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Optimal configuration assessments of hybrid renewable power supply for rural healthcare facilities

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ABSTRACT

This paper assessed optimal configurations of hybrid renewable system for rural health clinic (RHC) application in three grid-unconnected rural villages in Nigeria. The RHC consist of an emergency room, consulting room, nurse/injection room, male ward, female ward, a delivery room and a laboratory with average total daily energy consumption of 15.5 kWh and 2.75 kW peak demand. The assessment of configurations that optimally meet the daily load demand with zero loss of power supply probability (LPSP) was carried out using HOMER software, by considering three energy resources; photovoltaic (PV), wind and diesel with battery energy storage. The result obtained revealed hybrid PV/wind/diesel/battery system as the most cost-effective configuration for powering rural health clinic in both Maiduguri and Enugu sites, while that of Iseyin site was found to be hybrid PV/diesel/battery system. In all the sites, the selected optimal configuration is far better than the conventional diesel stand-alone system in terms of cost and emission reduction.

1. Introduction

Access to reliable electricity supply is an important factor in rural area healthcare development, absence of which could limit efficient delivery of healthcare services in rural communities, thus putting patient lives into danger (NREL, 1998). Recent advances in the vaccines and other cold-chain distribution across the world have posed new challenge for electricity in healthcare facility without or limited electricity access. Operators of rural health facilities in developing nations across the world are faced with many problems, such as poor medical infrastructure, even where available, unreliable power supply has hindered its functionality, thus, limiting the effective delivery of quality healthcare to the rural populace. For instance, unreliable power supply could render cold-chain activities inoperable and in most cases, healthcare facility without means of illumination (lighting) do keep the patients arriving late in the night for medical attention to wait until the next day before they receive medical attention.

In a recent study by world health organization (WHO), conducted for 11 countries in Sub-Saharan Africa (Nigeria inclusive) covering about 4000 clinics and hospitals (Adair-Rohani et al., 2013). It was observed that one-fourth healthcare facilities in the considered location lack access to electricity supply, and about three-quarter with unreliable power supply. Even in the facilities linked to the national grid, epileptic power supply (that characterizes insufficiency generation) has often been the case. Diesel generators have traditionally been used to power this off-grid clinics and hospital and in supplementing the unreliable grid supply in grid-connected facilities, with the attendant huge price of diesel fuel, unreliable delivery and high CO_2 pollutant emission contributing to air pollution exposures and climate change.

Over the years in Nigeria, government have expended huge financial resources in its power sector to ensure rural area electrification through various reforms. Reforms such as the development of the National Energy Policy which has the Renewable Energy Master Plan (REMP) as a key component, the establishment of the National Energy Master Plan in conjunction with United Nations Development Programme (UNDP), the implementation of independent power projects (IPPs) among others (Ohunakin et al., 2014). Nevertheless, even with all these reforms, provision of electricity to the rural communities is not expected to improve drastically as there are several constraints, which has hindered its connection to the national grid; among which are; inaccessible terrain, distance of rural communities to the grid center leading to high cost of incorporation into the national grid (Ohunakin et al., 2014; Sambo, 2009) etc. However, considering the fact that improving rural access to electricity through extension of the national grid does not look promising at present due to its associated cost, it is thus imperative for a system of autonomous, off-grid power generation be established. A solution that is based on renewable energy (RE)

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resources and technologies, due to the vast deposit, and environmental friendliness would be a viable option; more so that rural locations have lower electricity demand.

Nigeria is a country endowed with vast renewable energy resources ranging from hydropower, wind, solar and biomass (Ohunakin, 2010). An overview of literatures on rural electrification proves that combination of these renewable energy sources (RES) is one of the most effective solutions to provide electricity to these rural areas. The methodology has proved to provide quality and reliable electricity for different applications in the rural areas (Dihrab and Sopian, 2010; Olatomiwa et al., 2014; Hiendro et al., 2013; Olatomiwa et al., 2015a; Manas, 2015). The two most commonly explored renewable energy are wind and solar. The potential of these sources of energy has been analyzed in our previous study (Olatomiwa et al., 2016). However, this present study step it up by further analysis on determination of optimal configurations of the hybrid combination of the two energy sources in conjunction with backup diesel generator to meet the energy demand of three rural healthcare facilities in Nigeria. In addition to this, the paper aim to answer this research question; "will the selected optimal configuration still be the best if the input parameters changes?" To answer this, sensitivity analysis on the various inputs to the model was conducted.

These locations were strategically selected from different climatic zones in the country as seen in Table 1 with the aim that results of the analysis can be adopted to other rural villages having similar climatic condition as those considered in the study. Table 1 contains the parameters of studied locations. Analysis of potentials of solar energy resources at the selected site based on certain key solar resources parameters, such as monthly and annual global solar radiation (GSR), beam radiation, diffuse radiation, as well as clearness index has been carried out in our previous study (Olatomiwa et al., 2016). The optimal tilt angle for south-facing solar collector orientation was also determined in the said study. Examination of wind energy potentials, on the other hand based on monthly mean daily wind speed data has also been previously done. Therefore, the present study aims to determine the suitability of each of the renewable sources and the best optimal configurations suitable for rural healthcare applications in each of the selected locations with sensitivity analysis.

2. Description of study sites and data collection

The locations for renewable energy potential assessment in this study were selected from three geo-political zones in Nigeria characterized by different climatic condition. Iseyin in the West, Maiduguri in the North and Enugu in the East. The meteorological data (wind speed and solar radiation) used in the analysis were obtained from Nigerian Metrological Agency (NIMET, 2014). Wind speed data were recorded daily at 10 m height with a cup-generator anemometer at respective locations, while the daily solar radiations on a horizontal plane were measured with Gunn-Bellini radiometer (Olatomiwa et al., 2015). Wind data ranges between 28 and 39 years, and solar radiation data ranges between 18 and 31 years were use in the study (Table 1). These data were computed as an average of data for each month.

2.1. Solar radiation

The power output of the PV array depends on the direct and diffuse solar radiation over a particular area. The insolation reaching the earth's surface hinge on the cloudiness or clearness of the sky, which in turn depends on the season of the year (Duffie and Beckman, 2013; Shukla et al., 2015). Characteristics and potential of solar energy at selected sites are analyzed based on mean monthly global solar radiation as well as the monthly clearness index (Olatomiwa et al., 2016). Other parameters explored in the analysis include the monthly mean daily diffuse and beam radiation, this is essential for efficient design and performance evaluation of solar energy applications. In this study, the period of solar data available for the analysis defers from one location to another. For all the sites considered, the available daily data were averaged to obtain the monthly mean and annual mean value. Fig. 1 shows the percentage difference of annual global solar radiation in the three sites.

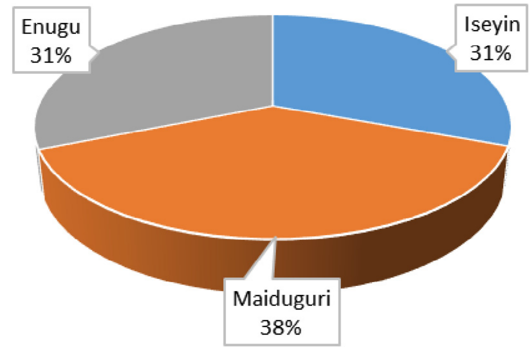

Fig. 1. Percentage of annual averaged solar radiation for all three site.

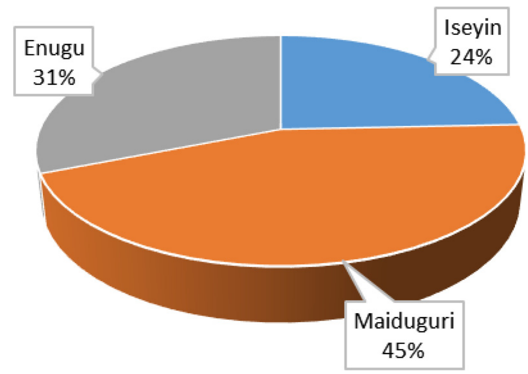

Fig. 2. Percentage of annual averaged wind speed for all three site.

2.2. Wind speed

Comprehensive study of available long-term solar insolation data and wind regime in a particular location is essential in designing and predicting energy output of the respective energy conversion devices; the in-depth knowledge will help in determining their suitability for any particular applications. Generation of electrical energy from wind energy occurs, when wind blows through a wind turbine. The kinetic energy of the wind at rated wind speed is converted into mechanical power by turning the turbine blade, thus producing electricity through the shaft connected to the alternator (Lang et al., 2011). Weibull distribution function (WDF) has been employed in describing the monthly wind speed variation and seasonal changes occurring in the selected sites as well as for estimation of wind power density (Olatomiwa et al., 2016). Fig. 2 shows the percentage difference of wind speeds in the three sites.

2.3. Rural health clinic load profile

The healthcare facility considered in this study is classified as a category 1 rural health clinic according to United States Agency for International Development (USAID, 2014). It consists of an emergency room, a doctor's consulting room, nurse/injection room, male ward, female ward, a delivery room, and a laboratory.

Table 1
The site geographical characteristic.

S/N	Location	Zone	Latitude (°N)	Longitude (°E)	Altitude (m)	Climatic type
1	Iseyin	West	7.96	3.60	330	Tropical
2	Maiduguri	North	11.83	13.15	353.8	Hot semi-arid
3	Enugu	East	6.45	7.5	247	Humid

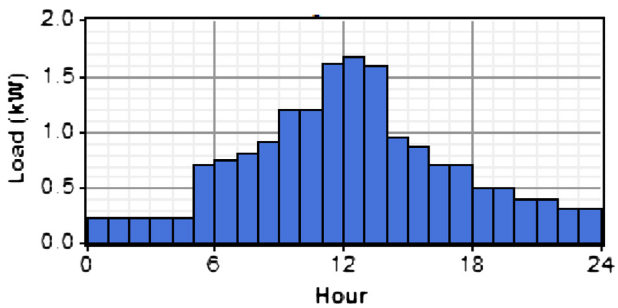

Fig. 3. Rural healthcare facility daily load profile.

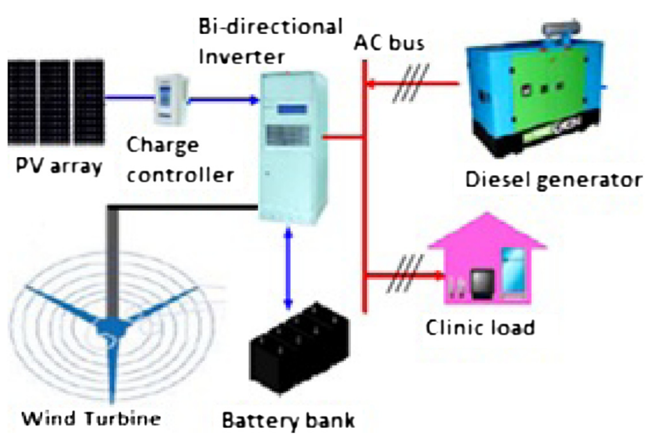

Fig. 4. PV/wind/diesel hybrid system configuration.

The total number of bed space in the clinic is 10. In this facility, electricity is required for: (1) lighting for evening hour's operations to support limited surgical procedures (such as; suturing, cesarean section etc.) and lighting of surroundings. (2), Refrigerator for keeping cold chain vaccines, blood bank and other perishable medical supplies at required temperature. (3), Basic laboratory equipment including; centrifuge, microscope, incubator, hematology mixer, hand-held power aspirator etc. Other appliances that require electrical power includes; television, VCR, and fans.

However, these loads are not expected to operate simultaneously, because each has specific daily hours of operation. Fig. 3 shows the hourly load profile of the clinic, where average energy consumption per day and the peak demand is found to be approximately 15.5 kWh and 2.75 kW respectively. Major load occurs during the daytime (6 am–6 pm). Based on this variation, a day-to-day random variability of 5% and hour-to-hour random variability of 10% specified in simulation software employed (HOMER). This is done to avoid underestimating the peak load demand of the proposed system.

3. Hybrid system configuration

Fig. 4 shows a typical hybrid power system comprising solar PV, wind, diesel generator and battery bank. The combination of solar PV, wind and diesel generator components enhances the output power of the system as well as compensates unpredictable variation in climatic condition. The inclusion of a bi-directional inverter is to maintain the flow of energy between the system AC and DC bus, while the battery acts as a backup in ensuring uninterrupted power supply as well as to maintain desired power quality at specific load point (Olatomiwa et al., 2015b). According to dispatch strategy employed in this study, the battery bank charges whenever the renewable energy output exceeds the load demand and discharges when the load exceeds the renewable power output. Combination of these energy resources in parallel with battery storage provides a smooth and uninterrupted power supply, hence makes the hybrid system reliable and efficient. Initial choice of the components size based on the site load profile presented in Fig. 3. A brief description of the hybrid system components with their techno-economic details are summarized in Table 2.

4. System modeling

Assessment of optimal system configurations is carried out by optimizing the objective function of total life cycle cost of the entire hybrid system represented by Fig. 4. HOMER (Hybrid Optimization Model for Electric Renewable), a software developed by National Renewable Energy Laboratory, USA has been employed to perform the optimization (NREL, 2009). The software performs multiple iterations with ranges of input variables (sensitivity variables) to determine the effect the changes in input parameters may have on the system, and thereby search for best system configuration. In the optimization process, only the feasible system configurations as sorted according to lowest NPC are displayed in optimization result table.

PV arrays are model in HOMER as a device that generates DC voltage when exposed to solar irradiance, and the output power can be found from the relation (Lambert et al., 2006):

$$P_{pv\text{-}out} = P_{pv\text{-}rated} \times f_{pv}\left(\frac{G}{G_{ref}}\right) \times [1 + K_T(T_c - T_{ref})] \tag{1}$$

where $P_{pv\text{-}rated}$ (kW) is the PV rated power at standard test condition (STC), f_{pv} is the PV derating factor (%), G is the global solar irradiance incident on the PV surface, G_{ref} is the radiation at STC (kW/m^2), T_{ref} is cell temperature at STC ($T_{ref} = 25$ °C), K_T is the temperature coefficient of the PV module while T_c is cell temperature given by $T_c = T_{amb} + (0.0256G)$.

On the other hand, wind energy conversion system (WECS) is modeled as rotational kinetic energy produced, when wind blows at the rated speeds over a wind turbine within a given area as represented by;

$$P_{WT} = \frac{1}{2}\rho A v^3 C_{pmax} \tag{2}$$

where P_{WT} output power of the wind turbine (kW), A is the swept area of wind turbine (m^2), ρ is air density (kg/m^3), v is the wind velocity (m/s) while C_{pmax} is the wind power coefficient, usually taken as 0.59 (Shamshirband et al., 2014).

Diesel generator is model based on its fuel consumption (F_G) pattern, which is proportional to its output power (Ismail et al., 2013):

$$F_G = B_G \times P_{G\text{-}rated} + A_G \times P_{G\text{-}out} \tag{3}$$

Table 2
Summary of technical and economic details of the system component.

Components Paramters	Values
PV array	
Capital cost	$3200/kW
Replacement cost	$3000/kW
Sizes consideration	0, 1, 2, 3, 3.5, 4, 4.5 & 5 kW
Lifetime	20 years
De-rating factor	90%
Wind turbine	
Model	BWC WL.1
Rated capacity	1 kW
Initial cost per unit	$5725
Replacement cost	$3650
Maintenance cost	$100/year
Units consideration	0, 1, 2, 3, 4 and 5 turbines
Lifetime	20 years
Battery	
Model	Trojan T-5
Rating	6 V, 225 Ah, 1.35 kWh
Initial cost per unit	$174
Replacement cost	$174
Maintenance cost	$5/year
Units consideration	0, 8, 16, 24 & 32
Battery string	8 batteries
Lifetime	5 years
Converter	
Capital cost	$200/kW
Maintenance cost	$10/year
Sizes consideration	0, 1, 2, 3 & 4 kW
Lifetime	10 years
Efficiency	90%
Diesel generator	
Rating	3 kW, 22.6 A
Maximum load ratio	10%
Initial cost per unit	$200/kW
Replacement cost	$200/kW
Operational cost	$0.5/h
Lifetime	15,000 h
Sizes considered	0, 3 and 5 kW
System economic	
Interest rate	8%
Inflation rate	2%
Diesel price	$1.1/L

where $P_{G\text{-}rated}$ is the nominal power of the diesel generator, $P_{G\text{-}out}$ is the output power, while A_G and B_G represents the coefficients of the fuel consumption curve as defined by the modeler (l/kWh).

The battery in this study is modeled as an energy storage device capable of storing certain amount of DC power at a fixed round trip efficiency during excess energy production from the renewable energy resources and discharging whenever the system energy resources are unavailable to meet the load demand. The battery storage capacity is given as (Ismail et al., 2013):

$$C_{Wh} = (E_L \times AD)/(\eta_{inv} \times \eta_{Batt} \times DOD) \quad (4)$$

where E_L is the average daily load energy (kWh/day), AD is the number of days of battery autonomy, DOD is battery depth of discharge, while η_{inv} and η_{Batt} represent inverter and battery efficiency respectively.

5. Economic evaluation

Economic evaluation of the entire hybrid system is achieved by optimizing total life cycle cost of the system configurations. Total NPC is used to represent the system life-cycle cost, which is a composite of initial system component's capital cost, replacement cost, operation and maintenance cost as well as fuel cost where

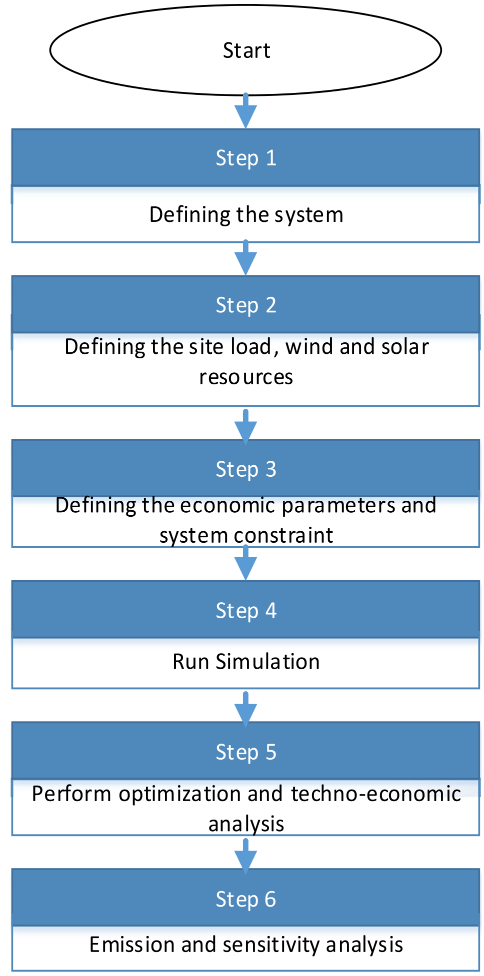

Fig. 5. System optimization flowchart.

applicable over their useful lifetime, usually given as (Lambert et al., 2006);

$$C_{NPC} = \frac{C_{ann.tot}}{CRF\ (i, N)} \quad (5)$$

where $C_{ann.tot}$ is total annualized cost ($/yr.), i annual interest rate, N is project life span (yr.), while $CRF\ (i, N)$ system capital recovery factor given as:

$$CRF\ (i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}. \quad (6)$$

On the other hand, the levelized cost of energy, which is average cost per kWh of energy produced by the hybrid system, is calculated as;

$$COE = \frac{C_{ann.tot}}{E_{loadseverd}} \quad (7)$$

where $E_{loadseverd}$ is actual electrical load serve by the hybrid system (kWh/yr.).

The flowchart of the entire simulation and optimization process is shown in Fig. 5.

6. Results and discussion

6.1. Optimization results

The optimal configuration assessment for the selected rural sites, were carried out based on the collected data from each

Table 3
Comparison of various system configurations for iseyin.

System configuration	PV (kW)	Wind (kW)	Diesel (kW)	Battery (unit)	Converter (kW)	Initial capital cost ($)	Total NPC ($)	COE ($/kWh)	RF (%)
PV–diesel–battery	4.0	–	3	24	3	18,196	33,160	0.454	75
PV–wind–diesel–battery	4.0	1	3	24	3	23,921	35,927	0.492	87
Diesel–battery	–	–	3	16	1	3,604	48,068	0.658	0
Diesel alone	–	–	3	–	–	600	69,500	0.951	0

Table 4
Comparison of various system configurations for Maiduguri.

System configuration	PV (kW)	Wind (kW)	Diesel (kW)	Battery (unit)	Converter (kW)	Initial capital cost ($)	Total NPC ($)	COE ($/kWh)	RF (%)
PV–diesel–battery	4	–	3	24	3	18,196	27,571	0.377	91
PV–wind–diesel–battery	3	1	3	16	3	19,329	28,475	0.390	93
Wind–diesel–battery	–	2	3	24	2	16,646	42,205	0.577	51
Diesel–battery	–	–	3	16	1	3,604	48,068	0.658	0
Diesel alone	–	–	3	–	–	600	69,500	0.951	0

Table 5
Comparison of various system configurations for Enugu.

System configuration	PV (kW)	Wind (kW)	Diesel (kW)	Battery (unit)	Converter (kW)	Initial capital cost ($)	Total NPC ($)	COE ($/kWh)	RF (%)
PV–wind–diesel–battery	3	1	3	16	3	19,329	31,566	0.432	86
PV–diesel–battery	4	–	3	24	3	18,196	32,986	0.451	76
Diesel–battery	–	–	3	16	1	3,604	48,068	0.658	0
Diesel alone	–	–	3	–	–	600	69,500	0.951	0

locations and system load profile in Fig. 3. The feasibility of employing hybrid renewable energy system for powering rural health clinic is based on the availability of the energy resources in the selected sites and lifetime cost of the configurations. HOMER performed an hourly time series simulation for every possible system configuration on a yearly basis to evaluate operational characteristics such as; annual electricity production, annual load served, excess electricity, renewable fraction and so on. The renewable energy sources and diesel generator were evaluated to determine the feasibility of the system. HOMER searched for optimum system configuration and component sizes that meet the load requirement at the lowest net present cost (NPC) and then presents the results of the simulation in terms of optimal systems and sensitivity analysis.

The optimal results for Iseyin, Maiduguri and Enugu sites are presented in Tables 3–5 respectively. From these tables, it is observed, that the best configuration for both Maiduguri and Enugu site is hybrid PV–wind–diesel–battery system, while PV–diesel–battery is considered optimal for Iseyin site. The obtained optimal configuration for Maiduguri has the lowest NPC and COE of all the optimal configurations, this is because of high solar and wind resources availability in the site compare to the other sites (see Figs. 1 and 2).

Diesel only system is seen as worst configuration with highest NPC and COE, notwithstanding its low capital cost, this is as a result of high fuel and maintenance cost associated with the configuration. This has demonstrated that the configuration with lowest capital cost, may not necessary be configuration with lowest cost of energy. A diesel–battery configuration cost 45%, 52% and 96% more than the best optimal configuration in the entire Iseyin, Enugu and Maiduguri respectively. It is also noted that the COE of diesel alone system (without battery) is more than twice that of the optimal configuration in all the sites. The addition of renewable sources and batteries to the diesel system is considered a good investment in terms of fuel saving and emission reduction.

Table 6
Pollutant emission in optimal system configuration for the selected sites.

Site	CO_2	CO	UHC	PM	SO_2	NO_x
Iseyin	1247.1	3.08	0.34	0.23	2.50	27.5
Maiduguri	381.64	0.94	0.10	0.07	0.77	8.41
Enugu	791.1	1.95	0.22	0.15	1.59	17.4
Diesel alone (all site)	9551.6	23.6	2.61	1.78	19.2	210.4

6.2. Emission analysis

Table 6 shows the annual pollutant emission from the best optimal configurations and the existing conventional diesel-only system in each of the selected sites. This emission includes; carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbon (UHC), particulate matter (PM) sulfur dioxide (SO_2) and finally nitrogen oxide (NOx). The conventional diesel based power generation configuration produces 9551 kg/yr. of CO2 in all the sites, while the optima hybrid renewable system configurations produced CO2 1247.1, 791.1 and 381.6 kg/year in Iseyin, Enugu and Maiduguri sites respectively. From this table, we observed that, a total of 87%, 92% and 96% CO_2 emission be prevented; if a hybrid renewable energy system configurations is adopted in Iseyin, Enugu and Maiduguri sites respectively. The percentage reduction in pollutants emission is proportional to the rate of renewable energy penetration in the system. Therefore, inclusion of renewable energy resources such as PV and wind in the hybrid system configuration will definitely lead to more economically viable option in providing electricity to rural health centers. Moreover, the system will also help in abating the prevalent global warming, which occurred due to high rate of CO_2 emission into the environment.

6.3. Sensitivity analysis

Sensitivity analysis was performed to examine the impact of variation in the values of inputs parameter on the cost of energy

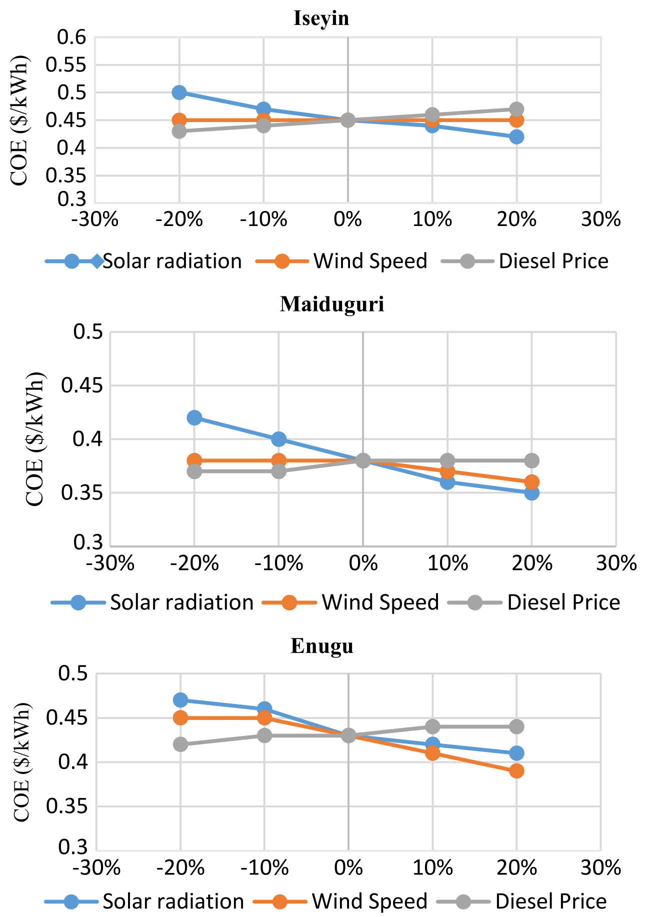

Fig. 6. Sensitivity analysis result.

production. To this aim, three most dominant input parameter of HOMER model, namely; solar radiation, wind speed and diesel price were selected and varied by ±20% for each site. Fig. 6 shows the result of the sensitivity analysis. It was observed that increase in diesel prices slightly increase the cost of electricity production in the entire site, while there is significant changes in COE when the solar radiation in each site varied. In addition, the impact of wind speed on COE is considered low for the three site, due to low potential wind regime earlier observed at the various sites.

7. Conclusion

In this paper, optimal configurations of hybrid renewable system for rural health clinic (RHC) application in three grid-unconnected rural villages in Nigeria is assessed. The following conclusions were drawn based on this analysis;

- The PV/wind/diesel/battery hybrid renewable system configuration is considered optimum for both Maiduguri and Enugu RHC according to NPC, COE and RF calculation, while PV/diesel/battery for Iseyin RHC.
- Based on the sensitivity analysis, the wind system hybrid configuration is not considered best option in Iseyin site, unlike in the other two sites, this is due to the relatively low wind speed as compared with other sites. However in all the three sites, the higher the solar radiation, the less the consideration for diesel generator.
- The diesel only system provides the highest COE ($0.951/kWh), and emits 9552 kg of CO_2 per year in all the site considered; this is huge and will have adverse effect on the environment as well as the health of patients in the rural health facilities.
- The overall results indicated that not only does the hybrid system configurations perform better than diesel-only simulation with regards to the NPC for all three sites, but also displayed better performance in the categories such as electrical, fuel consumption and CO_2 reduction.
- The high solar irradiation levels in the country create an ideal environment for inclusion of renewable energy systems, such as PV and wind in the design and implementation of standalone power supply systems for rural clinic application to improve rural health delivery.

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