Hindawi Publishing Corporation
Journal of Energy
Volume 2016, Article ID 6278138, 16 pages
http://dx.doi.org/10.1155/2016/6278138

Research Article

Design of a Reliable Hybrid (PV/Diesel) Power System with Energy Storage in Batteries for Remote Residential Home

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Received 17 March 2016; Accepted 26 May 2016

Academic Editor: Mohamed Benghanem

This paper reports the experience acquired with a photovoltaic (PV) hybrid system simulated as an alternative to diesel system for a residential home located in Southern Nigeria. The hybrid system was designed to overcome the problem of climate change, to ensure a reliable supply without interruption, and to improve the overall system efficiency (by the integration of the battery bank). The system design philosophy was to maximize simplicity; hence, the system was sized using conventional simulation tool and representative insolation data. The system includes a 15 kW PV array, 21.6 kWh (3600 Ah) worth of battery storage, and a 5.4 kW (6.8 kVA) generator. The paper features a detailed analysis of the energy flows through the system and quantifies all losses caused by PV charge controller, battery storage round-trip, rectifier, and inverter conversions. In addition, simulation was run to compare PV/diesel/battery with diesel/battery and the results show that the capital cost of a PV/diesel hybrid solution with batteries is nearly three times higher than that of a generator and battery combination, but the net present cost, representing cost over the lifetime of the system, is less than one-half of the generator and battery combination.

1. Introduction

Energy is essential to economic and social development and improves quality of life. It is very important for the developing society [1]. In Nigeria, most residential homes are connected to the electric grid. However, there still exist several "off-grid" or remote locations, which, for financial and/or environmental reasons related to their distance from an existing power line, are not connected to the utility grid. Most of these residences derive their electricity from gasoline or diesel powered generators, which can be noisy and have the disadvantage of increasing the greenhouse gas emission which has a negative impact on the environment. Amid the environmental problems of using petrol and diesel generators, the cost of running them is quite high. Due to the high cost of running petrol/diesel generators, many Nigerians are willing to shift from using these traditional generators to the use of renewable energy technologies.

Renewable energy technologies (such as solar-photovoltaic systems) can be localized and decentralized unlike the national electricity grid. This allows end-users to generate their own electricity wherever they are located. Also, the technologies do not require any running cost, unlike the traditional petrol/diesel generators.

The installation of a solar power system to replace or offset a portion of the diesel electricity generation is an option to consider for remote residential homes. A complete replacement of diesel generation with solar power is usually not feasible, due to low solar input during the rainy season. However, a solar/diesel combination system known as hybrid system can prove to be very reliable and cost effective given the right conditions (such as optimal sizing). Hybrid energy applications are of increasing interest, and a well-managed hybrid solar-diesel system can achieve lifetime fuel savings, while ensuring reliable electricity supply. Insofar as diesel fuel is reduced, and such systems reduce CO_2 as well as particulate emissions that are harmful to health. They are an economical option in areas isolated from the grid.

This paper describes the way to design the aspects of a hybrid power system, a photovoltaic (PV) generator with energy storage for a residential use. The decision to select a PV generator hybrid system rather than a pure PV system for

Table 1: Energy needed for the household use.

Description of item	Item abbreviation	Power rating (watts)	Qty	Total load (watts)	Daily hour of actual utilization (hr. per day)
Medium size deep-freezer	DF	130	1	130	24 h (00:00 h–24:00 h)
Water pumping machine	PM	1000	1	1000	1 h (13:00 h-14:00 h)
Washing machine	WM	280	1	280	1 h (09:00 h-10:00 h)
Electric stove	ES	1000	1	1000	2 h (17:00 h–19:00 h)
Microwave oven	MO	1000	1	1000	2 h (06:00 h-07:00 h; 11:00 h-12:00 h)
Electric pressing iron	PI	1000	1	1000	1 h (12:00 h-13:00 h)
Air-conditioner	AC	1170	1	1170	9 h (08:00 h–17:00 h)
Refrigerator	RF	500	1	500	9 h (08:00 h–17:00 h)
Water bath	WB	1000	1	1000	2 h (03:00 h-04:00 h; 18:00 h-19:00 h)
Ceiling fan	CF	100	14	1400	14 h (08:00 h–22:00 h)
Energy efficient lighting	EL	6	23	138	8 h (04:00 h–08:00 h; 18:00 h–22:00 h)
Lighting-outdoor (security)	LO	9	4	36	13 h (18:00 h–07:00 h)
21″ TV with decoder	21″ TV-D	150	1	150	9 h (08:00 h–17:00 h)
21″ television	21″ TV	100	1	100	11 h (18:00 h–05:00 h)
14″ television	14″ TV	80	8	640	22 h (06:00 h–17:00 h; 18:00 h–05:00 h)
Sony music system	SM	100	1	100	1 h (04:00 h-05:00 h)
DSTV receiver	D-R	50	1	50	22 h (06:00 h–17:00 h; 18:00 h–05:00 h)
DVD player	D-P	50	1	50	2 h (19:00 h–21:00 h)
Computer printer	CP	100	1	100	1 h (15:00 h-16:00 h)
Computer PC	PC	115	1	115	9 h (08:00 h–17:00 h)
Computer laptop	CL	35	1	35	9 h (08:00 h–17:00 h)
Miscellaneous	M	100	1	100	24 h (00:00 h–24:00 h)

the considered location is consistent with its solar irradiation. This system will replace an existing diesel powered electric generator and was sized to meet the residence's known lighting and plug loads, refrigeration, cooking, and heating needs. The residence is located about a km from the utility grid and the location is characterized by a yearly global irradiation of about 2150 kWh/m^2. Also, this study is to produce a detailed experimental accounting of energy flows through the hybrid system and quantify all system losses. In addition, the hybrid system designed will be compared with the diesel/battery system in terms of costs and environmental impacts.

(1) Description of the Residential Home. The residence is a duplex building and has six rooms, a kitchen, and a sitting room at the ground floor, while it has three masters' rooms, a library, and a small sitting room upstairs. The building is furnished with electric power consumptions such as washing machine, electric stove, electric pressing iron, DVD, stereo cassette, television, decoder/cable, water pumping machine, fans, electric bulbs, water bath, deep-freezer, and microwave. Each room has fan, electric bulb, and television. The sitting room at the upstairs uses air-condition, while the one at the ground floor uses four fans. The residence is not connected to the grid and currently utilizes a diesel power generating system to meet its energy needs.

In this research, load assessment and the pattern of using electricity power within the house were carried out based on data provided by the occupant of the house and a site visit to evaluate the characteristics of the power system, power requirements, and power system management and operation. The daily power demands for the residential home are tabulated in Tables 1 and 2 and shown in Figure 1. These tables show the estimation of each appliance's rated power, its quantity, and the hours of use by the residence in a single day. The miscellaneous load is for unknown loads in the house.

(2) Overview of the Study Area. This research focuses on the design of a hybrid power system with energy storage in batteries for a residential home. The residential home where the study was done is located in a remote setting of Ndiagu-Akpugo. Ogologo-Eji Ndiagu-Akpugo is in Nkanu-West LGA of Enugu State in South-Eastern Nigeria on latitude 6°35′N and longitude 7°51′E. The data for solar resource (used in generating Figure 2) were obtained from the National Aeronautics and Space Administration (NASA) Surface Meteorology and Solar Energy web site [2]. After scaling on this data, the scaled annual average resource of 4.7 kWh/m^2/d was obtained for the site. As can be seen in Figure 2, months below 4.5 kWh/m^2/d are the months of June, July, August, and September which are the months of raining season in Nigeria, and there are likely to be more cloudy days on these months.

Table 2: The electrical load (daily load demands) data for the household.

Time	The appliance abbreviations are given in Table 1																					Total (W/Hr)
	DF	PM	WM	ES	MO	PI	AC	RF	WB	CF	EL	LO	21″ TV-D	21″ TV	14″ TV	SM	D-R	D-P	CP	PC	CL	M	
0.00-1.00	130											36		100	640		50					100	1056
1.00-2.00	130											36		100	640		50					100	1056
2.00-3.00	130											36		100	640		50					100	1056
3.00-4.00	130								1000			36		100	640		50					100	2056
4.00-5.00	130										138	36		100	640	100	50					100	1294
5.00-6.00	130										138	36										100	404
6.00-7.00	130				1000						138	36			640		50					100	2094
7.00-8.00	130										138				640		50					100	1058
8.00-9.00	130						1170	500		1400			150		640		50			115	35	100	4290
9.00-10.00	130		280				1170	500		1400			150		640		50			115	35	100	4570
10.00-11.00	130						1170	500		1400			150		640		50			115	35	100	4290
11.00-12.00	130				1000		1170	500		1400			150		640		50			115	35	100	5290
12.00-13.00	130					1000	1170	500		1400			150		640		50			115	35	100	5290
13.00-14.00	130	1000					1170	500		1400			150		640		50			115	35	100	5290
14.00-15.00	130						1170	500		1400			150		640		50			115	35	100	4290
15.00-16.00	130						1170	500		1400			150		640		50		100	115	35	100	4390
16.00-17.00	130						1170	500		1400			150		640		50			115	35	100	4290
17.00-18.00	130			1000						1400												100	2630
18.00-19.00	130			1000					1000	1400	138	36		100	640		50					100	4594
19.00-20.00	130									1400	138	36		100	640		50	50				100	2644
20.00-21.00	130									1400	138	36		100	640		50	50				100	2644
21.00-22.00	130									1400	138	36		100	640		50					100	2594
22.00-23.00	130											36		100	640		50					100	1056
23.00-24.00	130											36		100	640		50					100	1056
Total	3120	1000	280	2000	2000	1000	10530	4500	2000	19600	1104	468	1350	1100	14080	100	1100	100	100	1035	315	2400	69282

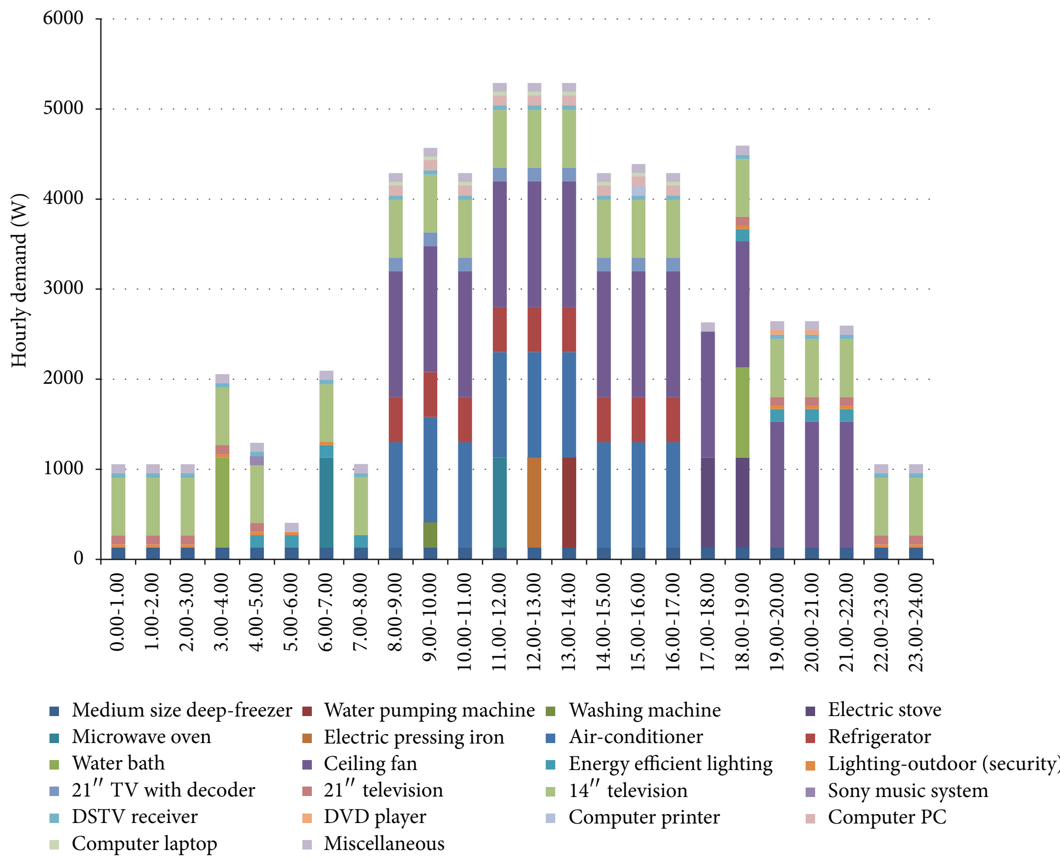

FIGURE 1: Hourly power demand profile of the household.

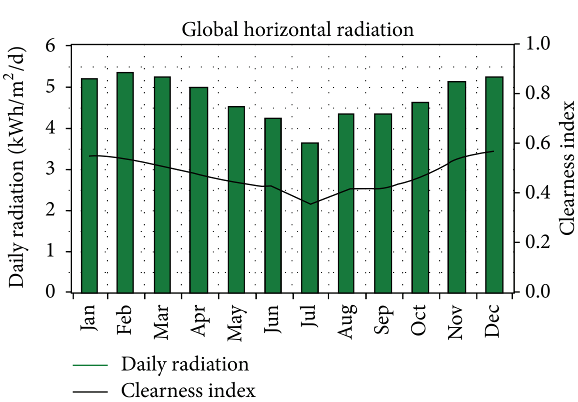

FIGURE 2: Solar daily radiation profile for Ndiagu-Akpugo in Nkanu-West (Enugu State) [2].

2. Energy Models

Energy model depends mainly on the economic feasibility and the proper sizing of the components in order to avoid outages as well as ensuring quality and reliability of supply. Energy design system looks into its sizing and the process of selecting the best components to provide cheap, efficient, reliable, environmentally friendly, and cost effective power supply [3]. The technoeconomic analysis looks at both environmental cost and the cheapest cost of energy produced by the system components. Designing a hybrid system would require correct components selection and sizing, with appropriate operation strategy [4, 5].

In energy systems, the sizing of the individual systems can be made in a variety of ways, depending upon the choice of parameters of interest. Energy models are employed as a supporting tool to develop energy strategies as well as outlining the likely future structure of the system under particular conditions. This helps to provide insights into the technological paths, structural evolution, and policies that should be followed [3]. A lot of research has been conducted on the performance of hybrid power systems and experimental results have been published in many articles [6–13]. The energy output of a hybrid system can be enough for the demands of a house placed in regions where the extension of the already available electricity grid would be financially unadvisable [9]. A method of sizing hybrid PV systems regarding the reliability to satisfy the load demand, economy of components, and discharge depth exploited by the batteries is therefore required.

Several models have been developed, simulating and sizing PV systems using different operation strategies. The estimation of performance of PV systems based on the Loss of Load Probability (LLP) technique is developed by [14–17]. These analytical methods are simple to apply but they are not general. On the other hand, the numerical methods presented by [18–24] present a good solution, but these need a long period solar radiation data record. Other methods estimate the excess of energy provided by PV generators and the storage capacity of the batteries using the utilizability method [25].

The conventional methodology (empiric, analytic, and numeric) for sizing PV systems has been used for a location where the required weather data (irradiation, temperature, humidity, clearness index, etc.) and the information concerning the site where we want to implement the PV system are available. In this case these methods present a good solution for sizing PV systems. However, these techniques could not be used for sizing PV systems in remote areas, in the case where the required data are not available. Moreover, the majority of the above methods need the long term meteorological data such as total solar irradiation and air temperature for their operation. So, when the relevant meteorological data are not available, these methods cannot be used, especially in the isolated areas. In this context, a model was developed, and the methodology aims at finding the configuration, among a set of systems components, which meets the desired system reliability requirements, with the lowest value of levelised cost of energy (LCE). This methodology can be used for determining the optimum number of solar panels and batteries configurations (the storage capacity of the batteries necessary to satisfy a given consumption). Since the investigation of this paper is based on a detailed study of an analysis of the energy flows, the analysis reveals the energy losses (charge controller, rectifier, battery, and inverter) in the system and the storage requirement. In addition, the model developed was used to select the optimal sizing parameters of PV system in which the results obtained have been compared and tested with HOMER software.

2.1. Development of a Model for Energy System Components. Modelisation is an essential step before any phase of component sizing. Various modeling techniques are developed, to model hybrid PV/diesel system components, in previous studies. For a hybrid PV/diesel system with storage battery, three principal subsystems are included, the PV generator, the diesel generator, and the battery storage. A methodology for modeling hybrid PV/diesel system components is described below. The theoretical aspects are given below (Sections 2.1.1, 2.1.2, 2.1.3, 2.1.4, and 2.1.5) and are based on the works of Ani [3], Gupta et al. [26], and Ashok [27].

2.1.1. Modeling of Solar-Photovoltaic Generator. Using the solar radiation available, the hourly energy output of the PV generator (E_{PVG}) can be calculated according to the following equation [3, 27–29]:

$$E_{\text{PVG}} = G(t) \times A \times P \times \eta_{\text{PVG}}. \tag{1}$$

2.1.2. Modeling of Diesel Generator. Hourly energy generated by diesel generator (E_{DEG}) with rated power output (P_{DEG}) is defined by the following expression [3, 27, 28]:

$$E_{\text{DEG}}(t) = P_{\text{DEG}}(t) \times \eta_{\text{DEG}}. \tag{2}$$

2.1.3. Modeling of Converter. In the proposed scheme, a converter contains both rectifier and inverter. PV energy generator and battery subsystems are connected with DC bus while diesel generating unit subsystem is connected with AC bus. The electric loads connected in this scheme are AC loads.

The rectifier is used to transform the surplus AC power from the diesel electric generator to charge the battery. The diesel electric generator will be powering the load and at the same time charging the battery. The rectifier model is given below:

$$\begin{aligned} E_{\text{REC-OUT}}(t) &= E_{\text{REC-IN}}(t) \times \eta_{\text{REC}}, \\ E_{\text{REC-IN}}(t) &= E_{\text{SUR-AC}}(t). \end{aligned} \tag{3}$$

At any time t,

$$E_{\text{SUR-AC}}(t) = E_{\text{DEG}}(t) - E_{\text{Load}}(t). \tag{4}$$

The inverter model for photovoltaic generator and battery bank are given below:

$$\begin{aligned} E_{\text{PVG-IN}}(t) &= E_{\text{PVG}}(t) \times \eta_{\text{INV}}, \\ E_{\text{BAT-INV}}(t) &= \left[\frac{\left(E_{\text{BAT}}(t-1) - E_{\text{LOAD}}(t)\right)}{\left(\eta_{\text{INV}} \times \eta_{\text{DCHG}}\right)} \right]. \end{aligned} \tag{5}$$

2.1.4. Modeling of Charge Controller. To prevent overcharging of a battery, a charge controller is used to sense when the batteries are fully charged and to stop or reduce the amount of energy flowing from the energy source to the batteries. The model of the charge controller is presented below:

$$\begin{aligned} E_{\text{CC-OUT}}(t) &= E_{\text{CC-IN}}(t) \times \eta_{\text{CC}}, \\ E_{\text{CC-IN}}(t) &= E_{\text{REC-OUT}}(t) + E_{\text{SUR-DC}}(t). \end{aligned} \tag{6}$$

2.1.5. Modeling of Battery Bank. The battery state of charge (SOC) is the cumulative sum of the daily charge/discharge transfers. The battery serves as an energy source entity when discharging and a load when charging. At any time, t, the state of battery is related to the previous state of charge and to the energy production and consumption situation of the system during the time from $t-1$ to t.

During the charging process, when the total output of all generators exceeds the load demand, the available battery bank capacity at time, t, can be described by [3, 29, 30]

$$E_{\text{BAT}}(t) = E_{\text{BAT}}(t-1) - E_{\text{CC-OUT}}(t) \times \eta_{\text{CHG}}. \tag{7}$$

On the other hand, when the load demand is greater than the available energy generated, the battery bank is in discharging state. Therefore, the available battery bank capacity at time, t, can be expressed as [3, 29]

$$E_{\text{BAT}}(t) = E_{\text{BAT}}(t-1) - E_{\text{Needed}}(t). \tag{8}$$

Let d be the ratio of minimum allowable SOC voltage limit to the maximum SOC voltage across the battery terminals when it is fully charged. So, the depth of discharge (DOD) is

$$\text{DOD} = (1-d) \times 100. \tag{9}$$

DOD is a measure of how much energy has been withdrawn from a storage device, expressed as a percentage of full capacity. The maximum value of SOC is 1, and the minimum SOC is determined by maximum depth of discharge (DOD):

$$\mathrm{SOC}_{\mathrm{Min}} = 1 - \frac{\mathrm{DOD}}{100}. \quad (10)$$

2.2. Mathematical Cost Model (Economic and Environmental Costs) of Energy Systems. This work developed a mathematical model of a system that could represent the integral (total sum) of the minimum economic and environmental (health and safety) costs of the considered options.

2.2.1. The Annualized Cost of a Component. The annualized cost of a component includes annualized capital cost, annualized replacement cost, annual O&M cost, emissions cost, and annual fuel cost (generator). Operation cost is calculated hourly on daily basis [3, 27, 29, 31].

2.2.2. Annualized Capital Cost. The annualized capital cost of a system component is equal to the total initial capital cost multiplied by the capital recovery factor. Annualized capital cost is calculated using [3, 27, 29, 31]

$$C_{\mathrm{acap}} = C_{\mathrm{cap}} \cdot \mathrm{CRF}\left(i, R_{\mathrm{proj}}\right). \quad (11)$$

2.2.3. Annualized Replacement Cost. The annualized replacement cost of a system component is the annualized value of all the replacement costs occurring throughout the lifetime of the project minus the salvage value at the end of the project lifetime. Annualized replacement cost is calculated using [3, 27, 29, 31]

$$C_{\mathrm{arep}} = C_{\mathrm{rep}} \cdot f_{\mathrm{rep}} \cdot \mathrm{SFF}\left(i, R_{\mathrm{comp}}\right) - S \cdot \mathrm{SFF}\left(i, R_{\mathrm{proj}}\right). \quad (12)$$

f_{rep}, a factor arising because the component lifetime can be different from the project lifetime, is given by

$$f_{\mathrm{rep}} = \begin{cases} \dfrac{\mathrm{CRF}\left(i, R_{\mathrm{proj}}\right)}{\mathrm{CRF}\left(i, R_{\mathrm{rep}}\right)}, & R_{\mathrm{rep}} > 0, \\ 0, & R_{\mathrm{rep}} = 0. \end{cases} \quad (13)$$

R_{rep}, the replacement cost duration, is given by

$$R_{\mathrm{rep}} = R_{\mathrm{comp}} \cdot \mathrm{INT}\left(\frac{R_{\mathrm{proj}}}{R_{\mathrm{comp}}}\right). \quad (14)$$

SFF( ), the sinking fund factor which is a ratio used to calculate the future value of a series of equal annual cash flows, is given by

$$\mathrm{SFF}(i, N) = \frac{i}{(1+i)^N - 1}. \quad (15)$$

The salvaged value of the component at the end of the project lifetime is proportional to its remaining life. Therefore, the salvage value S is given by

$$S = C_{\mathrm{rep}} \cdot \frac{R_{\mathrm{rem}}}{R_{\mathrm{comp}}}. \quad (16)$$

R_{rem}, the remaining life of the component at the end of the project lifetime, is given by

$$R_{\mathrm{rem}} = R_{\mathrm{comp}} - \left(R_{\mathrm{proj}} - R_{\mathrm{rep}}\right). \quad (17)$$

2.2.4. Annualized Operating Cost. The operating cost is the annualized value of all costs and revenues other than initial capital costs and is calculated using [3, 27, 29, 31]

$$C_{\mathrm{aop}} = \sum_{t=1}^{365} \left\{ \sum_{t=1}^{24} \left[C_{\mathrm{oc}}(t)\right] \right\}. \quad (18)$$

2.2.5. Cost of Emissions. The following equation is used to calculate the cost of emissions [3, 27, 29, 31]:

$$C_{\mathrm{emissions}} = \frac{c_{CO_2} M_{CO_2} + c_{CO} M_{CO} + c_{UHC} M_{UHC} + c_{PM} M_{PM} + c_{SO_2} M_{SO_2} + c_{NO_x} M_{NO_x}}{1000}. \quad (19)$$

Total cost of a component = economic cost + environmental cost, where economic cost = capital cost + replacement cost + operation and maintenance cost + fuel cost (generator). Also environmental cost = emissions cost.

Annualized Cost of a Component Is Calculated Using [3, 27, 29, 31]

$$C_{\mathrm{ann}} = C_{\mathrm{acap}} + C_{\mathrm{arep}} + C_{\mathrm{aop}} + C_{\mathrm{emissions}}. \quad (20)$$

Annualized Total Cost of a Component Is Calculated Using [29, 31]

$$C_{\mathrm{ann,tot},c} = \sum_{c=1}^{N_c} \left(C_{\mathrm{acap},c} + C_{\mathrm{arep},c} + C_{\mathrm{aop},c} + C_{\mathrm{emissions}}\right). \quad (21)$$

From (21), the economic and environmental cost model through annualized total cost of different configurations of power system results in the hybridizing of the renewable energy generator (PV) with existing energy (diesel) is given below.

Economic and environmental cost model of running *solar + diesel generator + batteries + converter* is calculated as

$$C_{\text{ann,tot},s+g+b+c} = \sum_{s=1}^{N_s}\left(C_{\text{acap},s} + C_{\text{arep},s} + C_{\text{aop},s} + C_{\text{emissions}}\right) + \sum_{g=1}^{N_g}\left(C_{\text{acap},g} + C_{\text{arep},g} + C_{\text{aop},g} + C_{\text{emissions}} + C_{\text{af},g}\right) + \sum_{b=1}^{N_b}\left(C_{\text{acap},b} + C_{\text{arep},b} + C_{\text{aop},b} + C_{\text{emissions}}\right) + \sum_{c=1}^{N_c}\left(C_{\text{acap},c} + C_{\text{arep},c} + C_{\text{aop},c}\right). \quad (22)$$

2.3. Description of the Computer Simulation. A computer program was developed and used to build the hybrid (PV/diesel) system model. Data inputs to the program are hourly load demand data, latitude, and longitude of the site and reference component cost. The designed software determines as its output the size of system components (sizing parameters) and the performance of the system over the course of the year (see the supplementary data in Supplementary Material available online at http://dx.doi.org/10.1155/2016/6278138) by showing the power supplied by each of the energy systems over the year, given the load conditions and taking into account the technical factors. The designed software can be used to study how the hybrid (PV/diesel) system is being supplied.

2.4. Validation of the Model. The designed software results were carried out followed with HOMER data to validate the analysis. The comparison shows a close agreement between results obtained from the designed software module and results obtained from HOMER setup. In addition, before using the measured data gotten from NASA datasets in simulating the individual components of a PV/diesel hybrid system, the developed program accuracy was established; the simulated data predicted by the software program fall within the bounds of the measured data. The algorithm that the developed program uses to synthesize solar data is based on the work of Graham and Hollands [32]. The realistic nature of synthetic data created by this algorithm is demonstrated and the test shows that synthetic solar data (simulated) produce virtually the same simulation results as real data (measured) as shown in Figure 3.

3. System Description

The designed system considered in this paper is a hybrid system which consists of a renewable (photovoltaic) energy system integrated in a conventional (diesel) power generation system, energy storage in battery, a DC/AC converter (an inverter for the conversion of generated DC power into

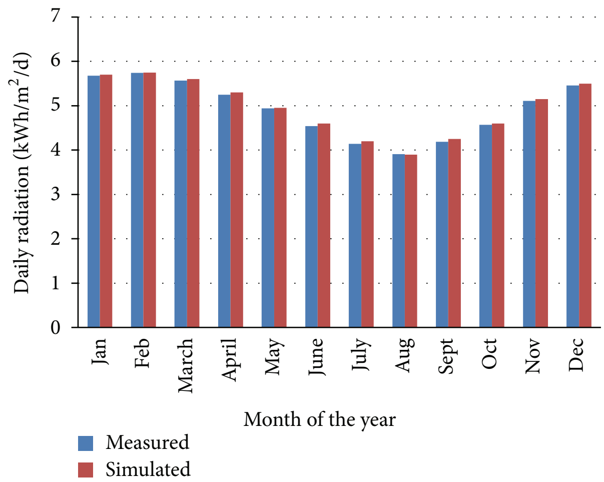

Figure 3: Calibrated solar radiation.

required AC power), and an AC/DC converter (a rectifier for the conversion of generated AC power in order to charge the battery) as shown in Figure 4. The inverter used is bidirectional, also known as power converter, which maintains energy flow between AC and DC components, since the flow comes in two different directions (from AC to DC and from DC to AC).

The flow from the solar array passes through the charge controller to charge the battery and at the same time supply electricity to the load through the inverter. The actual AC power obtained after the conversion from a solar array can be seen in Table 3. The charge controller monitors and controls the charging and discharging of the battery in order not to allow the battery to be damaged (due to overcharging or overdischarging).

Another flow comes from diesel generator when the PV and the battery could no longer serve the load; the generator supplies electricity direct to serve the load and at the same time charge the battery through the rectifier. That is how the designed hybrid system is expected to work.

The system design was to be representative of the type of residential systems that were likely to be installed in the foreseeable future. Hence, the system was sized using conventional simulation tool and representative insolation data.

3.1. Cost of Key Components (including Installation and Labour) and Interest Rate for Capital Investments

3.1.1. PV System Cost (US$ 2/Wp). The cost of PV panels on the Nigerian market was estimated as US$ 0.600/Wp based on prices cited by Nigerian suppliers (based on the cost of a module of 1210 × 808 × 35 mm size generating 130 watts of peak power (Wp DC) in controlled conditions) [34]. This was adjusted upward to US$ 2/Wp to account for other support components that are required, also known as balance of system (BOS) parts, such as cables, charge controller with maximum power point tracker, lightening protection, and delivery/labour and installation costs.

Table 3: Results of the hybrid electricity production, battery charge, supply, excess, losses, and consumption (kW).

Month	Hybrid PV/diesel electricity generation					Rectifier			Battery			Inverter			AC load
	Electricity generated and supplied, charging the battery, and excess electricity by the hybrid system (kW)					Energy received by the rectifier to charge the battery (kW)			Energy received by the battery and supplied to the AC load via inverter (kW)			Energy received by the inverter and supplied to the AC load (kW)			AC load served (kW)
	Electricity generated	*Supplied to the load	*Charging the battery	Losses	Excess electricity generated	Energy in	Energy out	Losses	Charge	Discharge	Losses	Energy in	Energy out	Losses	
January	2715.399	1862.277	538.799	0.159	314.164	299.517	254.646	44.871	493.928	−427.515	66.413	1415.143	1273.589	141.554	2148.238
February	2527.428	1695.987	489.700	0.154	341.587	289.982	246.547	43.435	446.265	−379.553	66.712	1351.523	1216.327	135.196	1940.344
March	2802.411	1887.039	533.918	0.154	381.300	301.472	256.311	45.161	488.757	−411.872	76.885	1506.288	1355.615	150.673	2148.238
April	2629.097	1827.413	509.332	0.146	292.206	289.705	246.309	43.396	465.936	−395.701	70.235	1441.311	1297.137	144.174	2078.940
May	2631.846	1876.123	535.826	0.179	219.718	314.101	267.048	47.053	488.773	−419.038	69.735	1468.844	1321.921	146.923	2148.238
June	2522.854	1804.867	528.865	0.177	188.945	313.288	266.355	46.933	481.932	−408.659	73.273	1345.553	1210.967	134.586	2078.940
July	2544.529	1860.281	541.031	0.167	143.050	314.666	267.531	47.135	493.896	−420.576	73.320	1325.833	1193.214	132.619	2148.238
August	2565.565	1849.784	551.749	0.164	163.868	324.882	276.211	48.671	503.078	−425.589	77.489	1270.987	1143.852	127.135	2148.238
September	2568.195	1799.896	529.854	0.171	238.274	312.814	265.950	46.864	482.990	−409.230	73.760	1301.553	1171.367	130.186	2078.940
October	2681.092	1873.098	541.203	0.184	266.607	324.375	275.785	48.590	492.613	−422.554	70.059	1473.828	1326.414	147.414	2148.238
November	2649.461	1812.321	529.743	0.158	307.239	305.717	259.919	45.798	483.945	−409.988	73.957	1433.337	1289.968	143.369	2078.940
December	2668.107	1868.682	541.449	0.185	257.791	314.356	267.268	47.088	494.361	−423.486	70.875	1438.938	1295.008	143.930	2148.238
Total	*31505.984*	*22017.768*	*6371.469*	*1.998*	*3114.749*	*3704.875*	*3149.880*	*554.995*	*5816.474*	*−4953.761*	*862.713*	*16773.138*	*15095.379*	*1677.759*	*25293.770*

*In terms of electricity supply and battery charge, the PV supplies electricity to the AC load via the inverter and charges the battery directly, whereas the diesel generator supplies electricity to the AC load directly and charges the battery through the rectifier, as shown in Table 4. Also, the battery supplies electricity to the AC load through the inverter, as shown in this table.

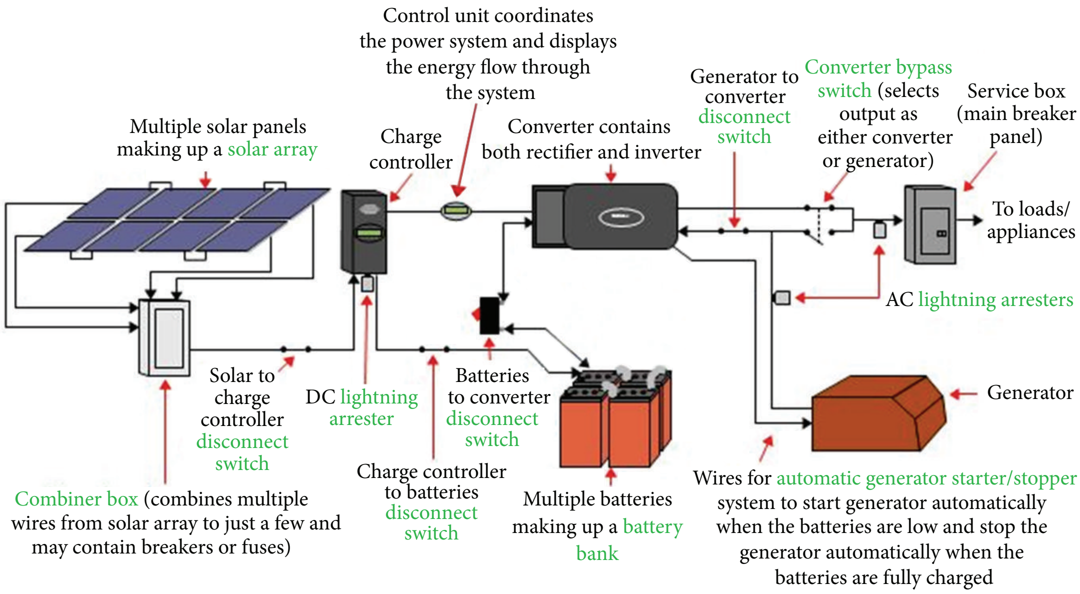

FIGURE 4: Photovoltaic hybrid power system structure [33].

TABLE 4: Results of each of the energy components of the hybrid system (PV and diesel) for electricity production, supply, and battery charging (kW).

Month	Electricity generated and supplied and battery charge by the PV in hybrid system (kW)			Electricity generated and supplied and battery charge by the diesel in hybrid system (kW)		
	Electricity generated	Supplied to the load via inverter	Charging the battery directly	Electricity generated	Supplied to the load directly	Charging the battery via rectifier
January	1538.295	987.628	239.282	1177.104	874.649	299.517
February	1510.492	971.970	199.718	1016.936	724.017	289.982
March	1705.644	1094.416	232.446	1096.767	792.623	301.472
April	1554.395	1045.610	219.627	1074.702	781.803	289.705
May	1488.347	1049.806	221.725	1143.499	826.317	314.101
June	1333.962	936.894	215.577	1188.892	867.973	313.288
July	1271.351	905.257	226.365	1273.178	955.024	314.666
August	1230.539	845.398	226.867	1335.026	1004.386	324.882
September	1343.075	892.323	217.040	1225.120	907.573	312.814
October	1534.355	1051.274	216.828	1146.737	821.824	324.375
November	1552.498	1023.349	224.026	1096.963	788.972	305.717
December	1499.299	1015.452	227.093	1168.808	853.230	314.356
Total	*17562.252*	*11819.377*	*2666.594*	*13943.732*	*10198.391*	*3704.875*

3.1.2. Converter Cost (US$ 0.320/Wp). The cost of a converter, based on prices cited by Nigerian suppliers, was US$ 0.320/Wp [35].

3.1.3. Battery Cost (US$ 180/kWh). The cost of a 6 V/225 Ah lead acid battery on the Nigerian market was found to be in the range of US$ 172 [35]. Including balance of system (BOS) components and labour/installation costs, the capital cost for the battery arrays was adjusted upward to US$ 180/kWh. The precise number of batteries required for each option is then determined by the simulation.

3.1.4. Generator Cost (US$ 1000/kW). The capital cost of the genset includes the generator itself (usually diesel or gasoline), as well as BOS costs and labour/installation costs. On the Nigerian local market, a generator of smaller range

(2–5 kVA) was priced at about US$ 991 [36]. Including BOS and labour/installation costs, the total price was estimated at around US$ 1,000 per kW load.

3.1.5. Fuel Cost (US$ 1.2/L). The source for this estimate was the Nigerian official market rate as of October 2015.

3.1.6. Interest Rate: 7.5%. Interest rates vary widely and can be particularly high in developing countries, having a profound impact on the cost-benefit assessment. Interest rates on Nigerian commercial bank loans may be between 6% and 7.5%. An estimate of 7.5% was selected for this case study.

4. Energy Losses in Stand-Alone PV/Diesel Hybrid Systems

Stand-alone PV/diesel hybrid systems are designed to be totally self-sufficient in generating, storing, and supplying electricity to the electrical loads in remote areas. Figure 5 shows an energy flow diagram for a typical PV/diesel hybrid system. The following equation (23) shows the energy balance of a PV/diesel hybrid system:

$$E_{\mathrm{IN}} \approx E_{\mathrm{OUT}}. \quad (23)$$

The energy that has to be supplied from the generator can be determined as

$$E_{\mathrm{MG}} = E_{\mathrm{LOAD}} + E_{\mathrm{LOSS}}\mathrm{R} - E_{\mathrm{PV}}. \quad (24)$$

The energy that has to be supplied from the photovoltaic can be determined as

$$E_{\mathrm{PV}} = E_{\mathrm{LOAD}} + E_{\mathrm{LOSS}}\mathrm{CC} + E_{\mathrm{LOSS}}\mathrm{B} + E_{\mathrm{LOSS}}\mathrm{I} - E_{\mathrm{MG}}. \quad (25)$$

The objective of this study (efficient energy balance) is to minimize the energy that has to be supplied from auxiliary energy source (diesel generator) by the addition of PV panels. Additionally, the motor generator should be operated near its nominal power to achieve high fuel efficiency by the inclusion of battery bank. As shown in (24) and (25), energy losses are flowing into the energy demand and supply of the system; therefore, it is necessary to identify the energy losses in the system. A classification of all relevant energy losses in a stand-alone PV hybrid system is given as capture losses and system losses [37]. Capture losses account for the part of the incident radiation energy that remains uncaptured and which is therefore lost within a global energy balance. Capture or irradiation losses translate the fact that only part of the incoming irradiation is used for energy conversion. System losses define systematic energy losses that are due to the physical properties of the system components or the entire installation. Energy conversion losses constitute important contributions to this category [38].

System losses cover all energy losses which occur during the conversion of generated energy into usable AC electricity. In this study, only the energy conversion losses were considered, to assess the potential of the designed hybrid system. The losses are indicated in Figure 5.

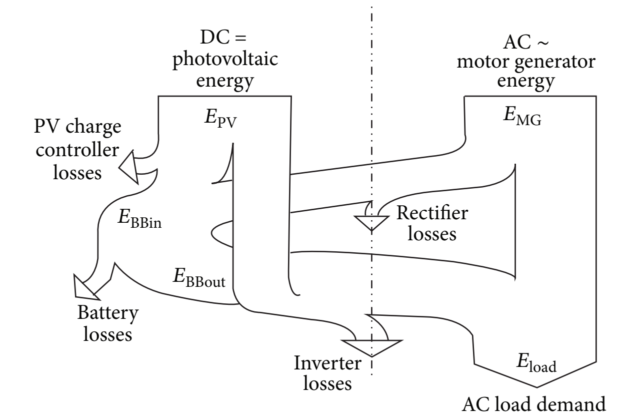

Figure 5: Energy flow diagram for a typical PV/diesel hybrid system [37].

5. Results and Discussion

The design provides an interesting example of how optimal combinations of photovoltaic and diesel generation with appropriate energy storage yielded multiple gains: a shift to renewable energy, a reliable supply for household energy needs, and lower overall cost of energy.

5.1. Results

5.1.1. Designed Hybrid System. To overcome the problem of the climatic changes, to ensure a reliable supply without interruption, and to improve the overall system efficiency, a hybrid system (that comprised a PV system, the diesel power system, and storage battery as backup sources) is essential as shown in Figure 4. The reasons for the inclusion of battery bank in this design are due to fluctuations in solar radiation and also for the generator to operate at optimum efficiency, because continued operation of generator at lower loads or severe variation in the load results in an inefficient engine performance and one of the options for the load management is to integrate battery bank (which becomes a load when charging to improve the generator efficiency) to improve the overall system efficiency. Considering various types and capacities of system devices (PV array, diesel generator, and battery size), the configurations which can meet the desired system reliability are obtained by changing the type and size of the devices systems. The configuration with the lowest LCE gives the optimal choice. Therefore, the optimal sizing of the hybrid system (PV-diesel generator-battery system) in terms of reliability, economy, and environment is shown in Tables 3, 5, and 6, respectively. This was determined through rigorous mathematical computations.

From the design results, the PV power supply is between 8:00 h and 19:00 h while the radiation peak is between 12:00 h and 14:00 h as can be seen in the supplementary data. Between 12:00 h and 14:00 h there is no deficit in the system and the PV energy supplies the load and charges the battery, thereby reducing the operational hours of the diesel generator and the running cost of the hybrid energy

Table 5: Comparative costs of hybrid power and stand-alone generator supply systems.

Configuration	PV capacity (kW)	Generator capacity (kW)	Number of batteries (6 V/225 Ah)	Converter capacity (kW)	Initial capital (US$)	Annual generator usage (hours)	Annual quantity of diesel (L)	Total net present cost (US$) for 20 years	Cost of energy (US$/kWh)	Renewable fraction
PV + generator + battery	15	5.4	16	5.5	41,048	5,011	5,716	192,231	0.745	0.59
Generator + battery	—	5.4	30	5.5	14,450	5,298	9,183	210,146	0.815	0.00

Table 6: Comparative emissions of hybrid power and stand-alone generator supply systems.

Configuration	Pollutant emission (kg/yr)						Fuel consumption (L/yr)	Operational hour of diesel generator (hr/yr)
	CO_2	CO	UHC	PM	SO_2	NO_x		
PV + generator + battery	15,052	37.2	4.12	2.8	30.2	332	5,716	5,011
Generator + battery	24,183	59.7	6.61	4.5	48.6	533	9,183	5,298

Note: PM refers to total particulate matter. UHC refers to unburned hydrocarbons.

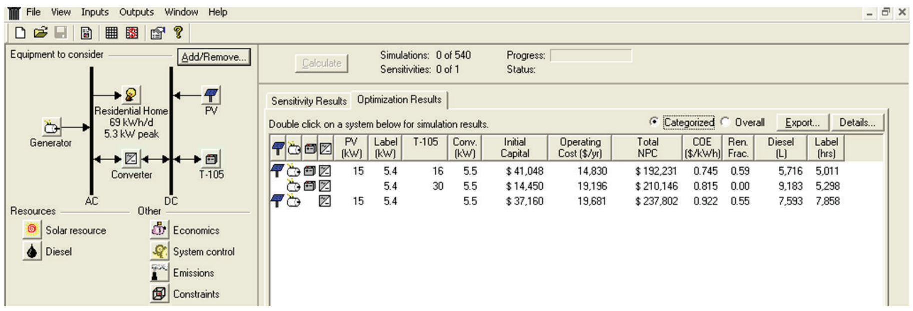

Figure 6: The optimization results from HOMER for hybrid PV/diesel energy system.

system as well as the pollutant emissions. There is likely to be deficit in other remaining hours due to poor radiation, and the deficit is being completed by either the battery or the diesel generator. The result of the demand met by the hybrid energy system (PV/diesel) over the course of the year is shown in the supplementary data; it shows how the sources were allocated according to the load demand and availability. It was observed that the variation is not only in the demand but also in the availability of solar resources. The battery or the diesel generator compensates the shortage depending on the decision mode.

5.1.2. Results from HOMER. The derivations from the developed software were compared to HOMER optimization method, and the same inputs used in calculations by the developed software were used by HOMER which produced the same results with the developed software as shown in Figure 6 (Figure 6 compared with Table 5). Therefore, the results from the software can be used as comparison and point of reference.

5.2. Discussion

5.2.1. Overall Energy Production and Utilization. From the design, solar power will not replace the need for diesel generator for this remote residential home but could offset a portion of the diesel fuel used. Although the residential loads provide the best possible match with PV output (since these loads typically peak during daytime and afternoon hours), there is still need for a backup with diesel generator (during the raining season and cloudy days).

In the solar resources, apart from the month of February that has 28 days, the month of March has the highest global and incident solar (207.568 kWh/m^2; 213.213 kWh/m^2), while the month of August has the least global and incident solar (159.232 kWh/m^2; 153.817 kWh/m^2) as shown in Table 7.

Table 7: Solar resources for the studied zone.

Month	Global solar (kWh/m^2)	Incident solar (kWh/m^2)	Power generated with 15 kW PV array (kW)
January	173.783	192.285	1538.295
February	176.292	188.814	1510.492
March	207.568	213.213	1705.644
April	198.460	194.312	1554.395
May	197.020	186.037	1488.347
June	178.982	166.744	1333.962
July	168.215	158.916	1271.351
August	159.232	153.817	1230.539
September	166.994	167.880	1343.075
October	182.472	191.792	1534.355
November	175.089	194.054	1552.498
December	165.744	187.409	1499.299
Total	*2149.851*	*2195.273*	*17562.252*

In the hybrid system configuration, the sizing was done in favour of PV system (to overcome the problem of the climatic changes), and in order to accommodate the load demand for all the months, excess electricity was generated by the PV system. The excess electricity generated differs from month to month and depends on the incident solar. The highest excess electricity is observed in March (381.30 kW), while the least is in the months of July (143.05 kW) and August (163.868 kW), the two months most affected by raining season.

In the month of March, the PV generated the highest electricity (1705.644 kW) and supplied to the load via inverter the highest electricity (1094.416 kW). This was because the month of March has the highest global and incident solar (207.568 kWh/m^2; 213.213 kWh/m^2), while in the month of August, the PV generated the least electricity (1230.539 kW) and supplied to the load via inverter the least electricity (845.398 kW) and this was due to least global and incident solar (159.232 kWh/m^2; 153.817 kWh/m^2). In this month of August, to ensure a reliable supply without interruption, the diesel due to the low electricity generated by the PV (caused by low incident solar) supplies to the load the highest electricity (1004.386 kW) and charges the battery via rectifier (to improve the overall system efficiency). In the month of August, battery charging (503.078 kW) and discharging (−425.589 kW) are highest due to low supply coming from the PV. The generator becomes ON often to serve the AC load and at the same time charge the battery (which is a DC load; battery becomes a load when charging). It is worthwhile noting from Table 3 that the PV-diesel hybrid solution supported by battery storage produces 17,562 kWh/yr (59%) from solar PV array and 13,944 kWh/yr (41%) from diesel generator making a total of 31,506 kWh/yr (100%).

5.2.2. Energy Flows. One of the main objectives of this study was to produce a detailed experimental accounting of energy flows through the hybrid system. In particular, my interest is in quantifying all system losses.

Hybrid PV/Diesel System with Battery. For the PV part of the hybrid system, device losses include PV charge controller losses, DC-AC conversion losses, both for energy flowing directly to the load and for energy transiting through the battery, and storage round-trip losses. On the generator side, the AC-DC conversion losses affect electrical energy that does not flow directly to the load. The reason for these losses on the generator side is that the hybrid system was designed to be cycle charging meaning that the diesel generator is allowed to charge the battery.

All losses through the hybrid system are classified as follows:

(i) PV charge controller losses.

(ii) Battery storage losses.

(iii) Rectifier (battery charger conversion) losses.

(iv) Inverter losses.

PV charge controller losses are due to the DC/DC conversion efficiency (converting energy generated by the PV to charge the storage battery). DC/DC conversion losses are generated during the control of the flow of current to and from the battery by the PV charge controller. Result shows that the losses are minimal when compared to other component losses (storage losses, inverter, and rectifier losses) as shown in Table 3.

Storage losses comprise all energy losses within a battery. They are described by the charge and discharge efficiencies of the battery as well as the self-discharge characteristics. In the month of August, the battery charging and the discharging as well as its losses (due to charge and discharge efficiencies) are highest due to the fact that diesel becomes ON often to charge the battery; when the battery reaches its maximum point of charge, the diesel stops while the battery starts discharging in order to power the load, and once the battery reaches its minimum point of discharge, it stops discharging and the diesel comes ON again. The process continues the same way until the PV starts to generate electricity to supply it to the load and charge the battery; otherwise, it returns to the diesel charging the battery. Results of the design show that the storage battery was charged with 227.093 kWh/yr and 314.356 kWh/yr by the PV and diesel system, respectively, making a total charge of 5816.474 kWh/yr, while the battery discharged (supplied) to the load via the inverter a total discharge of −4953.761 kWh/yr, having losses of 862.713 kWh/yr as shown in Tables 3 and 4.

Battery charger conversion losses are due to the rectifier's AC/DC efficiency. AC/DC conversion losses are generated during battery charging from an AC source. In the month of August, the rectifier receives the highest electricity from the diesel generator due to the month's least global and incident solar (159.232 kWh/m^2; 153.817 kWh/m^2) and this affects the production from the PV; at this point the diesel comes ON in order to ensure a reliable supply without interruption. Results of the design show that the rectifier was supplied with 3704.875 kWh/yr and rectified to the battery with 3149.880 kWh/yr, having losses of 554.995 kWh/yr as shown in Tables 3 and 4.

Inverter losses are due to the inverter's DC/AC efficiency. DC/AC inverter losses occur before the initially provided energy can be consumed by an AC load. It means that all electrical energy that does not flow directly to the AC load passes through the inverter such as electricity flowing from the PV system, electricity rectified to the battery, and the one coming from the battery. In the month of August, the inverter receives the least electricity from the PV and battery due to the month's least global and incident solar (159.232 kWh/m^2; 153.817 kWh/m^2). Although the battery receives the highest charging of 503.078 kW from both the PV (226.867 kW) and diesel (rectified to the battery with 276.211 kW), the inverter still receives the least electricity because the diesel comes often to supply the AC load and charge the battery; the charging of the battery by the rectifier shows how often diesel supplies electricity to the load in this month of August as shown in Tables 3 and 4.

In conclusion, while the DC/DC conversion efficiency is generally low, the AC/DC rectifier (battery charger conversion) efficiency is somewhat lower than the DC/AC inverter efficiency as shown in Table 3.

5.2.3. Economic Costs. The capital cost of a PV/diesel hybrid solution with batteries is nearly three times higher than that of a generator and battery combination (US$ 41,048), but the net present cost, representing cost over the lifetime of the system, is less than one-half of the generator and battery combination (US$ 192,231), as shown in Table 5. The net present cost (NPC) of the PV/diesel/battery hybrid system is slightly lower than the NPC of the diesel/battery combination as a result of less fuel consumption and because fewer storage batteries are needed, and replacing batteries is a significant factor in system maintenance.

5.2.4. Environmental Pollution. On the environmental impact perspective, an increase in the operational hours of diesel generator brings about increase in the fuel consumption as well as an increase in GHG emission, whereas a reduction in the operational hours of diesel generator brings about reduction in the fuel consumption, thereby a reduction in GHG emission. Diesel system operates for 5,298 h/annum, has a fuel consumption of 9,183 L/annum, and generates in kilogrammes (kg) the pollutant emissions as shown in Table 6, while in the hybrid PV-diesel system, diesel generator operates for 5,011 h/annum, has a fuel consumption of 5,716 L/annum, and emits in kilogrammes the pollutant emissions annually into the atmosphere of the location of the residence as shown in Table 6. Reducing fuel consumption also means less emission from the energy system as shown by the solar PV-diesel system which has the lowest pollutant emissions.

6. Conclusion

This paper investigates the designing of a stand-alone hybrid power system focusing on photovoltaic/diesel energy system with energy storage in batteries. Starting from the analysis of the models of the system components, a complete simulation model is realized. From the designed system, a detailed experimental accounting of energy flows through the hybrid system was produced and all system losses caused by PV charge controller, battery storage round-trip, rectifier, and inverter conversions were quantified and documented. Results show that PV charge controller losses are due to the DC/DC conversion efficiency and are generated during the control of the flow of current to and from the battery by the PV charge controller, while storage losses comprise all energy losses within a battery and are described by the charge and discharge efficiencies of the battery as well as the self-discharge characteristics. In addition, battery charger conversion losses are due to the rectifier's AC/DC efficiency and are generated during battery charging from an AC source, while inverter losses are due to the inverter's DC/AC efficiency and occur before the initially provided energy can be consumed by an AC load. From the results, it has proven that the DC/DC conversion efficiency is generally low, while the AC/DC rectifier efficiency is somehow lower than the DC/AC inverter efficiency. Also, it has been demonstrated that the use of hybrid PV/diesel system with battery (one unit of 15 kW PV array, one unit of 5.4 kW generator, with 16 units of battery) can significantly reduce the dependence on solely available diesel resource. The designed hybrid system minimizes diesel operational hour and thereby reduces the fuel consumption which significantly affects (reduces) the pollution, such as carbon emission, thus reducing the greenhouse effect. Although utilization of hybrid PV/diesel system with battery might not significantly reduce the total NPC and COE, it has been able to cut down the dependence on diesel. On the other hand, it was also proven that the use of hybrid PV/diesel system with battery would be more economical if the price of diesel increased significantly. With a projection period of 20 years and 7.5% annual real interest rate, it was found that the use of hybrid PV/diesel system with battery could achieve significantly lower NPC and COE as compared to a stand-alone diesel system. As a conclusion, the hybrid PV/diesel system has potential use in replacing or upgrading existing stand-alone diesel systems in Nigeria.

Nomenclature

A: The surface area in m^2
$C_{acap,c}$: Annualized capital cost of a component
$C_{arep,c}$: Annualized replacement cost of a component
$C_{aop,c}$: Annualized operating cost of a component
$C_{acap,s}$: Annualized capital cost of solar power
$C_{arep,s}$: Annualized replacement cost of solar power
$C_{aop,s}$: Annualized operating cost of solar power
$C_{acap,g}$: Annualized capital cost of diesel generator
$C_{arep,g}$: Annualized replacement cost of diesel generator
$C_{aop,g}$: Annualized operating cost of diesel generator
$C_{af,g}$: Annualized fuel cost for diesel generator
$C_{acap,b}$: Annualized capital cost of batteries power
$C_{arep,b}$: Annualized replacement cost of batteries power
$C_{aop,b}$: Annualized operating cost of batteries power
$C_{acap,c}$: Annualized capital cost of converter power
$C_{arep,c}$: Annualized replacement cost of converter power
$C_{aop,c}$: Annualized operating cost of converter power
C_{cap}: Initial capital cost of the component
c_{CO_2}: Cost for emissions of carbon dioxide (CO_2) ($/t)
c_{CO}: Cost for emissions of carbon monoxide (CO) ($/t)
c_{UHC}: Cost for emissions of unburned hydrocarbons (UHC) ($/t)
c_{PM}: Cost for emissions of particulate matter (PM) ($/t)
c_{SO_2}: Cost for emissions of sulfur oxide (SO_2) ($/t)
c_{NO_x}: Cost for emissions of nitrogen oxide (NO_x) ($/t)
$C_{oc}(t)$: The cost of operating component
C_{rep}: Replacement cost of the component
$\mathrm{CRF}(i, R_{proj})$: Capital recovery factor
$E_{BAT}(t-1)$: The energy stored in battery at hour $t-1$, kWh
$E_{Needed}(t)$: The hourly load demand or energy needed at a particular period of time
$E_{REC\text{-}OUT}(t)$: The hourly energy output from rectifier, kWh
$E_{REC\text{-}IN}(t)$: The hourly energy input to rectifier, kWh
$E_{SUR\text{-}AC}(t)$: The amount of surplus energy from AC sources, kWh
$E_{DEG}(t)$: The hourly energy generated by diesel generator
$E_{PVG\text{-}IN}(t)$: The hourly energy output from inverter (in case of SPV), kWh
$E_{PVG}(t)$: The hourly energy output of the PV generator

$E_{BAT\text{-}INV}(t)$: The hourly energy output from inverter (in case of battery), kWh
$E_{BAT}(t-1)$: The energy stored in battery at hour $t-1$, kWh
$E_{LOAD}(t)$: The hourly energy consumed by the load side, kWh
$E_{CC\text{-}OUT}(t)$: The hourly energy output from charge controller, kWh
$E_{CC\text{-}IN}(t)$: The hourly energy input to charge controller, kWh
$E_{REC\text{-}OUT}(t)$: The hourly energy output from rectifier, kWh
$E_{SUR\text{-}DC}(t)$: The amount of surplus energy from DC source (PV panels), kWh
$E_{BAT}(t)$: The energy stored in battery at hour t, kWh
E_{IN}: Is equal to $E_{PV} + E_{MG}$
E_{OUT}: Is equal to $E_{LOAD} + E_{LOSS}$
E_{PV}: Energy generated by the PV array (kWh)
E_{MG}: Energy generated by the motor generator (kWh)
E_{LOAD}: Energy supplied to the load (kWh)
E_{LOSS}: Energy losses (kWh), which comprise all ($E_{LOSS}\mathrm{CC} + E_{LOSS}\mathrm{B} + E_{LOSS}\mathrm{R} + E_{LOSS}\mathrm{I}$)
$E_{LOSS}\mathrm{CC}$: Energy losses via charge controller (kWh)
$E_{LOSS}\mathrm{B}$: Energy losses via battery (kWh)
$E_{LOSS}\mathrm{R}$: Energy losses via rectifier (kWh)
$E_{LOSS}\mathrm{I}$: Energy losses via inverter (kWh)
$G(t)$: The hourly irradiance in kWh/m^2
i: Interest rate
INT( ): The integer function, returning the integer portion of a real value
M_{CO_2}: Annual emissions of CO_2 (kg/yr)
M_{CO}: Annual emissions of CO (kg/yr)
M_{NO_x}: Annual emissions of NO_x (kg/yr)
M_{PM}: Annual emissions of particulate matter (PM) (kg/yr)
M_{SO_2}: Annual emissions of SO_2 (kg/yr)
M_{UHC}: Annual emissions of unburned hydrocarbons (UHC) (kg/yr)
N: Number of years
P: The PV penetration level factor
R_{proj}: Project lifetime
R_{comp}: Lifetime of the component
SFF( ): Sinking fund factor
η_{PVG}: The efficiency of PV generator
η_{DEG}: The diesel generator efficiency
η_{REC}: The efficiency of rectifier
η_{INV}: The efficiency of inverter
η_{DCHG}: The battery discharging efficiency
η_{CC}: The efficiency of charge controller
η_{CHG}: The battery charging efficiency.

Competing Interests

The author declares no competing interests.

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