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Modelling and analysis of a PV/wind/diesel hybrid standalone microgrid for rural electrification in Nigeria

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ABSTRACT

The scarce electricity supply in Nigeria is a key factor to the low industrial development in a country well-known for having the least electrification in Africa per capita. Presently, Nigeria employs four different kinds of energy such as coal, natural gas, hydro, and oil. Three of the four resources mentioned above used for the production of energy in Nigeria is connected with increasing emissions of greenhouse gas: natural gas, oil, and coal, with coal releasing the worst. This paper presents a model and analysis of PV/Wind/Diesel hybrid system for rural electrification in Kaduna state, northern Nigeria. HOMER (Hybrid Optimization Model for Electric Renewable) software tool was used for optimization and modeling of this work. Simulation results show that the PV/Wind/Diesel system with Battery storage is the most cost-effective system since it recorded considerable cost of energy and reduces CO_2 emissions significantly.

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1. INTRODUCTION

In Nigeria, approximately 60% of the population is living in rural areas. The increasing awareness of global warming, fast depletion of fossil fuel resources and escalating population growth has necessitated the focus to seek energy from renewable resources [1-3]. Based on the statistics recorded from the international energy agency (IEA), biomass and waste are the most dominant with 82.2%, while renewable energy sources accounted for only a small portion of the energy supply [4]. Furthermore, hydropower accounted for 0.4% only. Even though wind and solar are used, they are insignificant at present. Biomass became the dominant energy source in Nigeria as a result of high dependence on it for cooking and heating activities by the majority of the Nigerian population. According to [4], slow progress has been achieved with respect to providing accessibility to non-solid cooking fuels. Consumption was 116,457 ktoe, where the residential region constitutes the majority of energy consumed.

Electricity is a major energy component used to measure the level of progress and modernization of a given country [5]. There are a number of factors that contribute to the poor distribution network such as poor topology, isolation of rural areas and very difficult terrains [6]. Nevertheless, the main reason for the poor distribution is as a result of the low economic investment. It is quite costly and requires a huge investment to install a large grid and connect transmission lines to supply electricity to remote areas over long distances [5].

The energy supply in Nigeria is mostly dominated by fossil fuels [3]. The environmental impact of fossil energy and depletion rate of fossil reserves in the country has motivated several indigenous researchers to consider the viability of renewable energy potential in Nigeria. A recent study reveals that Nigeria possesses an abundant solar energy that can be harnessed profitably [7]. The average daily annual solar irradiance was reported to be 5.25 kWh/m^2/day. This amount varies by the coastal region of the southern and northern boundaries as shown in Table 1 between 3.5 kWh/m^2/day and 7 kWh/m^2/day respectively. The average period of the sunshine hour was estimated at 6.5 hours in the country with the annual average intensity of solar energy as 1,935 kWh/m^2/year, and a projection of 1,770 TWh solar energy per year. The map of Nigeria showing geopolitical zones has been shown in Figure 1.

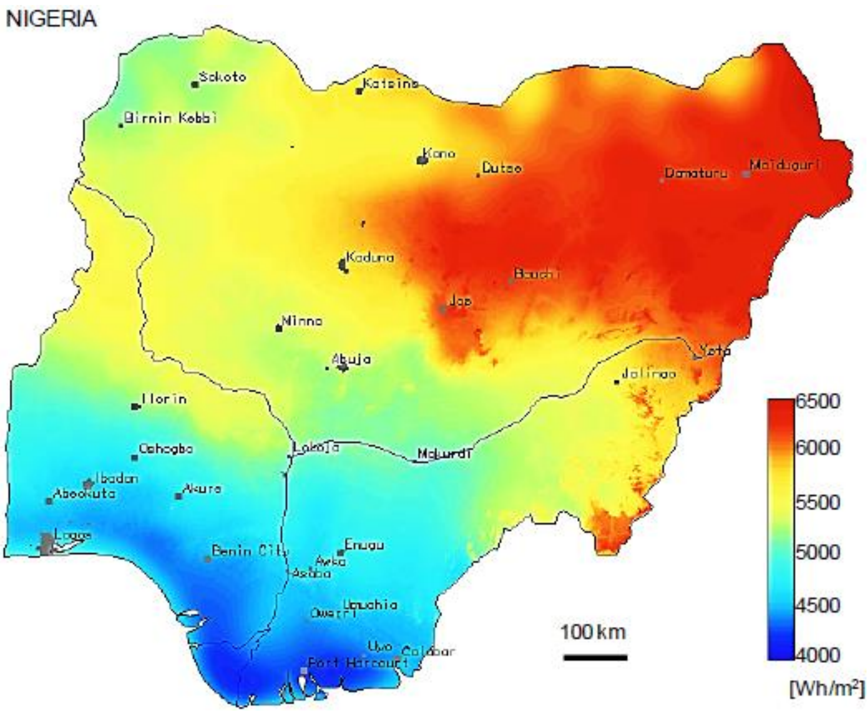


Figure 1. The map of Nigeria showing solar energy resource [8]

As shown in Figure 1, the wind energy potentials in Nigeria is high in northern hilly regions [9-12], while the middle belt upland topographies have huge wind potentials as shown in Table 1. Average wind speed lies between 4.0–7.5 m/s and 3.0–3.5 m/s at 10 m height in the north and south respectively [7]. A number of research studies have been carried out on assessment and prospect of hybrid renewable energy sources in Nigeria [8, 13-22]. A PV-wind hybrid diesel system is proposed in [16] as the best reliable model for remote area electrification compared to PV-alone and the wind alone systems. This existing research studies either focused on hybrid renewable energy generation for a single building, remote telecom applications or rural electrification in some selected locations across the country. A modeling and analysis of PV-wind hybrid system focusing on PV/diesel/battery, Wind/diesel/battery, PV/wind/diesel/battery, and Diesel alone is still lacking. Therefore, this paper focuses on the modeling and analiyisis of PV/Wind/Diesel hybrid system for a small remote community in Kaduna State, northern Nigeria. HOMER (Hybrid Optimization Model for Electric Renewables) software tool is used for optimization and modeling of this work.

Table 1. Solar irradiation and wind speed of the geo-political zones in Nigeria [8]

Geo-political Zones	Solar Irradiation (Wh/m^2)	Wind Speed (m/s)
North East	6100-6500	4-6
North West	5500-6000	4-6
North Central	5000-6000	4-6
South East	4300-5000	Above 4
South West	4000-4500	2.5-4
South South	4000-4300	Below 4

2. DESCRIPTION OF INPUT PARAMETERS

In this study, the community load profile was estimated based on personal site seeing. A remote community consisting of 200 buildings was selected as the case study to test the viability of the proposed system. For one selected building, an estimate was made based on the projected community requirements and further integrated over the total number of buildings in the remote community. The mean energy consumption per building based on Table 2 and 3 is approximately 1.5 kWh/day with a peak load of 20kW respectively. Figure 2 shows the 24 hours hourly load profile for the remote community.

Table 2. General wattage chart for household appliances [7]

Power rating (Watts)	Household Appliance
24	42 Ceiling Fan (Low Speed)
55–90	19 CRT Television
150–340	Desktop computer 17 CRT monitor
60	60-Watt light bulb (incandescent)
18	CFL light bulb (60-Watt Equivalent)

Table 3. Electricity consumption analysis for the rural community of 200 homes [7]

Description Case for Community	AC/DC	Base Case Load/Home (Watt)	No. of Appliance Home (Watt)	Hours of Use per day hr/day	Days use per week	Base Load (Watts)
TV	AC	90	1	6	7	18000
Bulb	AC	18	6	7	7	21600
Fan	AC	24	3	8	7	14400
Water Pump	AC	Community based	Community based	3	3	20000
Radio	DC	6	1	5	7	1200
Clinic	AC	Community Based	Community Based	5	5	2000
School Electronics	AC	Community Based	Community Based	5	5	2400

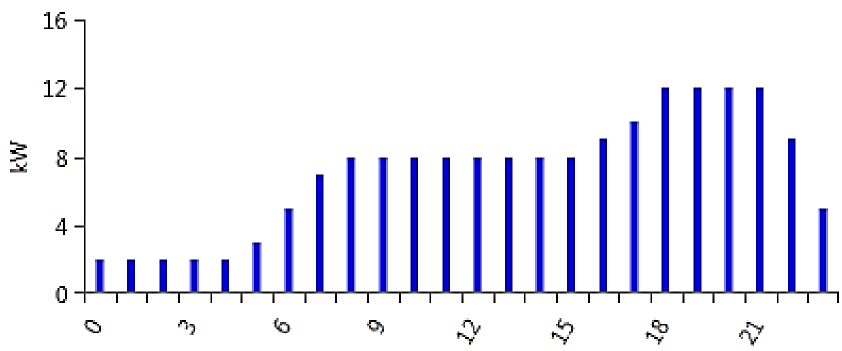


Figure 2. Daily load profile for the proposed community in Nigeria

2.1. Load profile

This study is focused on designing a PV/wind/Diesel hybrid system with Battery for a remote community in Kaduna state, northern Nigeria. A total of 200 buildings having a community school and health center was selected as the case study. The selected site location is Latitude and Longitude classified as the North-west zone of the country. The system consists of 50kW PV- modules, 1-unit generic 10kW wind turbine, 25kW diesel generator, 50 strings of battery and 50kW system converter were implemented for the study as a standalone renewable hybrid system.

2.2. Solar radiation

The remote community lies on Latitude 10o 30.6' N and on Longitude 70o 25' E. The solar radiation data was extracted from the National Aeronautics and Space Administrative (NASA). The data is a 22 year monthly average solar radiation ranging approximately from 4.47 kW/m^2/day to 6.32 kW/day as shown in Figure 3. The scaled average annual electricity demand of the proposed system is 165.40 kW/day as simulated by HOMER software.

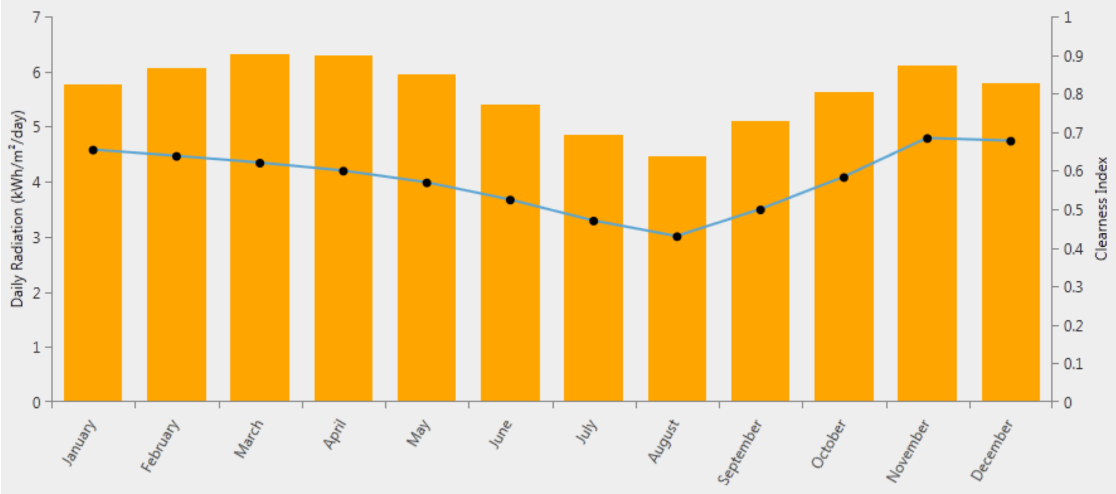


Figure 3. Annual solar radiation and clearness index for the remote community of Northern Nigeria

2.3. Wind speed

The wind energy data for the selected location is obtained from the NASA database, with an annual average speed of almost 4.0 m/seconds. It is a 10 year monthly averaged wind speed at 10 m above the surface of the earth. Figure 4 indicates that the range of wind speed is 2.72 m/s to 3.59 m/s. As shown in the figure, the highest peak period of wind speed is in March-May and in December. The Weibull parameter (k), autocorrelation factor, diurnal pattern strength, and hour of peak wind speed are 2, 0.85, 0.25 and 15 hours respectively, as simulated by HOMER [23].

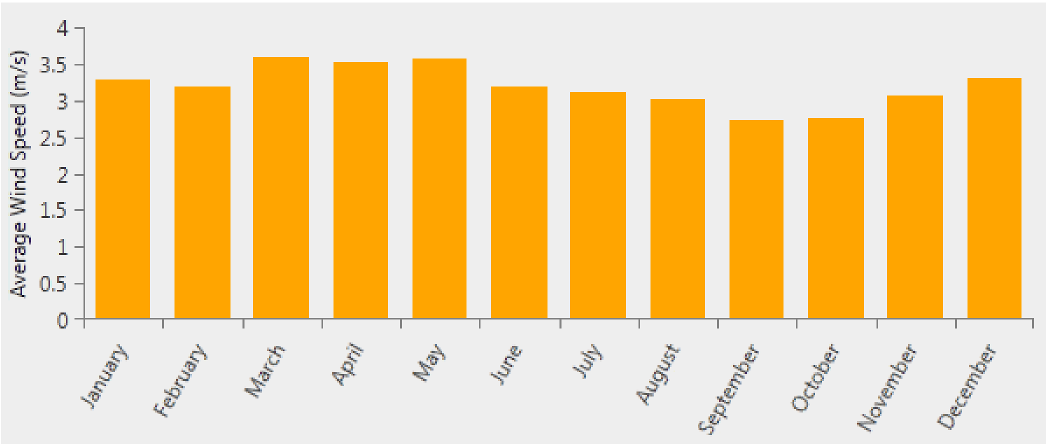


Figure 4. Monthly average wind speeds data for the remote community

2.4. Diesel

The current diesel price used for the simulation is $ 1.00/L. This price fluctuates due to forces of diesel demand and supply; thus, the current price is expected to rise or fall in the long run.

3. SYSTEM DESCRIPTION AND SPECIFICATION

The system architecture and system schematic for the PV/wind hybrid system is shown in Figure 5 (a) and (b) using the HOMER software tool. The system is made up of PV-modules, wind turbine, diesel generator, battery banks, regulation, and conversion unit. The regulation and conversion unit is composed of a controller that operates the system automatically. Table 4 describes the selected components economic and technical specifications of the proposed PV/wind hybrid system. The HOMER simulation software tool evaluates the costs of the system using US dollar as a benchmark currency.

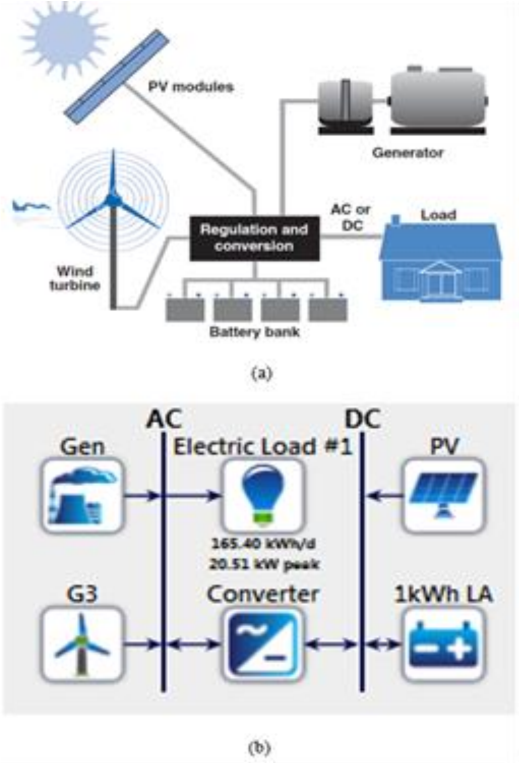


Figure 5. (a) System architecture, (b) System schematic in HOMER

Table 4. Components economic and technical specifications for the hybrid PV/wind system [24]

Description	Specification
1. PV Modules	
PV model	PV-MF100EC4
Power (kWpeak)	50kW
Capital cost	$7200/kW
Replacement Cost	$7200
Lifetime	25 years
2. Inverter	
Inverter model	Sungrow-SGK120K
Rated power	50kW
Capital Cost	$400/kW
Replacement Cost	$400/kW
Conversion efficiency	97.5%
Expected lifetime	15 years
3. Battery	
Battery model	Surrette 6CS25P
Nominal Voltage	6V
Minimum State of charge	40%
Round trip Efficiency	80%
Nominal Capacity	1156 Ah
Capital Cost	$1200
Replacement cost	$1100
O&M Cost	$10/year
Float life	12 years
4. Diesel Generator	
Generator Type	Cummins
Generator Model	QSB7-G5NR3
Rated Power	25kW
Capital cost	$270/kW
Replacement Cost	$260/kW
O&M Cost	$0.03/h/kW
Expected lifetime	15000 operating hours
5. Wind turbine	
Type of Turbine	BWC Excel-s
Rated power	10kW AC
Capital cost [23]	$30,730

3.1. Sizing of the PV modules

In order to achieve the main load demand for this study, the PV array size was fixed at 25kWp, this is sufficient enough to meet the remote community peak demand of about 20.5kW. The excess PV energy can be used to charge the battery in the event of an overflow of PV energy. A variation of the PV sizing is done for 30kWp and 50kWp so as to assess the effect of cost on the hybrid system. A 36-cell polycrystalline (PV-MF100EC4) PV-module is selected with a rated power of 100Wp [23]. 50 strings of PV modules were connected in series in order to achieve 25kWp. The average period of sunshine hours is between 6 to 18 hours of the day. As a result, PV energy can only be harvested during these useful hours. A derating factor of 90% is applied to the power output of the PV array [23].

3.2. Wind turbine

A model type BWC EXCEL-S, 10 kW (AC) was selected in this simulation [11]. The wind turbine technical characteristics are shown in Table 4. For economic analysis, 3% operating and maintenance cost is assumed.

3.3. Battery

A Surrette 6CS25P [23] battery model was selected for this simulation. The battery characteristics are illustrated in Table 3. The batteries are connected in series so as to provide high energy capacity, consisting of 11 batteries in a string. Individual battery strings can provide electricity of 50kW.

4. ECONOMIC ANALYSIS

Economic analysis is essential in the choice of energy resources since renewable and non-renewable energy sources possess diverse cost estimates. This analysis captures the variation in the cost of all components and devices used in the system model. The HOMER simulation software evaluates the total net present cost (NPC), Levelized Cost of Energy (COE), and operating cost of the system. These economic indicators are discussed in the following subsections.

4.1. Net Present Cost (NPC)

The net present cost or life cycle cost is defined as the present cost of installing and operating the system during the lifetime of the project. HOMER simulation and optimization results are ranked based on the total NPC and calculated as follows [23]:

$$C_{NPC} = \frac{C_{ann},\ tot}{CRF(i,\ N)} \tag{1}$$

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

Where $C_{ann}tot$ represent the total annualized cost covering the capital, operating, replacement, and maintenance cost and also the cost of fuel. CRF denotes capital recovery factor, a ratio used in calculating the current value of series having equal annual cash flows, the project lifetime is N, while i defines the percentage of real interest rate.

4.2. Levelized COE

Levelized COE is the average cost per kilowatt-hour ($/kWh) of the system useful energy produced which is calculated as follows [23]:

$$COE = \frac{C_{ann},tot}{E_{prion},AC + E_{prim},DC} \tag{3}$$

C_{ann} tot in the equation represent the total annualized cost ($/year), the AC and DC primary loads are E_{prim} AC and E_{prima}, DC respectively in (kWh/yr).

4.3. Annual real interest

An essential input parameter is the annual real interest rate since it uses the discount rate in conversion between one-time cost and annualized cost. Its calculation is given by the following equation [23]:

$$i = \frac{i' - f}{1 + f} \tag{4}$$

Where *i* denotes the real investment rate, f represents the nominal interest rate and the annual inflation rate is $i^!$. The nominal interest rate and the annual inflation rate in Nigeria are 14% and 17.6%, respectively (forecast by Central Bank of Nigeria, November, 2016) [26]. Thus, 60% annual interest rate is used for the simulation.

5. RESULT AND ANALYSIS

HOMER software was used for the simulation in order to assess the optimum configurations of PV/diesel/battery, Wind/diesel/battery, PV/wind/diesel/battery, and diesel alone. The capacity of the PV variation is for 0, 10, 20, 30, 40, and 50 kW. The variation of the wind turbine is from 1 to 5 turbines, and finally, the battery is varied from 50 units to 150 units.

5.1. Diesel alone

The diesel alone system is the second most cost-effective of all the various configurations studied. It has a total NPC of $531,555 at a diesel price of $1.00/L. The levelized (COE) for the stand-alone diesel is $0.6811/kWh. The annual mean electricity demand is the AC primary load which is estimated at 60,370 kWh/yr. The diesel alone system could generate $41,188 kWh of electricity per year, with the surplus electricity of 10,810 kWh/yr. The CO_2 emission as recorded from HOMER is 70202 kg/yr. It is essential to keep the carbon emission at an acceptable low level so as to minimize the effect of global warming.

5.2. Hybrid PV/diesel/battery system

The hybrid PV/diesel/battery system is the most cost-effective of all the various configurations studied. The cash flow summary for the hybrid PV/Diesel/Battery system with 50kW and 100 strings of the battery is depicted in Figure 6. The system capital cost is $139, 700 and about $127,200 higher than the capital cost for diesel alone system. This is as a result of the huge PV modules initial cost since the diesel generator produced about 70 % of the total generated electricity, it explained the high value of NPC for the fuel consumption. The NPC and levelized COE as simulated by HOMER, are $379,914 and $0.4868 respectively. The CO_2 emission is 25,888 kg/year as recorded by HOMER. It can be seen that there is about a 63 % reduction in CO_2 emission when compared with the standalone system.

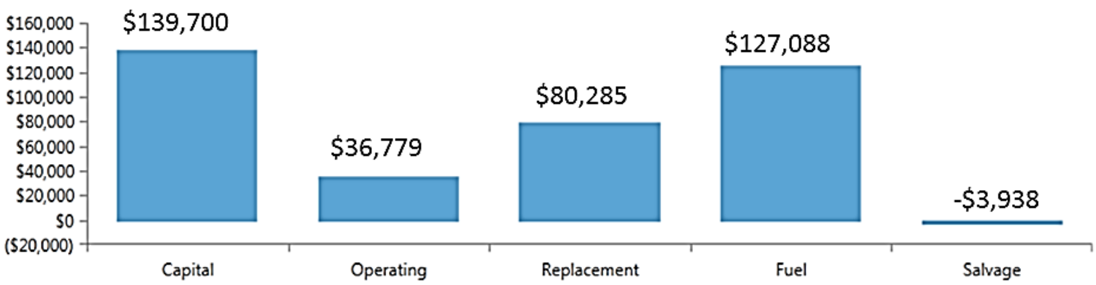


Figure 6. The NPC cash flow summary for Hybrid PV/diesel system with battery

5.3. Hybrid wind/diesel system with battery

Figure 7 shows the cash flow summary by cost for the hybrid Wind/Diesel system with battery and 10kW generic wind turbine with 50 strings of the battery. The NPC is $838,263 and levelized COE is $1.07. The CO_2 emission is 56,682 kg/year as recorded by HOMER, and the excess electricity produced by the wind turbine is $808 kWh/year. The NPC is higher than all the other hybrid system since it is a highly diesel-powered system. This high cost is due to high initial fuel and replacement cost for the diesel generator set, and also salvage cost for the 10kW wind turbine. The percentage of CO_2 reduction, when compared with the previous system, is about 20%, since CO_2 reduction is a function of the number of batteries in the system.

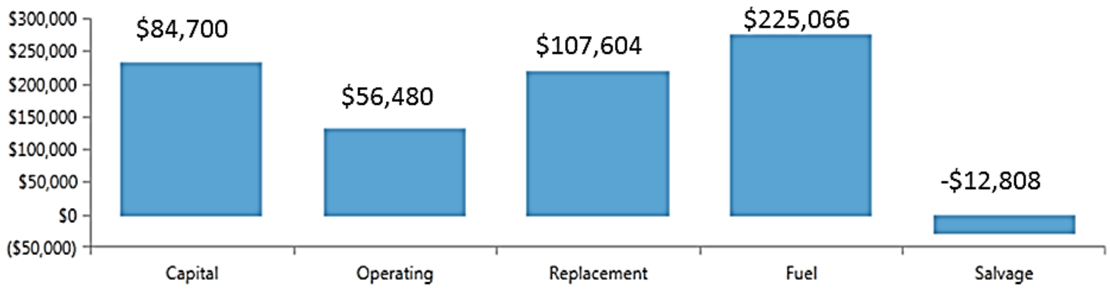


Figure 7. NPC cash flows summary for Hybrid Wind/diesel system with battery

The excess electricity generated is also inversely proportional to the number of batteries in the system. The more the number of batteries above 60 units, the less the excess electricity [23]. From the simulation results, the diesel generator energy production is 50,198 kWh/year which constitute 75% total electricity generation for the system, while the wind turbine produces 16.301 kWh/year of electricity and constitute 25% of the total electricity generation.

5.4 Hybrid PV/wind/diesel system with battery

The cash flow summary by cost for the PV/wind/diesel system with battery is illustrated in Figure 8. The total NPC value is $591,891 and the levelized COE is $0.7584. As indicated from HOMER simulation, the PV system constitutes 63% with total electricity production of 50, 5551 kWh/year, and the wind turbine is next with total electricity generation of 25,297 kWh/year and constitute 32% for the system. The diesel generator constitutes only 5% of the total electricity production with a generating capacity of 4,280 kWh/year. The CO_2 emission is 3424 kg/year, which represents 95% huge reduction in carbon emission as compared to the standalone-diesel system.

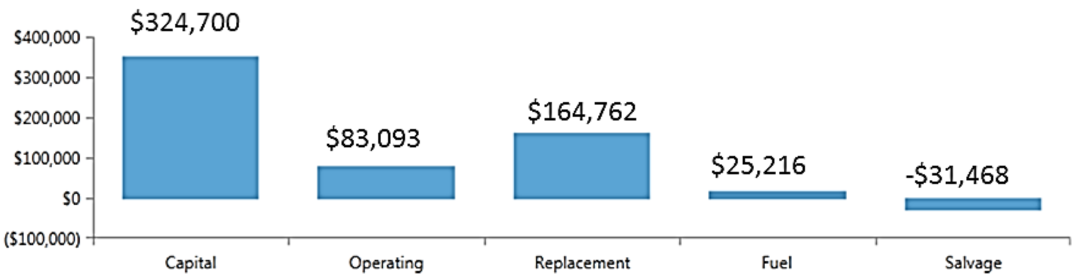
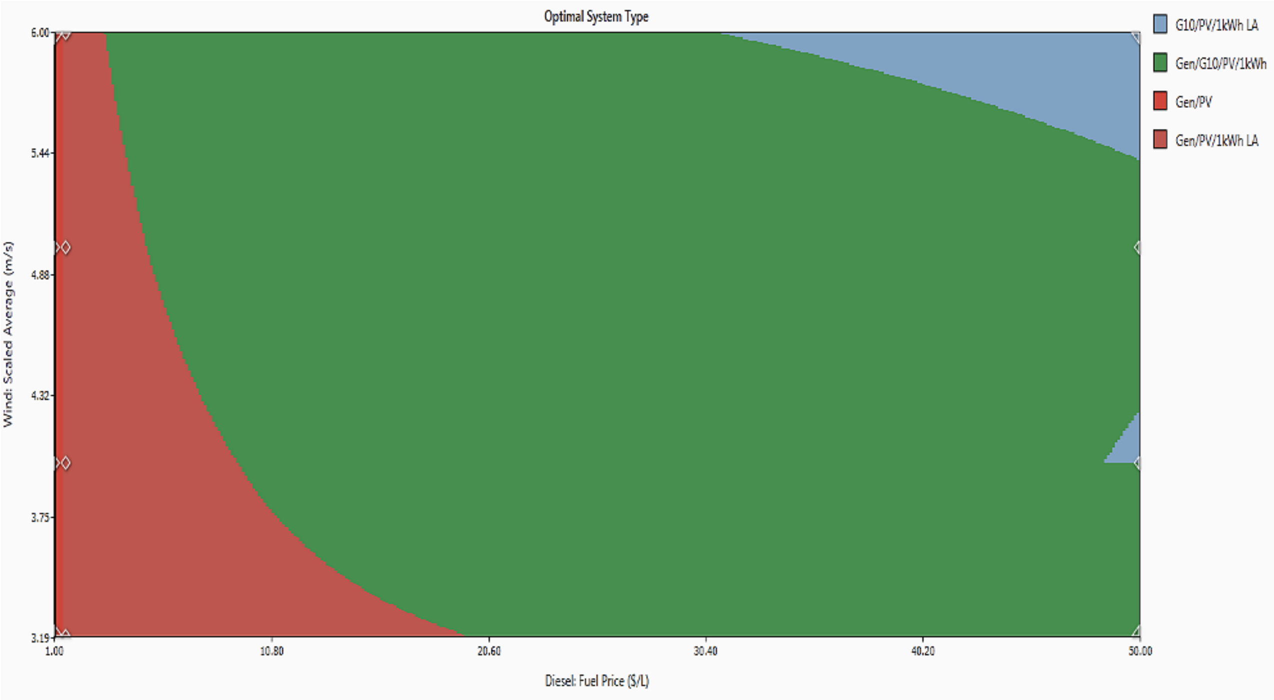


Figure 8. NPC cash flow summary for Hybrid PV/Wind/Diesel with battery

5.5. Sensitivity analysis

Figure 9 illustrates the optimal implementation of the four possible generating systems different wind scaled average and diesel prices. It can be deduced from the graph that the use of PV/diesel without battery is the cheapest and preferred option if the diesel price is below $1.5/L. The hybrid PV/Wind/Diesel system with Battery becomes feasible only if the diesel price is increasingly higher than $1.5/L. The result also indicates that the use of the battery in the energy mix does not produce a valuable result.



Figuer 9. Optimal system type determined by the HOMER

6. CONCLUSION

A model and analysis of PV/Wind/Diesel hybrid system for rural electrification has been presented using HOMER simulation software tool. The proposed system focused on PV/diesel system with battery, Wind/Diesel system with battery, Diesel alone system, and PV/Wind/Diesel system with battery. The PV/Diesel system with battery gave the most cost-effective energy system with an NPC of $379,914 and levelized COE of $0.4868. From the simulation result, the PV/Wind/Diesel system with Battery configuration with 50kW PV- modules, 1-unit generic 10kW wind turbine, 25kW diesel generator, 50 strings of battery and 24 system converter is concluded as the most preferred choice that can meet the load demand of the remote community in Kaduna state, Nigeria. It is cost effective since it uses renewable energy resources and recorded the lowest carbon emission.

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