Techno-Economic Analysis of Off-grid Renewable Energy Systems for Rural Electrification in North-eastern Nigeria

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Abstract- In sub-Saharan Africa, there still remains a large number of villages in the rural areas not connected to the national grid. This has led to the use of diesel generators as source of electricity by the dwellers in these rural areas. These sources of energy are expensive and pose threats to the environment. Renewable Energy Systems (RESs) as alternatives to such energy sources reduce greenhouse emissions as well as cost of energy production. In Northern Nigeria, very few feasibility studies have been carried out on the development of RESs as clean and cheaper energy systems in remote villages not connected to the national grid. This paper presents techno-economic analyses of five different power system models in a North-eastern Nigerian village in Nganzai Local Government Area. The available renewable energy resources in the area were studied and the technical, environmental and economic aspects of five energy sources viz. diesel system, PV with battery storage system, hybrid PV/diesel with and without battery storage systems and hybrid PV/wind with battery storage system were studied using HOMER. Results from this study revealed that Nganzai district has sufficient monthly global solar irradiance and wind speed potential for the deployment of RESs. In addition, PV/diesel with battery storage system was found to be the most cost effective power system for the village in focus, with various cost indices being cheaper to diesel system by as much as 38 % and emissions cut by 36 %.

Keywords HOMER; Off-grid; Nigeria; Renewable Energy Systems; Solar Energy; Wind Energy; Nganzai.

1. Introduction

Electricity is the backbone of economic, educational and social development. However majority of the population in developing countries (especially remote villages) do not have access to electricity. In most of these villages, electricity is generated by stand-alone diesel generators. However, the vulnerability of fossil fuel, high cost of maintenance of these generators coupled with environmental challenges and political tension has made this option to be unsustainable [1-4].

According to a study conducted by the United Nations Environment Programme (UNEP), there are about 1.7 – 2 billion people across the world that cannot access grid electricity, and majority of these people are dwellers of rural areas in underdeveloped countries. In order to achieve a sustainable human development, electricity has been identified as the major factor towards realizing this objective. The factors responsible for the poor distribution of electricity include the isolation of sparsely populated villages and harsh terrain, but the major reason is perhaps, the economic investment as it is not economical to install large grid power lines over long distances for the purpose of supplying small number of consumers [5]. This is predominantly the case in Africa and indeed Nigeria where the national grid is only connected to less than 40% of the entire population. Off-grid hybrid Renewable Energy Systems (RESs) have been proffered as solutions to overcome the energy deficit in rural areas as such systems are economical, environmentally friendly and have low maintenance.

Numerous RESs have been developed around the world, with Africa not an exception due to the availability of renewable energy (RE) resources [6-14]. In Nigeria, literature surveys [15-18] have shown potentials for RESs, however studies on technical and economic analyses especially the north-eastern part are lacking even though the region is endowed with abundant RE resources.

In view of the foregoing, this paper presents a feasibility assessment on the solar and wind resources along with the technical and economic analyses of various RESs, which hitherto, have not been carried out in the Northeastern part of Nigeria.

2. Study Background

Nigeria is a huge country with a total land of 923,768 km^2 bordering countries like Chad and Cameroon in the east, Benin in the west and Niger in the north. Cities and towns are connected to either the national electricity grid or the isolated grid. However, almost all the remotely located villages or settlements receive electricity from diesel generating plants. Consequently, it is very difficult to maintain constant fuel supply and to guarantee constant supply of electricity because of the nature of the road in rainy season, routine shutdown of the gas plant for maintenance and high costs. The position of Nigeria on the equator is within an extraordinary sunshine belt where the spreading of solar irradiance is relatively good. The annual diurnal solar irradiance varies from round 12.6 MJ/m^2/day (3.5 kWh/m^2/day) at the coastal area to nearly 25.2 MJ/m2/day (7.0 kWh/m2/day) in the faraway north. As such, Nigeria can be categorized among the Sun Belt countries [19, 20]. Sunshine length in Nigeria ranges from a minimum of 4 hours in the southern part of the country which is Zone III to 9 hours per day in northern part of the country which comprises Zone I and some part of Zone II (Table 1) implying electricity generation from Photovoltaic system at different parts of the country will differ. Nigeria is divided into three solar divisions based on different states as shown in Figure 1. Each division has entirely different type of weather conditions like the solar irradiance, the wind, the type and duration of rainy season etc., that could be needed for a specific project choice and sizing [19, 21]. Zone I located in the northern part of the country has the highest solar irradiance of 5.7 kWh/m^2/d to 6.5 kWh/m^2/d and zone III has the lowest as shown in Table 1.

This study focuses on a remote village called Gajiram of Nganzai Local Government Area (LGA) located in the State of Borno in the North-eastern part of Nigeria.

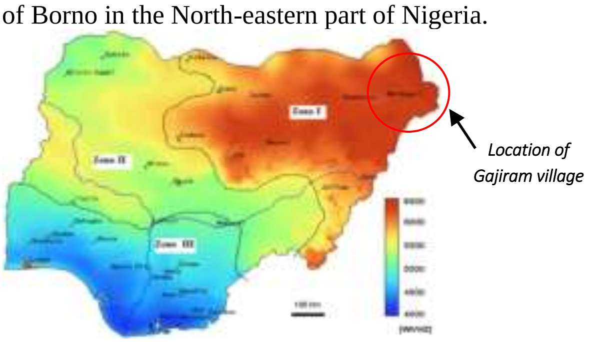

Fig. 1. Average daily solar irradiance map of Nigeria [8] and location of Gajiram village

Table 1. Yearly solar irradiance kWh/m^2 (Global horizontal radiation) [21]

Zone	Solar irradiance kWh/m^2/d	Time h/d	Daily solar irradiance kWh/m^2/d	States
I	5.7 – 6.5	6.0	2186	Borno, Yobe, Bauchi, Gombe, Katsina, Kano, Kaduna and Plateau
II	5.0 – 5.7	5.5	2006	Sokoto, Kebbi, Zamfara, Nasarawa, Abuja, Niger, Kwara and Taraba
III	<5.0	5.0	1822	Oyo, Osun, Ekiti, Benue, Port Harcourt, Enugu and Lagos

2.1 Solar Resources of Nganzai

The accessibility of solar energy at a given location is determined by its climate condition. Thus availability of photovoltaic power is influenced by the geography and weather conditions of that area. Nganzai LGA has an area of 2572.345 km^2 and a population size of 30,861 [22, 23]. Its geographical coordinates are latitude (12.508837 N) and longitude (13.104142 E). Gajiram is a village in Nganzai not connected to the national grid. The population of the village is less than 1000. The main activity of the village inhabitants is farming. Data on the diurnal radiation and clearness index of Nganzai was obtained from the US National Aeronautics and Space Administration (NASA) satellite via HOMER software. An average data of 22 years daily solar irradiance was obtained which is assessed within the range of 5.448 kWh/m2/d to 6.601kWh/m^2/d as demonstrated in Figure 2 and Figure 3. The daily solar irradiance and clearness index can be seen from the diagram, with the month of November having highest solar irradiance of 6.601kwh/m^2/d and clearance index 0.675 respectively, which confirms the stable accessibility of solar irradiance through the year. Less solar irradiance is experienced in the months of August and December due to the fact that, the former month is the peak of rainy season while the latter is winter peak. Yearly average solar irradiance of Nganzai is 5.993 kWh/m^2/day. Hence, solar irradiance qualifies to be a substantial additional source of energy in that area.

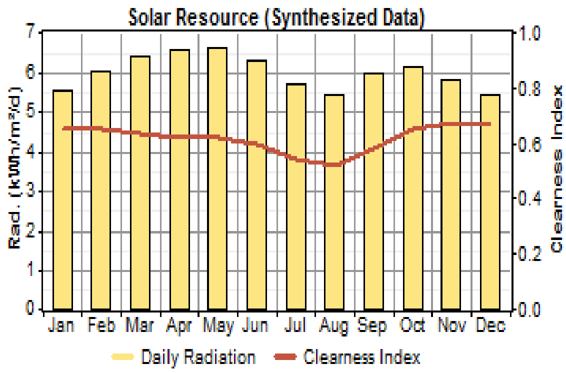

Fig. 2. Daily radiation and clearance index of Nganzai village (NASA)

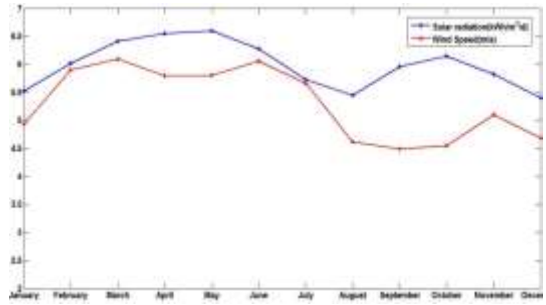

Fig. 3. Average daily solar irradiance and average wind speed of Nganzai for different months over year

2.2 Wind Resources of Nganzai

The wind speed data of Nganzai location was obtained from Nigerian Meteorological Agency (NIMET) Oshodi, Lagos. The wind speed data were recorded at an altitude of 10 m and 50 m by a cup-generator anemometer at the stations of NIMET located at the locations measured. Figure 3 shows an average of 22-year monthly wind speed data measured. From the Figure, it can be seen that the wind speed varies from 4.49 m/s to 6.10 m/s. Wind speed is higher from February to June. The recorded wind speeds were calculated as the average of the speed for each month as given in Table 2. Wind turbines operate normally between 3.5 m/s as cut-in speed and 25 m/s as cut-out speed, though, this range of operation is based on life time cost optimization criteria. Therefore, the wind speed of Nganzai village is within the range needed for turbine operation.

2.3 Load profile of Gajiram Village

The load profile of the Gajiram village consists mainly of electrical appliances such as lighting, fans, television and iron (in residential houses). The system design considers the load profile of 148 units of houses (which is the estimated number of houses in the village), a primary school and a Mosque. The peak load demand is presented in Table 3. The daily average energy consumption of 148 houses, the school and Mosque is 628.65 kWh (4.28 kWh x 148), 2.65 kWh and 0.46 kWh respectively, thus resulting in the village total energy demand of 631.76 kWh/day. This data was inserted into the HOMER in order to obtain the hourly and monthly load profile as depicted in Figure 4 and Figure 5. The peak demand occurs in the late evening hours when residents are back from their farms and are mostly all in their houses because of the harsh weather as the village is located in desert area where temperatures reach as high as 45ºC. The base demand occurs from midnight until morning hours as people are sleeping during that period, thus only fans, and few lighting points will be in operation.

Table 2. Monthly variations of solar irradiance and wind speed for Nganzai location

Month	Insolation (kWh/m^2)	Wind Velocity at 10 m (m/s)	Wind Velocity at 50 m (m/s)
January	5.526	4.94	8.00
February	6.02	5.90	9.56
March	6.412	6.10	9.89
April	6.55	5.80	9.40
May	6.601	5.81	9.42
June	6.282	6.06	9.82
July	5.724	5.66	9.17
August	5.45	4.62	7.49
September	5.958	4.49	7.27
October	6.148	4.55	7.37
November	5.826	5.10	8.26
December	5.448	4.68	7.59
Average	5.993	5.31	8.60
Maximum	6.601	6.10	9.89
Minimum	5.45	4.49	7.27

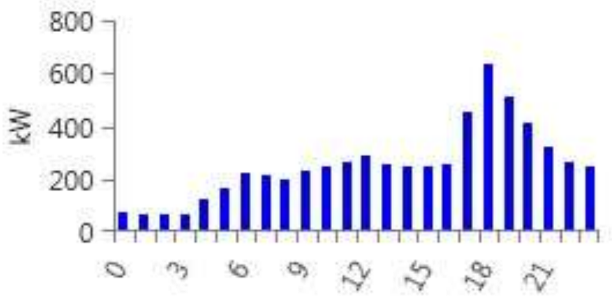

Fig. 4. Hourly load profile of Gajiram village

The monthly load variation for the community is shown in Figure 5. Random variability factors are important when estimating the discrepancies from day-day and time–step-step variability. Each of these variables was set at 15% and 20% respectively in HOMER.

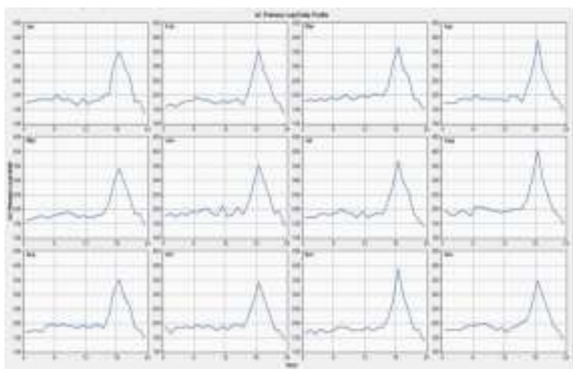

Fig. 5. Monthly AC primary load profile of Gajiram village

Table 3. Estimated Load Details of a unit house, school and a Mosque

Units	Quantity	Power consumed (W)	Uses (h/day)	Energy consumed (Wh/day)	Total energy (kWh/day)
Residential House					
Energy saving bulbs	6	25	6	25 x 6 x 6 = 900	
Fan	2	35	12	35 x 2 x 12 = 840	
TV set	1	100	5	100 x 1 x 5 = 500	4.24
Pressing iron	1	1000	2	1000 x 1 x 2 = 2000	
Mosque					
Energy saving bulbs	10	25	1	25 x 10 x 1 = 250	0.46
Fan	6	35	1	35 x 6 x 1 = 210	
School					
Energy saving bulbs	10	25	5	25 x 10 x 5 = 1250	2.65
Fan	8	35	5	35 x 8 x 5 = 1400	

3. HOMER Simulation

HOMER is a software developed by National Renewable Energy Laboratory in United States for the purpose of designing various type of energy systems such as hydro power, wind turbine, solar, biomass, conventional generator and cogeneration. It is a tool for modelling systems that simplifies the design, analysis and evaluation of grid-connected and off-grid renewable energy generation systems including stand-alone and distributed generation. It requires some resources like solar resources, wind, and primary load as well as initial cost as an input for each design. The major functions performed by HOMER software are simulation, optimization and sensitivity analysis. Optimization of the system is determined based on system configuration to determine the best and suitable option. For the system configuration, different Photovoltaic system (PV), battery storage and inverters were considered. The system technical feasibility is determined by the simulation.

3.1 System design specification

In this study, the techno-economic analyses of various hybrid stand-alone renewable energy system (RES) of Gajiram village of Nganzai LGA based on the available renewable energy resources were conducted and comparisons made with the currently in-use electricity source, which is diesel-based stand-alone power system. The five stand-alone power plant configurations analysed in this study were Diesel System, PV system, PV/Diesel system without Battery, PV/Diesel system with Battery and PV/Wind/Battery system. The monthly load variation for the community is shown in Figure 5. Random variability factors are important when estimating the discrepancies from day-day and time–step-step variability. Each of these variables was set at 15% and 20% respectively in HOMER.

3.1.1 Solar PV Array

Table 4 shows the specs of the PV used in this study. For optimization purpose, the size of photovoltaic array was varied.

Table 4. Solar PV array specifications

Cost of photovoltaic array (US$/kW)	3000
The replacement cost of photovoltaic array (US$/kW)	3000
Photovoltaic cost of operation and maintenance (US$/kW/year)	10
Life span of photovoltaic panels (years)	20

3.1.2 Wind Turbine

HOMER models the wind turbine which converts the kinetic energy of wind to AC or DC electricity by a particular curve representing the graph of output power and wind speed at hub height. In this study, Bergey Excel 6 wind turbine having a capacity of 300 kW AC current each were used. The wind power curve and its power output with respect to wind speed is shown in Figure 6 and Table 5 respectively. The turbines are rated 6 kW, weighing 590 lbs and have a blade diameter of 6.2 m.

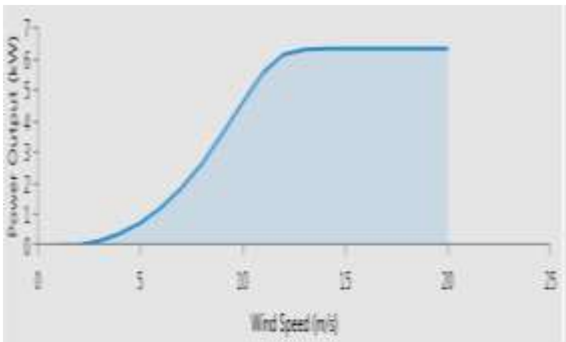

Fig. 6. Turbine power curve

Table 5. Turbine output power with respect to wind speed

Wind Speed (m/s)	Power Output (kW)
4	0.369
5	0.707
6	1.190
7	1.820
8	2.597

3.1.3 Battery Model

Proper sizing of battery is key to designing reliable off-grid systems. The main aim when sizing a battery bank is the installation of appropriate number of batteries to carry a certain load through a period during which the sun or wind is not accessible. The battery storage selected for the design was Trojan IND13-6V model. The battery is specifically designed to support renewable energy systems with large daily loads and its high ampere-hour capacity is ideal for use in large off-grid photovoltaic (PV) systems.

The efficiency curve of the selected battery is shown in Figure 7. Furthermore, it also meets both IEC and BCI standards [24]. The battery specification is given in Table 6 while Figure 7 depict the efficiency curve of the battery.

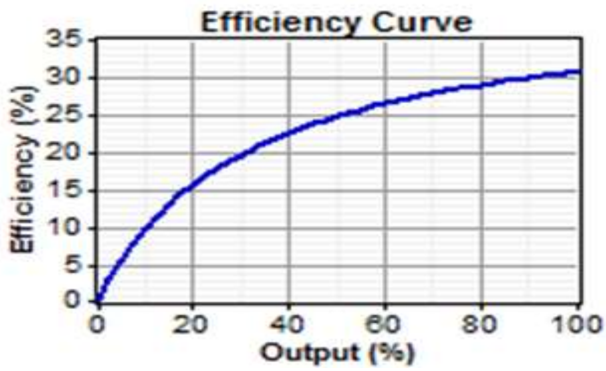

Fig. 7. Battery efficiency

Table 6. Battery specifications

The nominal capacity of the battery (Ah)	83.4
Nominal voltage of the battery (V)	12
Round trip efficiency (%)	80
Quantity of battery considered	400, 500, 600 and 700
Battery minimum life span (years)	5
Cost of each battery (US$/battery)	300
Replacement cost of battery (US$/battery)	300
Operation and maintenance cost (US$/battery)	10

3.1.4 Inverter model

The inverters were selected taking into cognisance the capacity of the photovoltaic array. The output from the photovoltaic module varies with sunlight intensity, hence the capacity of the converter was set to be 100 per cent and the overall efficiency was specified by the manufacturer as 97.5 per cent as shown in the specification of Table 7 below.

Table 7. Inverter specifications

Cost of power converter (US$/kW)	300
Replacement cost of power converter (US$/kW)	300
Operation and maintenance cost of the power converter (US$/kW/year)	0
Life span of converter (years)	15
Converter efficiency (%)	97.5

3.1.5 Diesel Generator

Another important module in off-grid system is the generator also referred to as gen-sets. The diesel generator was used in this study for different purposes based on the model in question. In the hybrid power systems it was used for charging the battery through period of low insolation, a back-up, as a supplementary energy system on days during which the solar irradiance is low or to purposely operate occasionally whenever the designed storage battery bank cannot sufficiently supply the energy demand. Cummins diesel powered generator was therefore selected for the purpose of this design. The set of generators selected have a power rating of 500 kW, 100 kW and 50 kW. The operating procedure is such that, when the load is below 500 kW, only the 500kW diesel generator will operate and when the load is above 500kW, two gen-sets will be operating simultaneously i.e. the 500kW generator with either of the two other generators depending on the load at that point in time. This technique of operation cuts the overall fuel consumption. The fuel and efficiency curves of the generators help the HOMER software in identifying the fuel consumption and generating efficiency of diesel generator. The specification of the generator sets are shown in Table 8.

Table 8. Generator specifications

Sizes considered (kW)	500, 100 and 50
Life span operating hours (hours)	15000
Maximum Load ratio (%)	30
Capital cost (US$/kW)	500
Cost of replacement (US$/kW)	500
Operation and maintenance cost (US$/kW)	0.030

3.1.6 Financial assumptions

In this study, the estimation of cost was presented in a simpler and straight forward way in which only the initial capital cost, replacement cost as well as operation and maintenance (O&M) costs were taken into consideration. In real case scenario, the cost of each and every component of the system will differ from the ideal case situation and would be in detail.

International Renewable Energy Agency (IRENA) and [25] reported that there are various methods of estimating power generation cost and each and every method has its own perception. Other cost parameters which can be considered in practical case include hardware assembly cost, installation cost, control system deployment cost etc. However for technological comparison, researchers prefer the typical cost valuation which can be estimated from the basic economics. In this case, there is no system permanent capital cost and system fixed O&M cost assumed. These were not taken into consideration so as for ease of comparison with studies.

4. System Analysis

This section presents the simulation results from HOMER and discussion of the results. The results presented include sensitivity analysis as well as the techno-economic analysis of the five different power system configurations mentioned earlier.

4.1 Sensitivity analysis

The adoption of renewable energy system as an alternative source of energy proffers solution to the long overdependence on fossil fuel thereby tremendously reducing the hazardous effect of carbon dioxide waste brought about by the combustion of fossil fuel; hence cutting down emissions. The addition of RESs into the design makes the capital cost to become very high. However, the price of some of these systems such as photovoltaic module are falling every year as a result of the on-going research in the field; therefore, the manufacturing cost has been reduced significantly over the years. As earlier discussed, for the purpose of this study, different configurations were considered in the course of the sensitivity analysis in order to obtain the optimum best combination for the system design.
The HOMER software has the ability to optimize function in order to determine the cost of different scenarios of project by using the function of cost minimization and optimizing anticipated energy configuration system with respect to various factors such as the cost and carbon dioxide minimization. For optimization purpose in HOMER, PV modules of 400 – 1000 kW capacity and batteries of 400 – 800 units were simulated for the different power RES models considered.

4.1.1 Stand-alone Diesel System

The system model for the diesel system is shown in Figure 8 while Table 9 depict the economic aspect. The system has a total Net Present Cost (NPC) of $ 9,870,698 at a diesel price of $ 0.8 per liter and Cost of Energy (COE) is calculated as $ 0.41/kWh. The system can produce 1,863,690 kWh/year of electricity. The system has very high emissions totaling 1,388,490.19 kg/yr with carbon dioxide been the highest in the composition of the emission as shown in Table 10.

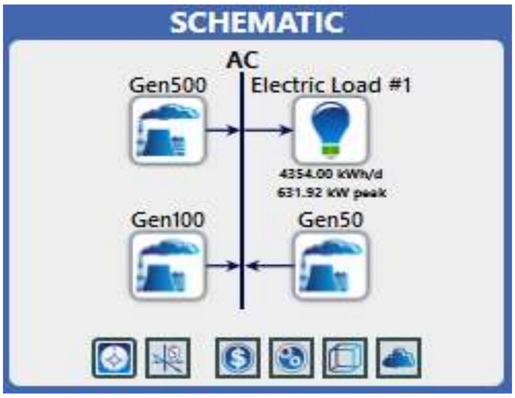

Fig. 8. Configuration of diesel-based system

Table 10. Pollutant emission for the Stand-alone Diesel-based energy system

Pollutant	Emissions (kg/yr)
Carbon dioxide	1,352,037.40
Carbon monoxide	3,337.31
Unburned hydrocarbons	369.67
Particulate matter	251.58
Sulfur dioxide	2,715.13
Nitrogen oxides	29,779.10
Total emission	**1,388,490.19**

Table 9. Cost analysis of Diesel-based energy system

Architecture			Cost					
Gen500 (kW)	Gen100 (kW)	Gen50 (kW)	COE ($)	NPC ($)	Oper. cost ($)	Initial Cap. ($)	Fuel cost ($)	O&M ($)
500	100	50	0.410	9,870,698	738,401.60	25,140.17	513,432.74	112,018.50
500	100		0.431	10,378,640	779,626.60	23,206.31	518,943.06	127,872.00

Figure 9 shows the cash flow of the diesel-based system. It can be seen that operating and fuel costs were the highest. This can be attributed to the fact that the diesel generator operates throughout the year non-stop except for periods when maintenance and repairs are carried out. The initial capital cost was the lowest at just $ 25,140.17.

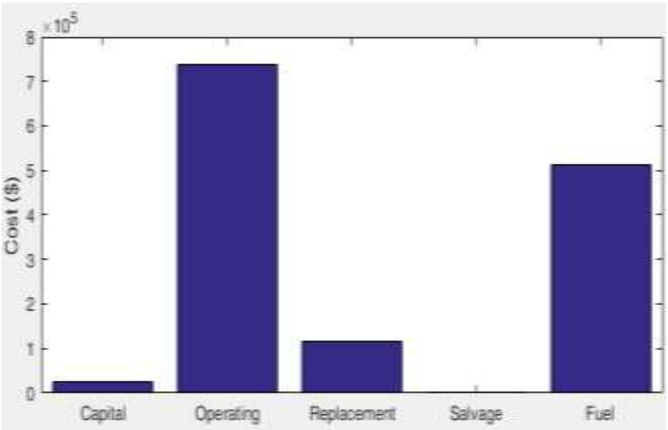

Fig. 9. Stand-alone diesel system cash flow

The average monthly electricity generated from the diesel system is depicted in Figure 10. It can be seen from Figure 10 that the 500 kW generator produces most of the energy. From the 1,863,690 kWh/year of electricity produced by the diesel generator system, 89.3 % is produced by the 500 kW generator set, while 9% and 1.7 % of the yearly production is from the 100 kW and 50 kW generator sets respectively.

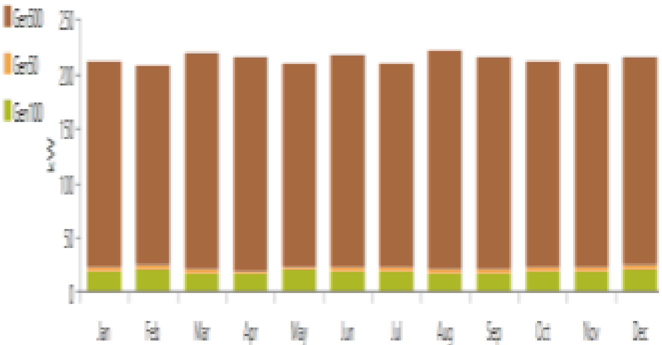

Fig. 10. Average monthly electricity generation from the Diesel system

4.1.2 Stand-alone PV system

This configuration examines the prospect of employing stand-alone photovoltaic energy system shown in Figure 11 as an alternative source; the system consists of battery bank as backup for constant power supply during night hours and in the peak rainy season when solar irradiance is not sufficient. The study shows that this configuration is far better than the diesel base system in terms of electricity generation. The photovoltaic arrays have the capacity of generating 10,500,950 kWh energy per year, whereas the whole demand by the load is 1,862,697 kWh/yr. This implies that the system generates an excess energy of 8,168,110.5 kWh/yr which corresponds to 77.8 % of the whole generation. Figure 12 shows the average monthly PV array production.

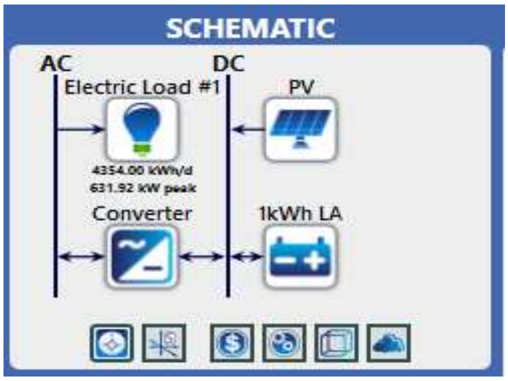

Fig. 11. Configuration of Photovoltaic with battery system

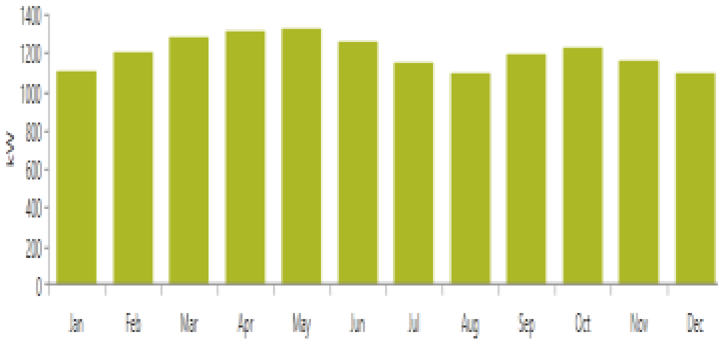

Fig. 12. Average monthly electricity generation from PV with Battery system

Table 11 shows that the COE was calculated as $ 1.11/kWh, cost of operation at $ 496,028.10/kWh and the initial capital cost of system at $ 1,571,067.41. The capital and replacement costs of this PV with battery system can be seen to be higher than the diesel based system. This is due to the cost of the PV solar panels. However the maintenance cost is lower. The cash flow of the stand-alone PV configuration is shown in Figure 13 which has capital as the highest.

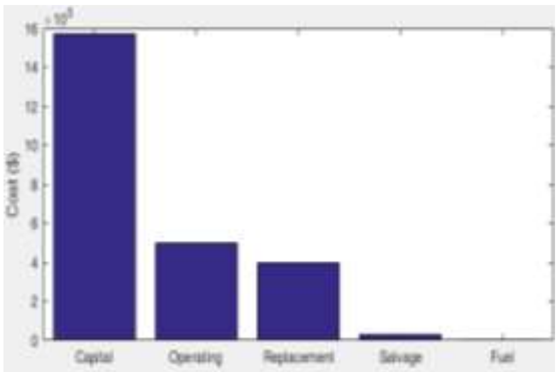

Fig. 13. PV with battery system cash flow

Table 11. Annualized cost analysis of PV-based energy system

Architecture			Cost					
PV (kW)	Converter (kW)	Battery (kWh)	COE ($)	NPC ($)	Oper. cost ($)	Initial Cap. ($)	Fuel cost ($)	O & M ($)
600	700	7000	1.11	26,722,410	496,028.10	1,571,067.41	0.00	130,000

Table 12. Annualized cost analysis of PV-Diesel without battery system

Architecture			Cost					
PV (kW)	Converter (kW)	Gen (kW)	COE ($)	NPC ($)	Oper. cost ($)	Initial Cap. ($)	Fuel cost ($)	O & M ($)
700	700	650	0.366	8,816,117	478,136.40	203,828.79	327,578.67	78,397.00
700	700	600	0.392	9,442,011	528,485.90	201,894.93	341,276.97	94,966.00

4.1.3 Hybrid PV/diesel system without battery storage

Figure 14 shows the PV/diesel without battery system configuration in which 700 kW capacity of PV was considered the most optimal for this model based on HOMER simulation results.

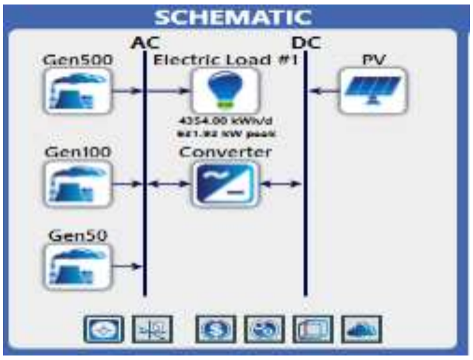

Fig. 14. PV/diesel without battery storage system configuration

Figure 15 shows the cash flow of the stand-alone PV/diesel without battery model. Similar to the stand-alone diesel system earlier discussed, this system also has its highest cash flow from fuel and operating costs. However, the system has higher capital costs compared to the diesel system due to the incorporation of the PV system. Figure 16 show the monthly electricity production from the model while Table 12 show the cost analysis of the PV/diesel without battery storage model. The COE, NPC and operating cost of this system is $ 0.336/kWh, $ 8,816,117 and $ 478,136 respectively. These costs can be seen to be lower than the diesel generator system.

The total demand by the load is 1,863,690 kWh/yr while the energy produced by the PV/diesel hybrid system without battery storage is 2,398,774 kWh/yr. This system produces excess electricity of 458,414.2 kWh/yr which is 19% of load demand.

It can be seen from the month electricity generation (Figure 16), on the average, 50 % of electricity is generated from the solar energy.

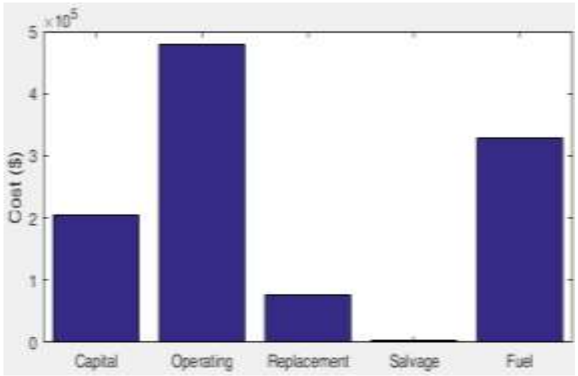

Fig. 15. Cash flow of PV/diesel without battery system

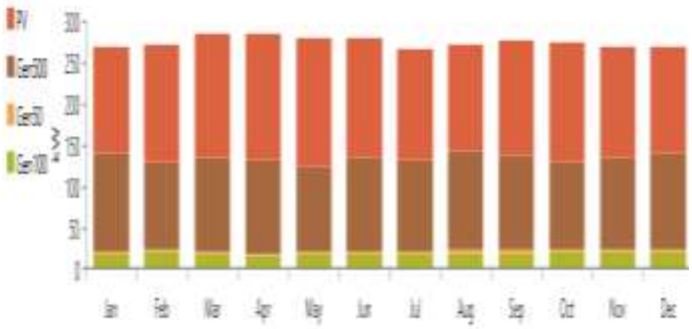

Fig. 16. Average monthly electricity generation from PV/diesel without battery system

4.1.4 Hybrid PV/diesel system with battery storage

Figure 17 depicts the system model for the PV/diesel hybrid system with battery. The optimization result is presented in Table 13. Figures 18 and 19 present the cash flow and average monthly electricity generation of the hybrid system respectively.

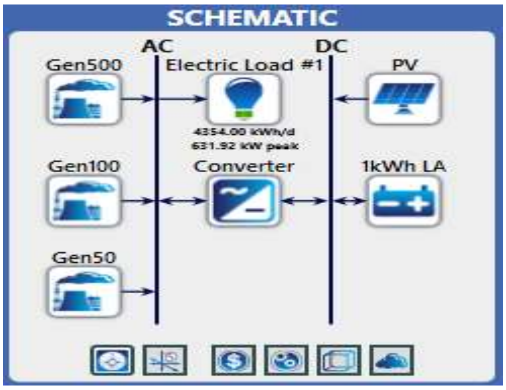

Fig. 17. PV/diesel with battery system configuration

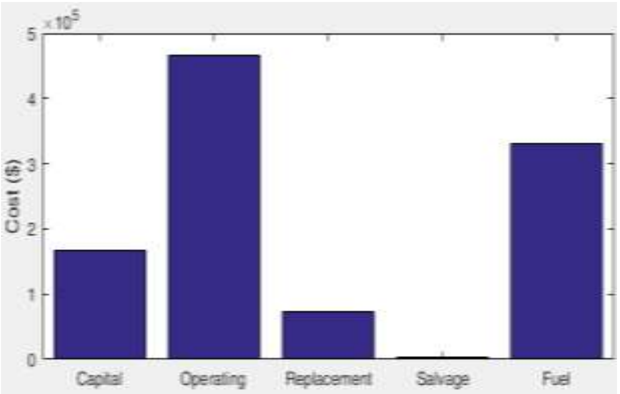

Fig. 18. PV/diesel with battery system cash flow

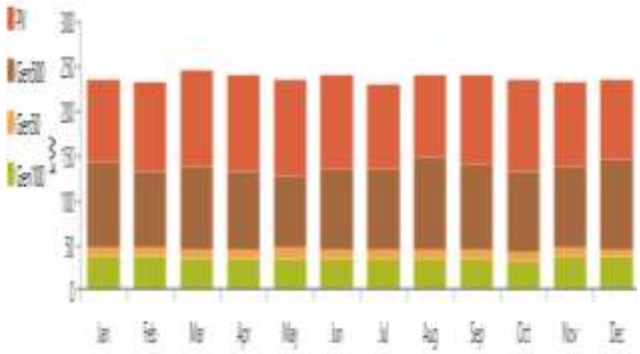

Fig. 19. Average monthly electricity generation from PV/diesel with battery system

From Table 13, it can be seen that this system has a slightly higher COE and initial capital costs; lower NPC and operating costs compared to the system without battery storage. In addition, this system also generated excess electricity of 121,852 kWh/yr. On the average, solar energy accounts for 42 % of yearly energy production.

4.1.5 Hybrid PV/wind with battery

Figure 20 depict the hybrid PV/wind/battery energy system model. The input variables were average solar irradiance of 5.993 kWh/m^2/d, an annual average wind speed of 5.31 m/s at 10 m and peak load of 631 kW as well as base load of 170 kW. Table 14 presents the annualized cost summary of the energy systems simulated by HOMER. The PV/wind hybrid with battery storage has a COE of $ 1.64, NPC of $ 39,443,500 and initial capital cost of $ 2,576,171.52.

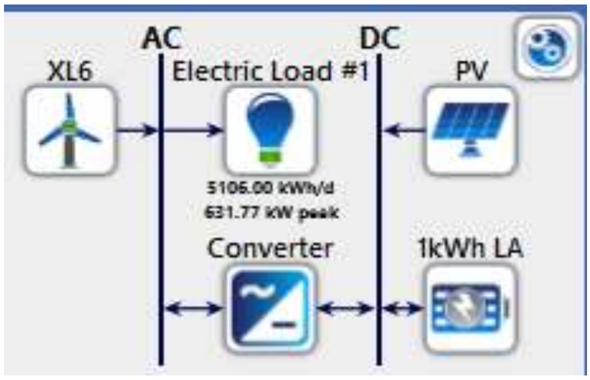

Fig. 20. PV/Wind with battery system configuration

Figures 21 and 22 depict the cash flow and average monthly production of electricity from the optimized PV/wind/battery hybrid system. It can be seen from the cash flow analysis, capital costs was the highest due to the cost of wind turbine and PV panels. The primary load consumption based on this model is 1.863,112 kWh/yr. The total annual production from this hybrid system is 22,095,798 kWh/yr. This implies that an excess electricity of 20,126,262.7 kWh/yr is been produced (which is 91 % of total energy production). Out of the total energy produced, 92 % was generated from wind energy, implying the wind energy functions as the base energy.

Table 13. Annualized cost analysis of PV/diesel hybrid system with batter storage

Architecture				Cost					
Gen (kW)	PV (kW)	Con. (kW)	Battery (kWh)	COE ($)	NPC ($)	Oper. Cost ($)	Initial Cap. ($)	Fuel cost ($)	O $ M ($)
650	500	700	400	0.339	8,169,966	465,284	166,698.68	330,676.45	66,390
600	500	700	400	0.352	8,486,808	491,726	164,764.82	330,319.96	77,730

Table 14. Annualized cost summary of PV/Wind/Battery energy systems simulated by HOMER

Architecture				Cost					
PV (kW)	XL6 Turbine	Converter (kW)	Battery (kWh)	COE ($)	NPC ($)	Oper. cost ($)	Initial Cap. ($)	Fuel cost ($)	O & M ($)
1000	1,300	700	5000	1.64	39,443,500	474,955.50	2,576,171.52	0.00	73,000

Table 15. Summary of Sensitivity analysis of the various Power system models

Stand-alone systems	**Diesel Generator**	**PV with battery**	**PV/diesel without battery**	**PV/diesel with battery**	**PV/wind with battery**
COE ($/kWh)	0.410	1.11	0.336	0.339	1.64
Total NPC ($)	9,870,698	26,722,410	8,816,117	8,169,966	39,443,500
Operating cost ($)	738,402	496,028	478,136	465,284	474,955.50
Initial Capital cost ($)	25,140.17	1,571,067.41	203,828.79	166,698.68	2,576,171.52
Fuel cost ($)	513,432	0.00	327,578.67	330,676.45	0.00
O & M cost ($)	112,018.50	130,000.00	78,397.00	66,390.00	73,000.00
Replacement cost ($)	115,977.80	394,968.00	75,621.40	72,074.96	814,547.16
Total emissions (kg/yr)	1,388,490.19	0.00	885,879.96	894,257.38	0.00
Production (kWh/yr)	1,863,690	10,500,950	2,398,774	2,069,776	22,095,798
Excess electricity (kWh/yr)	0.00 (0%)	8,168,110.5 (77.8%)	458,414.2 (19.1%)	121,852 (5.9%)	20,126,292.7 (91.1%)

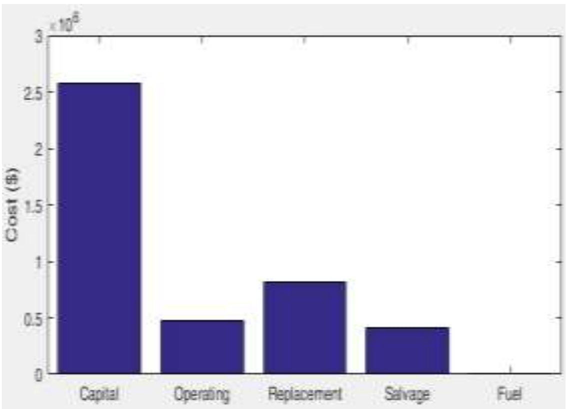

Fig. 21. PV/wind with battery model cash flow

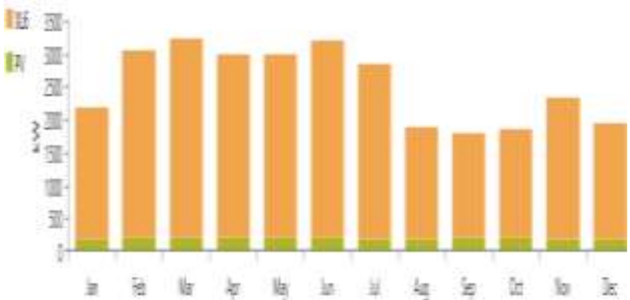

Fig. 22. Monthly electricity production from the PV/wind/battery system

4.2 Results discussion

Table 15 shows the summary of the sensitivity analysis of the 5 different stand-alone power system models considered in this study viz. one fossil fuel based and 4 renewable energy-based.

From the table it seen the in comparison to the other energy systems, the diesel-based system, which is the current energy source of the Gajiram village under study, has a moderately low COE, highest emissions, slightly high NPC, highest operating costs, high replacement and O & M costs. However the system has the lowest initial capital cost.

The PV with battery and wind-photovoltaic-battery system configuration with 100% renewable penetration have zero carbon emission; this implies that 1,863,690 kg/yr of emissions (that will be produced by the diesel-based system) could be avoided. In addition they produce very high excess electricity of more than 75 % of their total annual energy production. However these two systems have the highest COE ($ 1.11 and $ 1.64 per kWh), very high NPC, initial capital costs and replacement costs. These can be mainly attributed to the costs of wind turbine and PV panels.

The PV/diesel systems with and without battery storage have been shown to have low COE, NPC and replacement cost compared to the other three energy systems. The fuel costs and emissions per year is lower than the diesel-based system due to the solar energy. In addition, the energy systems are also capable of generating excess electricity.

It can be suggested that the PV/diesel with battery system is the best for the Gajiram village due to its cost effectiveness. In comparison to the diesel-based system, it has a lower emission, COE, NPC, fuel costs, replacement costs and O & M costs. COE and NPC of the PV/diesel with battery system are 18 % and 17 % cheaper than the diesel system respectively. Emission will be reduced by 36 %; O & M and replacement costs are 40 % and 38 % cheaper. Although the PV will battery and PV/wind with battery energy systems will produce zero emissions as well as have low O & M and operating costs and high energy production compared to the proposed PV/diesel with battery system, they are not cost effective.

5. Conclusion

Electrical power is an issue that is increasingly becoming an obstacle for the economic and social development of developing countries. The electrification of remote villages has become an effective mechanism for the sustainable growth of such areas in both developing and industrialized countries. This study has shown that Nganzai has significant monthly regular diurnal global solar irradiance and wind speed for deployment of photovoltaic/wind RESs. Techno-economic analyses of five stand-alone power system models comprising of fossil fuel-based, renewable and hybrid renewable energy systems have been presented using HOMER software. From the technical and financial analysis presented, the PV/diesel with battery storage was found to be the most suitable for the village under study due to its cost effectiveness. The PV/diesel with battery system was found to be cheaper by as much as 38 %. In addition a more environmentally-friendly power systems can be used to supply energy to the village. This study has highlighted the prospects of RESs for deployment to the numerous remote villages in the north-eastern part of Nigeria as well the suitability of the type of RESs based on the techno-economics analyses presented.

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