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Sensitivity Analysis of an Optimal Hybrid Renewable Energy System for Sustainable Power Supply to a Remote Rural Community

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ABSTRACT: This study focuses on the various responses of an optimal hybrid renewable energy system (HRES) to changes in the system input parameters of primary load and price of diesel fuel. The energy system was designed for sustainable power supply to a remote community of Edem Urua, a rural village located in the southern part of Nigeria. Mathematical modelling method was used for system components modelling; renewable energy resources such as solar and wind together with diesel-generator and battery storage were combined while the design and optimal sizing of system components was done using Ampere-Hour optimal design method. Simulation and optimization were carried out using the Hybrid Optimization of Multiple Electric Renewables (Homer Pro) microgrid analysis tool. Detailed sensitivity analysis of the optimal HRES was carried out. Findings revealed that the total net present cost (NPC), total capital cost (TCC), renewable penetration fraction (RPF) and CO_2 changes correspondingly to changes in the daily load demand while cost of energy (COE) changes slightly and inversely with changes in daily load demand, due to the excess electricity production. Also, NPC and COE changes directly with changes in the price of diesel fuel while TCC and RPF increases and CO_2 decreases with both an increase and a decrease in the price of diesel fuel. This is to determine the optimal HRES's responses to variations in the input parameters with respect to these objective functions, so as to minimize losses and guide against poor system performance and increase energy production and system reliability which are indices for sustainability.

KEYWORDS: Sensitivity Analysis, Hybrid Renewable Energy System, Cost of Energy, CO_2 emissions, Sustainability.

I. INTRODUCTION

Background of Study

The importance of predicting the responses of an energy system with variations in the system input parameters such as daily load demand and price of diesel fuel, so as to guide against losses and poor system performance cannot be over-emphasised. Changes in the objective functions such as the total net present cost, cost of energy, renewable penetration factor and CO_2 emissions have significant impacts on energy production and system reliability which are among the benchmarks used in measuring sustainability. Designing an optimal hybrid renewable energy system for sustainable electrical power supply for a remote rural community is not enough, but to also know how the energy system responds to changes in the system input parameters and the technical and economic impacts on energy consumers, producers and other stakeholders. Knowledge of this information about the optimal HRES updates the stakeholders on their responsibilities to ensure sustainability of power supply, which is the backbone and vehicle that drives economic development in every country that wants to advance. Lack of sustained energy production in some rural communities in sub-Saharan Africa contributes greatly to the slow pace of their socio-economic development as it affects most critical activities of their day-to-day life, including agriculture, healthcare, education, entertainment and transportation. According to the International Energy Agency (IEA), the number of people that lacked access to electrical power supply in 2019 was 758.98 million, this represents 13% of the world's population, out of which 589.46 million were from sub-Saharan Africa. Ritchie and Roser (2020) reported that Nigeria's figure in the year under review stood at 89.63 million. As efforts are being geared globally towards energy transition and attention being paid to the design of higher renewable penetration energy systems, more attention is expected on the responses of energy systems to variations in the system input parameters as to ensure system reliability and energy sustainability.

Study Community

The study community is Edem Urua village, a rural community located in Iwerre Clan, Ini Local Government Area (LGA) of Akwa Ibom State, southern part of Nigeria with a population of about 650 people. This village is surrounded by other communities of Ikweme, Mbiabong, Nturi, Obotme, Okpoto, Ukpa Okon. Ini LGA is bounded by Abia State to the north and by Obot Akara, Ikono and Ibiono Ibom Local Government Areas of Akwa Ibom State to the south. Figures 1 and 2 show the geographical locations while Table 1 displays the background information of the study community. The major occupations of residents of Edem Urua community are farming, trading, small and medium-scale enterprises like barbing, furniture and upholstery making, auto-mechanics, fashion designing and milling. The estimated peak load demand of this community is expected to be about 40kW. Use of petrol and diesel fuel generators as sources of electrical power supply is presently employed by the residents with its attendant cost of acquisition, high prices of petrol and diesel fuel, high cost of operation and maintenance and CO_2 emissions.

Table 1: Background Information of Edem-Urua Community.

Particulars	**Details**
Country	Nigeria
State	Akwa Ibom
Local Government Area	Ini
Clan	Iwerre
Community	Edem-Urua
Latitude	5° 24′42.0″ N (5.411656)
Longitude	7° 49′29.0″ E (7.824727)
Elevation above sea level	110.42 m
Number of Households	102
Estimated Population	650
Main Socio-Economic activities	Farming, Small Business and Crafts

Source: (Owoeye, et al. 2022)

II. LITERATURE REVIEW

Many research works have been carried out in the area of sensitivity analysis of optimal hybrid renewable energy systems, with attention paid mostly on the techno-economic analysis and changes in some of the system input parameters. Most of these works which include Odou (2020), Oladigbolu, et al. (2020), Samir (2021), Yimen et al. (2020), Kiros et al. (2020), Vendoti (2020) and Aghenta et al. (2019) were consulted in the course of carrying out this research in order to gather reasonable information about sensitivity analysis of optimal hybrid renewable energy systems.

There is little or no record of sensitivity analysis in the work of Yimen et al. (2020) which involved optimal sizing and techno-economic analysis of HRESs unlike the detailed sensitivity analysis of this study. Odou (2020) carried out a comprehensive sensitivity analysis of the hybrid renewable power system he proposed in his work that covers the responses of the hybrid renewable power system to variations in the price of diesel fuel and daily energy consumption with respect to the COE, NPC and nominal discount rate whereas the sensitivity analysis in the study is in respect of COE, NPC, TCC, RPF and CO_2 emissions. Vendoti (2020) carried out sensitivity analysis in his attempt to model and optimise an off-grid hybrid renewable energy system for rural area electrification. However, it was not done in details. Also Samir (2021) did not carry out sensitivity analysis in his work on development of hybrid renewable sources of residential loads for energy sustainability. Mention was only made of the sensitivity analysis process; however it was not done as against what this research work did. Sensitivity analyses were not done in some of the available literature. The ones that carried it out were not detailed. This paper attempts to fill these research gaps by carrying out detailed sensitivity analysis of an optimal HRES for sustainable power supply.

Figure 1: The geographical location of Edem-Urua 1.
Source: www.google.com/maps.

Figure 2: The geographical location of Edem-Urua 2.
Source: www.google.com/maps.

III. METHODOLOGY

This research study was on the sensitivity analysis of an optimal hybrid renewable energy system to determine its responses to variations in the input parameters such as load demand and price of diesel fuel, with respect to some objective functions such as cost of energy, total net present cost, total capital cost, renewable penetration fraction and CO_2 emissions. Mathematical modelling method was used for modelling, design and optimal sizing of system components was carried out by using Ampere-Hour optimal design method, while Homer Pro microgrid analysis tool was used for simulation and optimisation with detailed sensitivity analysis carried out by the researcher. The research methodology steps adopted and used are summarized in Figure 3.

Modelling of System Components

A hybrid renewable energy system consists of two or more system components such as solar-PV (Photovoltaic) array, wind turbine, diesel generator, hydro turbine, micro turbine and battery bank. Modelling is the first step in selecting various system components for optimal sizing of the entire energy system.

Mathematical Modelling of Solar-PV System

Power output of a solar-PV array is based on solar irradiance and ambient temperature per location. According to Salameh (2014), the power output in this model is calculated as;

$$P_{pv} = \eta_{pv} A_{pv} R_{pv} \qquad (1)$$

Where η_{pv} = the solar-PV array power generation efficiency (%), A_{pv} = the Solar-PV array area (m^2), R_{pv} = the solar irradiation in tilted module plane (W/m^2). The assumption in this study is that solar-PV modules have a maximum power point tracking (MPPT) system and the temperature effects were ignored. The selected solar-PV array model has 500 W power capacity, module efficiency of 19.71%, lifespan of 25 years and installation cost of \$189.73/kW with 1.48 kWh/d effective energy output of a module per day obtained for the worst month solar radiation through the application of equation 1.

Mathematical Modelling of Wind Power System

Salameh (2014) declares that the instantaneous power output of the wind turbine generator is given as;

$$P_{out} = \left(\frac{1}{2}\right) \times \rho \times A \times (V^3) \times C_p \times \eta \qquad (2)$$

Where ρ = Air density (kg/m^3), A = Area of the wind turbine blades (m^2), V = Wind speed (m/s), C_p = Aerodynamic power coefficient = 0.593, which represents the efficiency of the wind turbine and η = the efficiency of the generator if no gearbox is used and the combined gearbox generator efficiency if gearbox is used. The selected wind turbine model has 80 kW rated power, cut-in speed of 2.5 m/s, rated speed of 12 m/s, cut-out speed of 30 m/s, swept area of 530 m^2, hub height of 40 m, lifespan of 25 years and installation cost of $30,000/unit with capacity factor of 0.115 and extractable power output of 9.1923 kWh obtained through the application of equation 2.

Battery, Diesel-Generator and Converter Models

For this study, the selected battery model is DAH solar battery with rated capacity of 210 Ah, 12V, 85% charge efficiency, 80% depth of discharge (DOD), 33.2 A maximum charge current, 335 A maximum discharge current, lifespan of 5 years and installation cost of $79.88/unit. An 80 kW, 100 kVA diesel-generator was used with a unit capital and replacement cost of $4,992.64, an operations and maintenance cost of $0.003/hour and a lifetime of 25 years. Also, a generic converter power model with an average installation unit cost of $349.38/kW and a lifetime of 5 years was considered, as advised by Yimen et al. (2020).

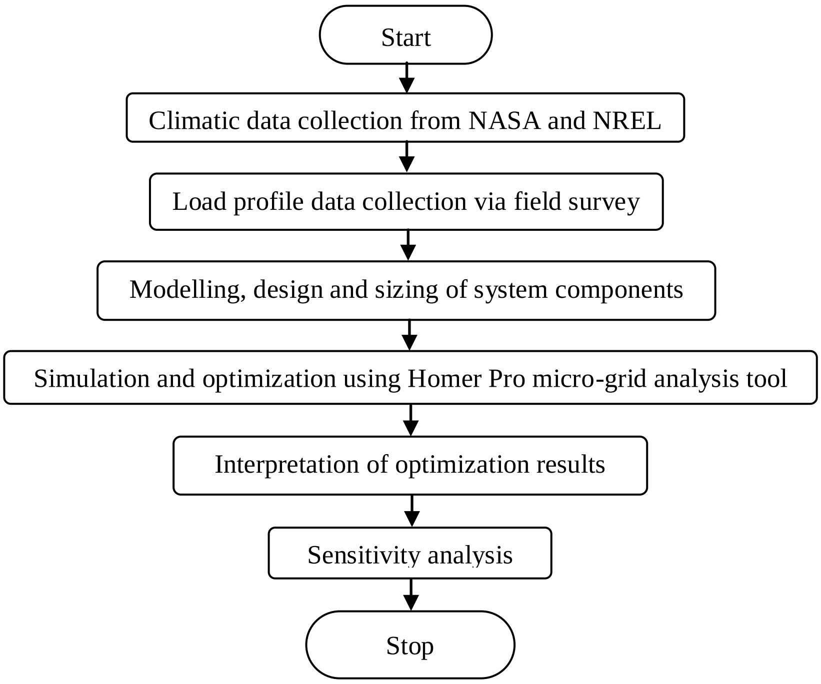


Figure 3:Flow diagram of the research process.

IV. RESULTS

Summary of various results of this research are displayed and analysed as follows;

Energy Usage and Load Profile of the Study Community

Table 2 shows the summary of load demand of the study community while the hourly load profiles are displayed in Figures 4, 5 and 6.

Table 2: Load demand summary

Load Category	kWh/d
Household	363.416
Commercial	165.582
Community	33.251
Total Load Demand	562.249

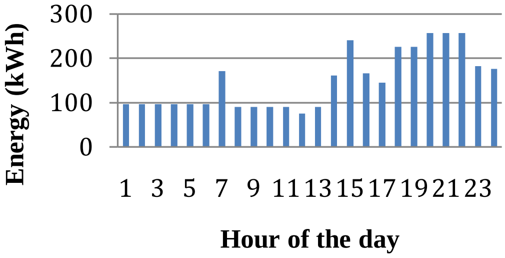


Figure 4: Hourly households load profile

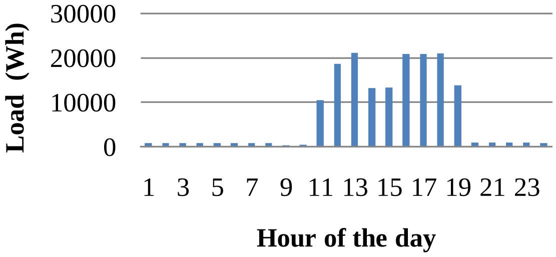


Figure 5: Hourly commercial load profile

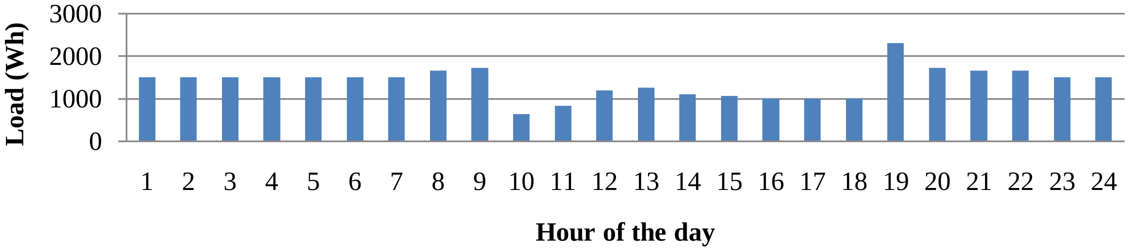


Figure 6: Hourly community load profile

Solar Energy Potential of the Study Community

The solar radiation data used for the design of hybrid renewable energy system is the monthly average solar global horizontal irradiance data, measured in 10-minute time interval over the period of sixteen years as shown in Table 7 and obtained from NREL-National Renewable Energy Laboratory and NASA-National Aeronautics and Space Administration and considered in the Homer Pro as the solar resource input. The maximum solar radiation is for the month of December with a daily average radiation of 5.02 kWh/m^2/d, whereas the minimum average radiation occurred in the month of July with radiation of 3.70 kWh/m^2/d while the average of 4.51 kWh/m^2/d was also obtained with the clearness index of the site as shown in Table 3. In this research work, the clearness value varies from 0.38 to 0.54.

Table 3: 16-year average monthly global solar radiation for Edem Urua (2004 to 2019)

Month	**Jan**	**Feb**	**Mar**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Average**
Solar Radiation - NASA (kWh/m^2/d)	5.01	4.83	4.80	4.85	4.66	4.15	3.70	3.74	4.08	4.49	4.80	5.02	4.51
Clearance Index from NASA	0.53	0.48	0.46	0.47	0.46	0.42	0.38	0.37	0.40	0.45	0.50	0.54	0.45

Wind Energy Potential of the Study Community

The wind speed data used for the energy system design is a 16-year data (2004 to 2019). This data was recorded over 24 hours for the whole 16 years by NASA and downloaded from NASA Prediction of Worldwide Energy Resources (POWER) database. It was measured at 40 meter above the surface of the earth and 10 meter anemometer height. The average annual wind speed was 3.83 m/s, with a minimum wind speed of 2.77 m/s in the month of December and a peak speed of 4.76 m/s in June. The wind speed potential of the study area is shown in Table 4.

Table 4: Average monthly wind Speed of Edem Urua (2004 to 2019)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Aver
Average Wind Speed (m/s) (From NASA)	3.33	3.35	3.62	3.93	3.63	4.76	4.7	4.67	4.41	3.71	3.08	2.77	3.83

Simulation and Optimisation Results

Tables 5 and 6 display the abridged form of most feasible HRES configurations that satisfy the input constraints imposed on the system by the designer. These feasible configurations are shown in an increasing order of the cost of energy COE from the top to the bottom. The top scenario which is the most cost effective configuration is proposed and recommended for implementation. The eleven possible scenarios are as follows; Solar-PV/Diesel-Generator/Battery-Bank (SDB), Solar-PV/Wind/Diesel-Generator/Battery-Bank (SWDB), Solar-PV/Wind/Battery-Bank (SWB), Solar-PV/Battery-Bank (SB), Wind/Diesel-Generator/Battery-Bank (WDB), Solar-PV/Wind/Diesel-Generator (SWD), Wind/Diesel-Generator (WD), Diesel-Generator/Battery-Bank (DB), Solar-PV/Diesel-Generator (SD), Diesel-Generator only (D) and Wind/Battery-Bank (WB). The different configurations of the optimal HRES computed and ranked by the simulation tool Homer Pro, according to the values of the COE and total NPC with the system components displayed in Figure 7.

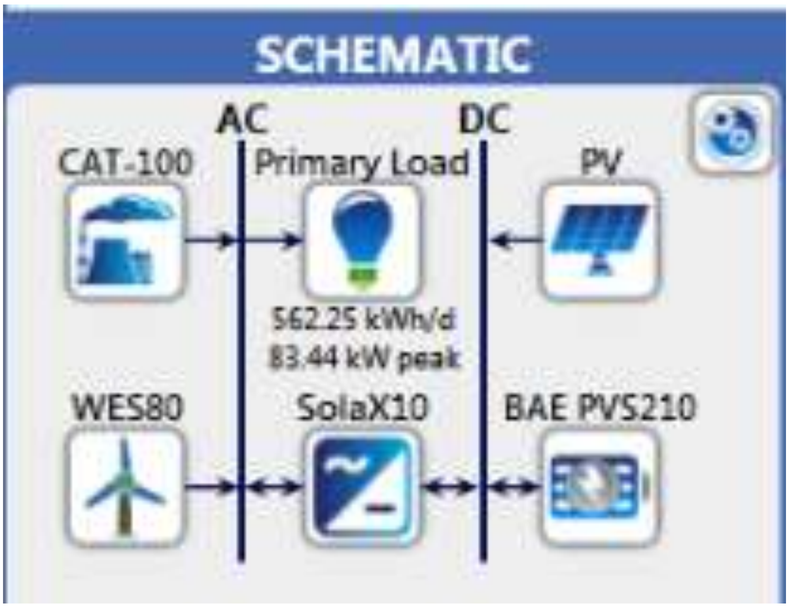


Figure 7:HRES components (Homer Pro, 2017)

Table 5: Simulation and optimization results of the optimal hybrid renewable energy system

Configurations	NPC ($)	COE ($)	Operating Cost ($/yr)	Initial Capital ($)	RPF (%)	CO_2 Emission (kg/yr)	Capacity Shortage (kWh/yr)	Unmet Load (kWh/yr)	Excess Elec. Prod. (kWh/yr)
Scenario 1	223,867	0.062	6,522.59	109,541	95.21	8231	0.00	0.00	250,169
Scenario 2	227,082	0.063	5,828.32	124,924	97.34	4621	0.00	0.00	222,628
Scenario 3	264,046	0.073	6,162.24	156,035	100.0	0	195.72	15.86	418,626
Scenario 4	295,836	0.082	6,323.19	185,004	100.0	0	173.75	106.16	762,475
Scenario 5	404,929	0.113	14,141.7	157,056	74.72	42925	0.00	0.00	113,946
Scenario 6	640,203	0.178	26,097.7	182,767	38.41	105623	0.00	0.00	677,326
Scenario 7	670,984	0.187	31,150.0	124,992	22.69	132031	0.00	0.00	235,019
Scenario 8	690,980	0.192	38,773.0	11,366	0.00	166873	0.00	0.00	1970.25
Scenario 9	693,568	0.193	32,815.0	118,385	18.95	137121	0.00	0.00	678,456
Scenario 10	775,292	0.216	43,947.0	4,992	0.00	192331	0.00	0.00	32,359
Scenario 11	965,945	0.269	21,304.0	592,531	100.0	0	202.09	178.90	833,242

Source: (Homer Pro, 2017)

Table 6: Details of system architecture of different configurations

Configuration	Solar-PV Array (KW)	Wind Turbine (kW)	Diesel-Gen. (kW)	Battery	Converter (kW)
Scenario 1	340		80	242	59
Scenario 2	269	1	80	246	55
Scenario 3	414	1		317	63
Scenario 4	717			312	69
Scenario 5		4	80	188	49
Scenario 6	394	3	80		37
Scenario 7		4	80		
Scenario 8			80	31	11
Scenario 9	520		80		42
Scenario 10			80		
Scenario 11		15		1111	154

Source: (Homer Pro, 2017)

Optimisation Analysis of the Proposed Optimal System Configuration (Scenarios 1)

The top most cost effective configuration of the optimal HRES is Scenario 1 with its architecture which consists of Solar-PV, Diesel-Generator and Battery-Bank (SDB) as displayed in Table 10. Scenario 1 configuration reduces the COE by 71.3% and the total NPC by 71.12% as compared to the base case Scenario 10 of diesel-generator only and it is the most cost-effective configuration in terms of COE and total NPC. From all the eleven different configurations, Scenario 1 is considered as the best configuration of the optimal system, taking into account the COE and NPC as the topmost comparison benchmarks. Therefore, using the total NPC and COE as the comparison benchmarks, Scenario 1 is selected and recommended for implementation.

V. SENSITIVITY ANALYSIS OF THE OPTIMAL SYSTEM

Sensitivity is the degree of response of a system to a change in an input signal. Relating this definition to this research, sensitivity means the degree of response of the optimal HRES to some changes in the values of the input parameters such as the primary load and price of diesel fuel. The behaviour of the optimal HRES depends on how various input data interact; it is good to know how this optimal HRES perform with various variations in the input data. In this study, two separate sensitivity cases were carried out. They are:

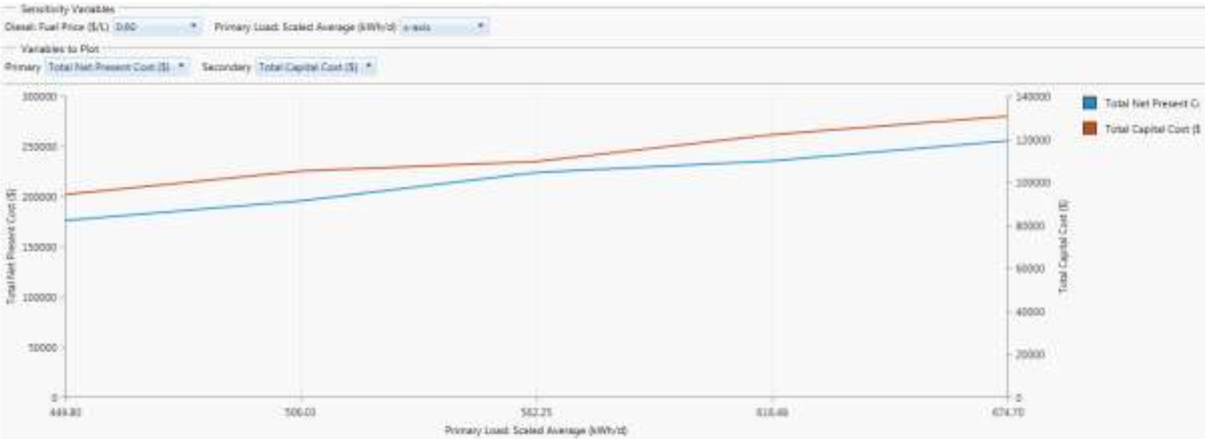
i. Sensitivity based on changes in the primary load
ii. Sensitivity based on changes in the current price of diesel fuel.

Changes in primary load with the current price of diesel fuel $0.6/litre

With the current price of diesel fuel at $0.6/litre, the effects of changes in the primary load on the optimal HRES in terms of system costs and components are analysed in this section. From Figure 8, a 10% decrease in primary load from 562.25 kWh/d to 506.03 kWh/d led to a decrease in NPC and total capital cost TCC of the optimal HRES. A further 20% decrease in primary load, from 506.03 kWh/d to 449.80 kWh/d follows the same trend of decrease in NPC and TCC.

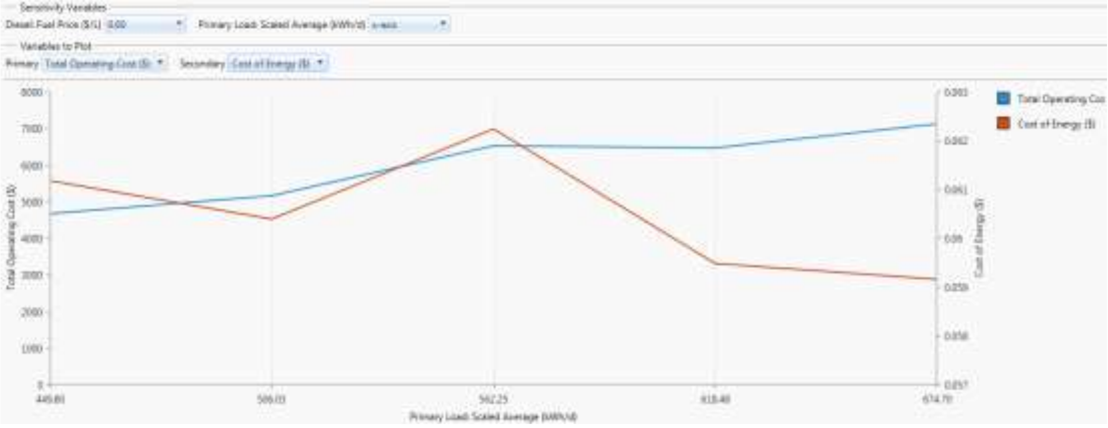
Also, a 10% increase in primary load from 562.28 kWh/ day to 618.48 kWh/ day led an increase in NPC and TCC of the optimal system as can be seen in Figure 8. This implies that a decrease in primary load will always lead to a corresponding decrease in the NPC and TCC of the optimal system and an increase in the primary load will always lead to a corresponding increase in the NPC and TCC of the optimal system. In other words, the value of primary load is directly proportional to both the total NPC and TCC.

From the Figure 9, it was observed that a decrease in primary load demand led to a decrease in the total operating cost which experiences a steady decrease in value as the primary load decrease further. Also, an increase in the load demand leads to a corresponding increase in the total operating cost. The implication of this is that the lesser the load demand, the lower the total operating cost and vice versa. With a 10% decrease in the primary load from 562.25 kWh/d to 506.03 kWh /day, the COE decreased from about $0.062 to about $0.0604 while a further 10% decrease in primary load from 506.03 kWh/ day to $449.80 kWh/d had a significant increase in COE which is attributed to reduction in the production of excess electricity. A 10% increase in primary load leads to a noticeable drop in COE from $0.062 to about $0.059 while a further 10% increase in primary load moved the value of COE downwards slightly. This is an indication of excess electricity production by the optimal HRES.



Sensitivity Variables
Diesel: Fuel Price ($/L) 0.60
Primary Load: Scaled Average (kWh/d) x-axis
Variables to Plot
Primary Total Net Present Cost ($)
Secondary Total Capital Cost ($)

Figure 8:Changes in primary load with NPC and Total Capital Cost (Homer Pro, 2017)



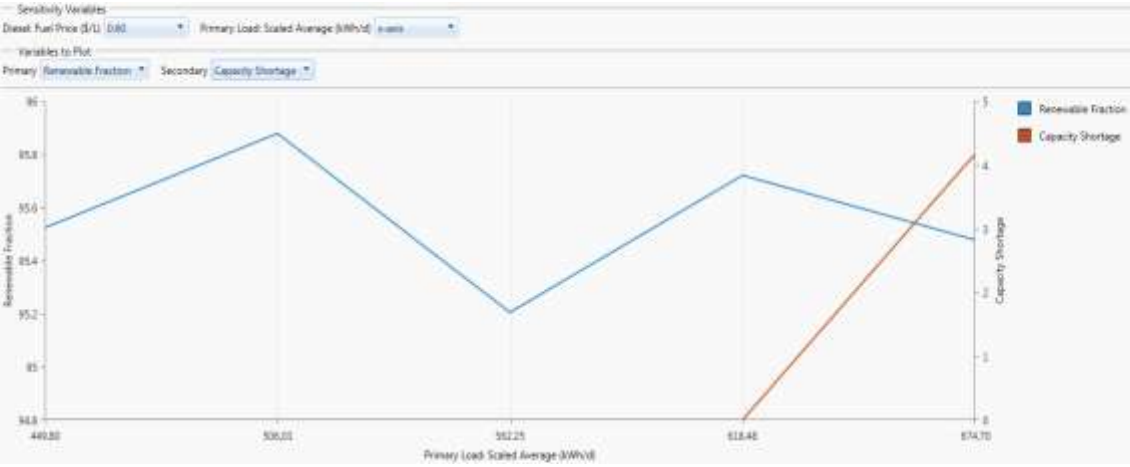
Sensitivity Variables
Diesel: Fuel Price ($/L) 0.60
Primary Load: Scaled Average (kWh/d) x-axis
Variables to Plot
Primary Total Operating Cost ($)
Secondary Cost of Energy ($)

Figure 9:Change in load with operating cost and COE (Homer Pro, 2017)

From Figure 10, it was observed that a 10% decrease in primary load increased the RPF from 95.2% to about 95.84% while a further 10% decrease in primary load from 506.03 kWh/d to 449.80 kWh/d decreased the percentage of RPF from about 95.84% to about 95.52%. On the other hand, as seen from the Figure 10, a 10% increase in primary load had significant increase in the RPF from 95.20% to about 95.65% while a further 10% increase in the primary load led to a decrease in the level of involvement of the renewable energy sources in the electrical energy production process, from about 95.65% down to about 95.50%. This means that as the primary load changes, the optimal system will continue to engage the service of the diesel generator for support depending on the available productivity level of the renewable energy system(s).

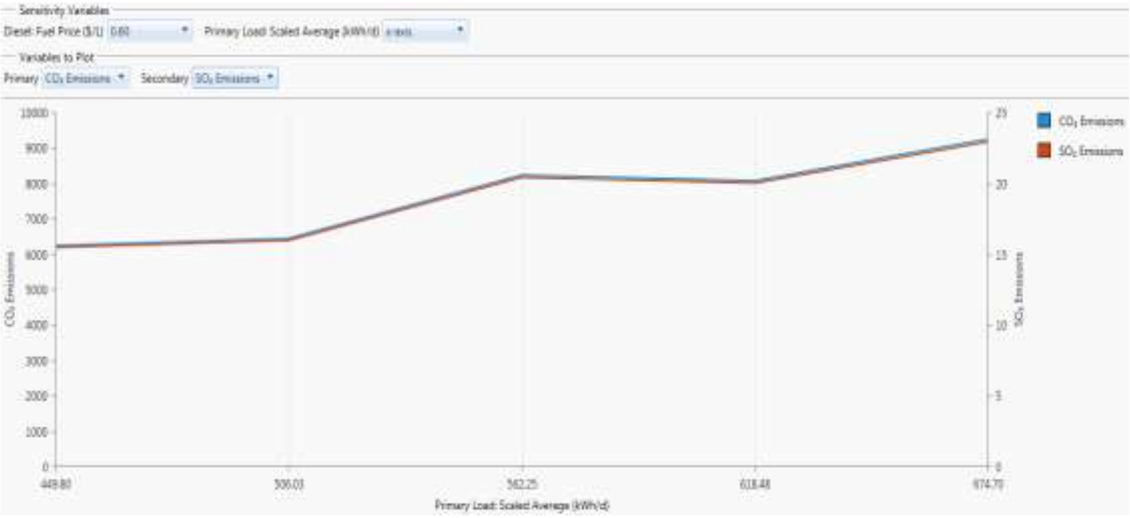
It is also observed from the Figure 10 that value of capacity shortage remain zero and constant for both a decrease and an increase in the value of primary load with an exception of when the primary load moved from 618.48 kWh/d to 674.70 kWh/d. This implies that the optimal HRES met the required operating capacity which includes both the load requirement capacity and operating reserve capacity up to the point when the primary load was 618.48 kwh/d.

Figure 11 shows an increase in the rate of CO_2 emissions, as the primary load increase in value. Also a decline in the rate of emissions was noticed with a decrease in the primary load demand. In the optimal HRES, lack of 100% RPF and involvement of the diesel generator in the energy production process are responsible for these emissions that are responsible for environmental pollution and climate change. As seen in Figure 11, changes in the primary load leads to corresponding changes in CO_2 emissions.



Sensitivity Variables
Diesel Fuel Price ($/L) 0.60
Primary Load Scaled Average (kWh/d) x-axis
Variables to Plot
Primary Renewable Fraction
Secondary Capacity Shortage

Figure 10:Changes in primary load with RPF & capacity shortage. (Homer Pro, 2017)



Sensitivity Variables
Diesel Fuel Price ($/L) 0.60
Primary Load Scaled Average (kWh/d) x-axis
Variables to Plot
Primary CO_2 Emissions
Secondary SO_2 Emissions

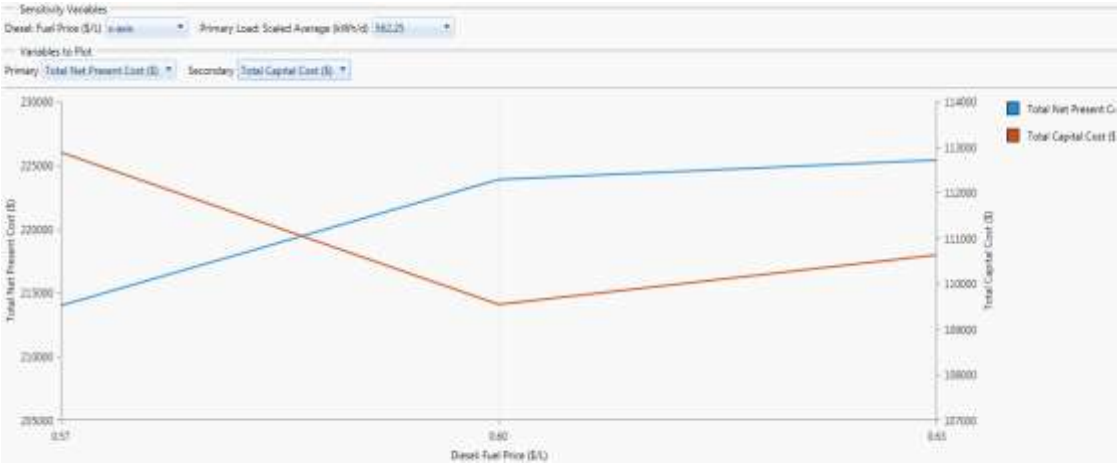
Figure 11: Changes in load with emissions of CO_2 gas emissions. (Homer Pro, 2017)

If a clean energy production and a greener environment are desired, the use of a diesel generator in the energy production process should be discouraged while taking full advantage of the abundant renewable energy sources of the study community, however this comes with a price tag – increase in cost.

Changes in the Current Price of Diesel Fuel with Constant Primary Load

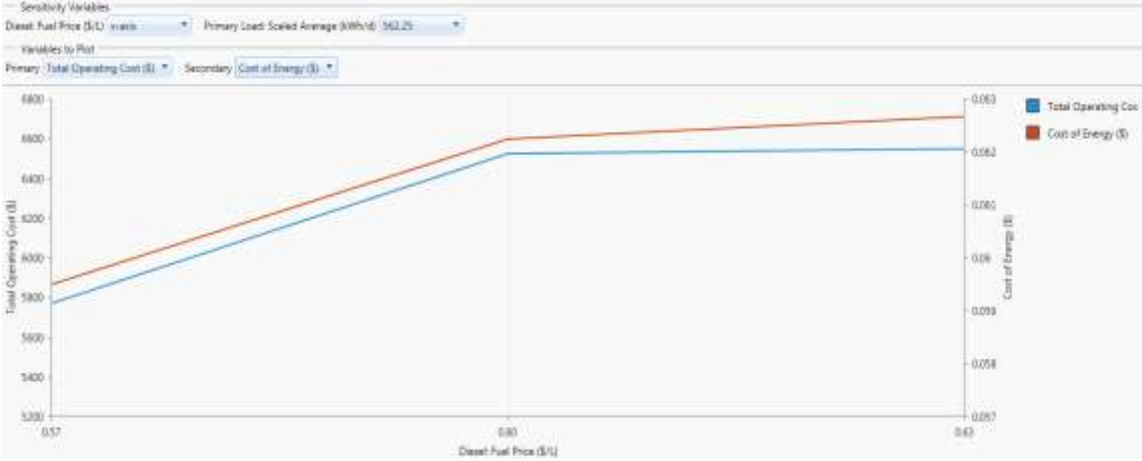
This sensitivity case follows the same strategy we used under the previous section on changes in primary load with constant and current price of diesel $0.60/litre. With the current value of the primary load demand at 562.25 kWh/d, the effects of the changes in the current price of diesel fuel on the optimal HRES in terms of system costs and components are discussed in the following section.

From Figure 12, a 5% decrease in the current price of diesel fuel from $0.6/litre to $0.57/litre caused a decrease in the total NPC from about $223,827.86 to about $214,000.00. Also, a 5% increase in the current diesel fuel prince from $0.6/litre to $0.63/litre slightly increased the total NPC from about $223,827.86 to about $225,000.00. On the effects of changes in the current price of diesel fuel on the total capital cost, Figure 12 shows an increase in the total capital cost of the optimal system from 109,541.00 to about $113,000.00 with a 5% decrease in the price of diesel fuel from $0.6/litre to $057/litre while a 5% increase in the diesel fuel price from $0.6/litre to $0.63/litre led to an increase in the total capital cost from about $109,541.00 to about $110,600.00. The fact here is that, a change in the price of diesel fuel leads to a corresponding change in the total NPC while a change in the price of diesel fuel leads to an increase in the total capital cost.



Sensitivity Variables
Diesel: Fuel Price ($/L) x-axis
Primary Load: Scaled Average (kWh/d) 562.25
Variables to Plot
Primary: Total Net Present Cost ($)
Secondary: Total Capital Cost ($)

Figure 12:Changes in diesel fuel price with NPC and total capital cost (Homer Pro, 2017)



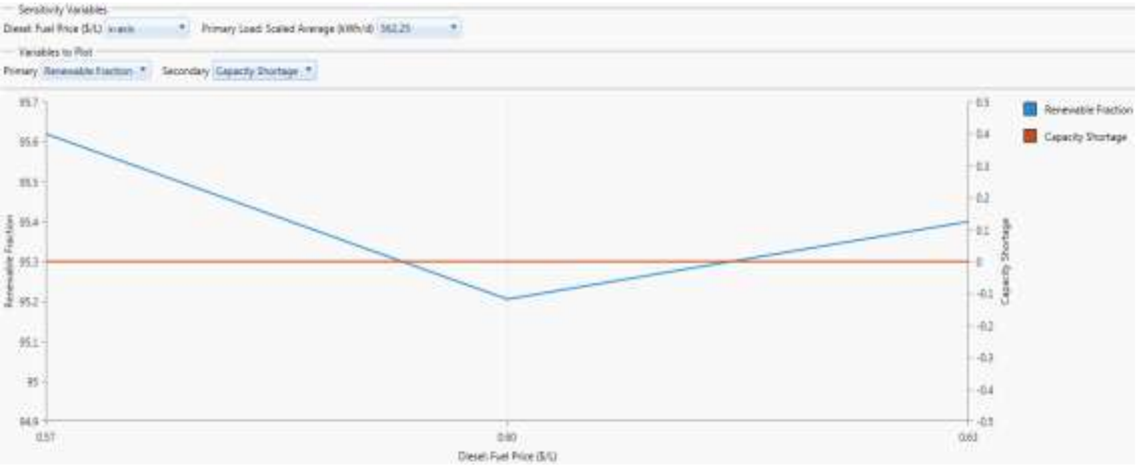
Sensitivity Variables
Diesel: Fuel Price ($/L) x-axis
Primary Load: Scaled Average (kWh/d) 562.25
Variables to Plot
Primary: Total Operating Cost ($)
Secondary: Cost of Energy ($)

Figure 13: Changes in the price of diesel fuel with total operating cost and COE (Homer Pro, 2017)

A decrease in the current price of diesel fuel led to a corresponding decrease in the TOC from $6,523 to about $5,760 while an increase in the current price of diesel increased the TOC a little as seen in Figure 13. A 5% decrease in the current price of diesel fuel also shows a corresponding decrease in the COE from $0.062 to about $0.059 while an increase of 5% in the price of diesel fuel also moved up the COE a little. The implication of this is that a decrease in the price of diesel fuel leads to a very sharp and corresponding decrease in the TOC and COE whereas an increase in the price of diesel fuel leads to slight increase in the TOC and COE.

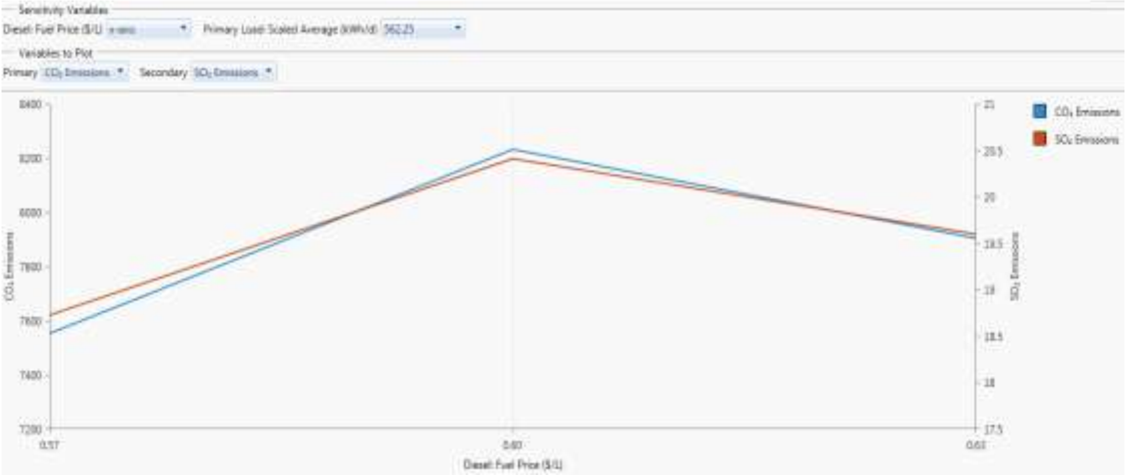
Figure 14 shows an increase in the RPF, from 95.20% to about 95.62% with a decrease in the price of diesel fuel. Also an increase in the price of diesel fuel leads to an increase in the RPF from about 95.20% to about 95.4%. This implies that a change in the price of diesel fuel leads to an increase in the RPF of the optimal HRES. It was also observed from Figure 14, that the value of capacity shortage remains zero and constant with a change in the current price of diesel fuel.

Figure 15 shows a decrease in CO_2 and SO_2 emissions with an increase in the price of diesel fuel while a decrease in the price of diesel fuel also leads to a decrease in the CO_2 and SO_2 emissions. It means that a change in the price of diesel fuel leads to a decrease in CO_2 and SO_2 emissions.



Sensitivity Variables
Diesel Fuel Price ($/L) x-axis
Primary Load Scaled Average (kWh/d) 562.25
Variables to Plot
Primary Renewable Fraction
Secondary Capacity Shortage

Figure 14: Changes in the price of diesel fuel with RPF and capacity shortage (Homer Pro, 2017)



Sensitivity Variables
Diesel Fuel Price ($/L) x-axis
Primary Load Scaled Average (kWh/d) 562.25
Variables to Plot
Primary CO_2 Emissions
Secondary SO_2 Emissions

Figure 15: Changes in the price of diesel fuel with CO_2 and SO_2 emissions (Homer Pro, 2017)

V. DETAILED SENSITIVITY ANALYSIS OF THE OPTIMAL SYSTEM

As earlier stated, sensitivity is the degree of response or reaction of the selected optimal HRES to variations or changes in the values of the input parameters. Fifteen sensitivity cases were analysed using variables of input parameters like the current price of diesel fuel and primary load. Under this section, optimal system type plot was used to analyze the optimisation results in details. It should be noted that the red and green colours in all the succeeding figures under this section represent SDB and SWDB optimal system architectures respectively.

Total net present cost (NPC)

In Figure 16, the optimal surface type plot shows variations in the price of diesel fuel and primary load with respect to the total NPC. With variations in values of the two sensitivity cases, corresponding variations in the NPC are shown. Any change in the primary load leads to a corresponding change in the total NPC, ditto to any change in the price of diesel fuel with an exception of a decrease in from $0.60/litre to $0.57 litre at primary load of 506.03 kWh/d. Also, at primary load of 449.80 kWh/d, the total NPC decreased from $176,042.70 to $174,752.80 ditto to primary load of 562.25 kWh/d with the NPC decreasing from about $223,867.90.00 to $213,983.60. The same response was noticed with an increase in the primary load.

With an increase in the price of diesel fuel, say from $0.60/litre to $0.63/litre, the NPC increased from about $195,504.20 to $196,789.70 at primary load of 506.025 kWh/d. Also the same effect was seen at other primary load values. The final verdict on effects of variations in the input parameters of the system, on the total NPC is that price of diesel fuel and primary load are directly proportional to the total NPC. That is, an increase in any of the two input variables leads to an increase in the total NPC, and a decrease in any one of them leads to a decrease in the total NPC with an exception at primary load of 506.03 kWh/d and price of diesel fuel of $0.57/litre.

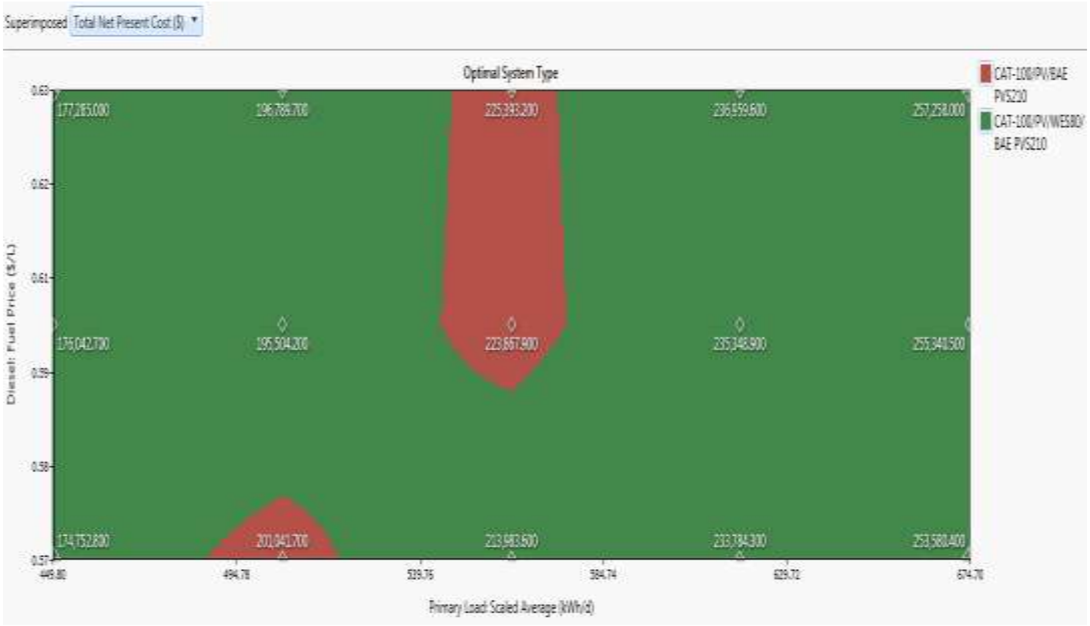


Figure 16: Optimal system type plot for total NPC (Homer Pro, 2017)

Cost of Energy (COE)

Various changes in the optimal system COE with variations in the input parameters of price of diesel fuel and primary load are displayed in Figure 17. A decrease in the primary load witnessed a corresponding decrease in the COE in three out of six sensitivity cases and an increase in the primary load led to a reduction in COE in two instances and no change in the remaining four sensitivity cases. The higher the primary load, the more stable the COE while the lower the primary load, the more possibility of higher COE. When the primary load of the study community increases, the energy consumers pay less for kWh unit of energy. This is largely due to the excess electricity production of the optimal HRES.

For instance, a decrease in primary load of 562.25 kWh/ day to 506.03 kWh/ day witnessed an increase in COE from $0.059 to $0.062 at a diesel fuel price of $0.57, while an increase in primary load of 618.48 kWh /day to 674.70 kWh/ day leads to a decrease in COE from $0.062 to $0.059 at a diesel price of $0.60/litre. The verdict here is that the higher the load, the cheaper the cost of energy, this benefits the consumers more. As earlier said, this is mainly due to the excess electricity produced by the optimal system.

On the impacts of variations in the price of diesel fuel on COE, a closer look at Figure 17 revealed that cost of energy decreases or remains the same with a decrease in the price of diesel fuel with an exception of when the diesel fuel price decreased from $0.60/litre to $0.57/litre at the primary load of 506.03 kWh/d and increases with an increase in the price of diesel fuel as seen in Figure 17. This implies that the price of diesel fuel has a direct impact on the COE, that is, they are directly proportional to each other. For instance, a decrease in the price diesel fuel from $0.60/litre to $0.57/litre leads to a corresponding decrease in COE from $0.062 to $0.059 at the primary load of 562.25 kWh/d. Also, an increase in the price of diesel fuel from $0.60/litre to $0.63/litre witnessed an increase in the COE from $0.059 to $0.060 at primary load at 618.481kWh/d. This implies that COE increases with an increase in the price of diesel fuel. The higher the price of diesel fuel, the higher the amount of money consumers pays for energy.

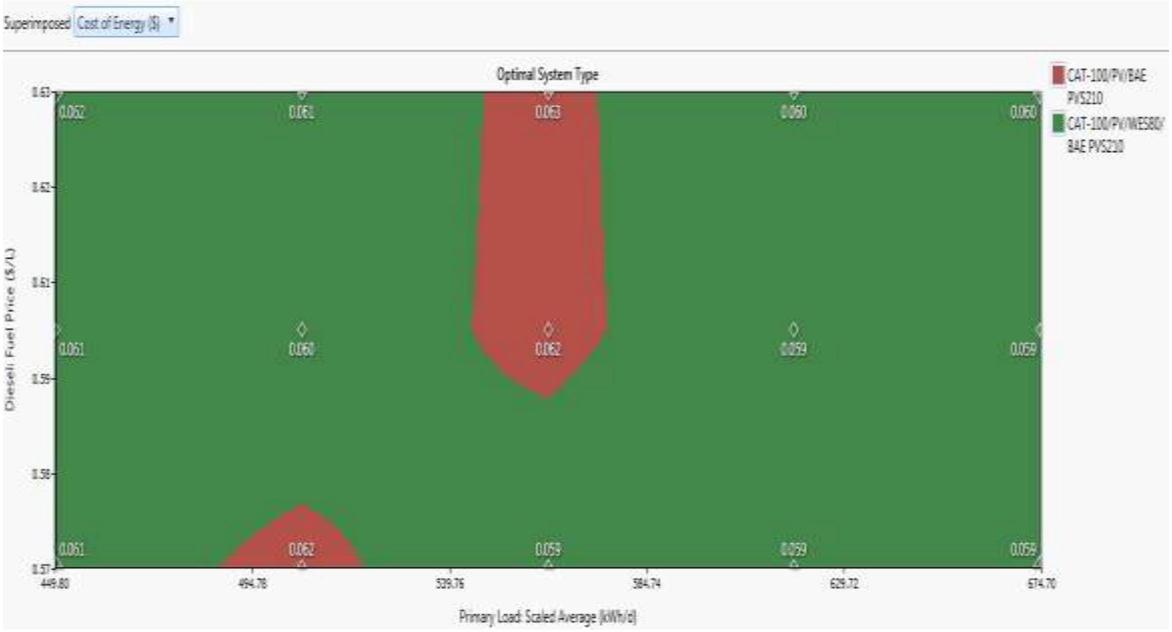


Figure 17:Optimal system type plot for COE (Homer Pro, 2017)

Renewable penetration fraction (RPF)

Figure 18 displays various responses of the optimal HRES in terms of RPF, to variations in the system input parameters of the price of diesel and primary load. An increase in the primary load witnessed a corresponding decrease in the percentage of RPF. This implies that the higher the load demand, the more the diesel generator is engaged and the less the renewable energy sources contributions to the overall energy production process. A 10% increase in the primary load from 562.25 kWh/d to 618.48 kWh/d leads to an increase in the RPF at all the prices of diesel fuel while a further increase in the primary load from 618.48 kWh/d to 674.70 kWh/d leads to a decrease in the RPF as shown in Figure 18.

For instance, an increase in primary load from 562.25 kWh/ day to 618.48 kWh/d leads to a increase in the RPF from 95.21% to 95.72% at a diesel fuel price of $0.60/litre and also at $0.63/litre of diesel fuel, the RPF decreased from 95.75% to 95.59% with an increase in the primary load from 618.48 kWh /d to 674.7 kWh/ d. Also, the RPF decreases from 95.75% to 95.58% with an increase in the primary load from 618.48 kWh/d to 674.70 kWh/d at $0.57/litre price of diesel fuel.

This analysis indicates that the involvement of renewable energy sources in the energy production process declined over time, with an increase in the consumers load demand. Observing the reduction in the primary load side of the plot, an increase in the RPF was noticed in three situations with a corresponding decrease noticed in the other three situations. This means there is 50% likelihood that a decrease in the primary load would lead to a corresponding decrease in the RPF and 50% probability that a decrease in the primary load leads to an increase in RPF.

At a price of diesel fuel of $0.63/litre, the RPF increased from 95.40% to 96.01% with a decrease in the primary load from 562.25 kWh/d to 506.03 kWh/d. The same effect was witnessed with a decrease in the primary load from 506.03 kWh/d to 449.80 kWh/d, the RPF increased from 95.03% to 95.66% at $0.57/litre price of diesel fuel. One of the three exceptions to this response was witnessed at a diesel price of $0.6/litre with the RPF reduced from 95.89% to 95.52% when the primary load was reduced from 506.03 kWh/d to 449.80 kWh/d. The verdict here is that a reduction in the consumer load demand leads to 50% likelihood of an increase in the RPF and 50% likelihood of a reduction the RPF.

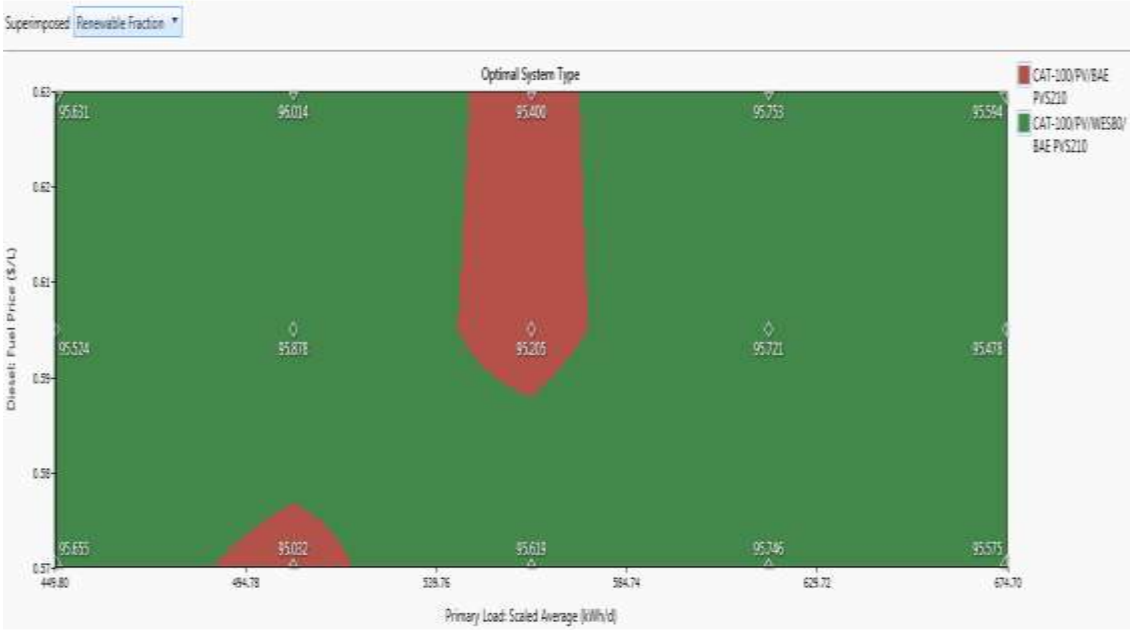


Figure 18: Optimal system type plot for RPF (Homer Pro, 2017)

CO_2 Emissions

Figure 19 displays various sensitivities of the optimal HRES in terms of CO_2 emission with variations in the system input parameters of price of diesel fuel and primary load. With an increase in the primary load, a corresponding increase in the amount of CO_2 emission was recorded with an exception of a change in the primary load from 562.25 kWh/d to 618.48 kWh/d at $0.60/litre of diesel fuel price. Also a decrease in the primary load leads to a corresponding decrease in the CO_2 emissions with an exception of a change in the primary load from 562.25 kWh/d to 506.03 kWh/d at $0.57/litre of diesel fuel price. This implies that the higher the consumers load, the more engaging the diesel generator is and the more CO_2 emission is released. For instance, when the primary load was increased from 562.25 kWh/d to 618.48 kWh/d, a corresponding increase in the CO_2 emission from 7,903.21 kg/yr to 8,023.51 kg/yr was witnessed at a price of diesel fuel of $0.63/litre. Also a decrease in CO_2 emission from 7,737.98 kg/yr to 6,054.38 kg/yr was witnessed when the primary load was reduced from 506.03 kWh/d to 449.80 kWh/d at $0.57/litre price of diesel fuel. The conclusion here is that variations in the primary load always lead to a corresponding variation in the CO_2 emissions.

Figure 19 also displays various reactions of the optimal HRES in terms of CO_2 emissions to variations in the price of diesel fuel. It was observed that an increase in the price of diesel fuel leads to a reduction in the CO_2 emission and a decrease in the diesel fuel price also leads to a decrease in CO_2 emissions with an exception of a change in the diesel fuel price from $0.60/litre to $0.57/litre at the primary load of 506.03 kWh/d. This shows that the CO_2 emissions reduce with a change in the diesel fuel price. The lower or higher the price of diesel fuel the lesser the engagement of the diesel generator, in the energy production process which subsequently leads to a reduction in the CO_2 emission.

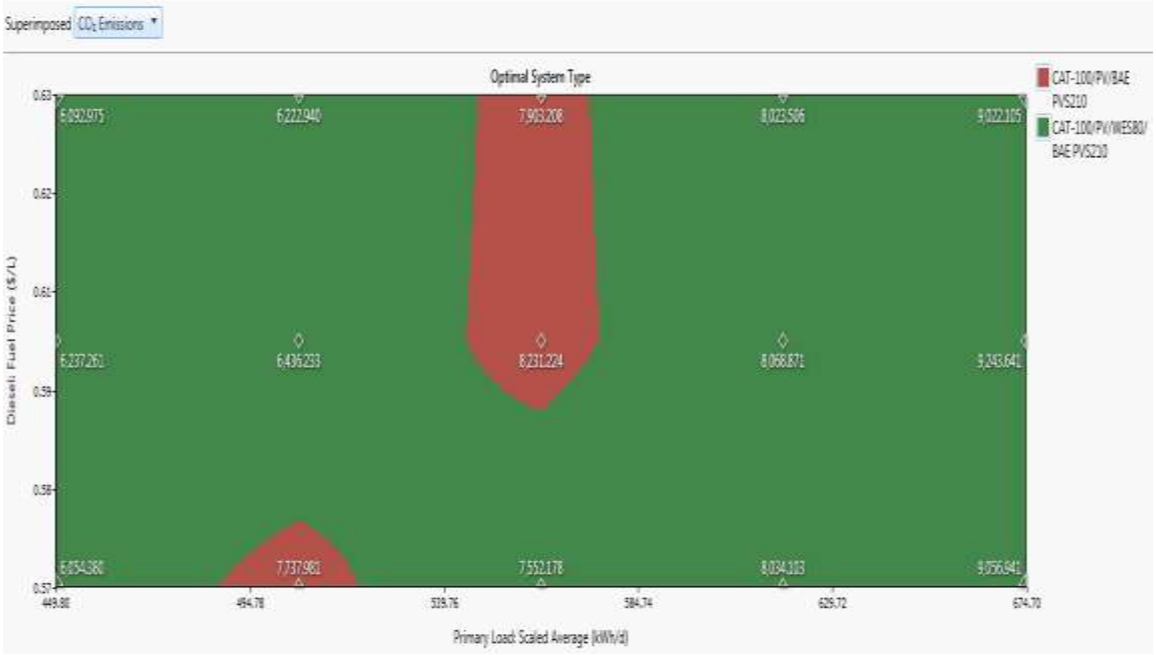


Figure 19: Optimal system type plot for CO_2 (Homer Pro, 2017)

VI. DISCUSSION

This research work presents detailed sensitivity analysis of an optimal HRES in order to know and be able to predict its responses to variations in some system input parameters and to some extent, the future system performance. Comparing this research with some works of great authors like (Samir, 2021) where there was little or no record of sensitivity analysis being carried out, knowledge and information on how his proposed system responds to changes in input parameters such as the load demand is not available. Also, there was no record of sensitivity analysis in the work of Yimen et al. (2020) which involved optimal sizing and techno-economic analysis of HRESs unlike the detailed sensitivity analysis of this study. Odou (2020) carried out a comprehensive sensitivity analysis of the hybrid renewable power system he proposed in his work that covers the responses of the system to variations in the price of diesel fuel and daily energy consumption with respect to only the COE, NPC and nominal discount rate whereas the sensitivity analysis in our study extends to other metrics such as the TCC, RPF and CO_2 emissions. (Vendoti, 2020) carried out sensitivity analysis in his attempt to model and optimise an off-grid hybrid renewable energy system for rural area electrification. However, it was not done in details unlike what is obtainable in this research.

VII. CONCLUSIONS

Considering the daily load as the sensitivity variable, it was concluded from the results of this research that the total NPC changes with corresponding change in the average daily load, that is, an increase in the average daily load leads to an increase in the total NPC and a decrease in the average daily load leads to a decrease in the total NPC. Also total capital cost changes with corresponding change in the average daily load, that is, an increase in the average daily load leads to an increase in the total capital cost and a decrease in the average daily load leads to a decrease in the total capital cost. There is little or no change in the COE with changes in the daily load demand. This is mainly due to the excess electricity production by the optimal system. RPF increases with both 10% increase and decrease in the daily load demand and decreases with a further 10% increase and decrease in the daily load while CO_2 emission changes with corresponding change in the average daily load, that is, an increase in the average daily load leads to an increase in the CO_2 emission and a decrease in the average daily load leads to a corresponding decrease in CO_2 emission.

Also considering the price of diesel fuel as the sensitivity variable, it was concluded from the results of this research that the total NPC increases slightly with an increase in the price of diesel fuel while experiencing a downward trend with a corresponding decrease in the price of diesel fuel. Also, the total capital cost increases with both an increase and a decrease in the price of diesel fuel while COE changes with corresponding changes in the price of diesel fuel, that is, an increase in the diesel fuel price leads to an increase in the COE while a decrease in the price of diesel fuel leads to a decrease in the COE. RPF increases with both an increase and a decrease in the price of diesel fuel while CO_2 emission changes with a corresponding change in the price of diesel fuel, that is, an increase in the price of diesel fuel leads to an increase in the CO_2 emission and a decrease in the price of diesel fuel leads to a corresponding decrease in CO_2 emission.

Armed with these facts and information about how the optimal HRES responds to variations in the system input parameters, the future performance of the energy system under various changing conditions can be well predicted so as to minimize losses and guide against poor system performance and also increase energy production and system reliability which are sustainability indices.

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