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ORIGINAL ARTICLE

Assessment of technical and economic feasibility for a hybrid PV-wind-diesel-battery energy system in a remote community of north central Nigeria

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KEYWORDS

Hybrid energy system;
Optimal configuration;
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Abstract The perpetual dwindling of fossil fuel and its environmental impacts has become a thing of great concern as most countries in the world depend on it for energy generation. The economic development of most of these countries relies on fossil fuel price. Nigeria is one of the countries in the world that solely depends on fossil fuels for electricity generation, and this has greatly affected the growth of its power sector. Hence, there is a need for harnessing renewable energy sources (RES) for electricity generation due to its high availability in abundant quantity in the country. In this study, the viability of developing a standalone hybrid RES system using solar and wind for Giri village (Nigeria) is assessed. The techno-economic and environmental analysis was examined using hybrid optimization model for electric renewable (HOMER) simulation tool by selecting the optimum configuration based on cost of energy (COE), net present cost (NPC), renewable fraction (RF), and greenhouse gas emission (GHG). From the obtained results and sensitivity analysis, the optimal configuration has an NPC of $1.01 m and COE $0.110/kWh, with an operating cost of $4723. The system is environmentally friendly with a renewable fraction of 98.3% and GHG emission of 2889.36 kg/year.

1. Introduction

In the present day world, adequate supply of electricity serves as an index for measuring sustainable economic development of any nation and the wellbeing of its citizens. Without access to substantial energy supply, no country can grow to its

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List of symbols and abbreviations

Symbols

$C_{ann.tot}$	total annual cost
CRF	capital recovery factor
i	interest rate
$Rproj$	project lifetime
i_o	nominal interest rate
f	annual inflation rate
$E_{prim.AC}$	AC primary load served
$E_{prim.DC}$	DC primary load served
$E_{grid.sales}$	total grid sales

Abbreviations

CO_2	carbon dioxide
RES	renewable energy sources
PV	photovoltaic
HOMER	hybrid optimization model for electric renewables
NPC	net present cost
COE	cost of energy
NASA	national aeronautics and space administration
NREL	national renewable energy laboratory
TCC	total capital cost
O & M	operation and maintenance
LCOE	levelized cost of energy
CC	cycle charging
LF	load following
SOC	state of charge
HRES	hybrid renewable energy systems
GHG	greenhouse gas
WS	wind speed
SR	solar radiation
DG	diesel generator
BS	battery storage

expected level [1]. The perpetual increase in population growth and technological advancement has also contributed to the increase in electricity demand, thereby creating a wide gap between demand and supply [2]. According to [3], about 75% of the world's total energy is from fossil fuels. The use of fossil fuels results in many problems such as environmental degradation and global warming as a result of CO_2 emission. Additionally, the gradual depletion of these fossil fuels that accounts for about 75% of world's total energy has given rise to other sources of energy from renewable energy sources (RES) for clean and sustainable energy production to meet the desired load demand [4–6]. RES integration and deployment has increased and has been given a tremendous attention globally [7–9]. There are still over half a million people of European residents without access to the national grid and about 45% of people living in sub-Saharan Africa, East, South, and Central Asia, South America and the Middle East living in darkness [10].

Nigeria being an oil-producing state with abundant natural resources such as coal, gas and other renewable energy sources are still unable to supply adequate energy to its citizens especially the rural communities due to lack of political will and corruption. The cost associated with transmitting power to the rural communities, with very low load demand, is another challenge. Transmitting electricity through grid extension is uneconomical and not feasible due to the loss that will be incurred due to low demand. The use of diesel generators in these communities is also uneconomical due to the high cost of diesel caused by the additional cost of transporting it from the urban area to the rural communities. Apart from grid unavailability to supply the rural communities, the energy supply mix is also dominated by fossil fuels. Keeping aside the effect of fossil fuels energy sources on the environment, the diminution in fuel reserve bring about a serious doubt in coping with the increase in population growth and a rise in economic activities in the country. This concern is due to the increase in energy demand of the present and future scenario. This out of many reasons deem it fit to conduct several studies that will incorporate RE technologies such as solar photovoltaic (PV), wind turbines, hydroelectric, etc. as alternative sources of energy to substitute the current fossil fuels for electricity generation.

The availability of abundant RES in Nigeria has showcased a possibility of harnessing these sources as alternatives for power generation in the rural communities. Solar, wind, and other RES remain the only solution to provide electricity to these communities. According to [11,12] Nigeria has an average sunshine hours of 6.25 with the solar radiation averaged at 5.25 kWh/m^2. Solar radiation in Nigeria varies between 3.7 kWh/m^2 and 7.0 kWh/m^2 from the coastal boundaries to the northern boundaries [13,14], with the northern boundaries experiencing higher solar radiation. It is also estimated that Nigeria has an average wind speed varying between 2.6 m/s and 15 m/s during the rainy season, with an average wind speed ranging from 2.7 m/s to 5.4 m/s depending on the location [11,15–17]. Various studies have suggested the deployment of solar PVs, wind turbines, and other RES for electricity generation in Nigeria [18–21]. These RESs are pollution free sources with zero environmental effect. They are freely available and free of greenhouse gas emission [22–25]. While many studies employed the use of single RES for electricity generation, others considered the use of hybrid systems by combining two or more RESs and in some cases, diesel generators are used as backup power supply for more efficiency and reliability [26–30]. Hybrid systems with backup power supply of diesel generators are mostly applicable to villages that have not access to the grid. The hybrid RES is preferred because total reliance on a single energy source can result in a system oversizing which may eventually increase the capital cost of the system [13,26,31,32]. There is also the effect of weather condition due to fluctuations in wind speed and solar radiation.

Renewable-based energy generation in different parts of the globe have necessitated the development and applications of several optimization models and software for technical, environmental and economic feasibility analysis of numerous hybrid configurations [22,27,33–36]. In Nigeria, some of the studies were carried out in various parts of the country on standalone systems by hybrid optimization model for electric renewable (HOMER) software [13,18,19,37]. Most of the studies focused on the use of hybrid RESs [20,38–40] for increased efficiency, while balancing the influence of fluctuation in the RES. This study focuses on the combination of the two main RES in Nigeria, solar and wind energy, in conjunction with battery and a diesel generator for energy storage and backup power supply respectively. The objective is to evaluate the techno-economic and environmental feasibility of integrating these energy sources (solar and wind) for supplying electricity to Giri village in Gwagwalada community and propose a standalone system for the community by selecting the optimal configuration on the basis of least net present cost (NPC) and cost of energy (COE). Sensitivity analysis is carried out by varying the diesel price and solar radiation in order to examine their effect on the system economic analysis. This will serve as a case study for considering rural electrification in various parts of Nigeria using available RESs.

2. Related studies

Several studies have been carried out in various parts of the world to assess the technical and feasibility analysis of various hybrid energy systems. A study on optimization and life cycle cost of a PV system was carried out by [41] using HOMER to assess the techno-economic analysis of the proposed PV system for that location. An off-grid PV/wind/diesel/battery system was proposed by [42] for rural electrification in Iran using discrete harmony search algorithm to find out the most cost-effective system configuration for the study location. The hybrid wind/diesel/battery configuration was found out to be the most cost-effective configuration for that community. A techno-economic feasibility analysis of an off-grid PV/battery system was also carried out by [43] for a location in Cameroon to evaluate the cost and technical analysis of the system. Another study was carried out by [44] to analyze the economic and technical viability of a hybrid PV/tidal powered micro-hydro hybrid system for a location in Bangladesh using HOMER analysis tool. The cost analysis of the system was analyzed by comparing with other system costs of similar capacity.

A feasibility analysis was carried out in south western Nigeria by [45] to examine the feasibility of a hybrid PV/wind/diesel/battery system in supplying electricity to the study location. The study revealed the PV/diesel/battery system as the most economically suitable configuration with COE ranging from $0.407/kWh to $0.606/kWh depending on the diesel price. The cost is low compared to the diesel only system because of the high cost of diesel. A techno-economic analysis of an off-grid system was also carried out by [37] in north eastern Nigeria. Several models which includes diesel only system, PV/wind/diesel/battery system, PV/wind/battery system, PV/-battery system, PV/diesel system, and PV/diesel/battery system, were analyzed in the study. The optimum configuration in terms of COE was the PV/diesel/battery system with a COE of $0.304/kWh, the overall COE of the study ranges between 0.366/kWh and $1.64/kWh. A technical and comparative analysis of PV/diesel/battery system and PV/wind/diesel/-battery system was also carried out by [46] for a mobile base transmission station in Nigeria. The PV/diesel/battery system was found to be the most economically viable system with a COE of $0.409/kWh. Babatunde et al. [47] also evaluated a grid independent solar PV for a primary health care center application in developing countries. The designed system has an installed capacity of 6 kW based on the clinics load demand, with an additional 25% load growth. The COE obtained for the system ranges between $0.239/kWh and $0.295/kWh.

The related studies discussed provide a good background for the current study by presenting various techno-economic case studies carried out in and outside Nigeria. For the studies carried out in Nigeria, the obtained COE is high as a result of wrong choice of equipment or wrong choice of components for the economic analysis. Most of the studies focused on NPC especially in Nigerian case studies. Therefore, in this study, HOMER optimization tool was used to determine the optimal configuration of a HRES in north central part of Nigeria, Gwagwalada. It estimates the technical feasibility of the HRES and performs economic analysis based on least NPC and COE. Different configurations were simulated by HOMER and the optimal configuration for the study location is the hybrid PV/diesel/battery system with a COE of $0.110/kWh

3. Material and methods

3.1. Study area

A hybrid PV/wind/diesel/battery energy system is designed for rural electrification in Giri village, Gwagwalada Nigeria with latitude 8.9508° N and longitude 7.0767° E. The village is located in the North central part of Nigeria which has a high potential of solar energy. The dwellers of this village depend on agriculture as their major source of income with no electricity access. The village has only one primary school with a literacy rate of about 10–15%. Additionally, the villagers use wood as their only source of energy with only a few of the villagers using diesel generators. The children and women mostly spend their time during the day to fetch firewood form the bush to be used for cooking and heating purposes, while they use kerosene lamps for lightening purposes. The kerosene used by these villagers is mostly expensive due to the high cost of transportation. Also, the schools have no access to electricity which makes it impossible for the students to study in a conducive environment. Electricity happens to be one of the topmost priorities required by these villages for modern agricultural farming and providing a sound education to the children. There are other activities that could also be carried out if there is access to good electricity.

3.2. Load profile

The village's load profile is estimated based on the number of households, schools, and the basic health center in the village. Electrical load of 80 households for Giri village is examined, a primary school and a health center load demand are also examined for the same village. Each of the appliances has an estimated operational hour which is mostly at night. The load data is calculated and distributed across 24 h to produce the load profile as illustrated in Figs. 1 and 2. The load profile is divided into two, load 1 represents the peak load and average consumption of 80 households while load 2 represents the peak load and average load consumption of the school and health

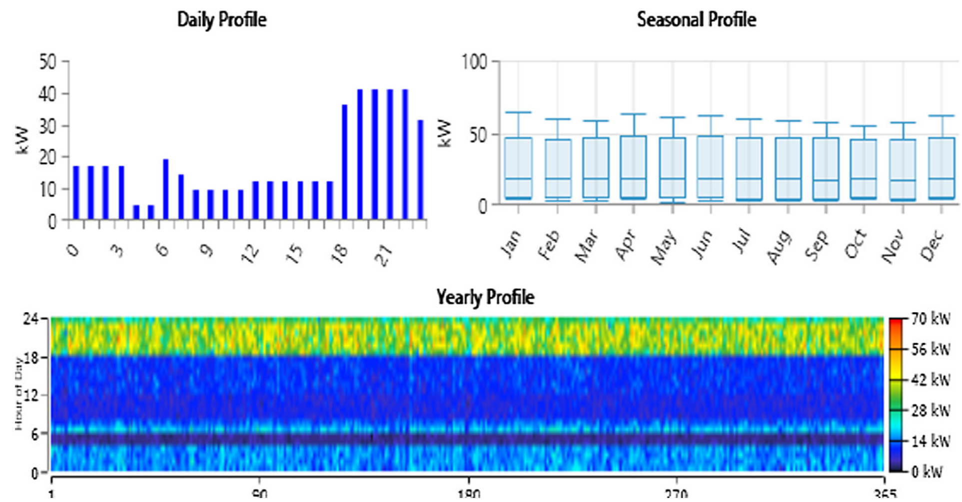

Fig. 1 The hourly and monthly load profile of load 1.

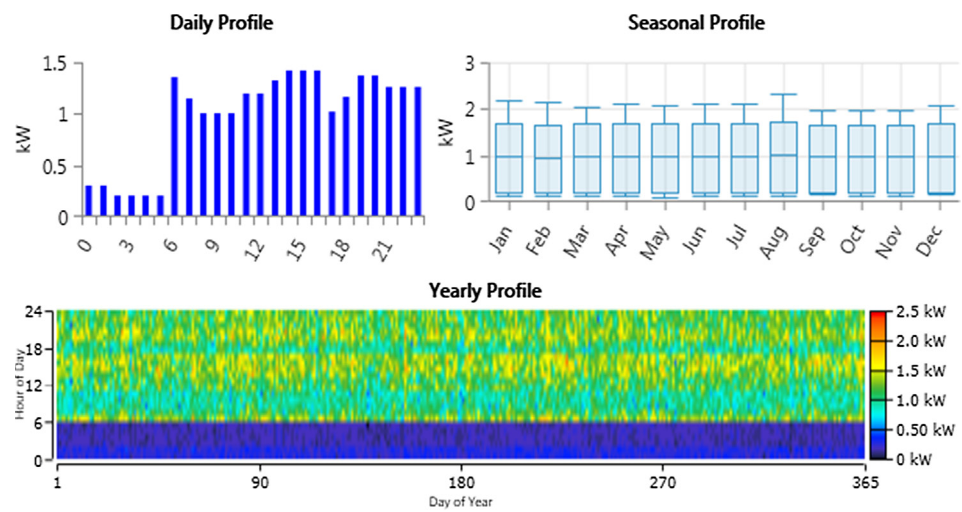

Fig. 2 The hourly and monthly load profile of load 2.

care center in the considered rural community. The peak and average consumption of the houses is 64.29 kW and 451.20 kWh/day, while the peak load and average consumption of the school and health center is 2.34 kW and 23.68 kWh/day with a load factor of 0.17. 10% hour to hour and 15% day to day random variable were used to enable the load data to have some degree of variability at different times of the year. The load data is served into the HOMER software for the graphical representation of the hourly and monthly load profiles as illustrated in Figs. 1 and 2. Table 2 presents a summary of the electricity demand for 80 homes in Giri village of Gwagwalada community.

3.3. Solar potential

For solar system modeling and design, the knowledge of SR and clearness index of the design area is required. The accessibility of this solar potential is determined by the availability of enough sunshine hours in the area [48]. For this study, the data used for the study was obtained from National aeronautics and space administration (NASA) using the latitude and longitude of the location [49]. The study area is in Nigeria situated at latitude 8.9508° N and longitude 7.0767° E with a population size of about 1300 with average solar radiation predicted to be 4.2 kW/m^2/day. The dwellers of the study area are mostly farmers. 22 years solar data average was obtained from NASA via HOMER software, the solar data consisting of the clearness index and solar radiation ranges from 0.412 to 0.663 and 4.27 kW/m^2/day to 6.11 kW/m^2/day respectively as presented in Fig. 3 and Table 1. The month of August has the least solar radiation with 4.27 kW/m^2/day and the month of March has the highest solar radiation value of 6.11 kW/m^2/day. However, the month having least solar radiation value is still good enough for harnessing solar energy for electricity generation.

3.4. Wind potential

Wind is another energy source that can be harnessed for electricity generation. Wind turbines are coupled with inbuilt gen-

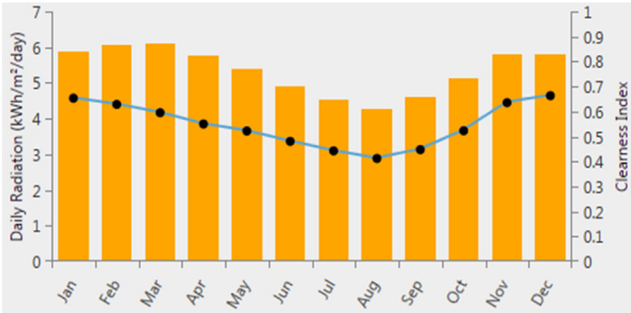

Fig. 3 Monthly average solar data for the study area.

erators which turns the wind flow kinetic energy into electrical energy [50]. For an efficient energy production from the wind, the study area must have the required wind potential to be able to turn the turbines. Different wind turbines exist for electricity generation and can operate at different WS depending on the manufacturer's specification, the WS for wind turbine operation may vary between the cut-in WS of 2.5 m/s and cut-out WS of 25 m/s [15]. For this study, the average WS of the study area is 3.19 m/s at 10 m high. The wind speed for the entire year varies between 2.66 m/s and 3.85 m/s [49]. The data used for this study was gotten from NASA via HOMER, 22 years average wind speed data varying between 2.66 m/s and

Table 1 Average values of meteorological data used.

Month	Clearness Index	Wind Speed (m/s)	Solar Irradiance (kWh/m^2/day)	Temperature (°C)
January	0.653	3.010	5.890	26.650
February	0.628	2.920	6.070	27.300
March	0.595	3.200	6.110	26.630
April	0.550	3.070	5.770	25.920
May	0.522	3.140	5.400	25.510
June	0.480	2.820	4.890	24.610
July	0.442	3.640	4.520	23.790
August	0.412	3.850	4.270	23.680
September	0.447	3.740	4.600	24.050
October	0.523	2.660	5.120	24.320
November	0.635	3.520	5.800	24.590
December	0.663	2.710	5.820	25.970

Table 2 The estimated electricity demand for Giri village.

Units	Quantity	Power(W)	Use (h/day)	Energy consumed (kWh/day)
Load 1				
Residential load				
Bulbs	6	30	8	1.44
Fans	3	50	16	2.4
TV set	1	120	9	1.08
Security lights	2	30	12	0.72
Total for 80 households				**451.20**
Load 2				
School				
Bulbs	8	25	5	1.0
Fan	8	50	6	2.4
Security light	4	30	12	1.44
Total				**4.840**
Health care center				
Bulbs	6	25	8	1.2
Fan	2	50	12	1.2
Refrigerator	1	800	18	14.4
TV set	1	120	8	0.96
Security light	3	30	12	1.08
Total				**18.84**
Total for load 2				**23.68**

3.85 m/s as presented in Fig. 4 and Table 1. There is higher WS value during the month of August having an average WS of 3.85 m/s and a lower WS value during the month of October with an average WS of 2.66 m/s. The average WS of the study area falls within the required WS that can be used to harness wind energy for electricity generation.

3.5. Diesel price

The diesel generator is the conventional way of providing electricity to remote areas. However, the diesel price varies according to location due to the high transportation cost of fuel from urban to rural communities, this makes it impossible to depend on diesel-based power plants for electricity supply. Even with the government subsidy, it was still not possible to depend solely on diesel generators let alone now that the government has stopped subsidizing for both diesel and kerosene, which are the major sources of energy in remote areas. The current price of diesel in Nigeria is about $0.70 per liter in the urban areas, which may rise to about $0.7–$0.85 per liter depending on the village it is transported to. The possible rise in price is due to additional transportation cost and is considered during the sensitivity analysis to observe its influence on the electricity price.

3.6. HOMER software

The hybrid optimization model for electric renewable (HOMER) is a simulation software developed by the National Renewable Energy Laboratory (NREL). The software is used for sizing, optimization and techno-economic and environmental analysis of RESs [51]. It has the ability to carry out simulation, optimization and sensitivity analysis of a hybrid energy system, and it can be used for analyzing grid connected and off-grid distributed generation systems. It has the capability of analyzing both economic and technical aspects of an energy system. During the simulation process, the system is completely modeled, and HOMER determines the system's lifecycle and technical feasibility. In the optimization step, HOMER simulates various configurations until an optimal solution is achieved based on the least NPC and COE. Finally, during the sensitivity analysis, several optimizations are performed using different input variables range, this is done to determine the effect of a change in input parameters on the configuration selected. The HOMER input data includes component prices and sizes, load profile, meteorological data, and other economic constraints. The HOMER software provides the system cost, components sizing, and other economic aspects based on the input values [28]. For this study, the influence is based on the least NPC and COE, other outputs of the HOMER include total capital cost (TCC), fuel consumption, renewable fraction, excess energy, etc. Fig. 5 presents the HOMER architecture based on its inputs and outputs.

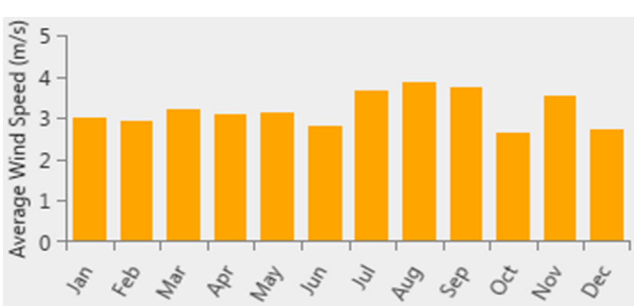

Fig. 4 Monthly average wind data for the study area.

4. System specification and description

A system consisting of two or more energy sources is termed a hybrid system [52]. For this study, the hybrid RES considered consists of a solar PV, wind turbine, storage batteries, and diesel generator. The batteries are storage devices used to store excess electricity that can be used when the RES fail to serve the required load, whereas the diesel generator serves as a backup power supply when the RES and the storage batteries fail to meet the load. Various forms of hybrid systems have been proposed in different parts of the globe based on the available RES in those areas [52–55]. In Nigeria, several studies have also been carried out using the available RESs [7,13,37,40,56]. The hybrid system considered for this study is due to the accessibility of the RES in the study location. The study aims to find the optimal configuration based on the least NPC and COE. The following system components are considered to serve the energy demand of the study area. Fig. 6 presents the schematic diagram of the proposed PV/wind/diesel/battery hybrid system.

4.1. Solar PV

The solar PV system converts the solar irradiance into solar energy to supply the electrical load [57]. It mainly operate when the sun shines, and the excess energy generated by the PV is used to charge the backup batteries, which can be used to satisfy the desired load especially during the night when there is no solar energy. The solar PV used for this study is a generic flat plate with its capital cost, replacement cost, and O&M cost presented in Table 4. Other parameters of the solar PV which includes the technical specifications and energy production are presented in Table 3. The size of PV considered for this study is between 0 and 160.

4.2. Wind turbine

This study considered a Generic 10 kW (G10) wind turbine system which is connected to the AC bus of the hybrid system. The selection was based on the cut-in and cut-out wind speed values, wind turbine cost, and hub height. Fig. 7 presents the wind turbine characteristic curve. The technical parameters of the wind turbine, capital cost, replacement cost, and O&M cost are presented in Table 4.

4.3. Converter

A generic converter is considered for this study with an efficiency of 95% and 100% rectifier relative capacity. Cost specifications of this converter which includes replacement cost of the converter, capital cost, O & M cost and other technical parameters are presented in Table 4. The size of the converter

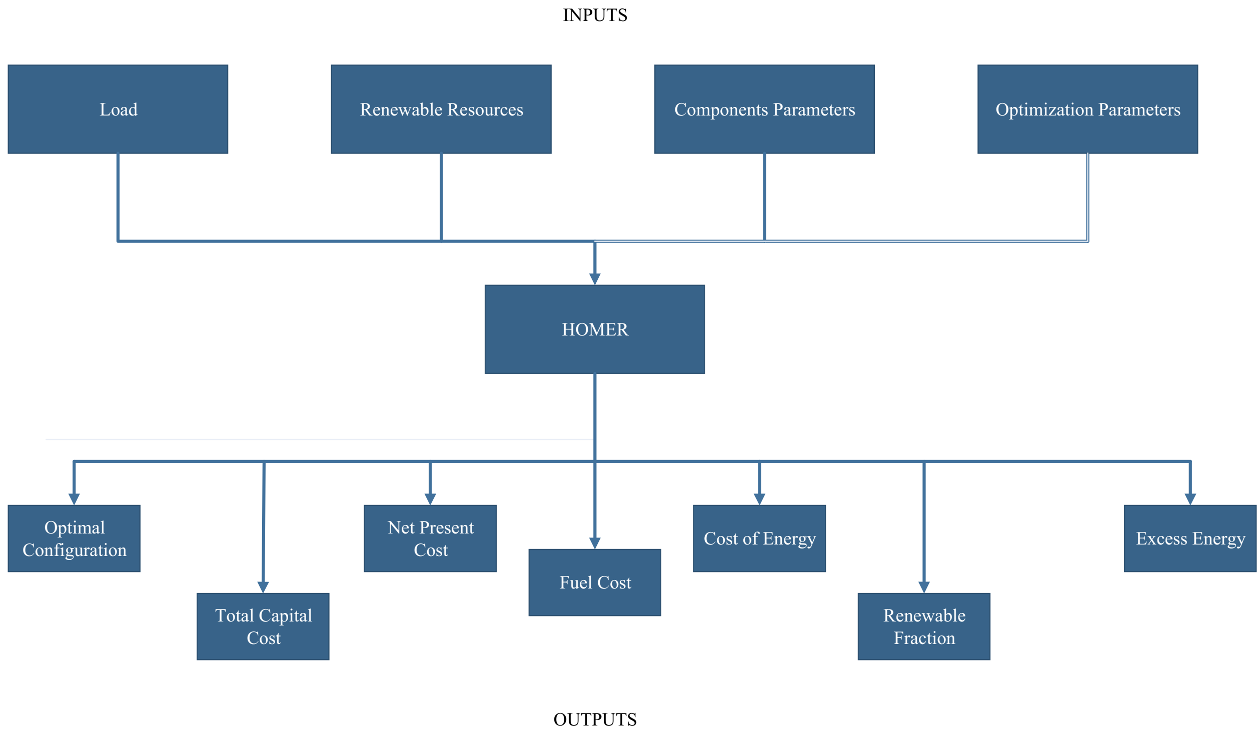

Fig. 5 HOMER architecture based on inputs and outputs.

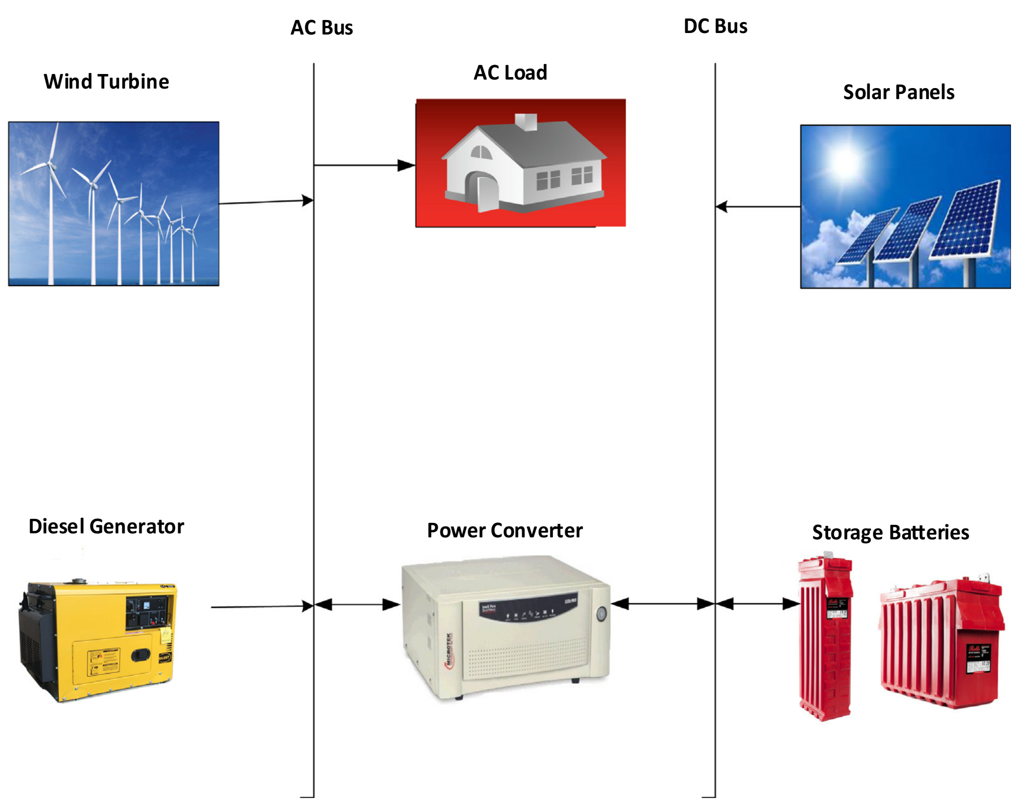

Fig. 6 Proposed hybrid system configuration.

Table 3 Technical parameters of the solar PV.

Parameter	Value	Units
Installed capacity	160	kW
Mean output	32	kW
Mean output per day	768	kWh/day
Capacity factor	20	%
Total production	280,269	kWh/year

chosen for the optimization purpose ranges between 0 and 200 kW.

4.4. Diesel generator

Diesel generator is integrated into the hybrid system to serve the load when the RES cannot serve the desired load demand. The diesel price varies from location to location because of transportation cost. The cost is usually higher in the rural areas where additional transportation cost needs to be added for transporting the fuel to those villages. The cost of diesel in Nigeria ranges from $0.7 to $ 0.8 depending on the location. The diesel generator considered for this study is the generic 50 kW generator. The generator capital cost, replacement cost, and maintenance cost are also presented in Table 4. Fig. 8 illustrates the generator efficiency curve.

4.5. Battery

Surrette 6CS25P battery with theoretical capacity of 6.91 kW and 6 V nominal voltage is considered for this study. It also has roundtrip efficiency of 80%. The battery has a durability of up to 12 years according to the manufacturer's specification. Excess energy from the RES system is stored in the battery bank which can be used to serve the load when the RES fails to serve the load. Backup diesel generator supplies the load when the RES fails to serve the load and the battery storage is also discharged. Table 4 presents the cost implication of the battery storage used. The unit size of battery considered for the optimization ranges between 0 and 400.

5. Economic analysis

The effectiveness of the developed hybrid system can be analyzed by identifying the economic parameters such as levelized cost of energy (LCOE), net present cost (NPC), system capital cost, and salvage cost. HOMER simulates and provides the optimal result based on these parameters. The two economical parameters considered are the NPC and LCOE which are discussed as follows.

5.1. Net present cost (NPC)

The NPC is the main cost parameter in the HOMER software [58]. The NPC is defined as the worth of all the cost incurred by the system over the system's lifespan less the worth of the revenues earned during the project's lifespan. The cost incurred includes the initial capital cost, O&M cost, fuel cost, replacement cost etc. The NPC is mathematically presented in Eq. (1) [59].

$$\mathrm{NPC} = \frac{C_{ann.tot}}{CRF(i, Rpro\ j)} \tag{1}$$

where

$C_{ann.tot}$ = Annual total cost
CRF = Capital recovery factor
i = Interest rate
$Rproj$ = Project lifetime (N)

Table 4 System components and control parameters.

System Components	Parameters	Value
Control Parameters		
	Project lifetime	25 years
	Dispatch strategy	Load following/cycle charging
	Diesel Price	$0.7, $0.75, $0.8
	Expected Inflation rate	12%
	Nominal Discount Rate	6%
Solar PV	Operational lifetime	25 years
	Ground Reflectance	20%
	Sizes considered	0–160 kW
	Cost per KW	$2500
	Replacement Cost	$2000
	O & M Cost per year	0
	Derating Factor	90%
Converter	Operational lifespan	15 years
	Sizes considered	0–200 kW
	Converter cost	$200/kW
	Replacement Cost	$200/kW
	Efficiency	95%
Diesel Generator	Size considered	50 kW
	Operational Lifespan	15,000 h
	Capital Cost	$20,000
	Replacement Cost	$20,000
	O & M Cost	$0.03/h
	Minimum Load Ratio	10%
	Emission	16.34 g/L
Surrette Battery	Sizes considered	0–400
	Roundtrip efficiency	80%
	Minimum SOC	40%
	Nominal Voltage	6 V
	Nominal Capacity	6.91 kW
	Operational lifespan	12 years
	Capital Cost	$1000
	Replacement Cost	$800
Wind Turbine	Operational lifespan	25 years
	Capital cost	$4000/kW
	Replacement Cost	$4000/kW
	O & M Cost	$100/year
	Size considered	10 kW

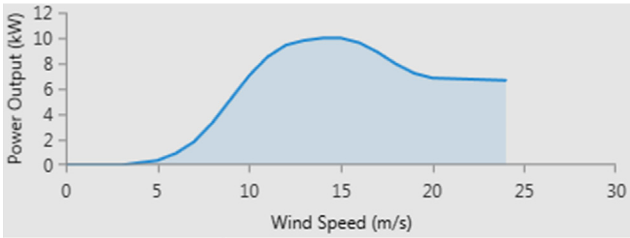

Fig. 7 The wind turbine characteristic curve.

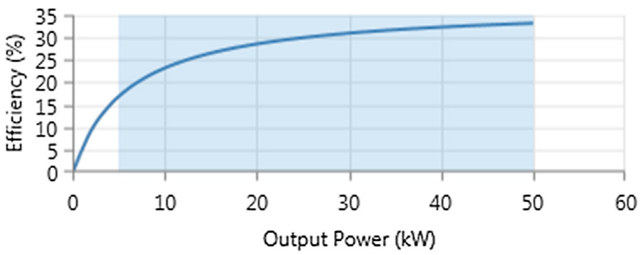

Fig. 8 Generator efficiency curve.

$$\mathrm{CRF} = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{2}$$

$$i = \frac{i_0 - f}{1 + f} \tag{3}$$

where

i = real interest rate
i_o = nominal interest rate
f = annual inflation rate

5.2. Levelized cost of energy (LCOE)

The useful electricity cost the system produces per kWh is the LCOE. As calculated by HOMER the LCOE is the ratio of the total annual cost of electricity produced to the total useful electricity produced [60]. The LCOE equation is presented in Eq. (4) [61].

$$\mathrm{LCOE} = \frac{C_{ann.tot}}{E_{prim.AC} + E_{prim.DC} + E_{grid.sales}} \tag{4}$$

where

$C_{ann.tot}$ = Annual total cost
$E_{prim.AC}$ = AC primary load served
$E_{prim.DC}$ = DC primary load served
$E_{grid.sales}$ = Total grid sales

The sum of the annual total cost of each component is the total annual cost which is also an important parameter in calculating the TNPC and LCOE in HOMER.

5.3. Renewable fraction (RF)

The total renewable power generated by the renewable energy sources compared to the total power generated by the entire system is called the renewable fraction [62]. For this study, the RF is required to be as high as possible to reduce the effect of greenhouse gas emission by the conventional diesel generator even though it will have effect on the NPC due to cost of the renewable energy sources. The RF is mathematically expressed as

$$RF(\%) = \left(1 - \frac{\sum P_{diesel}}{\sum P_{renewable}}\right) \times 100 \tag{5}$$

where P_{diesel}, is the diesel generator output power and $P_{renewable}$, is the output power of the renewable sources (solar and wind).

6. Operation strategy

The hybrid system operates in two main strategies, namely the cycle charging (CC) and the load following (LF). In the CC strategy, the diesel generator incorporated is used to supply the load and charge the batteries simultaneously. While in the LF, the renewables are serving the load at the same time charge the batteries when there is excess electricity. In the event where the output power from the RES is unavailable, the backup generator is configured to serve the load. Fig. 9 illustrates the operational flowchart of the of the hybrid system. The figure represents the overall management system that controls the flow of energy in the HRES. For this study, the LF strategy is adopted where only the RES are used in charging the batteries. The charged batteries serve the desired load in the event where the RES are unable to serve the desired load demand. The diesel generator can only serve the load when both the RES and the batteries could not serve the desired load demand. This reduces helps in reducing the excess energy produced and also helps in reducing the total NPC of the system.

There are situations that the load cannot be supplied by the RES due to climatic conditions. For example, when there is available SR, the solar PV serves the load and excess energy from the PV charges the batteries, the same goes to the wind turbine when there is available WS to turn the wind turbine. Excess energy from these two sources is used as a dump load. When the RES fails to serve the desired load, the batteries which serve as the storage will supply the loads until it is discharged to a minimum of 40% SOC. When it is at 40% or less the generator automatically turns on to serve the load.

7. Results and discussions

This study designs a hybrid PV/wind/diesel/battery energy system to serve the load demand of Giri village in Gwagwalada community, Nigeria. HOMER simulation tool was used to carry out the design of the hybrid system by finding the system optimum configuration using the village's load profile and the component parameters. Fig. 10 presents the hybrid system setup in HOMER software.

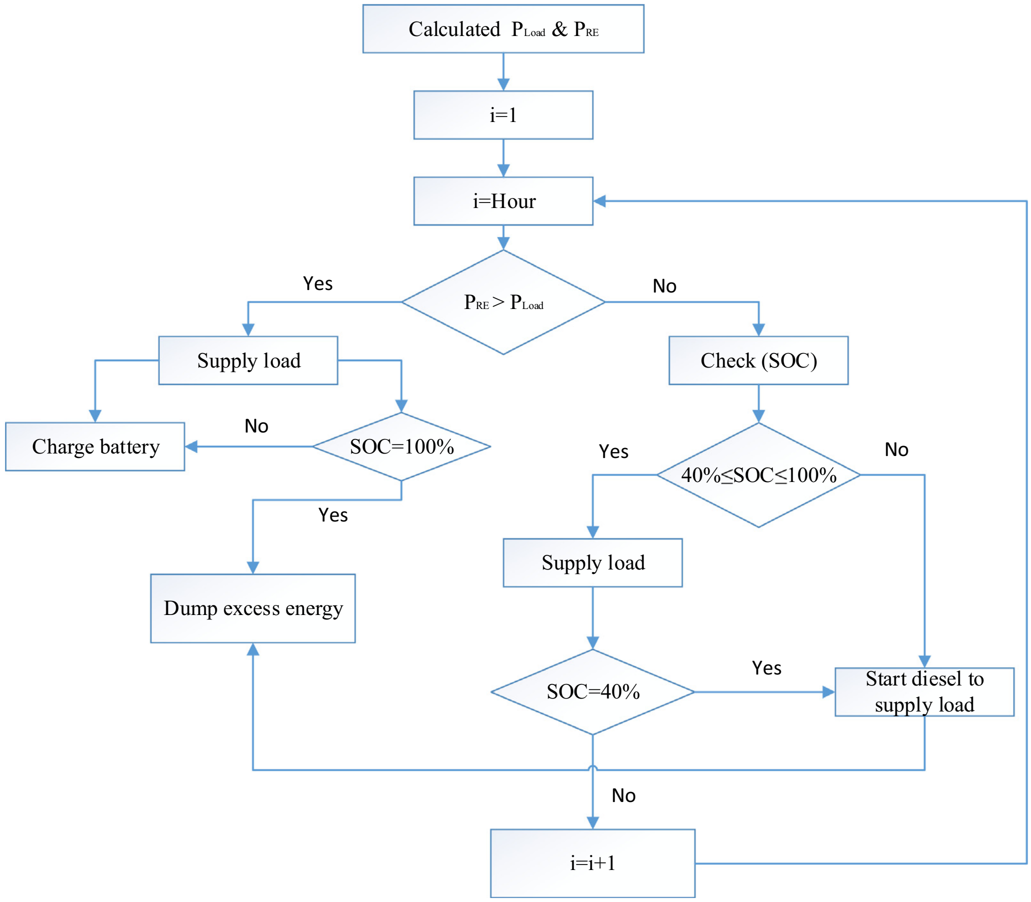

Fig. 9 Flowchart of the system operational strategy.

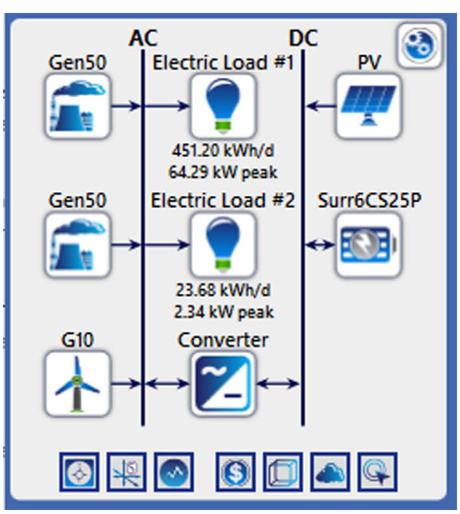

Fig. 10 The hybrid PV/wind/diesel/battery system setup.

7.1. System optimization

From the HOMER Pro simulation result, it was observed that there were 661,632 solutions simulated out of which there were only 175,961 feasible solutions and were classified according to the system architecture in four categories as presented in Table 5. The optimum configuration comprises of 160 kW PV panels, 50 kW generator, 320 units of batteries, and 80 kW converter, it has a total NPC of $1.01 m and COE of $0.110/kWh.

For this configuration, the solar PV has the highest capital cost followed by the batteries and the system converter, the diesel generator has the least capital cost. Based on the NPC, the batteries have the highest NPC due to replacement cost followed by the solar PV and diesel generator due fuel cost, the system converter has the least NPC. Fig. 11 presents a summary of the cash flow of the optimal configuration as analyzed by different cost types. The figure illustrates that capital cost is the main expense of the system which comprises mostly the batteries and the solar PV, followed by the replacement cost and the fuel cost. The O & M cost is very minimal because the designed hybrid system is mostly powered by the RESs, which have a very low maintenance cost.

Fig. 12 illustrates the monthly electrical output from the optimal configuration system. The solar PV system generates more power especially December and first three months of the year when there is high amount of solar energy. The months with the least solar energy power generation are the months of June, July, August, and September, which is usually during the rainy reason. The excess energy from this configuration is 69,805 kWh/year which is 24.7% and the unmet load is 0 kWh/year. The capacity shortage is also 0 kWh/year and the system has a renewable fraction of 98.3%.

Table 5 The hybrid system optimal configurations.

Configuration	PV (kW)	Wind turbine (kw)	Gen set (kw)	Battery	Converter (kW)	NPC ($)	COE ($)	Initial cost ($)	Operating cost ($)
PV-Diesel-battery	**160**		**50**	**320**	**80**	**1.01 m**	**0.110**	**756,000**	**4273**
PV-Wind-Diesel-Battery	160	1	50	320	80	1.04 m	0.113	796,000	4647
PV-Wind-Battery	160	2		600	80	1.58 m	0.172	1.10 m	9087
PV-Battery	160			800	80	1.85 m	0.201	1.22 m	11,874

The bold section signifies the optimal system configuration.

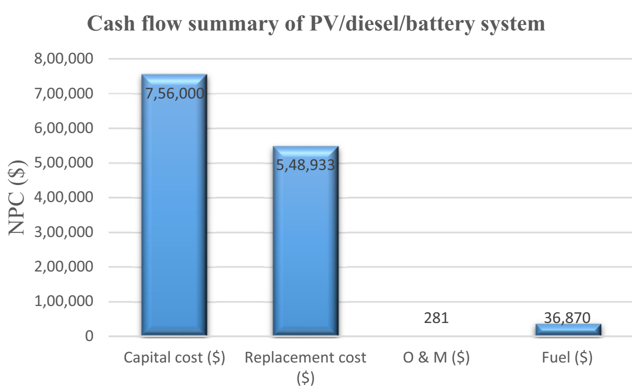

Fig. 11 Summary of cash flow according to the cost breakdown.

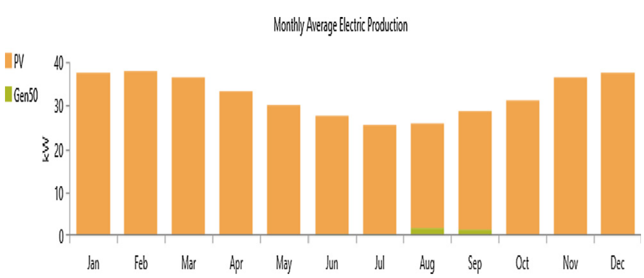

Fig. 12 Monthly average electricity production of the optimal configuration.

7.2. Sensitivity analysis

There are certain constraints and control variables that attract the system operating cost and the system output which need to be defined for the purpose of techno-economic analysis. Due to the uncertainties of the renewables like SR, WS, diesel price, etc., some of these variables need to be considered for sensitivity study of the hybrid system. For this study, the SR and the diesel price were considered to carry out the analysis neglecting the wind speed. The SR and the diesel price were both varied to obtain the effect of the variation on the system's economy. Although the diesel price is capped at $0.7 per liter, it varies from $0.7-$0.8 per liter, considering additional cost due to transportation cost. The solar radiation also varies between 4.2 kW/m^2/day and 5.9 kW/m^2/day. The results obtained from the sensitivity analysis are presented in Table 6. The Table presents the variation in the COE and NPC, which was caused due to diesel price and SR variation. The result indicates that a decrease in diesel price and an increase in SR value decreases the COE and NPC, while an increase in diesel price and a decrease in solar radiation increases the COE and NPC. The PV/DG/BS is the optimal configuration in all the sensitivity cases as presented in Table 6 with variation in the component sizing and cost due to the effect of diesel price and SR variation.

Fig. 13 presents the surface plot of the COE generated from the hybrid PV/wind/diesel energy system, diesel price is plotted on the x-axis while the solar radiation is plotted on the y-axis. From the plot, it is observed that with the increase in fuel price, there is an increase in NPC and an increase in solar radiation value also decreases the NPC.

7.3. Discussion

The assessment of the economic viability of a proposed hybrid system is examined in this study. The simulation results from HOMER were analyzed based on NPC and COE of the optimal system configuration as earlier stated. From the obtained results, the hybrid PV/DG/BS system configuration is the optimal configuration. The environmental impact, energy parameter assessment and the economic evaluation of the optimal configuration have been analyzed and discussed as follows.

7.4. Environmental impact

From the configuration simulated by HOMER, the hybrid PV/diesel/battery system has the highest greenhouse gas emission of 2889.36 kg/year, followed by hybrid PV/wind/diesel/battery configuration with GHG emission of 2569.69 kg/year. The PV/wind/battery and PV/battery configurations have zero GHG emission because the system is powered by 100% renewables. This shows that the hybrid PV/wind/battery and PV/battery systems are the most environmentally friendly configurations with zero emission, but unfortunately not economically viable because they have the highest NPC and COE compared to the optimum configuration system. The system with the optimal configuration based on the least NPC and COE is still environmentally friendly because it produced the least amount of GHG emission compared to a diesel-only system and other system configurations, it also has a renewable fraction of 98.3%. This configuration can help maintain an environmentally friendly community. Table 7 presents the GHG emission produced by the various configurations simulated by HOMER Pro, while Fig. 14 presents the bar chat of the comparison made.

Table 6 Results of the optimal configuration based on different sensitivity cases.

Sensitivity		Architecture						Cost		System
Fuel Price ($/l)	Average SR	Configuration	PV (kW)	DG (kW)	BS	Converter (kW)	Dispatch	NPC ($)	COE ($)	RF (%)
0.70	4.20	PV/DG/BS	160	50	320	80	CC	1.31 m	0.142	85.2
0.70	4.90	PV/DG/BS	160	50	320	80	LF	1.13 m	0.123	95.1
0.70	**5.90**	**PV/DG/BS**	**160**	**50**	**320**	**80**	**LF**	**1.01 m**	**0.110**	**98.3**
0.75	4.20	PV/DG/BS	160	50	320	80	CC	1.33 m	0.145	85.2
0.75	4.90	PV/DG/BS	160	50	320	80	LF	1.14 m	0.124	95.1
0.75	5.90	PV/DG/BS	160	50	320	80	LF	1.01 m	0.110	98.3
0.80	4.20	PV/DG/BS	160	50	320	80	CC	1.35 m	0.147	85.2
0.80	4.90	PV/DG/BS	160	50	320	80	LF	1.15 m	0.125	95.1
0.80	5.90	PV/DG/BS	160	50	320	80	LF	1.01 m	0.110	98.3

The bold section signifies the optimal system configuration.

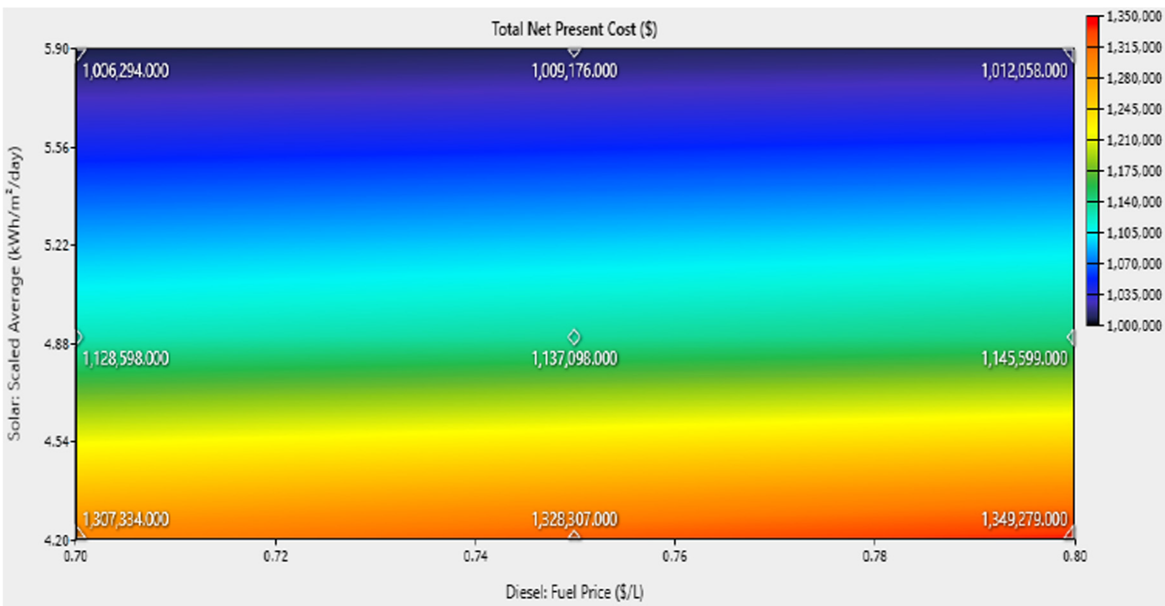

Fig. 13 Surface plot showing the effect of solar radiation and diesel price on the NPC.

Table 7 Comparison of the environmental impact.

Configuration	GHG emission (kg/year)
PV/diesel/battery	2889.36
PV/wind/diesel/battery	2569.69
PV/wind/battery	0
PV/battery	0

7.5. Economic assessment

HOMER software simulates many economic parameters. Table 8 presents a comparison of the economic parameters for each of the simulated configurations. The parameters include initial cost, Net present cost (NPC), replacement cost, and O&M cost. The hybrid PV/diesel/battery configuration has the least initial cost of $756,000 as presented in Table 8. The hybrid PV/wind/diesel/battery has the second least initial cost of $796,000. The other two PV/wind/battery and PV/battery configurations have the highest initial cost of $1.10 m and $1.22 m respectively.

The configuration with the least O&M cost is the hybrid PV/wind/diesel/battery system with O&M cost of $262.30. The next is the PV/diesel/battery system with O&M cost of $294.10 and happens to be the configuration with the highest O&M cost. The PV/wind/battery and PV/battery systems have zero O&M cost because they are both powered by 100% renewables. Additionally, the hybrid PV/battery configuration has the highest replacement cost of $1,439,174.51 which is due to a large number of batteries and PV panels used in the configuration. PV/wind/battery configuration has the second highest replacement cost, followed by PV/wind/diesel/battery and PV/diesel/battery configurations with replacement cost of $1,316,209.52, $710,757.49 and $596,730.89 respectively as presented in Table 8 and Fig. 15. It is noted that the configuration with the highest number of batteries has the highest replacement cost due to high cost of batteries, it is therefore concluded that the number of batteries affects the cost of a system.

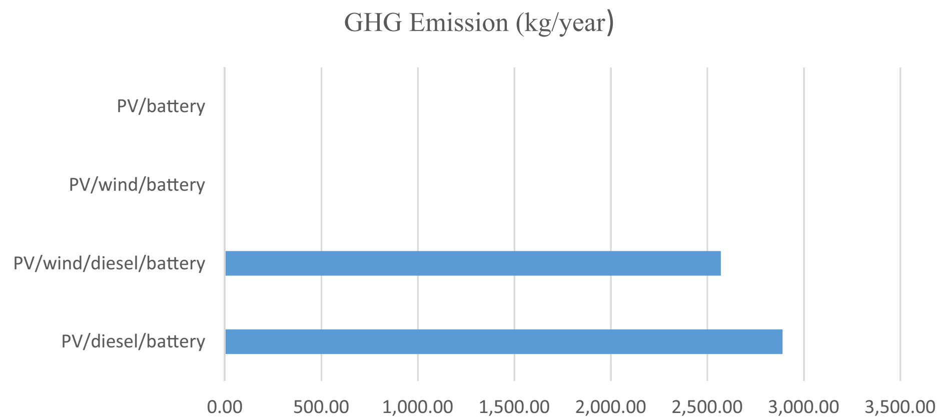

Fig. 14 Comparison of the environmental impact.

Table 8 Comparison of the economic assessment.

Configuration	Initial cost ($)	Replacement Cost ($)	O & M Cost ($)
PV/diesel/battery	756,000	596,730.89	294.10
PV/wind/ diesel/battery	796,000	710,757.49	262.30
PV/wind/battery	1.10 m	1,316,209.52	0
PV/battery	1.22 m	1,439,174.51	0

7.6. Assessment of energy production and consumption

Various energy parameters of the system configurations were also analyzed. From the results obtained from HOMER, the hybrid PV/wind/diesel/battery configuration has the highest energy production of 284,194 kWh/year with a yearly consumption of 173,323 kWh/year, and excess energy of 70,958 kWh/year. The hybrid PV/diesel/battery configuration has the second highest electricity production of 283,135 kWh/year with yearly energy consumption of 173,323 kWh/year and excess energy of 69,805 kWh/year that is used to charge the batteries. 99% of the energy produced by this system is from

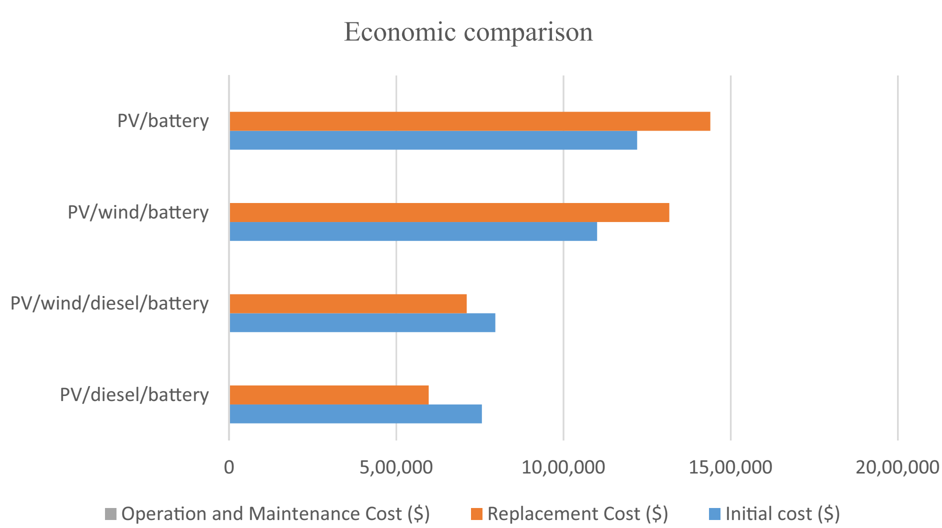

Fig. 15 Comparison of the economic assessment.

Table 9 Comparison of energy parameters assessment.

Configurations	Energy production (kWh/year)	Energy Consumption (kWh/year)	Excess Energy (kWh/year)
PV/diesel/battery	283,135	173,323	69,805
PV/wind/diesel/battery	284,194	173,323	70,958
PV/wind/battery	283,027	173,331	69,200
PV/battery	280,269	173,331	66,058

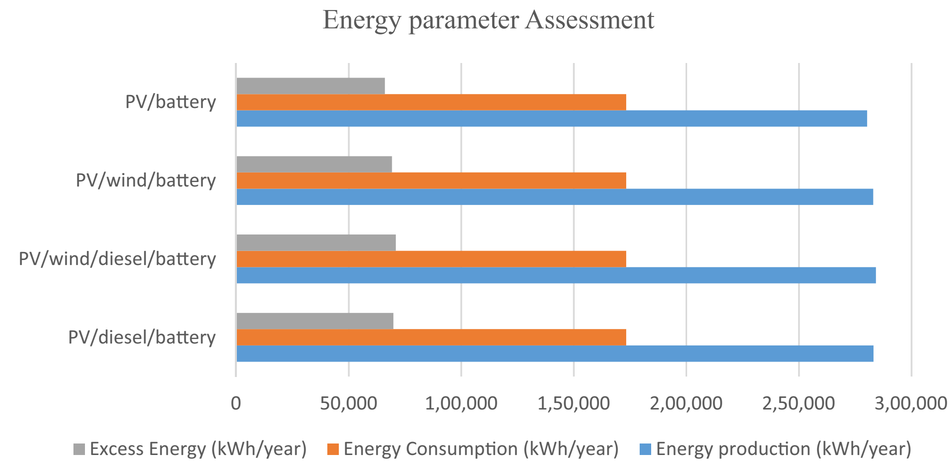

Fig. 16 Comparison of energy production and consumption.

the solar PV with 1.01% coming from the diesel generator. The PV/wind/battery and PV/battery configurations have electricity production of 283,027 kWh/year and 280,269 kWh/year with excess energy of 69,200 kWh/year and 66,058 kWh/year respectively. These two configurations have the least energy production and they both satisfy the yearly energy consumption of 173,331 kWh/year. Table 9 and Fig. 16 presents a comparison of the energy parameters assessment.

8. Conclusion

In this study, a hybrid RES system comprising of wind turbine, PV, battery, and a diesel generator is proposed for generating electricity for Giri village in North central Nigeria (Gwagwalada). Modeling and simulation of the system was carried out using HOMER simulation tool. The system's optimum configuration was obtained based on the least NPC and COE. Four optimal configurations were obtained which include the PV/diesel/battery, PV/wind/diesel/battery, PV/wind/battery, and PV/battery systems as simulated by HOMER to find the most possible solution. From the obtained results, it can be concluded that

- The configuration with the lowest COE of \$0.110/kW and NPC of \$1.01 m is the PV/diesel/battery and is the optimum configuration for all sensitivity cases. The configuration has a renewable fraction of 98.3% and GHG emission of only 2889.36 kg/year
- The PV/battery hybrid system has the highest COE and NPC of \$0.201/kWh and \$1.85 m respectively. The high cost of this configuration is due to high cost of PV batteries and PV panels. Fortunately, the system has zero GHG emission because it has 100% renewable fraction.
- Based on the sensitivity variables, which are solar radiation and diesel price, it can be concluded that with a lower cost of diesel and higher SR values, the NPC and COE decreases and with higher diesel price and lower SR values, the NPC and COE increases.
- The economic analysis and the environmental impact assessment has proved that the hybrid PV/diesel/battery system is environmentally and economically viable for electricity generation in Gwagwalada community. It is not only economically feasible but also environmentally friendly because it reduces a large amount of CO_2 emission. It also reduces the system's operation cost because less amount of diesel will be used to fuel the generator.
- This techno-economic analysis of harnessing renewable energy generation for rural community can be applied to other developing nations in which most of their rural populace do not have access grid.

Conflict of interest

The aothors declare no conflict of interest.

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