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Comparative study and sensitivity analysis of a standalone hybrid energy system for electrification of rural healthcare facility in Nigeria

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Abstract This paper investigated the techno-economic viability assessment of solar PV/wind/diesel generator (DG)/battery hybrid energy systems (HES) for powering an isolated rural health clinic in northern Nigeria. HOMER–software tool developed by the US National Renewable Energy Laboratory (NREL) has been utilized for the techno-economic assessment of the proposed HES. The results of the simulation reveal that PV/DG/battery HES with 5.43 kW PV, 2 kW DG, 3.06 kW power converter, and 10 units of batteries emerged as the optimum system and most preferable with the minimum Net Present Cost (NPC) of $16,457 and Cost of Energy (COE) of $0.259/kWh compared to other system cases. The outcome also shows that the optimized solution is environmentally friendly as it presented an acceptable carbon dioxide emission of 1304 kg/year, which was about 80% and 82.5% less than that of system case 3 (DG/battery) and system case 5 (DG-Only). To have a good understanding of the operation of various system configurations considered, details of the system's battery storage status and power flow are discussed via the energy balance of the various system configurations. This analysis shows operating cost, fuel cost, COE, fuel consumption, and renewable fraction are sensitive to the variation in all the considered sensitivity parameters.

1. Introduction

While the majority of urban residents are going with the tide of the modern, global, and friendly standard of living, the same cannot be said for most remote villages in developing countries. The deficit in power supply in most remote communities has expanded the economic and infrastructure development gap, promoted poverty, and made it increasingly hard to

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improve their lifestyle. According to [1] about 17% of the world population is unconnected to a grid power supply network, out of which 85% are dwellers of remote villages; with Sub-Sahara Africa having the largest rate. There is a universal consensus that adequate power supply can improve the services delivered by healthcare centers while inadequate can influence healthcare service provision [2]. In Nigeria, the inaccessibility of reliable electricity in remote communities is one of the key issues facing the development and good service delivery of rural healthcare centers. There is huge potential for the application of renewable power sources (RESs) to satisfy the energy need of rural locations with little or no access to grid power in Nigeria. For instance, with little variations all over the year, an annual daily mean of 20 MJ/m^2/day of solar radiation falls on the country's landmass [3], while the mean wind energy of 12.6 kWh and 197.7 kWh in the range is obtainable at 25 m high in Nigeria with an annual average wind speed of 4.7 m/s [4,5]. Hence, a suitable application of solar power and the substantial potential for wind power applications combined with effective government policies can speed up the development of RESs to fulfill the ever-increasing electricity need of the country. The country's grid production installed capacity as reported by [6] was 12,954 MW, but in most cases, only about 7652 MW is often available as the production capacity. This is inadequate (about 41% less than the installed capacity) considering the high demand for energy from consumers and this usually resulted in exposing some of the consumers to persistent electricity cuts.

Furthermore, at the beginning of 2019, around 5375 MW peak power generation was recorded. This was up by 2.8 MW (i.e. 5377.8 MW) in 2020 [7]. In 2019, the installed electricity capacity of renewable energy (RE) extended beyond 200 GW. Altogether, at the end of 2019, the installed RE capacity was sufficient to provide an estimated 27.3% of global power production as shown in Fig. 1 [8].

The distributed RE configurations provided more households in developing countries with access to electric power [9]. The 2019 investment in new RE capacity surpassed that of coal, natural gas, and nuclear power capacity investment, with more emphasis on RE such as solar and wind. According to [8], the cost of wind and solar power has seen a continuous drop in the past years, with solar PV showing the sharpest fall in cost at 82% between 2010 and 2019, followed by the onshore and offshore wind at 40% and 29% respectively. The cost of energy from utility-scale solar PV in 2019 was around \$0.07/kWh and dropped 13% per annum, whereas offshore and onshore wind both dropped around 9% per annum, reaching \$0.115/kWh and \$0.053/kWh, respectively [10].

Insufficient access to reliable and modern power at rural health clinics can cause substandard sterilization of medical equipment, poor lighting during surgery, inadequate electricity to power medical and communication devices, etc. However, the provision of reliable power to remote rural locations can have a positive impact on healthcare delivery as well as aid the infrastructure development of these areas. The utilization of a single-source standalone renewable energy system to provide power to load have some disadvantages including high initial capital cost, unpredictability nature of these sources which frequently affect the amount of power generated. A suitably sized hybrid combination of RES (solar and wind) and auxiliary source (diesel generator (DG)) with storage battery as backup is more effective and less costly in providing electricity for locations with little or no access to grid power besides fulfilling greater energy demand for a long period. The DGs are the other energy source mostly used to supplement the unreliable grid electricity in this area. An improved power condition in this area can boost the deliverance of quality healthcare services as well as economic and educational activities.

2. Research background

Many researches have been carried out on hybrid RESs (solar and wind) systems with a back-up source focusing on their economy, technical performance, and environmental impact [11,12,21–25,13–20]. Some researchers compared various HESs to obtain optimal configuration [20,26–31]. The HOMER analysis tool was utilized in [32] to conduct a feasibility and environmental analysis as well as a detailed sensitivity analysis of

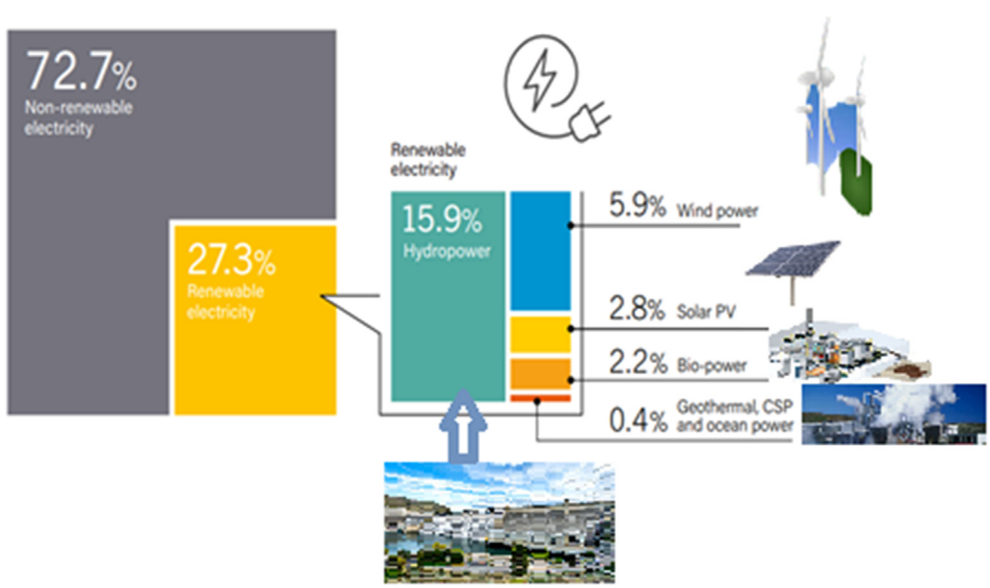


Fig. 1 Renewable power share of world electricity generation [8].

various HESs for the electrification of an Iraqi rural community. Their results reveal that PV/hydro/DG/battery HES was most suitable economically and environmentally among all combinations of HES considered. Also, there was a 22.5% increment in the NPC of the module with total years of project lifetime compared with that of the one-year. Oladigbolu et al. [33] conducted a feasibility and comparative study of different HESs to supply electricity to a typical Nigeria rural community. They concluded that the PV/hydro/wind/DG hybrid configuration was the best HES in supplying electricity to the selected rural site as it had the best environmental prospects as well as having an acceptable techno-economic outcome.

Furthermore, the design and costs evaluation of a HES was proposed in [34] for providing power to a typical remote location in Tazouta, Morocco. They indicated that the proposed HES was able to satisfy a significant portion of the dwelling load with around 79.1% of the mean solar fraction. The potential application of HES consisting of hydro, PV, DG, and batteries for rural electrification was investigated in [35]. They stated that the optimum configuration had an electricity and total net present costs of $0.112/kWh and $963,431 and was able to prevent around 77.1% of carbon dioxide emission from being emitted to the environment in comparison with the PV/DG configuration. Rezk et al.[36], studied in detail the technical and cost evaluation and power management of a grid-unconnected HES to power a remote load in Minya city, Egypt. Their results show that the least energy and net present costs for the chosen location are $0. 074.kWh and $207,676 respectively, in addition to the optimum sizing of 120 kW PV, 64 batteries, 10 kW, and 50 kW converter. Nurunnabi et al. [37], evaluated the potentials of RESs (solar and wind) at different locations in Bangladesh and performed the feasibility and sensitivity assessment of off-and-on grid HES. Their outcome shows that optimum system design achieved for the different areas considered ranges between wind/grid and wind/PV/grid while the needed values of the electricity and total net present costs for the grid-unconnected mode is somewhat high for all locations. The optimal systems of HES for remote healthcare center application in three different rural communities in Nigeria were investigated in [38]. They indicated that PV/wind/DG with battery storage is the least expensive system for electrifying remote rural healthcare center in both the north-eastern (Maiduguri) and south-eastern (Enugu) parts, while PV/DG/battery configuration was found to be suitable in south-western (Iseyin) part of the country. Also, the selected optimum HES for all the locations had an energy cost of 0.39, 0.432, and 0.454 $/kWh respectively, and perform better than the DG-only configuration.

The techno-economic evaluation of different HESs including a standalone DG system was investigated in [39] for the Pratas island, Taiwan. Their analysis reveals that PV/DG configuration had the least COE of $/0.3569kWhat a renewable and surplus energy fraction of 15.3% and 2.6% respectively, while the COE of the PV/DG/battery scheme was found to be higher than that of the DG scheme. The energy management strategy (EMS) and design optimization technique of HES to provide consumers with high reliability and power quality is studied in [40]. Their findings show that the optimized solution presented by the combination of wind, battery, and converter had the least COE and NPC of $/0.309 and kWh $14,846 respectively with zero pollutant emissions, and the performance evaluation of the EMS is examined and promising outcomes with an effective voltage profile of the load is noticed. Das et al. [41] conducted a feasibility assessment of HES for a rural village in Bangladesh. Their results indicated that HES with 10 kW PV, 20 kW (total) DG, 72 batteries, 15 kW inverters, and a 9 kW biogas generator presented the optimal configuration plan, having a total NPC of $612,280, a renewable fraction of 60% and a COE of $0.28/kWh in addition to showing good environmental prospect. Olatomiwa and Mekhilef [42] assessed the techno-economic potential of utilizing RESs for electrifying grid-unconnected rural healthcare clinics located in the northern region of Nigeria. The results of their investigation show PV/DG/battery configuration as the optimized solution among other system models evaluated. The optimal system had the least net present and electricity costs of $41,512 and $0.53/kWh. The optimal sizing of HES for rural area application is investigated in [43]. They stated that the optimal configuration lowers the CO_2 gas emission by about 62% as compared to the kerosene utilized in a present situation, having the least COE of $0.37/kWh. The performance evaluation of various HESs of PV, wind, DG, and battery storage to power a telecommunication load in various locations of Punjab, India was studied in [44]. They stated that the PV/wind/DG HES with battery generates more electricity in comparison to PV/DG/battery, PV/wind/DG, wind/DG/-battery, wind/DG, and PV/ DG configuration.

Despite the increasing research focused on HES in the rural locations of Nigeria, few have explored its application in the context of rural healthcare facilities. Furthermore, observation from these few researches on the techno-economic assessment of this particular application (powering rural healthcare centers) in Nigeria reveals that the obtained cost of electricity is on the high side due to the poor decision made during the selection of components and their costs for the economic evaluation. Therefore, this research is conducted to further investigate the techno-economic performance of different configurations of HESs (including solar PV, wind, diesel generator, and battery) to power a typical remote healthcare facility in Nigeria.

In this context, the main objective of this study was to evaluate the technical feasibility of the HES and conducts an economic assessment based on minimum net present and energy costs. Different system cases were investigated to obtain the optimal system that will be suitable for the study area. A suitably sized decentralized hybrid system is considered the most feasible electricity production option for powering remote healthcare centers. This study also conducted a sensitivity analysis to explore the possible impacts on the optimal configuration when certain parameters are set to different values. The sensitivity variables selected for this study are solar radiation, diesel fuel price, minimum battery state-of-charge, and rural healthcare facility load demand. According to Khan et al. [44], hybridization of PV, wind, DG, and battery is cost-effective and can generate more energy to satisfy load requirements. In this analysis, HOMER is utilized for the technical, economic, and emissions assessment.

3. Methodology

3.1. Site description and load data

The healthcare center considered for analysis in this study is located in Kudu village, Mokwa district of the Northern part of Nigeria. The location of this community in Nigeria is shown by a solid green arrow in Fig. 2. The community is situated at 9°16′0″N latitude and 5°21′0″E longitude. It is a government-owned rural clinic that caters to pregnant women and children and comprises a labor room, an emergency room, a female ward, a male ward, a doctor consulting room, an antenatal hall, a patient record-keeping room, and a store where various types of equipment are kept. Electrical appliances that can be found in the health center are refrigerators, light bulbs, and ceiling fans. Due to the unavailability of electricity in the village, the health center has its diesel-powered generator which is usually switched on whenever there is an urgent need for it or there is an emergency case as there is limited funding for powering the facility and in most cases, the staff provides this funds themselves. In general, electrical energy is needed for powering lighting and cooling loads as well as a few pieces of medical laboratory equipment. Also, the residents of this village largely depend on wood and charcoal for cooking, battery-powered torches for lighting, and in most cases, electrical appliances (if available) are powered by diesel generators.

Initially, the healthcare facility load is maintained at a minimum constant from 12 midnights to 5 am. The load peaked in the morning from 6 am to 12 pm due to the lifestyle of the villagers where they often visit the health center in the morning time. The load demand however starts to decrease after 1 pm until the end of the day. The clinic's daily load demand profile is given in Fig. 3. The daily average power consumption and peak powers are 23 kWh/day and 3 kW respectively at a load factor of 0.32. Due to the variation in the daily power demand of this center and for better estimation of the maximum load of the proposed configuration, a time-step and day-to-day random variability of 10% and 5% were entered in HOMER.

3.2. Meteorological data

The meteorological data used for this research was obtained from the NASA Langley research center website by specifying the coordinate (9° 16′ 0″ N latitude and 5° 21′ 0″ E longitude) of the area [45]. Fig. 4 displays the changes in mean solar irradiation per month as well as the corresponding clearness index. The gross insolation getting to the surface of the earth is subject to the cloudy conditions as well as the clarity of the sky, which are very uncertain [46]. The monthly daily global solar irradiation varies from 4.43 $kWh/m^2/day$ to 6.26 $kWh/m^2/day$ hence, the energy output per month of the solar power conversion system would equally vary from month-to-month. The yearly mean solar irradiation was found to be 5.51 $kWh/m^2/day$. This reveals that there is huge potential for solar power applications in this area even though these resources are being underutilized at the moment.

Also, the influence of temperature on the PV system is subject to the atmospheric conditions and mounting layout of a certain area. The ambient temperature influences the PV system performance in addition to its electricity generation level, hence the need to consider the change in temperature of Kudu village. The monthly mean temperature is presented in Fig. 5. The highest temperature was observed in April at 29.59 °C, while the lowest temperature occurred in December at 24.66 °C. The annual mean temperature was 26.7 °C.

The wind speed (WS) on the other hand ranges between 2.93 (October) and 4.47 m/s (April) at a yearly average of 3.8 m/s as shown in Fig. 6. The changes noticed in the wind pattern are usually due to factors such as topographic characteristics, vegetation cover, etc. [47]. Once the mean wind speed value (monthly) is inputted, the HOMER analysis tool will cre-

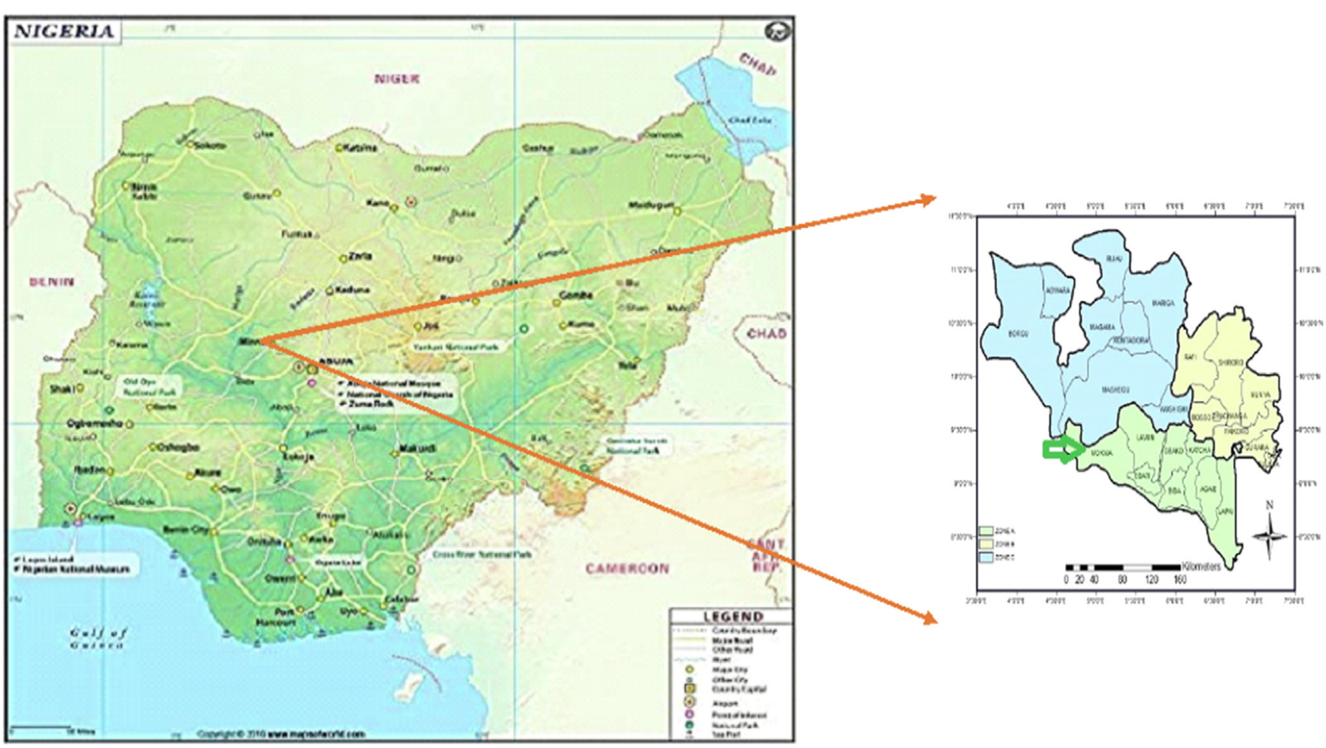


Fig. 2 Location of Kudu village in Nigeria.

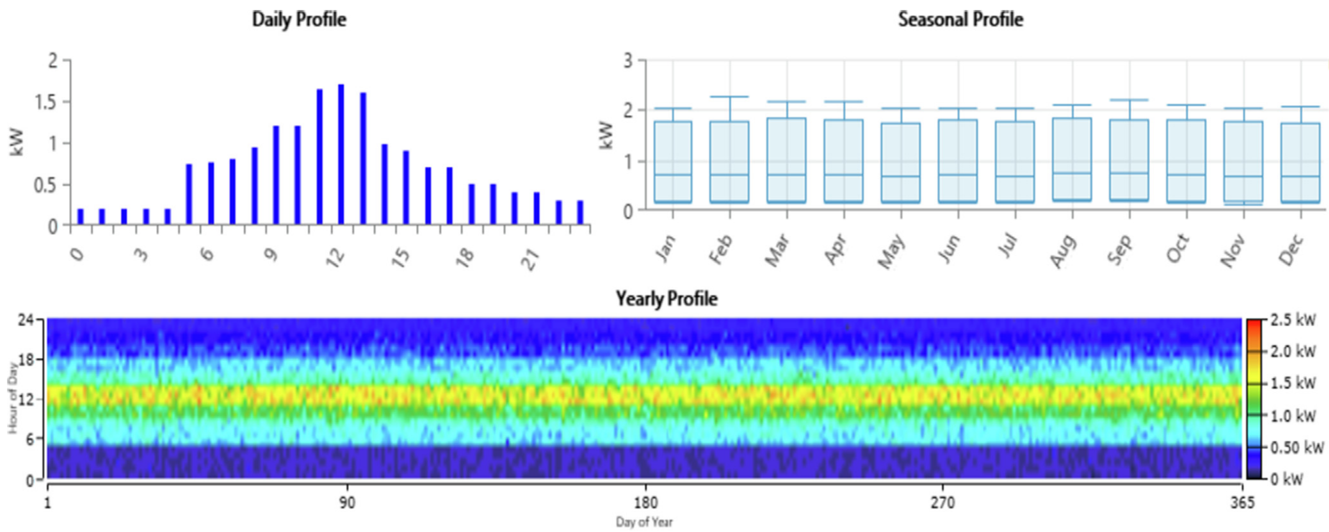


Fig. 3 The hourly and monthly load data of the selected healthcare facility.

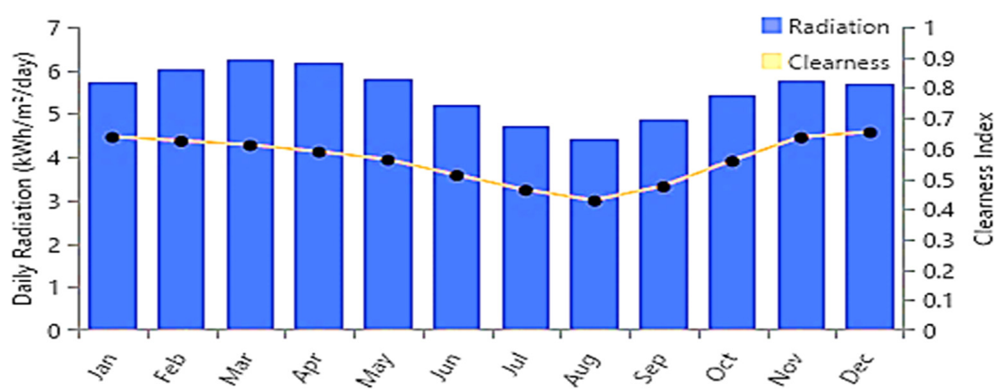


Fig. 4 Monthly mean solar irradiation and clearness index of the Kudu community.

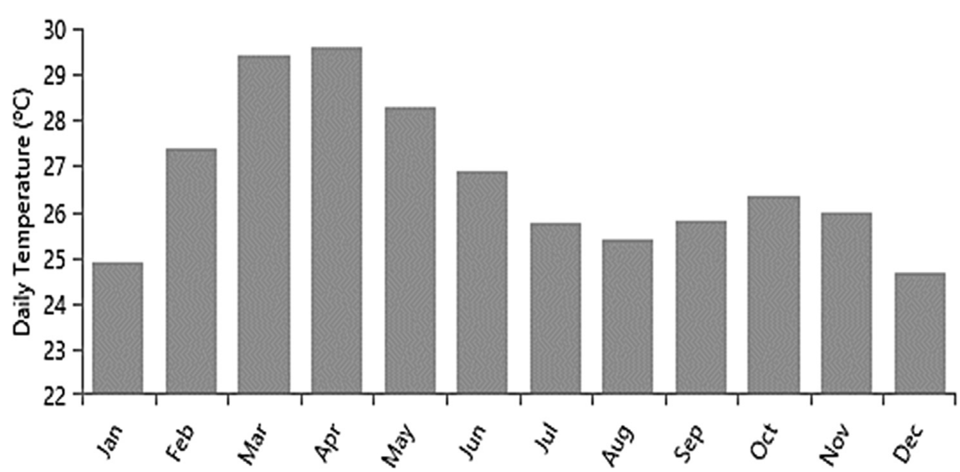


Fig. 5 The monthly mean temperature of Kudu village.

ate an annual synthetic per hour data from this value alongside other advanced parameters, such as the 1 h. autocorrelation factor (0.85), the diurnal pattern strength (0.25). the time of maximum WS (15 h) and the Weibull k (=2).

3.3. Specifications and mathematical representation of the proposed HES components

The proposed HES consist of five key components which include a solar PV system, wind turbine, batteries, diesel gen-

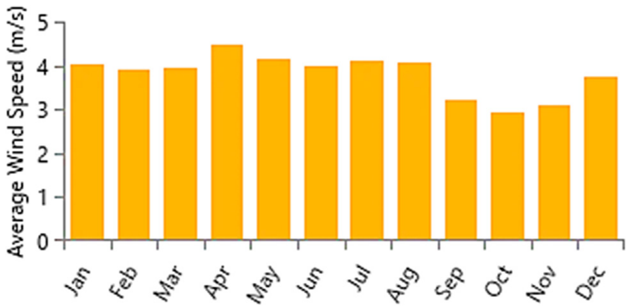


Fig. 6 The monthly mean wind speed of Kudu village.

erator, and a converter. Detailed information on cost variables for the individual components required for simulation is presented in Table 1. In this study, HOMER was utilized to conduct the techno-economic viability assessment of different system models including the proposed system to obtain the best combination of HES for powering the selected healthcare facility.

3.3.1. Solar PV energy system

The PV panels are used to generate electrical energy for meeting the power requirement of different loads such as the clinic load, residential load, commercial load, etc. The power generation level of a PV system is often impacted by the level of solar irradiation, cell temperature, and the geographical features of a place [12]. In this study, a flat plate PV panel with a rated power of 12 kW and an efficiency of 13% was selected. The ground reflectance, which denotes the percentage of the global solar irradiation falling on the earth's surface (solid part) that is thrown back, was selected as 20%. The nominal operating cell temperature and the temperature effects on power were specified as 47 °C and −0.48% / °C [35]. The cost parameters details of this component are presented in Table 1. The PV output power is calculated as [48]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) [1 + \alpha_P (T_C - T_{C,STC})] \quad (1)$$

where Y_{PV} denotes the PV output power under standard test conditions (STC) (kW), α_p refers to the power temperature coefficient (%/°C), f_{PV} represents the de-rating factor of the PV (%), $G_{T,STC}$ is the incident radiation under STC (1 kW/m^2), G_T denotes the solar radiation hitting the PV system (kW/m^2), T_C refers to the cell temperature of the PV (°C), while $T_{C,STC}$ denotes Tc under STC (25 °C).

3.3.2. Wind power system

The energy production via wind obeys the principle of the changing of wind power into mechanical power through the wind power conversion system (WPCS) and then to electric energy. The wind turbine (WT) height considerably influences the amount of power it gets, thereby affecting the output of the WPCS. A generic WT of 1 kW rated power and 17 m hub height was selected for the present study. The cost variables of the wind turbine are given in Table 1 for a lifetime of 20 years. The mechanical power of the WT is evaluated as [49]:

$$P_m = \frac{1}{2} \times \rho \times A \times V^3 \quad (2)$$

where ρ denotes the air density (1.22 kg/m^3), A refers to the surface swept by the rotor (m^2), and V represents the WS (m/s), while the WT electric power is given as [50]:

$$P_e = \frac{1}{2} \times \rho \times C_p \times A \times V^3 \times 10^{-3} \quad (3)$$

where C_p denotes the power coefficient of the WT.

3.3.3. Converter system

The power converter is expected to operate in two directions, i.e. as an inverter (DC-AC) or as a rectifier (AC-DC). It keeps the flow of electricity between the components of the AC bus and the DC bus. The cost variables of the converter are given in Table 1. The lifetime and efficiency of 15 years and 95% were specified for the inverter input, while the rectifier input has a relative capacity of 100% with an efficiency of 85% [40]. The converter power capacity levels can be calculated using equation Eq. (4). Where L_i and L_r both denote inductive and resistive loads.

$$C = (3 \times L_i) + L_r \quad (4)$$

3.3.4. The battery storage (BSS)

The BSS is a device for storing and supplying energy for the reliable and effective operation of a renewable energy-based hybrid system. The BSS's main target in this analysis is to store the excess electricity from the electricity-generating components and supply the stored energy to the load in the event of any shortage in capacity. The chosen battery storage considered for this analysis has a rated nominal voltage and capacity of 6 V and 2.45 kWh, 20% minimum state of charge, 1958 kWh throughput, and 80% roundtrip efficiency. The cost parameters of this component are presented in Table 1. The string size of the BSS was assumed to contain 8 batteries. Each battery has a lifespan (throughput) of 1958 kWh and specified cost variables. The battery storage capacity is determined using the autonomy days and demand as shown in Eq. (5) [51]:

Table 1 Technical specification and cost of various components.

Components	Initial cost	Replacement cost	Maintenance cost	Reference
PV system	$1500/kW	$1000/kW	$10/kW/year	[51]
Diesel generator	$200/kW	$200/kW	$0.05/kW/h	[35]
Wind turbine	$4000/kW	$3200/kW	$200/year	[33]
Converter	$200/kW	$200/kW	–	[40]
Battery	$176/unit	$176/unit	$8/unit/year	[40]

$$C_{Bat} = \frac{E_L AD}{\eta_{inv} DOD \eta_{bat}} \tag{5}$$

where E_L denotes the mean daily load energy (kWh/day), AD refers to the autonomy days, η_{inv} represents the inverter efficiency (90%), DOD denotes the depth of discharge (80%), and η_{bat} represents the BSS efficiency (80%).

3.3.5. Diesel generator (DG)

The DG operates as a continuous source of electricity in various HESs and is distinguished by its fuel intake and efficiency [51]. DGs are often used as a backup in a system with RESs since these sources heavily depend on weather conditions, which significantly affect their power generation levels. The current cost of diesel fuel per liter in Nigeria is $0.581/L [52]. The cost per liter of diesel may fluctuate subject to the world oil market and the irregular provision of diesel fuel. The minimum load ratio of 25% was specified and the lifespan of the DG system was 15,000 h. The DG cost parameters are given in Table 1. The fuel curve and linear correlation are used in HOMER during the calculation of the fuel intake, which is the amount of fuel used to produce power and is given in [51] as:

$$Fuelc._{DG} = (a \cdot T_{DG} + b \cdot P_{DG}) \tag{6}$$

where $Fuelc._{DG}$ refers to the DG fuel intake rate (L/h), a denotes the coefficient of fuel intercept (L/kWh) (taken as 0.0161 L/kWh rated), T_{DG}, represents the DG capacity (kW), b is the fuel slope (L/kWh) (taken as 0.2486 L/kWh output) and P_{DG} represents the generator output (kW).

3.4. Economic model

The economic assessment is a key aspect of HOMER software due to its main objective (cost minimization). Economic variables such as NPC are used to analyze the optimal solution of different system models. Also, the optimal combination of system components is ranked according to the minimum lifecycle cost (total net present cost). The NPC is computed using the following equation [53]:

$$C_{NPC} = \frac{TAC}{CRF(i,N)} \tag{7}$$

where the gross annualized cost ($/yr.) is represented by TAC, N refers to the number of years, and i denotes the annual real discount rate in percentage. The capital recovery factor (CRF) is given in [15] as:

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{8}$$

The electricity cost (COE) is the mean cost per kilowatt-hour of effective electricity produced by the system. It is computed using the below equation [35]:

$$COE = \frac{TAC}{E_{anloadserved}} \tag{9}$$

where $E_{anloadserved}$ denotes the gross yearly load (kWh) served by the system. The real interest rate is 12.5% [54].

3.5. System technical constraints and dispatch strategy

Constraints are pre-established rules the systems must satisfy in HOMER to secure a realistic best result, or else, HOMER discards those system configurations that do not satisfy the specified constraints. To ensure uninterrupted power is provided in the event of an unexpected rise in energy demand or fall in RES output, the operating reserves were set at 10% (as a percentage of load), while 50% and 25% were selected for the output of wind and solar energy (as a percentage renewable output). The high value selected for RES outputs is because of their inherent variability [55]. The peak unmet energy of 0% and a maximum annual capacity shortage of 0% were considered during the simulation.

Dispatch strategy is very important for any renewable energy-based configuration that consists of a DG and a storage system [56]. The cycle charging dispatch strategy, where the DG runs at its peak rated capacity to fulfill the energy demand with extra power utilized for charging the BSS has been selected as the power management strategy. In this control strategy, renewable components and battery storage are given priority to provide electricity to load. When the RE components output and the BSS cannot sufficiently satisfy the load requirement, a backup DG is operated to feed the load and to at the same time charge the storage battery. This strategy tends to preserve the DG and battery storage lifespan.

3.6. Sensitivity parameters

The sensitivity evaluation was performed to explore the possible impacts on the optimal configuration when certain parameters are set to different values. The sensitivity variables selected for this study are solar radiation, diesel fuel price, minimum battery state-of-charge, and rural healthcare facility load demand. For each sensitivity variable, the actual value (base case) was either increase or decrease except for the load demand growth. The base case (actual) values of global solar irradiation, battery SOC_{min}, fuel price, and healthcare load demand were 5.51 kWh/m^2/day, 20%, $0.581/L, and 23kWh/-day, respectively. The sensitivity parameter analyzes in this study are summarized in Table 2.

The block diagram of the HES adopted in this analysis is given in Fig. 7. The project lifetime of the proposed HES is 25 years. In this analysis, a techno-economic viability study of different HES to obtain the optimal combination of energy resources has been conducted.

4. Results and discussion

HOMER simulation software was utilized for the techno-economic analysis of the proposed configuration (PV/wind/DG/battery scheme) to satisfy the electricity need of a rural healthcare center located in Kudu village, Mokwa district of Northern part Nigeria. This tool executes a timely simulation for all feasible and infeasible system configurations based on the values presented at the initial stage. The feasible system configuration was later categorized using both technical and economic variables such as NPC, COE, operating cost, electricity generation, load served per annum, renewable fraction, etc. The RES components (solar and wind system) and the bat-

Table 2 Sensitivity variables.

Parameters	Sensitivity values						
Solar Radiation (kWh/m^2/day)	4.68	4.96	5.23	5.51	5.79	6.06	6.34
Diesel Price ($/L)	0.494	0.523	0.552	0.581	0.610	0.639	0.668
Min. battery SOC (%)	15	20	25	30	35	40	45
Load Demand (kWh/day)	23	25	27	29	31	33	35

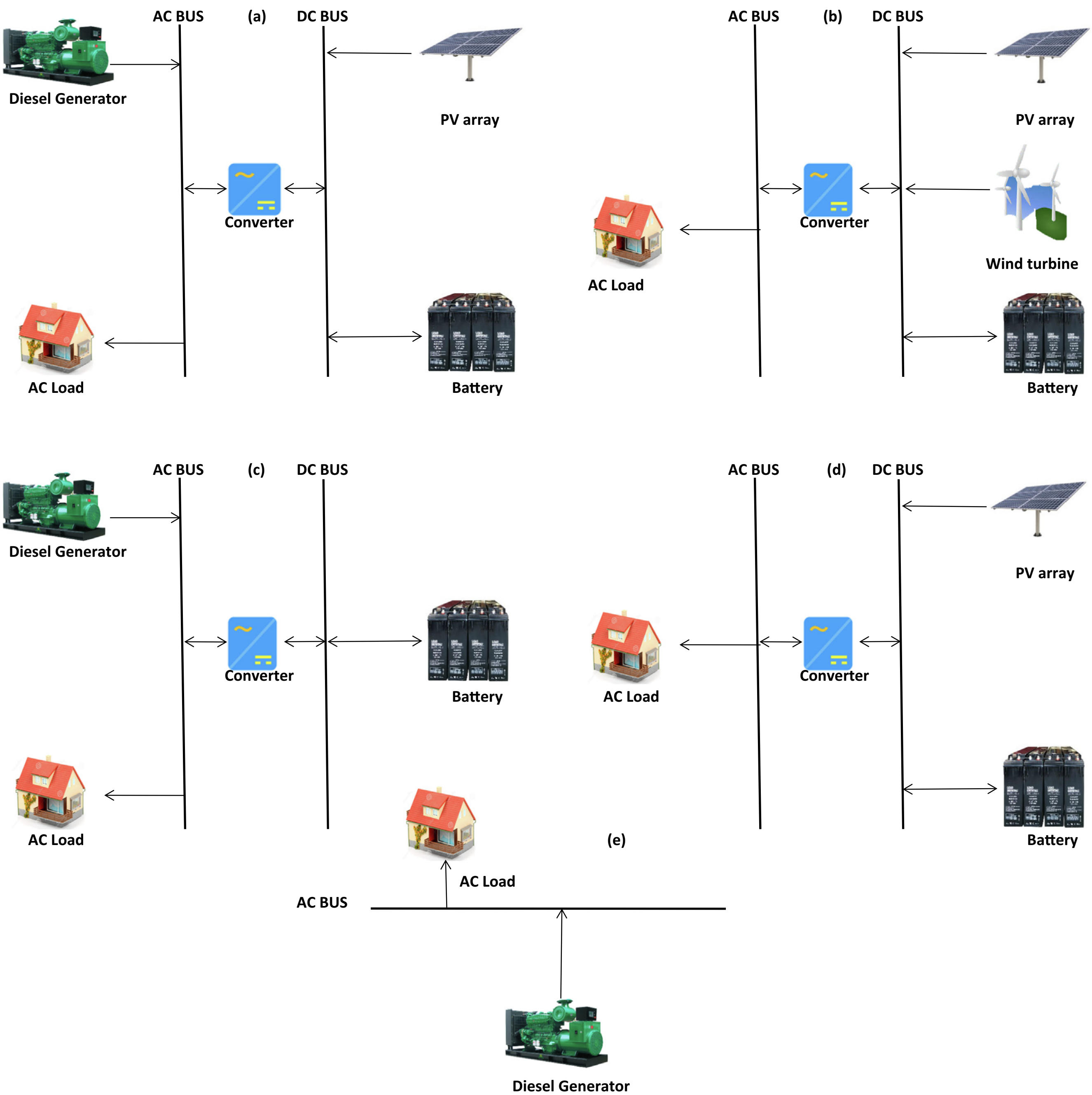


Fig. 7 The schematic diagram of (a) Case 1: PV/DG/battery model (b) Case 2: PV/wind/battery model (c) Case 3: DG/battery model (d) Case 4: PV/battery model (e) Case 5: DG-only model.

tery storage were adequately analyzed in-line with the power demand of the healthcare facility.

4.1. Cases evaluation

The RESs data and the daily power demand of the considered healthcare facility equipment were implemented for the analysis of the optimum system configuration. The potential of RESs in addition to the availability of fuel resources for operating the DG was investigated to ascertain the feasibility of HES. Five different cases were simulated to examine the influence on techno-economic and environmental parameters as component combination changes. The cases are:

1) Case 1: PV/DG/battery model
2) Case 2: PV/wind/battery model
3) Case 3: DG/battery model
4) Case 4: PV/battery model
5) Case 5: DG-only model (Current situation)

The optimal components sizing of all the cases considered in this study is given in Table 3.

4.1.1. Technical assessment

Table 4 present the technical characteristics of each of the five system configuration cases. The excess energy which represents the extra energy produced when the load requirement has been completely met and the battery storage (if available) is fully charged was found to be more for case 4 (PV/battery) because of the generation of surplus electricity during high solar irradiation, while case 3 (DG/battery) produces zero excess power since the DG power rating is slightly above what the load demand can accommodate and with the inclusion of batteries, which absorb all the excess electricity produced. Also, case 5 (DG-only system) shows that without the inclusion of a battery in case 3, the system will produce about 14% excess power. The hybrid system case 1 had zero capacity shortage and unfulfilled electric load, which indicated that the system had a full uptime without having any shortage of electricity and was able to completely handle its electric load. Case 5 was also capable of satisfying all of its load demand as the unmet load was 0%, while its capacity shortage value (0.017%) shows that the system had maximum uptime with very few shortages. For the other three cases (i.e. the 2, 3, and 4 system cases), the percentage of capacity shortage and unmet load is very small, which shows that they all have a tolerable unfulfilled load with a little percentage of electricity shortage (Table 4).

The 100% renewable hybrid cases (i.e. system case 2 and system case 4) generated more electricity as compared to other system cases. For the PV/battery system (case 4), the PV produces a total of 12,219 kWh annual electricity, which is about 132 kWh/year higher than the energy production of the PV/wind/battery HES (case 2). The PV system in case 2 produces almost all the electricity at 98% while the remaining part of 1.96% is provided by the WT. The huge contribution of PV to the total power generation in case 2 was due to the high solar radiation observed in the study area which exceeded the wind speed level. Cases 3 and 5 without any wind and solar components produce annual electricity of 9398 kWh and 9761 kWh respectively from the DG system. Power is generated by the DG (19.2% contributions) and PV (80.8% contribution) for PV/DG/battery system. The renewable fraction of case 1 was found to be 77.6%, while cases 3 and 5 had zero renewable fraction, as expected.

The monthly electric power generation is presented in Fig. 8. For all the cases except the case, 3, and case 5, the solar PV system contributed to the highest annual electricity percentage of the entire system power production as compared to the DG and WT systems. The PV solar produces most of its power in November and December as well as in the first five months of the year when there is high solar power, while low power production was observed during June, July, August, and September (rainy season) of the year. The obtained results reveal that system case 1 gives a better solution and reliability compared to other system cases investigated.

Furthermore, to have a good understanding of the operation of various system configurations, details of the system's battery storage status and power flow during seven days (June 1–7) are provided via the energy balance of the various system configurations as illustrated in Fig. 9. The energy scheduling of production and consumption for seven days is considered as a case study. At the early hour of June 1, the battery storage discharged its energy to satisfy the load requirement for all the cases except case 5 which has no battery storage in its design configuration. The PV system starts to generate power at the starting hours of the next day on June 2 until midday for cases 1, 2, and 4. On June 3, the load was adequately met with energy supply from both PV and DG while the excess electricity produced by the DG is been utilized to charge the batteries according to the dispatch strategy considered (CC strategy). The battery reaches the minimum state of charge (SOC) at midday on June 3. The PV output was used to serve the load demand as well as charge the storage system during the following day on June 4. After June 4, the PV power output reduces, hence the battery was discharged to make up for the needed energy while the DG run alone during June 5 and 6 to satisfy

Table 3 optimal sizing of various components for the five system cases considered in this analysis.

Components	Case 1	Case 2	Case 3	Case 4	Case 5
PV	5.43 kW	8.1 kW	–	8.35 kW	–
Wind turbine (1 kW)	–	1 unit	–	–	–
DG	2 kW	–	2 kW	–	3 kW
Battery (2.45 kWh each)	10 units	40 units	10 units	40 units	–
Converter	3.06 kW	3.11 kW	0.833 kW	3.09 kW	–

Table 4 Electrical characteristics for the five cases.

Cases	Excess electricity production (%)	Electricity generation (kWh/year)	Electricity generation by component (%)	Renewable fraction (%)	Capacity shortage (%)	Unmet electric load (%)
PV/DG/battery	2.12	9818	PV-80.8; DG-19.2	77.6	0	0
PV/wind/battery	21.2	12,087	PV-98; wind turbine-1.96	100	0.068	0.0447
DG/battery	0	9398	DG-100	0	0.0966	0.0047
PV/battery	21.9	12,219	PV-100	100	0.0936	0.0672
DG-only	14	9761	DG-100	0	0.0171	0

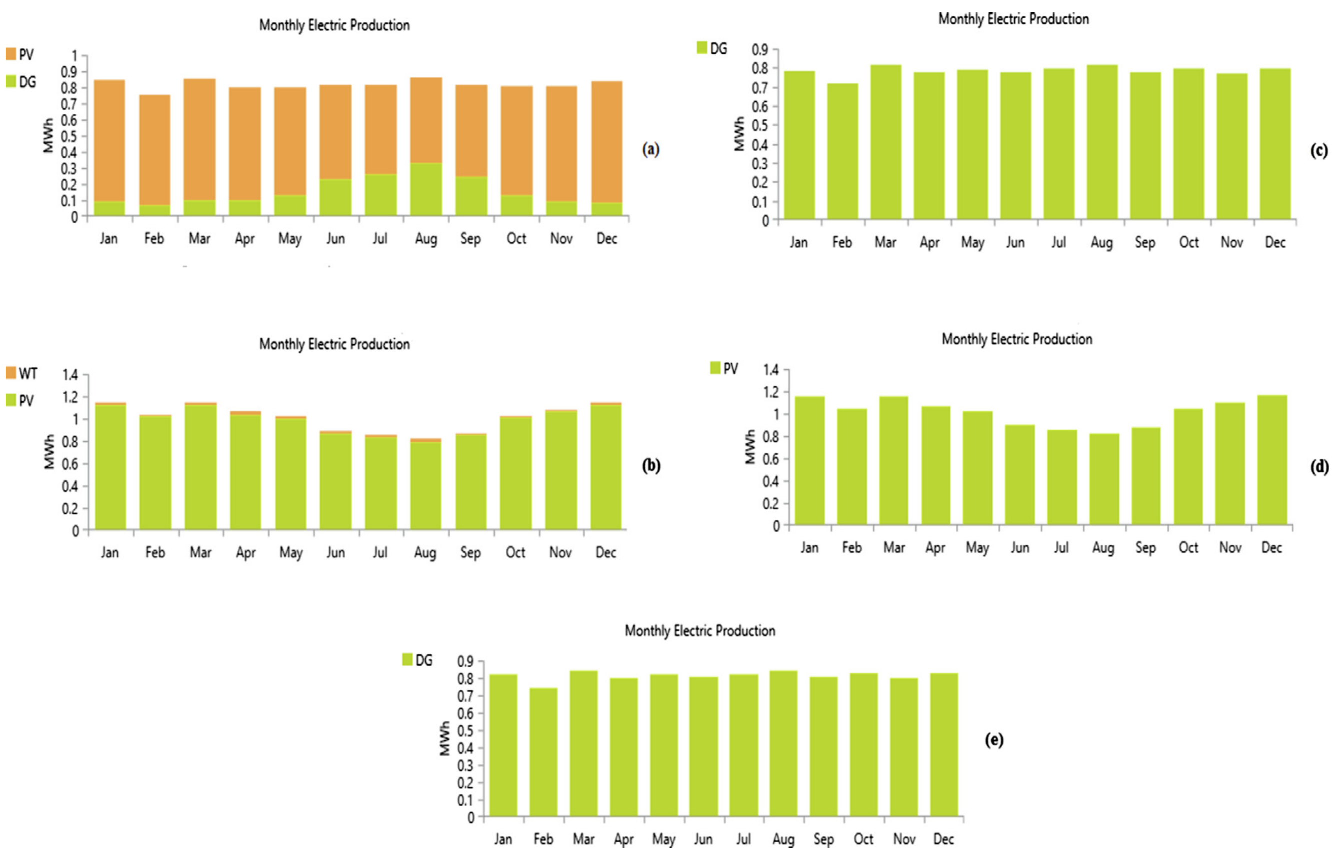


Fig. 8 Monthly electric power production for different cases. (a) Case 1: PV/DG/battery model (b) Case 2: PV/wind/battery model (c) Case 3: DG/battery model (d) Case 4: PV/battery model (e) Case 5: DG-only model (Current situation).

the load and also charge the storage battery and this continues until June 7 where the PV start producing power with little excess energy and zero unmet electric loads. Case 2 follows a similar trend except that the wind turbine produces very small power on June 4 while the battery discharged its energy during June 5, 6, and 7 to meet the load since the PV and wind turbine could not generate any power during these days because of the absence of the required solar irradiation and wind speed. The majority of the electricity and excess energy were produced in this configuration.

Besides, the DG produces power throughout the days (June 1–7) to meet the load as well as charge the batteries for Case 3 power flow scenario. Fig. 9 also shows that the battery reaches minimum SOC just after the beginning of every day from June 1 to June 7 and discharges at midday of each of these days to meet the load for a small period after which the DG charges it with the excess power and has very small unmet electric load. The energy balance trend was similar for all the days in this configuration with zero excess electricity production. The energy balance of case 4 reveals that initially, the battery discharged its energy to meet the demand with a very little unmet load. The PV panel started producing power just after June 1 which also charges the battery as well as produces excess energy due to the inability of the battery to consume all the excess power and does so until June 4. The battery was completely utilized to satisfy the load requirement for the rest of

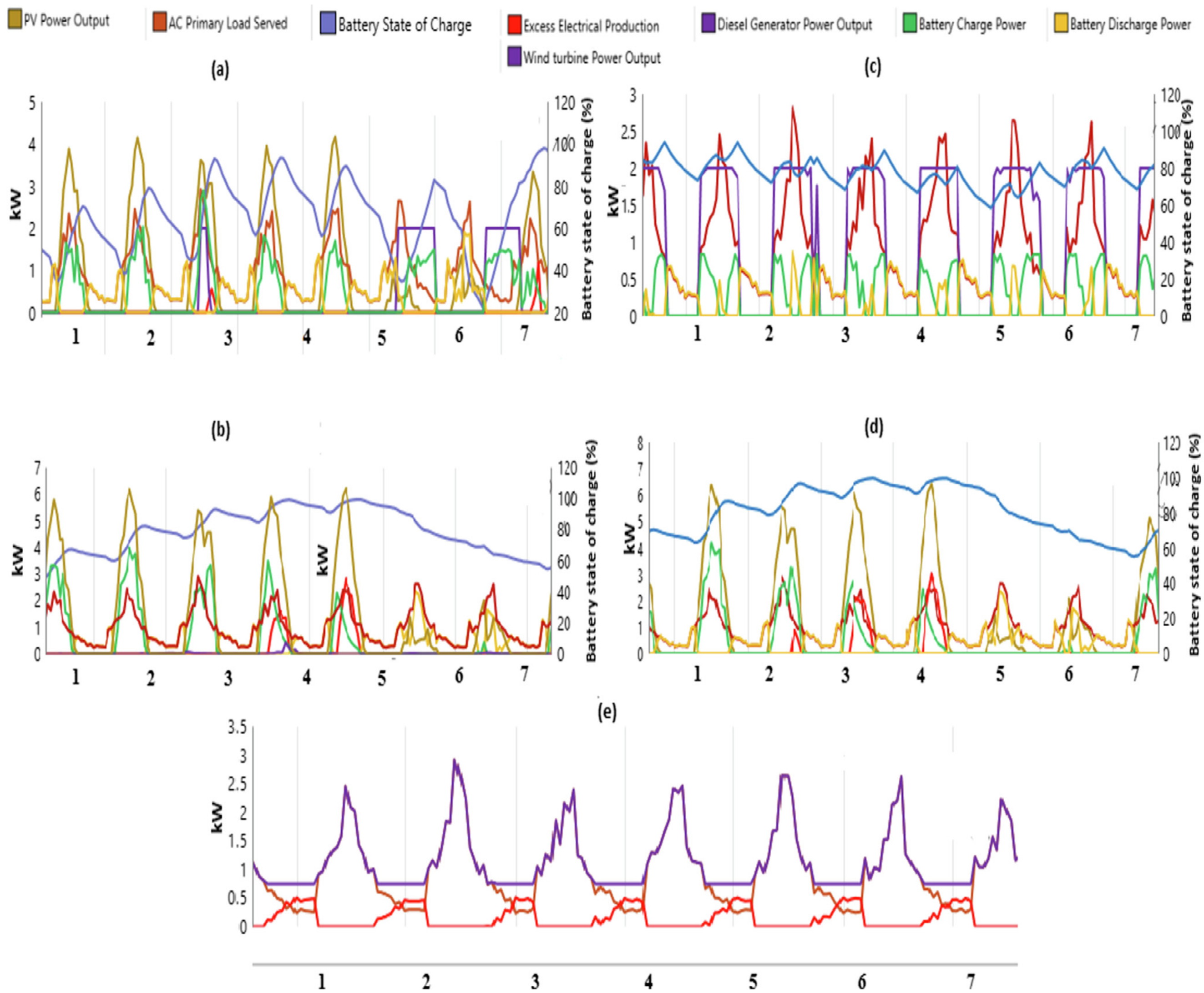


Fig. 9 Power balance and battery state of charge of different system cases. (a) Case 1: PV/DG/battery model (b) Case 2: PV/wind/battery model (c) Case 3: DG/battery model (d) Case 4: PV/battery model (e) Case 5: DG-only model.

the days except on June 7 where the PV starts to produce power again for the load as well as charge the batteries with the extra energy. The highest percentage of electricity and excess power was generated in this design configuration. Case 5 has only DG as the power generating component, so it produces all the needed energy via the DG with varying excess energy to meet the load demand with zero unfulfilled electric loads. Also, it was observed that more power was produced on June 2 and 5.

4.1.2. Economic assessment

The economic evaluation is a key aspect of HOMER software due to its main objective (cost minimization). Economic parameters such as NPC are utilized to analyze the optimal solution of various system models. The NPC comprises the initial cost, cost of replacement, running, and maintenance (O&M) cost, fuel, and salvage costs. The total NPC of each of the five system cases is given in Fig. 10. Case 2 presented the highest NPC of the five system cases, followed by case 5. The former was due to its high initial capital cost (where the PV and BSS had the highest fractions) while the latter was because more money was spent on fuel resources coupled with money expended in the maintenance of the moving part of its DG. For case 2, the initial capital cost had more share of the total NPC, no money was spent on fuel resource as DG is not included in this configuration and a lower replacement cost was reported since battery and PV had no cost of replacement. The trend of cost in case 5 is opposite the trend of cost analysis in case 2 as more money was expended on fuel along with a higher operating cost while the initial capital cost was on the low side.

Furthermore, the NPC of system case 3 and system case 4 is found to be \$19,202 and \$23,374 respectively. For case 3, the DG system had the highest share of the NPC through fuel and running and maintenance costs while the converter had the lowest fraction of the total NPC. Concerning the NPC of case 4, the capital cost contributed the largest share of the total NPC because of the expensive initial cost of PV and battery, this was followed by the running and maintenance cost where the battery storage had the highest fraction and no money was

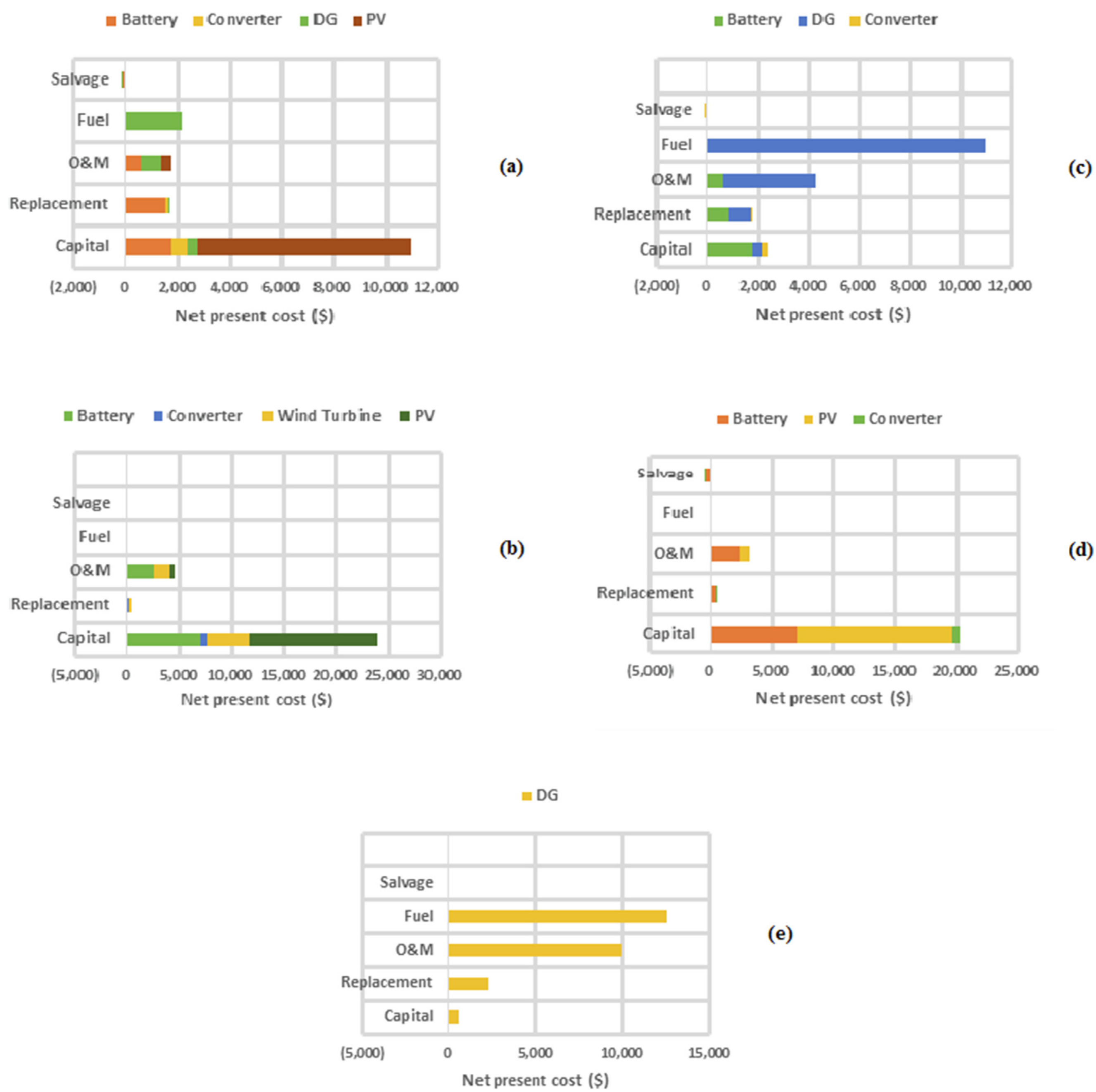


Fig. 10 Cost summary of different system cases. (a) Case 1: PV/DG/battery model (b) Case 2: PV/wind/battery model (c) Case 3: DG/battery model (d) Case 4: PV/battery model (e) Case 5: DG-only model (Current situation).

expended on fuel resource. The NPC of the system case 4 is on the high side; hence, the addition of a back-up power source (DG) could reduce its NPC and COE by about 29.6% each (i.e. case 1). Moreover, the back-up DG can be utilized to fulfill the energy demand and simultaneously charge the BSS whenever the solar PV output and the BSS cannot adequately satisfy the load requirement.

Also, the inclusion of a battery in the design configuration of case 5 (case 3) resulted in a decrease in both the NPC and COE value of this system by around 25% each. As for case 1, the expensive initial cost of the PV makes the fraction of the capital cost in the overall NPC the highest while the cost of fuel consumed by the DG during the period when both PV and BSS are inadequate to fulfill the electricity need was found to be the second-highest contributor. In terms of components share, the PV and battery had more share of the total NPC. This system case had the least NPC and COE values and was able to fulfill the load demand with a PV of 5.43 kW, 2 kW DG, 3.06 kW converter, and 10 units of battery storage. It is observed that its electricity and net present costs were about 42.4%, 14.2%, 29.6%, and 35.7% each lower than that of system cases 2, 3, 4, and 5. as illustrated in Figs. 10 and 11.

Fig. 12 presented the nominal cash flow during the lifetime of the project for all system cases evaluated. The results reveal

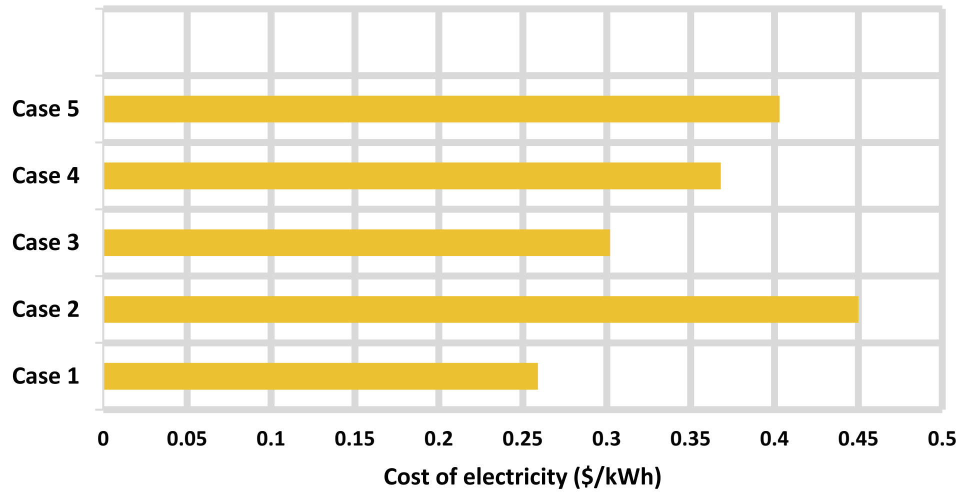


Fig. 11 Cost of electricity (COE) for different system cases.

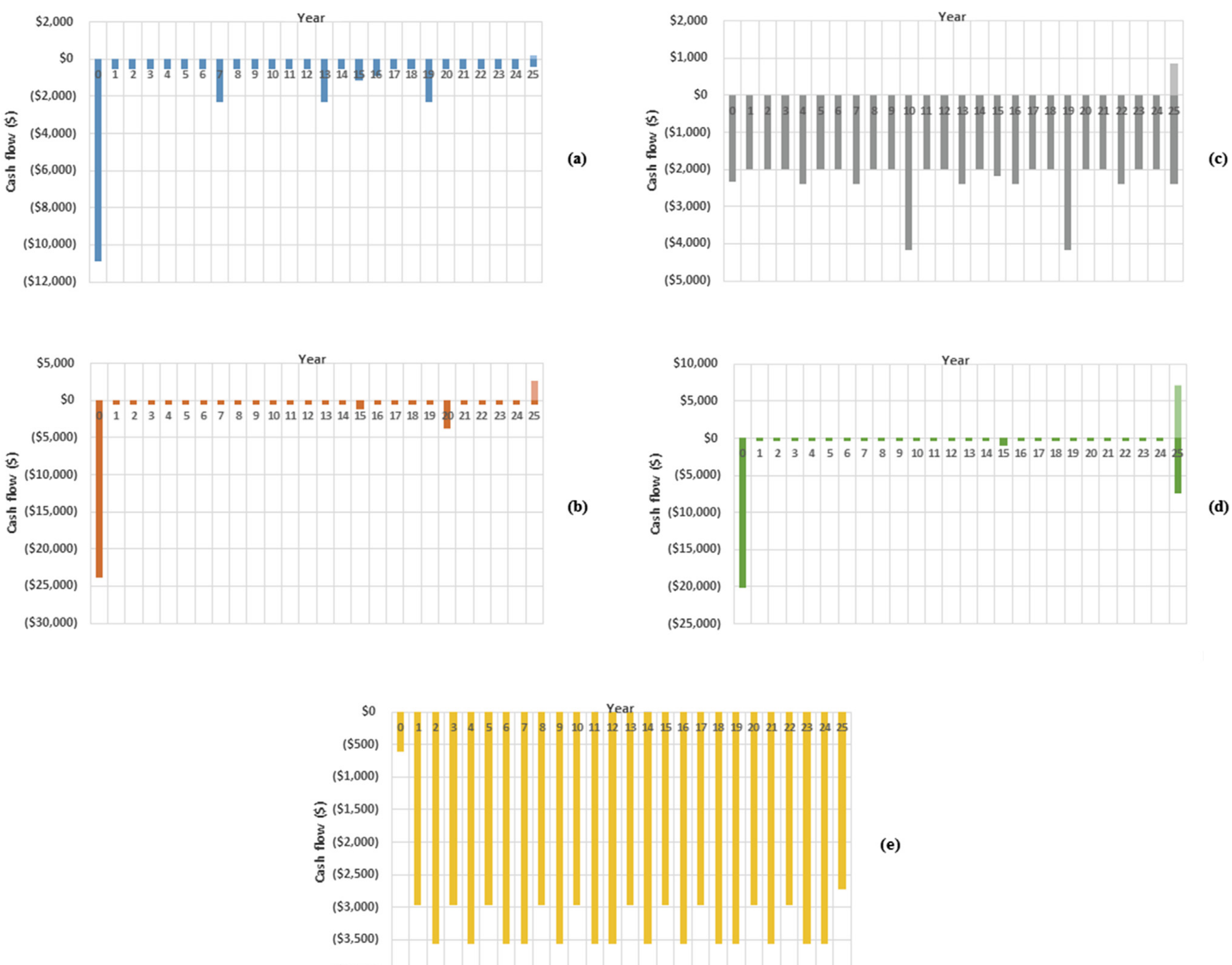


Fig. 12 Nominal cash flow results for different system cases. (a) Case 1: PV/DG/battery model (b) Case 2: PV/wind/battery model (c) Case 3: DG/battery model (d) Case 4: PV/battery model (e) Case 5: DG-only model (Current situation).

Table 5 Pollutant emissions (kg/year) analysis for different system cases.

System cases	CO_2	CO	UHC	PM	SO_2	NO_X
PV/DG/battery	1304	8.87	0.359	0.0355	3.20	0.710
PV/wind/battery	0	0	0	0	0	0
DG/battery	6516	44.3	1.79	0.177	16.0	3.55
PV/battery	0	0	0	0	0	0
DG-Only	7,454	50.7	2.05	0.203	18.3	4.06

that the cash flow for system cases 1, 2, and 4 is steadily kept at a minimum throughout the 25 years, while the value for system case 3 increases continuously at a half pace all through the project lifetime. It was also observed that the cash flow for system case 5 is constantly increasing and getting to the maximum peak until the end of the 25 years. The hybrid system case 1 not only performs better than other system cases with regards to technical parameters, but it also gives an insight into the economic feasibility of HES for rural health clinics in Nigeria.

4.1.3. Emission assessment

It is important to put into consideration the amount of greenhouse gas (GHG) and pollutant emissions released when investigating the feasibility of renewable and non-renewable hybrid systems as the amount of pollutant and GHG emissions released is linearly related to global warming. In this study, the discharge of emissions is associated with the combustion of diesel fuel. The annual consumption of diesel and emission factors which are based on density, carbon, and sulfur contents and low heating value are the two main components required for the computation of the emissions. The pollutant emissions of different system cases analyzed are given in Table 5. The total emission is usually computed based on the emission values of the various emission components such as; CO_2, CO, unburned hydrocarbon (UHC), particulate matter (PM), SO_2, NO_X). The PV/wind/battery (case 2) and PV/battery (case 4) models had no emission values for all emission components since 100% renewable energy sources are utilized with the absence of DG which uses fossil fuel (diesel).

Furthermore, the addition of the DG system to system case 1 reduces its renewable fraction by about 22.4% and increases its fuel consumption from 0 to 499L/year. Based on the fuel consumption rate, system case 1, the PV/DG/battery model releases yearly emissions of about 1304 kg of carbon dioxide (CO_2). The DG of system case 5, runs at 8760 h per year and consumes a total of 2850 L/year diesel to produce the highest annual CO_2 emissions of 7454 kg compared to other system cases. The addition of battery storage to system case 3 decreases both its yearly fuel consumption and CO_2 emissions by about 12.6% each. System case 2 and system case 4 (100% renewable resources) had the best environmental prospect concerning the emissions of different system cases. But these system configuration cases have not performed better than other system cases as regards the techno-economic aspects. The optimum configuration (PV/DG/battery) has an acceptable CO_2 emission rate and was able to reduce the carbon dioxide emissions of system case 3 and system case 5 by around 80% and 82.5% respectively.

4.2. Sensitivity analysis

Sensitivity evaluation was carried out to observe the impact of the change in different independent variables on the optimal system running, fuel, and maintenance costs. The sensitivity parameters selected for this analysis are global solar irradiation, diesel price, minimum battery state-of-charge (battery SOC_{min}), and rural healthcare facility load demand. For each sensitivity variable, the actual value (base case) was either increase or decrease except for the load demand growth. The base case (actual) values of global solar irradiation, battery SOC_{min}, fuel price, and healthcare load demand were 5.51 $kWh/m^2/day$, 20%, \$0.581/L, and 23kWh/day, respectively. The sensitivity evaluation to check the running, fuel, and maintenance costs of the optimal configuration are presented in Table 6. Observation of the sensitivity results shows that the load demand growth has the greatest impact on running, fuel, and maintenance costs. For instance, the operating, fuel, and O&M annual costs increase by about \$1047, \$688, and \$241 respectively as compared to the base case value when the load consumption increased by around 52%. An increase in the solar radiation value decreases the operating, fuel, and maintenance costs. This is because the increased solar radiation gives rise to a decreased in the operating hours of the DG system. This variable impacted the fuel and maintenance costs the most after the load demand parameter. The fuel cost changes from \$440.3/year to \$210.96/year, while the O&M cost varies from \$280.2/year to \$206.8/year for a change in the solar irradiation from 4.68 $kWh/m^2/day$ to 6.34 $kWh/m^2/day$.

Also, varying the fuel price has a significant influence on the operating and fuel costs, but slightly influences the O&M cost. The operating and fuel costs increased by about 13% and 35.5% while the O&M cost increased by only about 0.7% due to an increase in the fuel (diesel) price from \$0.494/L to \$0.668/L. This is because the rise in the price of diesel fuel gives rise to an increased DG running cost. It is obvious from Table 6 that an increase in the battery SOC_{min} from 15% to 45%, leads to an increased operating cost from \$732.69/year to \$754.22/year and O&M cost from \$230.5/year to \$239.9/year. This outcome revealed that a rise in the battery's minimum state of charge would raise the configuration's dependence on the DG to satisfy the load requirement, leading to increased fuel consumption and the cost associated with the DG. Besides, the annual fuel cost increased from \$288.78 to \$311.14. However, a battery SOC range from 30% to 50% is usually selected to circumvent too much discharge that could destroy the battery [35,56].

Furthermore, in all the considered sensitivity scenarios, the analysis reveals that the NPC value of the optimum system configuration increases when the diesel fuel price and the load

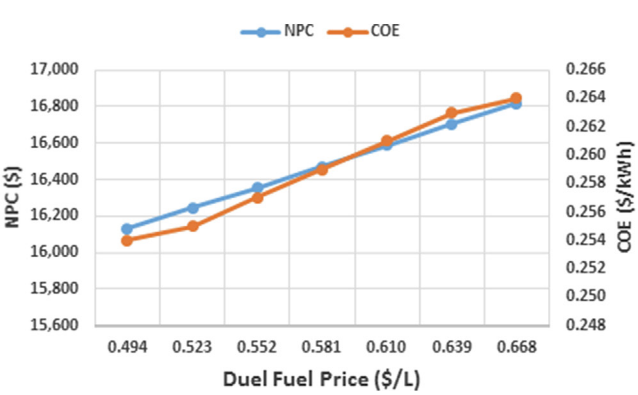
Table 6 Sensitivity evaluation to check the running, fuel, and maintenance costs of the optimal configuration.

Parameters	Metrics	Sensitivity Values						
		4.68	4.96	5.23	5.51	5.79	6.06	6.34
Solar Radiation (kWh/m²/day)	Configuration	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1
	Operating Cost ($/yr.)	940.12	877.66	798.64	732.71	688.28	653.49	623.14
	Fuel Cost ($/yr.)	440.30	392.53	337.45	290.38	258.74	232.37	210.96
	O&M Cost ($/yr.)	280.20	265.20	246.50	231.00	221.30	213.20	206.80
		Sensitivity Values						
		0.494	0.523	0.552	0.581	0.610	0.639	0.668
Diesel Fuel Price ($/L)	Configuration	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1
	Operating Cost ($/yr.)	688.23	702.74	717.25	732.71	748.39	763.50	778.65
	Fuel Cost ($/yr.)	246.65	261.16	275.66	290.38	305.14	319.52	334.18
	O&M Cost ($/yr.)	230.60	230.60	230.60	231.00	231.60	231.90	232.20
		Sensitivity Values						
		15	20	25	30	35	40	45
Battery SOC_{min} (%)	Configuration	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1
	Operating Cost ($/yr.)	732.69	732.71	743.78	748.70	751.27	744.60	754.22
	Fuel Cost ($/yr.)	288.78	290.38	299.35	305.03	307.57	304.59	311.14
	O&M Cost ($/yr.)	230.50	231.00	234.60	236.00	237.00	236.40	239.90
		Sensitivity Values						
		23	25	27	29	31	33	35
Load Demand (kWh/day)	Configuration	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1
	Operating Cost ($/yr.)	732.71	915.57	1,103	1,304	1,492	1,652	1,780
	Fuel Cost ($/yr.)	290.38	404.79	519.48	640.04	755.66	871.47	978.70
	O&M Cost ($/yr.)	231.00	270.50	311.10	353.80	391.30	431.60	472.10

consumption increase (Figs. 13 and 14). For example, the NPC increases by around 4.2% when the diesel price increases from \$0.494/l to \$0.668/l and by about 48.2% due to a load demand growth of around 12kWh/day as compared to the actual load consumption. In comparison based on COE, there is an approximately linear increase in the COE value due to a rise in fuel price, while the COE decreases as the load demand increases. Also, the optimal system consumed more fuel as the load consumption and fuel price increases, which is prominent with variation in fuel price and healthcare facility load demand as shown in Figs. 13 and 14. For instance, the total fuel rises by about 1185 L/year from the initial value (500 L/year) when the load demand rose from 23 kWh/day to 35 kWh/day, while the renewable fraction falls by around 27.1% from the initial penetration (77.5%).

The effects of varying solar radiation on the system costs, renewable fraction, and total fuel consumed are shown in Fig. 15. As illustrated in this figure, the NPC, COE, and total fuel consumed decrease by about 13.3%, 13.4%, and 52.1%, respectively, while the renewable fraction increased by about 27% when the solar irradiation of the selected location increased from 4.68 to 6.34 kWh/m^2/day. The amount of reduction in the cost parameters could be justified by the decrease in the total fuel consumed and the associated diesel cost.

The influence of the battery SOC_{min} variation (in the range of 15% to 45%) on the operational performance of the optimum configuration was also analyzed in the present study. The effect of varying SOC_{min} on the system costs, annual fuel consumption, and renewable penetration are depicted in Fig. 16. The outcomes reveal that an increase in the battery



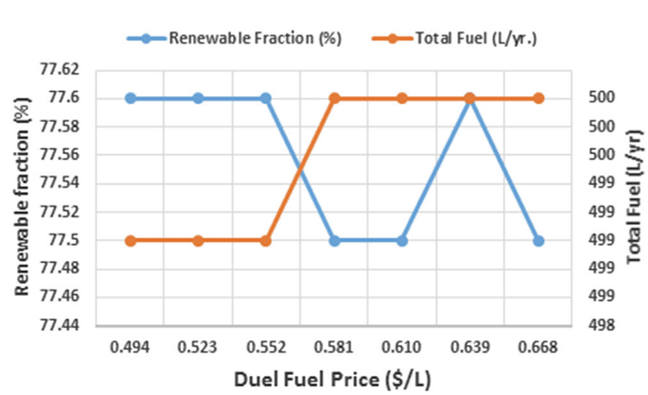


Fig. 13 Effect of varying the fuel price on the system costs, fuel, and renewable penetration.

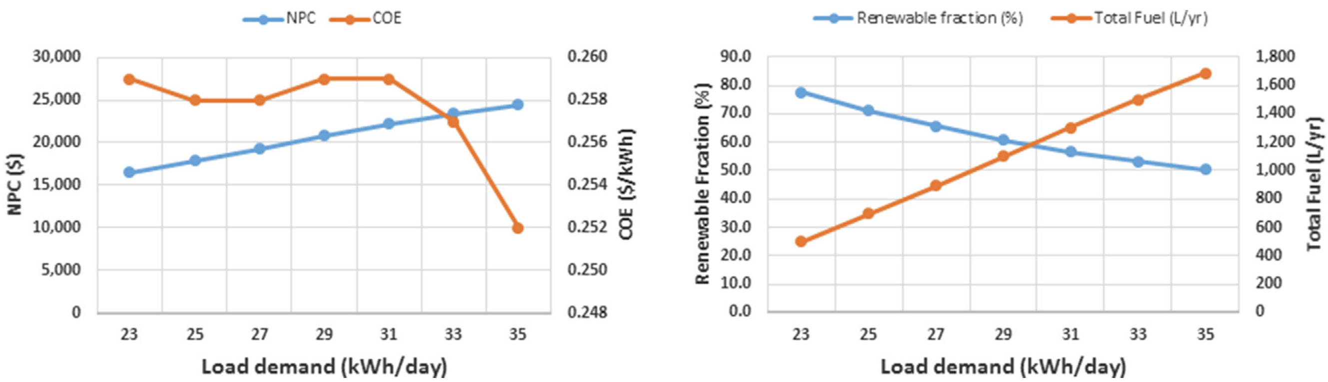


Fig. 14 The load demand growth impact on system costs, fuel, and renewable penetration.

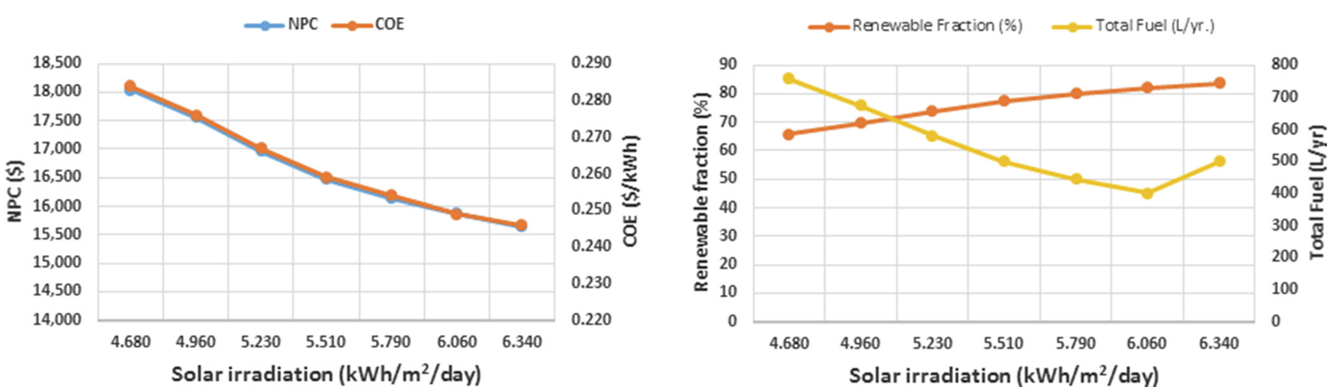


Fig. 15 Impact of varying solar radiation on system costs, fuel, and renewable penetration.

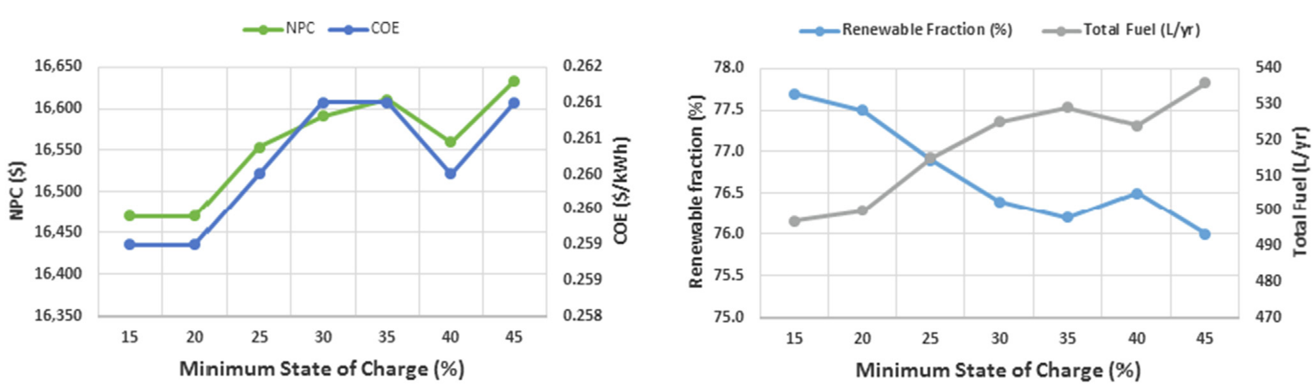


Fig. 16 The effect of varying the battery SOC_{min} on the system costs, fuel, and renewable penetration.

minimum state of charge from 15% to 45% give rise to a rise in the NPC, COE, and the annual total fuel consumed values of about 0.99%, 0.77%, and 7.8% respectively, while the renewable fraction reduces by around 2.2%. This indicated that additional pollutant emissions would be generated due to the increase in the amount of annual fuel consumption fuel, hence posing a serious environmental challenge.

5. Conclusion

In this paper, techno-economic viability assessment of solar PV, wind, DG, and battery HES for powering a remote rural healthcare facility located in Kudu village under Mokwa district, Nigeria was investigated. The performance analysis of different system cases was evaluated. The results of the simulation indicated that system case 1 (PV/DG/battery model), with 5.43 kW PV, 2 kW DG, 3.06 kW power converter, and 10 units of batteries emerged as the optimized solution for powering the considered healthcare facility. It has a minimum net present and energy costs of $16,457 and $0.259/kWh respectively, which were found to be about 42.4%, 14.2%, 29.6%, and 35.7% each lower than that of system cases 2, 3, 4, and 5 respectively.

The PV/wind/battery (case 2) and PV/battery (case 4) models show the best environmental prospect considering their emissions rate, which was zero for all pollutants due to the absence of DG in their design configuration. But the values of the NPC ($23,374 and $28,641) and COE ($0.368/kWh and $0.45/kWh) of these systems are on the high side. The optimized solution releases 1304 kg of carbon dioxide emission per year. This value of CO_2 emission was found to be about 80% and 82.5% less than that of system case 3 (6516 kg/year) and case 5 (7454 kg/year). The sensitivity analysis shows operating cost, fuel cost, O&M cost, NPC, COE, fuel consumption, and renewable fraction are sensitive to the variation in all the considered sensitivity parameters. The overall outcomes reveal that the optimal system case showed greater performance in the categories such as costs, diesel fuel intake, emission rate, and electrical features; making the system an appropriate and suitable option for sustainable electrification of rural healthcare facilities. The integration of RE technologies into the energy mix of decentralized HES will go a long way to upgrade the lifestyle of rural dwellers through the delivery of efficient and quality healthcare services.

Future research can focus on the performance evaluation along with a sensitivity analysis of the hybridization of other available RESs (hydro, biomass, etc.) for electricity production in remote locations. Also, fractional-order modeling [57,58] can be applied to the energy storage system to model the electrical impedance and other parameters of the storage system with equivalent circuits requiring a smaller number of variables than their series resistance–capacitance ladder counterparts in addition to analyzing new patterns for effective and rapid charging of the storage device without altering their performance.

Declaration of Competing Interest

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

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