potential (solar, wind) and temperature, on the COE of the optimal system type for the site. This is depicted in Figure 13 (a & b). According to the findings, a fall in the solar radiation potential does not change the optimal grid system type, irrespective of the load. However, the energy costs can rise to 0.13 $/kWh depending on the load, as presented in Figure 13 (a). By increasing the solar potential in the site, the estimated COE of the grid system could decline to about 0.08 $/kWh. In the optimal off grid system (Figure 13b), it is obvious unlike in the grid system, that two optimal system types are feasible, with energy cost ranging from 0.27 to 0.38 $/kWh depending on the solar radiation potential and the demand load.

Figure 14 (a & b) display the impact of the simultaneous variation of the wind potential and demand load on optimal system type for the grid and off-grid systems. A simultaneous increase in these factors by about 50% from their current values shows no change in the optimal system type in both modes. However, the COE show an infinitesimal change. This indicates that solar PV energy generation is somewhat cheaper than other considered sources. At wind speed greater than 6.6 m/s, three optimal system types are feasible for the grid system (see Figure 14 (a)), with energy costs ranging from 0.069 to 0.10 $/kWh. In the off-grid system, as the wind speed reduces to about 3m/s, there is a substantial increase in the COE, making the Gen/PV/battery system type more cost-effective.

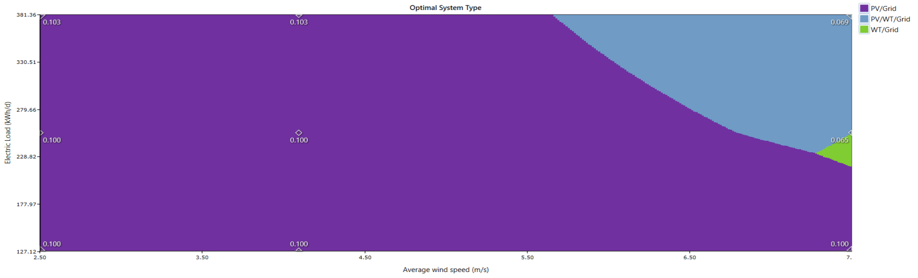


(a) Optimal grid system

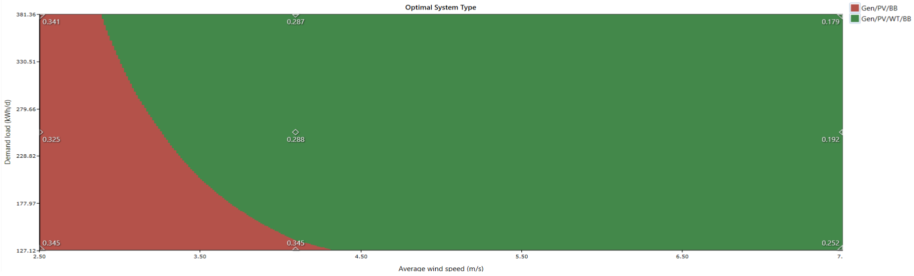


(b) Optimal off-grid system

Fig. 13. Impact of simultaneous variation of load ad solar radiation on optimal system type and COE



(a) Optimal grid system



(b) Optimal off-grid system

Fig. 14. Impact of simultaneous variation of load ad wind speed on optimal system type and COE

5. Conclusion

The comparative techno-environmental and economic performance of integrating optimal hybrid renewable power systems (HRPS) into an existing unreliable and epileptic grid or replacing the existing grid with an optimal off-grid HRPS for serving the electric load of university buildings in four sites (Maiduguri, Kano, Enugu and Port-Harcourt) located in four temperature based climate regions (warm desert, warm semi-arid, tropical savanna, and monsoon climate) of Nigeria are investigated in this study. The analysis was performed using a combination of HOMER Pro and Ret SCREEN experts software to characterise and rank feasible systems derived from a combination of considered power components (diesel engine generator (DEG), wind turbine (WT), solar photovoltaic (PV), battery bank (BB) and a converter (Conv) based on minimal net present cost (NPC) and cost of energy (COE). It is found that both optimised grid and standalone HRPS are beneficial and economically feasible for application in meeting the electric load of educational buildings in different Nigerian locations more reliably and sustainably than using only grid or diesel engine generator (DEG) based electricity. Among all the considered architectures, a system made of only one PV power component (PV/Conv) of different ratings in the load following (LF) dispatch strategy is the least cost optimal grid system (OGS) for the analysed locations whereas, in the off-grid mode, it is made of two or more power components with dedicated converters (PV/DEG/Battery or PV/WT/DEG/Battery) of different ratings, depending on the location and resource constraint. The grid-connected system offers a more reliable, stable and cheap power supply with the cost of energy ($/kWh) and NPC ($) ranging from 0.08-0.11 $/kWh and 90,000-110,000. Still, it depends on the grid infrastructure's location, resource potential and availability. On the other hand, the off-grid system provides an lesser emissions, more autonomous, and decentralised power supply, but is limited by the high cost of generated electricity (COE: 0.22-0.34 $/kWh; NPC: 200,000-320,000 $); arising from the capacity and cost of the WT and storage (DEG and BB). Therefore, the choice between the two systems should be based on the specific needs and constraints of the application and location. However, it is important to note that integrating both systems could provide Nigeria with a more robust and resilient power supply. The study outcomes are vital in providing information to assist policymakers, interested parties and the government in the RE development and integration framework and serve as input data in the design and choice of hybrid renewable energy electrification system configuration for use in University buildings in Nigeria. Monthly average values of the resources in the locations have been used in the analysis and could limit the accuracy of the findings. Future studies deploying actual measured hourly ground resource data are suggested for attaining a clearer, more accurate and robust picture of the viabilities of these systems. This could be achieved by installing small metrological stations at different sites in the country so HRPS can be designed based on real-site data. In addition, further research is needed to explore the potential and feasibility of such hybrid systems in different scenarios involving large-scale cheap energy storage systems, such as thermal energy storage and seasonal hydrogen storage, in conjunction with fuel cells, instead of batteries. Although energy practices are presumed to be the same in all the regions, data can be compared based on rural/urban and locality/state divisions.

Author Contributions: C.D.: Conceptualization, methodology, modelling and formal analysis/writing; T.O.O: review and editing; O.M.E.: writing original draft; K.CU: data and editing, E.C.D: review and editing

Funding: No funding was received

Conflicts of Interest: The authors declare no conflict of interest.

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