Economic evaluation of hybrid energy systems for rural electrification in six geo-political zones of Nigeria

Lanre Olatomiwa [a, b, *], Saad Mekhilef [a, *], A.S.N. Huda [a], Olayinka S. Ohunakin [c]

[a] Power Electronics and Renewable Energy Research Laboratory (PEARL), Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Department of Electrical & Electronic Engineering, Federal University of Technology, PMB 65, Minna, Nigeria
[c] Mechanical Engineering Department, Covenant University, P.M.B 1023, Ota, Ogun State, Nigeria

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ABSTRACT

Rural electrification improves the quality of life of rural dwellers having limited or non-access to electricity through decentralized electricity coverage. Since the price of oil is unstable and fluctuating day by day and grid expansion is not also a cost effective solution, integrating renewable energy sources thus become an important alternative for rural electrification. The present study investigated the feasibility of different power generation configurations comprising solar array, wind turbine and diesel generator in different locations within the geo-political zones of Nigeria. Six rural communities were randomly chosen from each of the six geo-political zones in Nigeria with the intention that the results of the study could be replicated in other remote locations of the selected zones with similar terrains. HOMER (Hybrid Optimization Model for Electric Renewable) simulation software was used to determine the economic feasibility of the systems. The simulations concentrated on the net present costs, cost of energy and renewable fraction of the given hybrid configurations for all the climatic zones. The analysis indicates that the PV/diesel/battery hybrid renewable system configuration is found as optimum architecture for both sensitivity cases of 1.1 and \$1.3/l of diesel. It also displayed better performance in fuel consumption and CO_2 reduction.

1. Introduction

Sufficient energy supply is indispensable for sustainable economic development of any nation. A country will not grow beyond the subsistence level without an appreciable access to energy [1]. An estimated two billion people around the world mostly in small villages in developing countries currently lack grid-based electricity services according to the United Nations Environment Program (UNEP) [2,3]. The escalating population resulting to increased socio-economic activities, however, calls for continuous energy supply to meet the teeming energy demand. Electricity is thus concluded as a key measure to sustainable socio-economic growth needed for human development. In Nigeria, approximately 40% of the population are connected to the national grid, leaving the rest (mostly living in rural areas) to biomass/fuelwood consumption [1] and at times self-powered generation (diesel generator). According to Suresh Kumar and Manoharan [2], installation and supply of electricity through grid poses serious logistics in developing economics, particularly if specific areas are remote and sparsely populated. Even in places that are connected to the grid, incessant power supply (that characterizes supply insufficiency) has always being the situation in most cities in Nigeria due to the poor power situation, thus making electric energy consumers to supplement grid connections with self-powered generation (through diesel/petrol electric generators).

Other than grid unavailability, energy supply mix in Nigeria is dominated by fossil sources [1]; apart from the environmental consequence of fossil energy utilization, the rate of depletion of fossil reserves in the country, put in doubt the ability to cope with the teeming population growth and rising socio-economic activities in terms of the energy demand at the present and future scenario. These reasons led to several researches into renewable energy technologies (RETs)/low carbon generators including photovoltaic, micro turbines, diesel generators, wind turbines, fuel cells, etc. and hybrid power systems (HPSs) that combine two or

Nomenclature

RET	Renewable energy technologies
HPS	Hybrid Power System
HOMER	Hybrid Optimization, Model for Electric Renewable
PHCN	Power Holding Company of Nigeria
NASA	National Aeronautics and Space Administration
NPC	Net present cost ($)
COE	Cost of energy ($/kWh)
RE	Renewable fraction
LCOE	levelized cost of energy ($/kWh)
CRF	Capital recovery factor
SOC	Battery state of charge
SS	South–South
SW	South–West
SE	South–East
NE	North–East
NW	North–West
NC	North–Central

more different types of renewable with storage devices. In Nigeria, government efforts on rural electrification have been stalled with inadequate transmission lines, which resulted into very low voltage profile and uneven distribution in electrification among rural areas. Insufficient electricity facilities and access in the rural areas has deter future development (both social and economic) of the rural area. Lack of power supply in rural areas has thus heightened the poverty level of the country populace. The technology for sustainable development is one of the proven tools in reducing energy poverty if carried out with an appropriate policy [4,5]. The worldwide use of RETs to meet energy demands, has been increasing over the years [6–9]. These technologies have demonstrated their capability to contribute substantially to global climate protection by reducing the greenhouse gas emission, as well as offering low operation and maintenance cost, while meeting the rapid energy demand growth. Among the various renewable energy sources, solar and wind are highly abundant and accessible irrespective of the location (remote or otherwise). Remote location in this regards may not necessarily be limited to a location far away from the national grid, but it include any site where it is not economical or feasible to extend grid network due to bad terrain and poor topography which mostly characterize rural villages and isolated desert places in Nigeria and other developing countries. Hence, small off-grid standalone renewable energy systems represent an important option for narrowing the electricity gap in rural parts of the developing world, where progress in grid extension remains slower than population growth [10,11].

However, several researches have been carried out on assessment and viability of wind energy and solar resources in Nigeria. Wind regime with wind speeds ranging from 2.12 to 4.13 m/s was estimated in the southern part of the country with the exception of the coastal regions/offshore, whereas the north exists with speeds ranging from 4.0 to 8.60 m/s [12–21]. In addition, the irradiation levels for each zone as distributed among the 36 States of the federation is divided into zones according to [22–25]. Zone I comprises all the states in the North–East geo-political zones; with the high solar radiation incident on the horizontal surface, it has excellent and viable potential for large scale solar photovoltaic, especially in the semi-arid region. Zone II consisting of the North–West and North–Central belt of the country, also have viable solar radiation that may be required for most solar projects. Low potential of annual global solar radiation exists in Zone III (comprising all locations in the South including the coastal region), and can only

be suitable for stand-alone PV systems. However, some states/locations in the South–West and South–East regions can readily support decentralized energy projects [23,25].

Photovoltaic solar energy conversion systems have been widely used for electricity supply in urban and isolated locations far from the distribution network in Nigeria (projects listed in Refs. [23,25]), while wind energy conversion systems have had little applications in remote locations of Sokoto, Katsina and Bauchi States for water pumping and mill grinding [16,26]. Furthermore, since these applications experience fluctuations due to available solar and wind energy sources, there is thus the need for a combination of properly sized wind turbine, PV panel, storage unit and auxiliary energy (diesel-generator) components, in order to provide a reliable service so as to meet a particular load and operate in an unattended manner for extended periods of time [3,27–29]. According to Saheb-Koussa et al. [3], photovoltaic/wind/diesel hybrid systems are more reliable in producing electricity than photovoltaic-only/wind-only systems, and often represent the best solution for electrifying remote areas such as considered in this work.

Several modeling methods have been developed in literature for HPSs optimization including numerical algorithms like PHOTOV-III [30,31], PHOTOV-DIESEL III in Kaldellis and Ninou [32], and also the use of simulation software such as HOMER (Hybrid Optimization Model for Electric Renewable) optimization tool [2,33–36]. HOMER, found to be the most widely used optimization tool for renewable energy optimization systems [34] has been chosen for modeling the HPS in this work. It is a sophisticated tool or computer model that facilitates design of stand-alone electric power systems [34], and performs simulations to satisfy the given load demand using alternative technology options and resource availability. HOMER simulates a HPS, based on the hourly time stepped load data profile and the average monthly weather data of the specific location over a period of 1 yr [2]. With this information and the choice of component sizing and pricing, HOMER is able to simulate the most economically and technically feasible solution for any specific climatic zone [2].

However, limited research studies were carried out on few locations situated only in the Northern region of Nigeria, to access the technical and economic performance of stand-alone hybrid system using HOMER tool [19,37]. In this work, a combination of three energy sources (solar, wind and diesel) with a continuous electric power production is proposed for selected villages covering all the six geo-political zones of Nigeria (Table 1). It aims at investigating the techno-economic feasibility (analysis and dimensioning) of introducing RETs (wind and solar energy) in conjunction with diesel generator using HOMER optimization tool, to provide off-grid electrification. The selection of the most suitable configuration is based on net present cost (NPC), levelized cost of energy (COE) and renewable energy fraction (RF). In these selected sites, grid power is available but it is erratic; power is available to these remote areas only for 4 h or less, a day.

The paper is organized into five sections. Section 1 presents the introduction with the description of the scenario of rural electrification as it relates poverty alleviation in rural communities of Nigeria. Section 2 discusses the methodology of the hybrid system for feasibility analysis. Section 3 presents the system description with energy resources, load data, component parameters, as well as assumptions made on the pricing and sizing of the system components, while Section 4 presents the results and discussions. Finally, a conclusion is given in section 5.

1.1. Socio–economic development through rural electrification in Nigeria

It is an established fact that the economic development of any nation is dependent on its energy (especially electrical energy)

Table 1
Selected villages in this study with locations.

Selected locations	Geo-political zone	Latitude (N)/Longitude (E)	Climate type
Ngo (River state)	South—South	4.48/7.39	Tropical monsoon/Equatorial
Ete (Enugu state)	South—East	7.06/7.46	Humid
Onilu (Lagos state)	South—West	6.55/3.25	Tropical monsoon
Zalau (Plateau state)	North—Central	10.39/9.01	Tropical
Gubio (Borno state)	North—East	12.50/12.78	Hot semi-arid
Tambo (Adamawa state)	North—West	13.13/7.33	Tropical dry

supply [38]. Nigeria is made up of 6 geo-political zones covering a total land area of 923.769 sq. km (98.5% highland and 1.5% lowland) [39]. According to the report of United Nation in 2014 the percentage of rural population in Nigeria is 50.4% with mere 36% of this population have access to electricity, while majority with less than 4 h a day [40,41]. The poor power situation in the country has undoubtedly contributed to the poor socio-economic status of the rural communities in Nigeria. According to the International Fund for Agricultural Development [42], up to 80% of rural communities in Nigeria live below the poverty line. Many entrepreneurs and owners of small businesses in the rural areas cannot afford the cost of acquiring or fuelling power generating sets. This situation was further worsened by the removal of subsidy on fuel by the Federal Government of Nigeria in 2012. As a result, many have abandoned their businesses out of frustration. In many cases, these experiences have led to massive rural-urban migration shift in such communities, whereby the young and productive youths move to the cities leaving the old and feeble behind. This has also led to the increase in the number of the poor in the urban centres; thus culminating in a situation where the rural communities are made socially backward, leaving their economic potentials untapped [43].

Electricity is thus seen as one of the vital tools for productive economic engagement as well as for social well-being of rural communities. An area having no electricity access usually lack essential infrastructures such as school, medical centre, communication, portable water supply, etc. The Human Development Index values in electrified communities, is found to be higher than non-electrified communities [44]. National grid extension through the thick jungles and difficult topography in most villages may be difficult and uneconomical due to the associated high cost as well as transmission loss considering the distance from available grid to the load centre [35]. The use of diesel generator may be reliable for electricity generation for rural villages when properly operated and regularly maintained; however, it may pose lots of disadvantages including noise and environmental pollution due to emission of CO_2 and other harmful gasses. It may also be difficult to maintain due to unpredictable hike in diesel price including additional cost of transportation to remote locations. Considering the fact that improving rural access to electricity through extension of the national grid to rural areas does not look promising at present, it is thus imperative that a systems of autonomous, off-grid power generation be established for rural communities in Nigeria. Such a solution would be viable if it is based on renewable energy (RE) resources and technologies since RE resources are always available and environmentally friendly. In addition, rural dwellers have a low demand of electricity which RE-based power sources would be able to meet easily. Despite the vast abundance of renewable resources in Nigeria, only the hydroelectric source is being utilized most for power generation, and that is even at an exploitation rate which is below the full potential [45]. Solar power is used majorly among urban households/cities, and in some selected demonstration locations in rural centres [23,25]. All other renewable sources also remain under-utilized.

A convenient, cost-effective and reliable power supply is therefore crucial to the development of any rural area [46]. Various

technological advancements over the years in the field of RE, have made the resources more feasible in replacing diesel power for rural load requirements. Therefore, off-grid options using RE resources, such as solar, wind, hydro and biomass could be better substitutes for conventional energy resources in rural vicinities.

2. Methodology description

2.1. Hybrid PV—wind—diesel system

Hybrid PV-wind-diesel based power systems are proposed for feasibility analysis in the selected sites. Fig. 1 shows the schematic diagram of the PV/wind/diesel system connected to battery storage. The combination of different energy sources can bring about improvement in entire system reliability as well as overall system efficiency. It also reduces the energy storage requirement as compared to system consisting of only one RE source [28]. With the complementary nature of wind and solar energy resources, hybrid wind/solar configuration with energy storage system offer a highly reliable source of power, which is suitable for electrical loads that need higher reliability. A diesel generator can be added to serve as back-up in the event of insufficient RE resources.

Under normal operation, solar and wind system complementarily supply the needed power. During sunshine hours of the day, solar system supplies power while on cold, cloudy and windy days, the wind turbine generator is in the position to supply power for the stand alone applications. The battery storage are designed in order to be able to store excess power from both the PV and wind hybrid system during the time of high solar insolation and wind speed. Any further excess energy will be fed into a resistive dump load. The stored energy can be used to support the load during the hours when the output of RE sources is not sufficient. When the power generation from RE sources is not sufficient to cover the load and the battery storage has reached its minimum state of charge, the diesel generator will automatically turn-on to supply power to the load directly, or recharge the battery through the bi-directional inverter based on the selected dispatch strategies [36].

2.2. Basic mathematical description of system components

The detailed mathematical model of the components of the proposed hybrid system (PV panels, wind turbines, diesel generator, and batteries) and the control strategy is as expressed in Elhadidy [47], Dufo-López and Bernal-Agustín [48], Mahmoud and Ibrik [49] and Erdinc and Uzunoglu [50]. However, brief descriptions of the mathematical models are presented in the following sections (2.1.1) to (2.2.4):

2.2.1. PV model

A photovoltaic system employs solar panels composed of a number of solar cells in series/parallel to generate power from solar PV. The power output of the PV panel is given in Equation (1) as expressed in Ref. [47]:
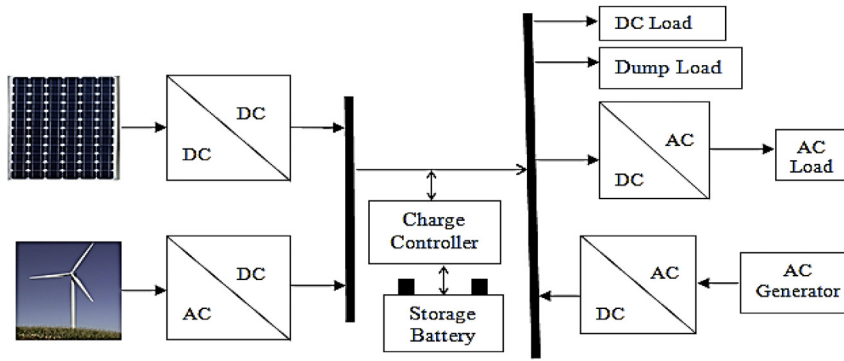
Fig. 1. Hybrid PV/wind/diesel system with the battery storage.

$$P_{pv-out} = P_{pv-rated} \times \left(G \middle/ G_{ref}\right) \times \left[1 + K_T \left(T_c - T_{ref}\right)\right] \qquad (1)$$

where P_{pv-out} is the power output of the PV cell, $P_{pv-rated}$ is the PV rated power at reference condition, G is solar radiation (W/m^2), G_{ref} is the solar radiation at standard temperature condition ($G_{ref} = 1000$ W/m^2), T_{ref} is cell temperature at reference conditions ($T_{ref} = 25$ °C), K_T is temperature coefficient of the PV module. The cell temperature is $T_c = T_{amb} + (0.0256 \times G)$, where T_{amb} is ambient temperature. The annual energy output of solar PV system is estimated as:

$$E_{pv-out} = \sum_{i=1}^{8760} P_{pv-out}(i) \qquad (2)$$

2.2.2. Wind turbine model

Wind energy is transformed into mechanical power through wind turbine and then converted into electrical power. The mechanical power over an area A is given in Dufo-López and Bernal-Agustín [48] as:

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

where ρ is the air density (1.225 kg/m^3), and V the wind speed (m/s). The electrical power of the wind energy conversion system is given by:

$$P_w = \frac{1}{2} \times \rho \times C_e \times A \times V^3 \times 10^{-3} \qquad (4)$$

where C_e the maximum power extraction efficiency of the wind generator and other electrical components connected to the generator.

2.2.3. Diesel generator consumption model

The renewable energy systems have intermittent output characteristics and are integrated with conventional power sources to deliver a steady power output [48]. In various HPSs, diesel generator (DG) acts as steady source of power. The DG systems are designed to supply the load and also charge the battery energy storage system, if the renewable energy source together with battery is unable to supply the load. Proper energy balance is required for optimum system operation as the consumption of fuel is proportional to the power being supplied by the DG. The fuel consumption of the diesel generator (F_G in l/h), is modelled as dependent on the DG output power as [48]:

$$F_G = B_G \times P_{G-rated} + A_G \times P_{G-out} \qquad (5)$$

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

2.2.4. Battery energy storage system

Battery is a storage device essential for storing electrical energy for maximum utilization of the intermittent renewable resources. The lead-acid battery which is often used in HPS is a complex, nonlinear device controlling operational states of the system [50]. Modeling of lead-acid batteries for real time analysis of HPS must account for the dependence of battery parameters on: (i) state of charge, (ii) battery storage capacity, (iii) rate of charge/discharge, (iv) ambient temperature, (v) life and other internal phenomenon, such as gassing, double layer effect, self-discharge, heating loss and diffusion. The battery storage capacity is given in Ref. [50] as:

$$C_{Wh} = (E_L \times AD)/(\eta_{inv} \times \eta_{Batt} \times DOD) \qquad (6)$$

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

2.3. Methodology of economic analysis

Fig. 2 depicts the flowchart of economic analysis of HPSs. At the beginning of techno-economic feasibility analysis of proposed hybrid systems, the rural communities were visited and load as well as meteorological data in different geographical locations were analysed. The studies revealed the two possible renewable energy sources that could be used to address the energy challenges of the rural locations and which include solar and wind energy systems. Thereafter, the modelling of the proposed hybrid systems begins with the gathering of information about primary load, solar and wind potential, capacity of power generated as well as typical market prices of the different components constituting the hybrid system. In a one-source renewable system, the system tends to be oversized to accommodate the load demand with attendant result in high capital cost, while this is not the case in hybrid system because the various connected energy sources, complement one another by utilizing their individual capacities and improving the individual generators load factor [51]. The sizing of components that need to be considered in order to meet the load demand in this particular study are: PV array, wind turbine, diesel generator, converter, and number of battery.
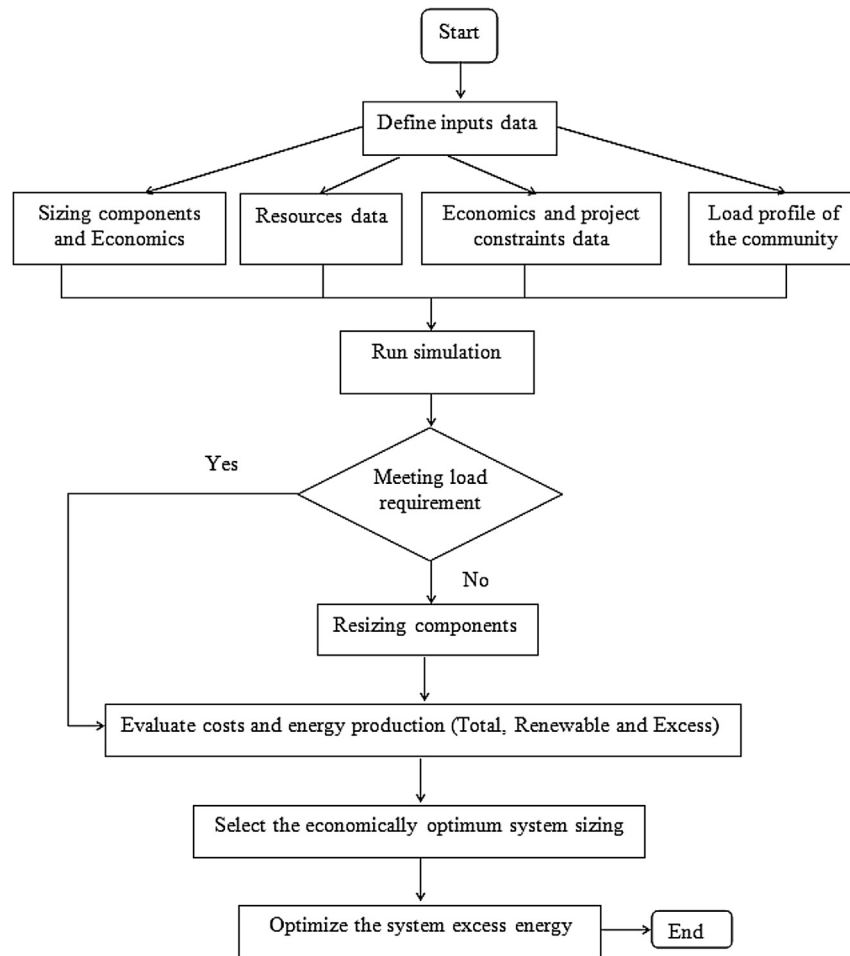
Fig. 2. Flowchart of economic analysis of hybrid power system.

The following system configurations were analysed in this study including: stand-alone diesel system, hybrid PV–diesel system with and without battery, hybrid wind–diesel system with and without battery, PV–wind–diesel system with and without battery. The economic feasibility of each configuration is based on the net present cost (NPC); two other parameters such as levelized cost of energy (COE) and renewable fraction are also considered. CO_2 emissions (tons/yr) and consumption of diesel (l/yr) are two essential factors considered for the analysis of environmental friendly solution.

All the input parameters are fed into the HOMER software in order to determine the optimization results for different systems configurations. The system configuration that gives minimum COE is optimized in order to minimize its excess energy. The amount of power generated by the HPSs components, is compared to the annual load demands to ensure that it is able to meet the load demands. In addition, the stand-alone diesel system, PV–wind–diesel system with battery, and PV–diesel system with battery, were analysed bearing in mind the variations in diesel prices.

2.4. Evaluation performance criteria

HOMER compares the economics of a wide range of system configurations comprising variable numbers of renewable and non-renewable energy sources [34]. For equality, such comparisons must account for both capital and operating costs of each energy sources. In this study, three parameters including NPC, COE and RF were used to evaluate the performance of the hybrid system.

2.4.1. Net present cost (NPC)

In HOMER, the system life-cycle cost is represented by total net present cost (NPC). The NPC comprises of initial capital cost, replacement cost, annual operating and maintenance cost as well as fuel costs [34]. NPC is expressed in Equation (6) [34]:

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

where TAC is the total annualized cost ($/year) and *CRF,* the capital recovery factor is a function of annual real interest rate (*i*), and the project lifetime (*N*) in years. *CRF* is given in Equation (7) [34] as:

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

2.4.2. Levelized cost of energy (COE)

Levelized cost of energy is defined as the average cost per kilowatt-hour of useful electrical energy produced by the system. HOMER uses Equation (8) to calculate the levelized cost of energy [34]:

$$COE = \frac{TAC}{E_{anloadserved}} \qquad (9)$$

where, $E_{anloadserved}$ is the total annual load served by the system in kWh.

2.4.3. Renewable fraction (RF)

Renewable fraction (RF) is the total amount of power generated by the renewable energy sources compared to total power generation from then entire hybrid system [34]. RF is usually desired to be as high as possible, but bearing in mind its effect on NPC, this is because the load is expected to make the maximum use of the renewable energy. The renewable fraction is obtained from:

$$RF(\%) = \left(1 - \frac{\sum P_{diesel}}{\sum P_{ren}}\right) \times 100 \qquad (10)$$

where P_{ren} is the power output of the connected renewable energy sources (PV and wind in this case)

3. System description

3.1. Load profile

In this study, two categories of loads viz: A (domestic) and B (social infrastructure) have been considered for energy provision in each of the selected rural community. A total of 40 households, 1 primary health centre, 1 public primary school, 3 shops, 1 community hall and few miscellaneous loads were assumed in each location. The demands were estimated separately for the two prevailing seasons in Nigeria, namely the wet season (March to October) and the dry season (November to February). Table 2 provides the summary of estimated demand for the wet and dry seasons. Figs. 3 and 4 show the respective category A and B load profiles on a day in March (wet season) and January (dry season). Measured hourly load profiles are not available for the selected sites; load data were thus synthesized by specifying typical daily load profiles and then adding 10% daily randomness, and 15% hourly noise. Characteristics of the two load categories are:

i. *Domestic load*: For each household, the load is based on 4 energy efficient compact fluorescent lamps (20 W each), 2 ceiling fans (30 W each), 1 television (80 W) and 1 radio (10 W). The load demand is approximatelyy 76 kWh/day and 14 kW peak having a load factor of 0.233.

ii. *Social infrastructure load*: This includes the demand load for the primary health centre, public primary school, community hall and shops. The load demand is approximately 15 kWh/day with 1.8 kW peak load and a load factor of 0.336.

3.2. Solar radiation

The power output of the PV array depends on the direct and diffuse solar radiation over a particular area. The insolation reaching the earth's surface depends on the cloudiness or clearness of the sky, which in turn depends on the season of the year [52]. Solar energy is one of the readily available sources of clean energy in Nigeria [23]. Nigeria has average solar irradiation of about 5.75kWh/m^2/day with average sunshine of 4–7.5 h daily. Table 3 shows the solar irradiation for each selected location as obtained from the National Aeronautics and Space Administration (NASA)'s global satellite database [53]. The solar radiation data for all six sites were obtained according to their respective latitude and longitude, as earlier presented in Table 1.

For all the villages considered, there are less solar intensity and solar irradiation during the wet periods as compared to dry season. Gubio (North–East) displays the highest potential value for PV application, followed by Zalau in North–Central region of the country. Ngo, in the southern part of the country shows the lowest irradiation potential among the locations considered. Nevertheless, the average solar radiation in this location is above the minimum requirement for substantive power generation. Generally, all the location considered are found to be heavily overcast between July

Table 2
Estimated electricity demand for each rural community.

| Load description	No. in use	Power (Watt)	Wet (March–October)		Dry (November–February)	
			(Hour/day)	(Watt-hr/day)	(Hour/day)	(Watt-hr/day)
Category A: Domestic load						
Lighting (CFL)	4	20	8	640	9	720
Television	1	80	4	320	4	320
Radio	1	10	12	120	12	120
Ceiling fan	2	30	18	1080	0	0
Total for 40 household				**86400**		**46400**
Category B: Social Infrastructure Load						
1. Primary health centre						
Lighting (CFL)	6	20	10	1200	12	1440
Refrigerator	1	600	16	9600	12	7200
Television	1	80	6	480	6	480
Ceiling fan	2	30	12	720	0	0
Total				**12000**		**9120**
2. Public primary school						
Lighting (CFL)	7	20	4	560	6	720
Ceiling fan	1	30	6	180	0	0
Total				**740**		**720**
3.Community hall and shops						
Lighting	10	20	5	1000	7	1400
Ceiling fan	4	30	7	840	0	0
Television	1	80	6	480	6	480
Total load				**2320**		**1880**
Miscellaneous load		80	6	480	6	480
Total load consumption				**101940**		**58120**
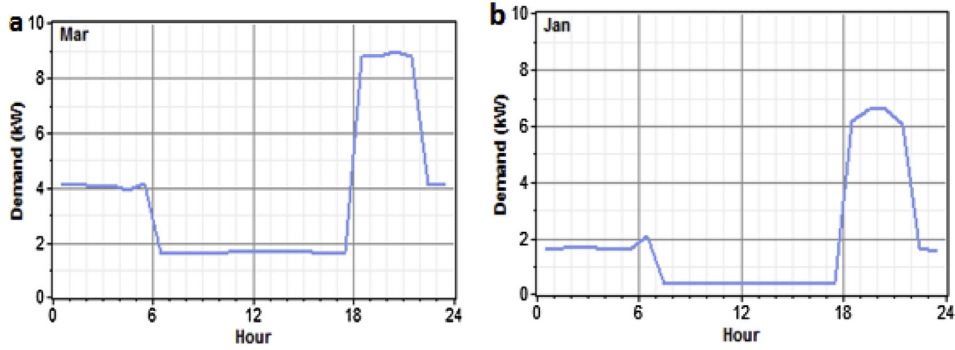
Fig. 3. Category A load profile on a day of (a) Wet and (b) Dry season.
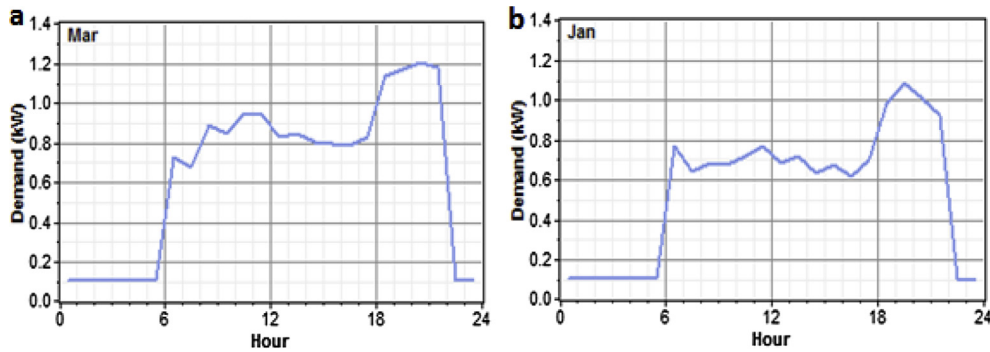

Fig. 4. Category B load profile on a day of (a) Wet and (b) Dry season.

and August (peak of rainy season), leading to a remarkable fall in global solar potential resulting from the high cloud cover [22,54].

3.3. Wind speed

Electrical energy can be generated from wind energy when wind blow through a wind turbine. The kinetic energy of the wind at rated wind speed is converted into mechanical power by turning the turbine blade, thus producing electricity through the shaft connected to the alternator [55]. The monthly average wind speed data for an average of ten (10) years were obtained from NASA database based on the latitude and longitude of the different selected villages using anemometer at 10m above sea level [53]. The annual average wind speed for each village is presented in Table 4. The wind speed from the selected site ranges from 2.41 to 5.63 m/s. The changes in the wind patterns occur as a result of earth's topography, bodies of water and vegetation cover [51]. Observation of the wind probability and average monthly speed for a year, show that the peak wind speed occur at 15.00 h, the wind speed variation over a day; the diurnal pattern strength is taken as 0.25, while the randomness in wind speed (auto-correlation factor) is 0.85 and Weibull parameter (k) is 2. The wind speed probability density function of Ngo village is shown in Fig. 5.

3.4. Diesel

The current diesel price in Nigeria is $ 1.1/l [56,57]. This price varies according to the global market. In this research, diesel price is assumed to vary from $1.1/l to $1.3/l in order to investigate its effect on the entire system cost and environment.

Table 3
Solar irradiation data for the six villages (kWh/m^2/day) [53].

Month	Village					
	Ngo	Ete	Onilu	Zalau	Gubio	Tambo
January	4.711	5.314	4.893	5.799	5.683	5.621
February	4.816	5.324	5.145	6.053	6.122	6.182
March	4.723	5.302	5.319	6.342	6.465	6.112
April	4.461	4.956	5.203	6.574	6.646	6.555
May	4.177	4.496	4.895	6.399	6.633	6.599
June	3.590	3.974	4.399	6.094	6.289	6.255
July	3.457	3.555	4.000	5.375	5.712	5.773
August	3.737	4.242	4.153	5.243	5.459	5.520
September	4.090	4.230	4.314	5.845	5.919	6.078
October	4.245	4.792	5.017	6.419	6.215	5.936
November	4.456	5.249	5.360	6.144	5.966	5.880
December	4.647	5.384	4.889	5.934	5.603	5.529
Average	4.256	4.731	4.796	6.017	6.057	6.000

Table 4
Wind speed data for the six villages (m/s) [53].

| Month	Village					
	Ngo	Ete	Onilu	Zalau	Gubio	Tambo
January	3.14	2.91	4.15	4.34	5.49	2.87
February	3.35	2.91	4.30	4.23	5.45	2.72
March	3.01	3.03	4.01	4.68	5.63	3.34
April	2.52	2.88	3.49	4.76	5.62	3.17
May	2.46	2.85	3.00	4.51	5.16	3.43
June	3.32	2.72	3.12	3.81	4.58	3.11
July	4.30	3.57	3.70	3.62	4.38	3.03
August	4.54	3.82	3.87	3.45	4.05	2.83
September	4.00	3.70	3.50	3.18	3.81	2.45
October	3.05	2.52	2.83	3.45	4.25	2.41
November	2.52	3.36	3.05	3.99	4.84	2.78
December	2.74	2.54	3.65	4.48	5.45	2.99
Average	3.24	3.06	3.55	4.04	4.89	2.92
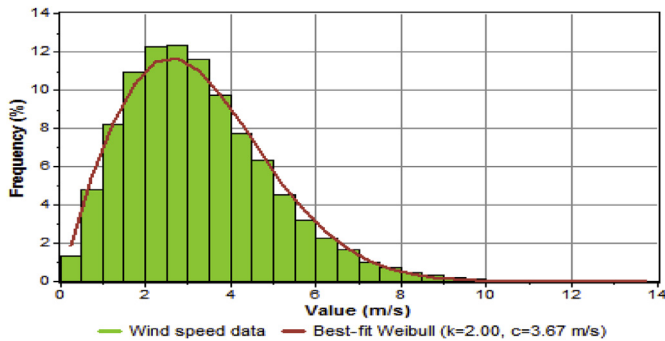
Fig. 5. Probability distribution function of wind speed data for Ngo village.

3.5. Components data

The proposed hybrid systems consist of PV panels, wind turbines, diesel generators and other system components such as batteries, converters. The PV panel, wind turbine and diesel generator combined to harness the overall system output as well as to compensate for the unpredictable variation in RE sources from one zone to another. Maintenance and replacement costs of the hybrid system can be reduced when renewable resources are adequately explored [51]. The initial capital cost of a hybrid system is usually high; hence, long-lasting, reliable, and cost-effective systems are needed to meet the entire project life. Assumptions regarding components pricing and sizing as adopted in the proposed hybrid system, are expressed below:

(a) The capital cost and replacement cost of 1W of PV array were taken as $3.2 and $3.0 respectively. The lifetime of PV arrays was taken as 20 years and no tracking system was considered. The de-rating factor that accounts for losses due to temperature effects and dirts on the PV modules surface was assumed as 90%, and the ground reflection of the modules were taken as 20%. Different sizes of PV arrays were considered to get the optimal size for each village.

(b) A Generic model wind turbine with rated capacity of 1 kW is considered. The initial cost of one unit is taken as $4000. Replacement and operational maintenance costs were assumed as $3200 and $200/year respectively. In order to find an optimal size, different sizes of turbine options were analyzed. The operational lifetime of the turbine was considered as 20 years.

(c) The initial cost of a 25 kW AC diesel generator is $11,324, with a replacement cost of $10,200 and maintenance cost of $0.500/hr. The operating lifetime of a diesel generator was taken as 15,000 h with 30% load ratio.

(d) A bi-directional converter is added to maintain the flow of energy between the alternating current (AC) and direct current (DC) components. It function as a rectifier when it converts AC to DC, and as inverter on the other way round. The initial capital and replacement cost of the converter used in this study were taken as $800/kW and $750/kW respectively. The operational and maintenance cost is assumed as $100/year. The efficiency of the converter is assumed to be 90% that of rectifier is taken as 85% while the lifetime was taken as 10 years. Different sizes of converters were considered during the analysis.

(e) Surrette 6CS25P type battery with rated 6 V nominal voltage, and 1,156Ah capacity is considered in this study. The initial cost of one unit is $1000. Replacement and operational maintenance costs were assumed as $800 and $50/year

respectively. In order to find an optimal configuration, the battery bank was assumed to contain different number of batteries. Each battery string contains 8 batteries and the lifetime energy of each battery is estimated as 9645 kWh throughput.

(f) The adopted DC voltage regulator allows for either a 12 V or 24 V DC bus, and is to be connected to the batteries or converter with a rating of 5A [58].

(g) Hourly load of 10% is considered in the simulation and has operating reserve that accounts for sudden spikes in the system, while 25 percent reserve is considered for the PV panels output due to its inherent dependence on solar irradiance and hence unpredictable output.

(h) Maximum hourly load of 2% is considered as the capacity shortage factor (CSF); this shows the amount of time to which the system will not be able to meet the load requirement including its reserves.

3.6. Dispatch strategy and constraints

A dispatch strategy is a set of rules that controls the function of several connected generator(s) and the energy storage device [10]. Two types of dispatch strategies are available in HOMER software, namely: cycle charging (CC) and load following (LF) [34]. Under the LF strategy, diesel generator is automatically operated to serve the load alone without charging the battery storage system; under the CC strategy, the generator operate at its maximum rated capacity to serve the load and charges the battery [34]. The type of dispatch strategy which will be optimal for the proposed system depends on various characteristics such as the generator sizes, the battery bank, the fuel price, the diesel generator's operating and maintenance cost and the renewable energy. In the proposed system, both strategies were considered using HOMER. Constraints are preconditions which systems must fulfil, otherwise HOMER neglects those systems that do not content the defined constraints. In the proposed system, the maximum renewable fraction is considered as a range from 0 to 100%, and the maximum un-served energy is assumed as 0%, while the different values (0, 4, 6 and 10%) are taken as the maximum annual capacity shortage.

PV sizing in HOMER is user dependent; HOMER allows user to specify any amount of PV size (in kW) to allow for worst case scenario (i.e period of low solar irradiance). The sizing of the PV may also depend on the power requirement of the site as well as the space availability to install the panels. But in this study, all the PV module in the hybrid system were sized for each sites to meet the worst cases during the year. Though amount of excess energy produced becomes prominent during the months of high solar radiation due to larger size of the PV choice, because the greater the PV capacity, the greater the amount of electricity generated by the PV modules during daytime. Table 5 shows the search space (i.e. set of all possible system configuration over which HOMER can search for the optimal system configuration), for different components considered in the hybrid system (PV module inclusive).

4. Results and discussion

HOMER performed an hourly time series simulation for every possible system configuration on a yearly basis in order to evaluate the operational characteristics such as annual electricity production, annual load served, excess electricity, renewable fraction and so on. The renewable energy sources and diesel load generator were evaluated in order to determine the feasibility of the system. HOMER searched for optimum system configuration and component sizes that meet the load requirement at the lowest net present

Table 5
Search space of different component size in HOMER.

PV array (kW)	Wind turbine (Quantity)	Diesel generator (kW)	Battery (string)	Converter (kW)
0	0	0	0	0
2	1	5.5	2	5
4	2	7.5	4	10
6	3	10	6	15
8	4	15	8	20
10	5	20	10	
12	6	25		
14	7			
15	8			
16	9			
17	10			
18				
19				
20				

Fig. 6. NPC for diesel price of $1.1/l.

cost (NPC) and then presents the results of the simulation in terms of optimal systems and sensitivity analysis. The optimal results are categorized based on the sensitivity variables chosen. Table 6 shows the system architecture in terms of kW rating of the PV array, wind turbine, diesel generator and the converter. The number of batteries required for energy storage is also indicated under the system architecture. The conventional stand-alone diesel generator is presently employed in most rural areas in Nigeria, and hence considered as the base case simulation in this work. It is selected to allow a comparison to be made about the total savings that can be made by including a renewable energy source in the system design and implementation of hybrid power system (i.e comparing cost and emissions of DG with the proposed hybrid PV/wind/diesel configuration). PV/diesel/battery configuration is adjudged the optimal best, out of all the cases considered for the six climatic zone, and hence compared to the base case simulation with respect to NPC, RF, carbon emissions and diesel consumption for the two diesel prices (1.1 and $1.3/l).

4.1. Total NPC calculations

The NPC of all the feasible system configurations considered for implementation of hybrid power system in the selected sites are illustrated in Figs. 6 and 7 for diesel prices of 1.1 and $1.3/l respectively. NPC is calculated for the entire system based on the expected life of 25 years. The system configuration includes: stand-alone diesel only system, PV/diesel, PV/diesel/battery, wind/diesel, wind/diesel/battery, PV/wind/diesel, and PV/wind/diesel/battery.
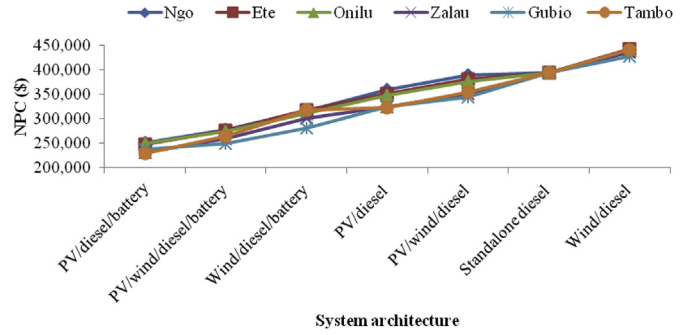
From the NPC analysis, it can be observed that stand-alone PV/diesel/battery system has the lowest NPC among the studied configurations for all the villages. The wind system is not the best option because of the low wind speed at most of the sites.

Figs. 8 and 9 show the graphical representation of NPC and COE respectively for PV/diesel/battery systems for all sites. In all the cases of NPC calculation, $1 = ₦159, where $ is US Dollars and ₦ is Nigerian currency in Naira. In both cases of diesel prices, the lowest NPC is obtained in Tambo village, found in the tropical dry climatic zone. At $1.1/l, the NPC is $229,941 and COE is $0.547/kWh. On the other hand, based on the diesel price of $1.3/l, NPC is $249,318 and COE is $0.593/kWh. The result shows the direct relationship between NPC and the level of solar radiation. The higher the solar radiation in a site, the lower will be the NPC value. This is because high irradiation will enable the PV system to supply the load for a longer period, thereby reducing the operating hours of the diesel generator; this will bring about reduction in the diesel consumption and cost associated with diesel, which thus relates directly to low NPC.

Zalau in the tropical climate is next to Tambo community with NPC value of $232,226, followed by Gubio which stands at $238,174 in NPC. The difference in average solar radiation between these two sites is found to be minimal. Ngo, which represents the tropical monsoon climate, showed the highest NPC out of the six sites considered in the simulation. This is attributable to the low average daily global solar irradiation as found in this site compared to locations selected within the remaining climatic zones. The total NPC for the site is $251,151; when compared to the base case NPC (i.e. diesel generator only), a saving of $144,216 can be achieved.

The NPC result at diesel price 1.3$/l follows similar trends as with $1.1/l sensitivity case. It does however varied from the $1.1/l diesel price in terms of level of savings obtained when compared with base case simulation. At diesel price of $1.3/l, the NPC of the base case simulation amounts to $452,030. The lowest NPC for the
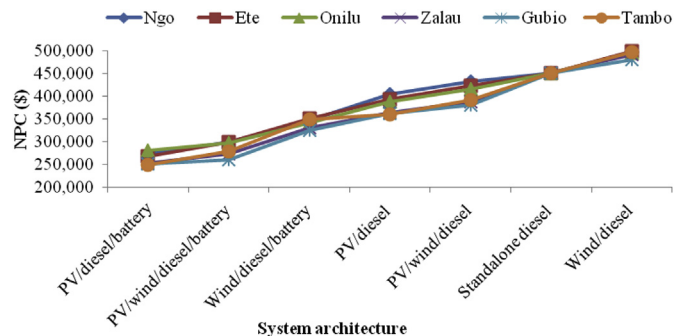
Table 6
System architecture for six geo-political zones.

Sensitivity case	Village					
	Ngo (SS)		Ete (SE)		Onilu (SW)	
	$1.1/l	$1.3/l	$1.1/l	$1.3/l	$1.1/l	$1.3/l
PV array (kW)	12	12	10	12	8	20
Generator (kW)	10	10	10	10	10	15
Wind Turbine (kW)	0	0	0	0	0	0
Converter (kW)	5	5	5	5	5	10
Number of batteries	32	32	32	32	32	32
	Zalau (NC)		Gubio (NE)		Tambo (NW)	
PV array (kW)	10	20	17	20	10	20
Generator (kW)	10	15	15	15	10	15
Wind Turbine (kW)	0	0	0	0	0	0
Converter (kW)	5	10	10	10	5	10
Number of batteries	32	32	32	32	32	32

Fig. 7. NPC for diesel price of $1.3/l.

Fig. 8. Graphical representation of NPC for diesel price of 1.1 and $1.3/l.

Fig. 10. Excess electricity (%) for diesel price of 1.1 and $1.3/l.

sensitivity case of $1.3/l is further observed at Tambo site, amounting to $249,318. The saving obtained in comparison to base case simulation is $202,712.

4.2. System architecture

Table 6 presents the number of components selected for the most feasible configuration (PV/diesel/battery) in each geo-political zone, based on the two diesel prices considered. HOMER considered many factor such as global solar irradiation, diesel prices as well as load profile in coming up with this optimised number of system components. The component optimization process, prioritizes continuous meeting of load demands by the hybrid system. This is aimed at ensuring marginal diesel consumption as well as making sure that PV system is not over-sized. The space requirement for installation is also considered in the sizing of the batteries component.

It can be observed from Table 6, that the maximum sizing of the PV panels (17 and 20 kW) for both of the sensitivity cases is at Gubio. This is because the village experiences the highest daily solar irradiation compared to that of the other villages. For both sensitivity cases, the number of batteries for all simulations stands at 32. The excess electricity (%), generated by the optimum hybrid systems in each village is shown in Fig. 10. The greater the PV capacity, the greater the amount of electricity generated by the PV modules during daytime. Whenever the PV modules output power exceeded the load demand, the excess power will be store in batteries. Excess electricity produced by the PV systems decreases with increasing number of batteries. This energy can be saved and stored in the battery for utilization during the period of insufficient solar radiation. Alternatively, this excess energy can be used by dump load (e.g street lighting, water pumping, water heating or refrigeration). Furthermore, the high excess energy experienced in
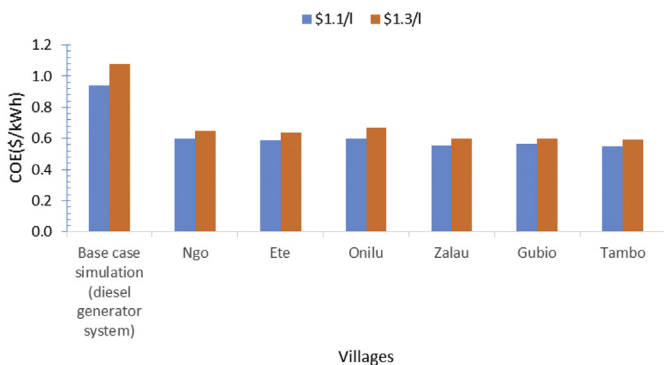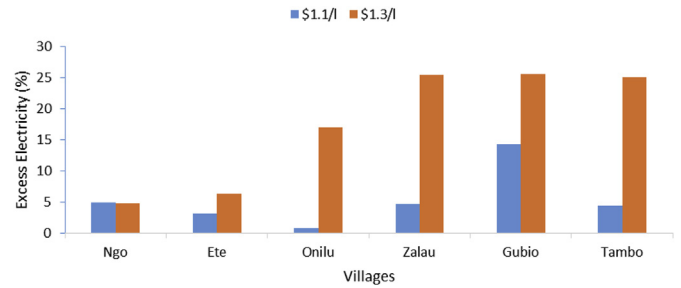
some sites (Fig. 10) resulted from sizing of the hybrid system components to meet the worst cases during the year. The amount of excess energy thus becomes prominent during the months of high solar radiation.

The smallest component sizing in system architecture was obtained at Onilu out of all the sites considered. The system architecture includes 8 kW solar panel, a 10 kW generator, a 5 kW converter and 32 batteries. It was noted from the simulation that most of the sites considered except Ngo, reported increase in the size of PV panel and batteries bank, as the diesel price is raised from 1.1 to $1.3/l. This is because the operating costs of the generator rises drastically as diesel price increases. This justifies the extra costs of installing a larger PV array and increasing the storage capabilities of the system in order to minimize the operating hours of the generator, thus keeping the NPC as low as possible.

4.3. RF calculations

Renewable fraction varies as the system architectures for each site considered in the simulation. It can be observed from Fig. 11, that RF for each site in the simulation is notably high for sensitivity case of $1.3/l. Increase in diesel price favours more addition of PV panels, resulting in higher value of RF. Out of the six sites considered, Gubio experience highest RF value, the values are 0.66 and 0.71 at diesel price of 1.1 and $1.3/l respectively. The lowest RF of 0.29 occurs in Onilu for sensitivity case of $1.1/l. RF of 0.37 occurs in Ngo for sensitivity case of $1.3/l. Zalau and Tambo also experience a relatively high RF of 0.71 for diesel price of $1.3/l.

4.4. Carbon emissions and diesel consumption

Annual CO_2 emissions relate directly to the amount of litres of fuel consumed by the diesel generator per year. Fig. 12 shows a comparison to the total amount of diesel consumed per year by the PV/diesel/battery configuration for each site with base case simulation at diesel prices of 1.1 and $1.3/l.
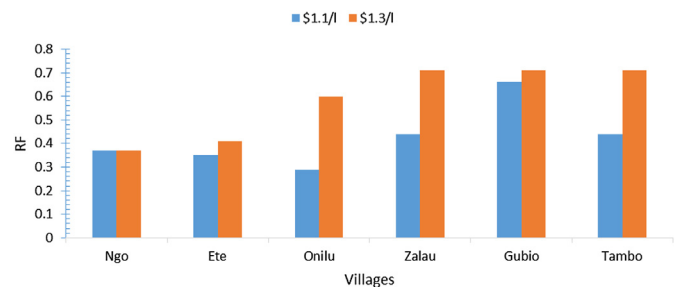

Fig. 9. Graphical representation of COE for diesel price of 1.1 and $1.3/l.

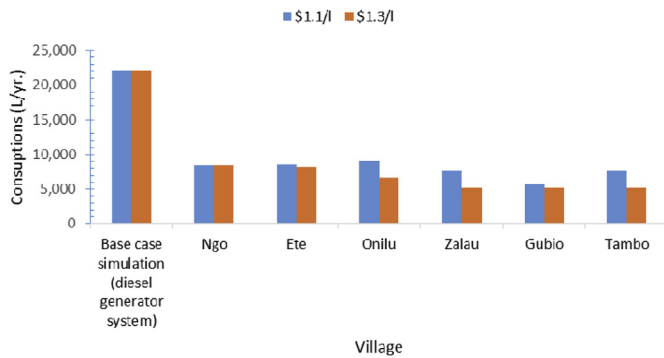**Fig. 11.** RF for diesel price of 1.1 and $1.3/l.

Fig. 12. Diesel consumption (L) for diesel price of 1.1 and $1.3/l.
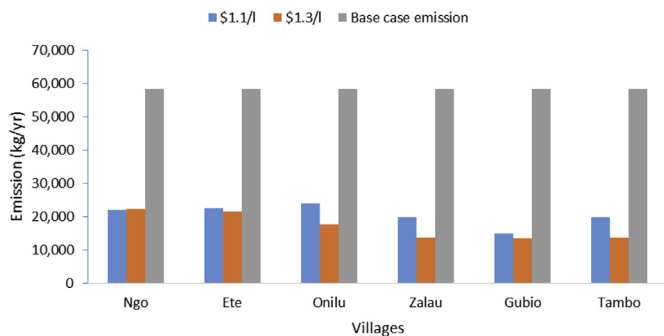

Fig. 13. CO_2 emission (kg/yr) for diesel price of 1.1 and $1.3/l.

CO_2 emissions in kg/yr for both the sensitivity cases at each site are shown in Fig. 13. Gubio site consumed the least volume of diesel per year (5661 and 5166 at diesel price 1.1 and $1.3/l respectively), while the highest volume of diesel consumption is observed at Onilu site.

Fig. 13 shows that the hybrid renewable energy system configuration, provide a greater savings in CO_2 emission as compared to base case simulation (diesel generator system). On the average, the sensitivity case of $1.3/l gave the greater savings on carbon emissions than $1.1/l, due to the obtained high RF value. Gubio displays the lowest amount of CO_2 emission (13,604 kg/yr), followed by Zalau (13,704 kg/yr). The highest value of CO_2 emissions occurred at Onilu, which stands at 24,022 kg/yr for the sensitivity case of $1.1/l.

5. Conclusion

In this article, the economic feasibility of hybrid power generation systems in six selected sites picked from each of the six geopolitical zones of Nigeria was conducted. Through investigation of resources availability in each zones and simulations of the total system scenarios, the optimum system architecture, total costs and environmental impacts, were quantitatively analyzed. Seven system configurations including: stand-alone diesel only system, PV/diesel, PV/diesel/battery, wind/diesel, wind/diesel/battery, PV/wind/diesel and PV/wind/diesel/battery, were considered by HOMER to obtain the most economically feasible solution. According to the results for the selected sites in this study, it can be concluded that:

- The PV/diesel/battery hybrid renewable system configuration is found as optimum architecture for both sensitivity cases of 1.1 and $1.3/l, based on the NPC, COE and RF calculation. In addition, the best optimum location to install a PV/diesel/battery power

system in Nigeria is Tambo village in the tropical dry climatic zone.
- The diesel only system provides the highest COE ($1.075/kWh), and emits 58,362 kg of CO_2 per year; this is huge and will have adverse effect on the environment. The wind/diesel system is not a good option in all the sites considered, due to the relatively low wind speed. However, simulation results for wind related configuration, still proves to be more cost effective than that of the base case simulation with regards to NPC analysis.
- The overall results indicated that not only does the hybrid system configurations perform better than base case simulation with regards to the NPC for all six simulations, it also displayed better performance in the categories such as electrical, fuel consumption and CO_2 reduction.
- The high solar irradiation levels in the country create an ideal environment for inclusion of RET such as PV in the design and implementation of standalone power supply systems.
- Due to the high initial costs of implementing hybrid systems, government subsidies and tariff concession need to be established in Nigeria to boost investments in renewable energy, to enhance their contribution to the total energy mix, alleviate poverty and rural electrification problems and promote CO_2 emission reduction on environment.

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