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Original Research

Design and Techno-Economic Evaluation of a Hybrid Mini-grid System for an Academic Institution

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Abstract

Inadequate electricity supply is a global challenge that needs solutions. This situation has compelled the purchasing of fossil fuel-generating units for use in residential, commercial, and industrial sectors to generate electricity. However, using fossil fuel generating units cause greenhouse gas emissions, bringing about environmental pollution and ultimately resulting in climate change. In particular, educational institutions require adequate and reliable power supply to ensure proper learning and teaching, which is lacking in developing countries like Nigeria. Fortunately, Nigeria has enormous renewable energy sources such as solar energy, which can be utilized through photovoltaic (PV) modules to generate clean energy fed into a mini-grid. This novel approach focused on an educational institution that will enable adequate electricity from the mini-grid for proper learning and teaching, reduced negative environmental impacts, and lower energy costs. Therefore, this research is focused on developing an effective hybrid utility grid-diesel generator-solar PV mini-grid system for the Faculty of Engineering and Technology of the Nigerian Defence Academy, Kaduna. Design analysis and techno-economic evaluation of the mini-grid were carried out using the HOMER Pro software tool, which was also used to simulate and optimize the mini-grid. The results revealed that the hybrid system comprising the grid, diesel generator, PV, and converter was technically and economically viable. The net present cost (NPC) of $182,065.20, producing a total energy of 836,430 kWh/year, was obtained and gave 0.00198 $/kWh as a levelized cost of energy (LCOE). Correspondingly, a renewable fraction (RF) of 98.3% was attained, thus meeting the Faculty's daily load demand of 575.64 kWh/day, thereby providing a reliable and improved energy supply at the best cost. Therefore, a hybrid system such as this one is proposed for tertiary institutions to ensure greater electric power supply availability.

Keywords

Energy; photovoltaic; hybrid; HOMER; net present cost; levelized cost of energy

1. Introduction

The need for energy today is increasing as the world's population is experiencing an explosion. There has been a mismatch between energy demand and supply because demand is inconsistent with supply due to the minimum generation levels. Nigeria, as one of the world's developing nations, is suffering energy bankruptcy due to this inefficient generation state that is failing to meet the ever-increasing demand resulting from an increase in population. Thus, generation from the conventional source is not feasible as most generating plants are not utilized maximally for their intended purposes due to several factors. Some factors include technical know-how regarding the workforce, poor resource allocation, lack of energy mix, poor maintenance, inadequate gas infrastructure, and use of obsolete equipment. In order to meet the increasing demand, it is necessary to utilize alternative energy sources. Fortunately, Nigeria is endowed with renewable sources, and harnessing them could be used to curb the current situation. Academic institutions have high energy requirements due to laboratory experiments and other academic needs that utilize electricity. The scarcity of electricity in such institutions can limit and retard learning which in turn affects the output of both the staff and students. Therefore, alternative energy sources in hybrid energy systems can curb these trends to ensure continuity of supply. Hybrid mini-grid energy systems combine two or more energy-generating sources to ensure a stable electric power supply in schools, hospitals, offices, and other settings, as the case may be. Therefore, to ensure a stable electric power supply in academic institutions, this research evaluates a hybrid system comprising a utility grid, diesel generator, PV, and converter.

1.1 Review of Related Literature

A study was conducted by Okedu *et al.* [1]. A model was proposed by comparing an on-grid and off-grid hybrid system integrating a diesel generator and photovoltaic (PV) module to supply electricity to a remote community. In the study, diesel generators and PVs, as well as diesel generators, PVs, and grids, were simulated using HOMER software to determine the optimal configuration that is economically viable. The simulation results revealed that the on-grid PV and diesel generator model was the most viable and optimal system. This system had a Net Present Cost (NPC) of $38,215, a Levelized Cost of Energy (LCOE) of 0.0017 $/kWh, an operating cost of 2,684 $/year, and a renewable fraction of 63%. Comparing these results with the off-grid PV and diesel generator model, the model gave an NPC of $79,144, LCOE of 0.064 $/kWh, operating cost of 5,534 $/year, and a renewable fraction (RF) of 95%, which is way higher than the on-grid hybrid model.

A comparative study was carried out by Sadat *et al.* [2] in ten (10) cities of eight (8) different climates of Iran. The HOMER Pro software simulated a combination of wind turbine (WT), PV, grid, battery energy storage (BES), and converter. From the input parameters, including meteorological data, economic data, optimization constraints, and load data, PV/WT was the optimum configuration for the hybrid microgrid (HMG). The results showed that the NPC and COE of the proposed system at Urmia had the lowest operating cost, which falls in the semi-moderate and rainy climatic region, giving an NPC of (-5839 $) and COE of (-0.0122 $/kWh), which resulted from an HMG of 4.8 kW of PV and 9 kW of WT respectively. This combination also gave an RF of 96.7%. Furthermore, it was discovered that wind speed, solar irradiance, and ambient temperature significantly impact the optimal configurations of the HMG. The results indicated that from the economic and technical perspectives, the northwestern cities with semi-moderate and rainy climatic conditions, like Urmia and Lighvan, are the most suitable locations for implementing HMGs.

In another study, ten (10) locations were considered in South Africa to conduct a techno-economic evaluation of a grid-connected micro-grid system [3]. In the research, PV was utilized for clean energy generation with reduced GHG emissions using the same KPIs in all the selected sites. The HOMER tool was used in the analysis using the available solar data. Out of these locations, it was found that the annual radiation lies between 4.3 $kWh/m^2/day$ in Durban and 5.7 $kWh/m^2/day$ in De Aar. Thus, De Aar was found to be the most feasible location for the installation of PV for energy generation, revealing that an efficient way to generate energy in the country is by utilizing the available solar resources.

Beza *et al.*[4], conducted a study in Ethiopia to address the challenge facing electricity access on an island. A diesel generator (DG) was used as the base case for power generation in the study location. It was compared with a hybrid of renewable PV, wind, and battery systems sources to supply a load of 76.94 kWh/day. The HOMER Pro software was used to simulate the proposed hybrid system. The results revealed that the most optimal hybrid mini-grid system was a PV/DG/battery system of 25 kW of PV, 10 kW of DG, and 40 batteries of 1 kW each, which gave LCOE, NPC, and RF of $0.175/kWh, $119,139 and 86.4% respectively and also reduced GHG emissions by 33,102 kg/year as compared with the DG standalone. This hybrid configuration was found to be the least expensive compared to the base case and other hybrid configurations considered in the study. Similarly, a sensitivity analysis was carried out with a variation of global horizontal irradiation (GHI), diesel price, and load demand and gave LCOE of $0.179/kWh, NPC of $151,468, and RF of 69.1%. This further confirmed the system as the most viable and optimal configuration.

Jumare *et al.*[5], carried out a study in northern Nigeria to determine the energy generation viability of a hybrid grid-connected PV, wind, and biogas. The input parameters they used for the proposed model include the solar PV system model, wind turbine system model, and biogas system model, alongside all their economic parameters to generate electricity that could meet the load demand. HOMER software, Microsoft Excel, and Ganzleitliche Bilanz (GaBi) tools were used for data collection, design, and optimization of the system and to observe the optimized model's impacts. The study revealed that a PV comprising 1500 kW, 1000 kW converter, 150 batteries, 30 wind turbines, and 3500 kW biogas GenSet was the most feasible for the off-grid scenario. Consequently, a PV of 2000 kW with a converter of 1000 kW, 30 wind turbines, and 2500 kW biogas GenSet was more feasible for the grid-connected system. Thus, this typically shows that the grid-connected model is more economically and technically viable to serve a load of 14,978 MW yearly, reducing emission and the size of components, which, in response, affected the NPC and LCOE, respectively.

Chewel and Fugal are two rural communities in The Gambia with no electricity from the grid. The two neighboring communities were used as case studies to determine the effectiveness of energy production using PV technologies [6]. In the study, it was found that the region has an average temperature of 31°C with an average solar irradiation of 6.16 kWh/m^2/day, having load estimates of 49.15 kWh/day with a peak load of 8.1 kW and 27.375 kWh/day with a peak load of 4.725 kW for Fuga and Chewel respectively. The simulation results obtained using HOMER software showed that to generate and supply electricity to these villages, a PV system with a capacity of 15 kW and a total of 96 × 12 V batteries are needed, with 4 batteries per string and an inverter of 15 kW. This revealed that the annual NPC, LCOE, and system operation costs are $164,192, $1,060, and $4,303, respectively. This gave rise to the overall capital cost of $122,337, $12,889, and $29,946 as a replacement, as well as operation and maintenance costs for 10 years, respectively.

A study was conducted in Oman to supply the lighting load for the renewable energy lab at Sohar University by determining the optimal sizing of photovoltaic systems using HOMER [7]. In the project, a PV system with a lifespan of 25 years, a battery with a lifespan of 5 years, and an inverter with a lifespan of 15 years used HOMER software as the simulation tool. The results of the optimized PV system revealed that the PV-rated capacity of 0.7 kW produced 1,316 kWh/year of energy with an initial cost of $13,500 and an operating cost of 817 $/year. Furthermore, the COE was found to be 1.354 $/kWh. Also, the NPC for the optimal system was four batteries with a converter size of 1 kW, depending on the size of the PV panel.

Five rural communities were studied in Chad to ascertain the techno-economic viability of PV technology for its adaptation as an alternative for energy generation [8]. The analysis used PVsyst and PVGIS as simulation tools, and the LCOE techniques were adopted. The study revealed that the annual generation in the studied sites ranged from 233 MWh/year to 3585 MWh/year. The estimated energy production of 3218 MWh/year, with a capacity of 204 kW, was observed at Guelendeng, making it the site with the highest PV energy production. The lowest PV energy production site was recorded at Mombou, having estimated energy produced at 211 MWh/year with a capacity of 134/kW. The projected lifespan was 25 years, and the LCOE was determined to be 0.30 €/kWh for four villages, while Mailo was calculated to be 0.31 €/kWh. This highlights the cost-effectiveness of deploying PV systems compared to the cost from the national electricity company, which stands at 0.45 €/kWh.

In Southern Louisiana, United States of America, a study was conducted where various PV modules were evaluated through simulation to determine the final yield, performance ratio, and capacity factor. The PV modules used were monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si), and copper indium gallium selenide (CIGS), which are all PV modules [9]. The study location was Louisiana Solar Energy Lab, which has 1.1 MW (AC) PV capacity and is used to supply 3% of the energy demand of the University of Louisiana at Lafayette. In the study, PVsyst and System Advisor Model (SAM) were used in the simulations, and the results differed from the same technologies in other regions. Furthermore, the results revealed that mono-Si and poly-Si modules have performance ratios of 0.77 and 0.73, respectively, both indicating fewer performances as compared with the CIGS module, which had a 0.79 performance ratio, suggesting that it is the most suitable PV module that can be used for installation in the location of the research.

A study conducted by Aliyu *et al.* [10] focused on developing a framework that could be used to ascertain the different technologies that could be deployed and utilized at different locations to meet energy demand. The research in Nigeria considered three configurations: off-grid, on-grid, and all-off-grid. Linear Programming in the MATLAB environment was utilized for optimization, revealing that certain regions in the country were suitable locations for wind and solar PV installations. Kaduna was found to have wind and solar PV installation potentials of 46.5% and 53.49%, respectively. Wind was not a viable RE source in the southern part of the country. Furthermore, Nigeria's most optimal configuration was a combination of off-grid and on-grid, particularly as the total installation cost was $211.49 billion against the all-off-grid configuration, which costs $244.33 billion for installation.

Gbadamosi *et al.* [11] researched the techno-economic benefits of a hybrid system for an educational institution. The research, which was carried out in Nigeria, considered four (4) different hybrid scenarios such as diesel generator + utility grid, diesel generator + utility grid + solar PV, inverter and battery system, diesel generator + solar PV, inverter and battery system and utility grid + solar PV, inverter and battery system respectively. The HOMER tool was utilized to simulate the different scenarios, and the results indicated that the optimal configuration was the grid + solar PV. This configuration reduced energy costs by 45% with a corresponding reduction of CO_2 emission by 32.09%, showing how environmentally friendly and economically viable it is for an academic institution.

A study conducted by Shamim *et al.* [12] noted that the issue surrounding energy security has made it imperative for alternative energy sources to be utilized where RESs are at the forefront of their usage. In Bangladesh, PV systems are the most RESs used for electricity generation, becoming more evident daily. The study proposed a grid-connected PV system. HOMER was used to evaluate raw data, create a demand cycle using the survey load data, and determine the most effective configuration. The study indicated that 0.0725 $/kWh was the estimate for electricity generation in Younus Khan Scholar's Garden in Bangladesh. Grid-connected PV was found to be the most optimal system. However, the study only compared grid-connected solar PV systems with grid-only and diesel-generator-only systems.

Furthermore, Mazzeo et al. [13] conducted a worldwide techno-economic mapping and optimization of Stand Alone and Grid Connected PV-wind Hybrid Renewable Energy Systems (HRES) to supply the electrical demand of an office building district. In this study, energy and economic optimization problems were formulated to find the optimal SA and GC systems worldwide among 343 HRES system power configurations located in 48 different localities, uniformly divided into the sub-group of the Koppen classification. The study revealed that to install a Stand Alone HRES, the most suitable climate conditions are in Toamasina (Madagascar) from an energy point of view, with

76% of load satisfied, and Cambridge Bay (Canada) from an economic point of view, with 11.1% of the capital cost recovered each year. For installing a Grid Connected HRES, New Delhi (India) has the most suitable climate conditions from an energy perspective. Here, 48% of the energy is exchanged with the grid for each kWh required by the load. On the other hand, Lihue (Hawaii, United States) is the most suitable location economically. Here, 24.3% of the capital cost is recovered each year.

Also, Johannsen *et al*. [14] investigated the feasibility of a hybrid PV/wind system diffusion of technology, assessing the state of the Kenyan mini-grid sector and categorizing identified barriers accordingly. Results of the techno-economic modeling showed that PV/wind hybrids have both technical and economic potential at average wind speeds above 4.5 m/s but little relevance below.

Based on the previous literature review, a hybrid system comprising the utility grid, diesel generator, PV, and converter is considered in this study in order to bridge the knowledge gap and ensure adequate electric power supply at the minimum cost. Therefore, the optimization is focused on economic constraint. The range of diesel costs was taken as \$1.80/l to \$2.00/l, solar irradiation taken as 4.53 kWh/m^2/day to 5.90 kWh/m^2/day and load demand taken from 518.076 kWh/day to 805.896 kWh/day respectively.

The objective function uses the available power to meet the demand and also minimize the cost. The NPC was utilized to rank the system overall using HOMER Pro.

$$C_{NPC} = C_{i,O\&M} - C_R \ (\$) \tag{1}$$

This shows that the system cost over the lifetime is a summation of the grid, diesel generator, PV panels, battery, and converter costs, all given in equation (2).

$$C_{NPC} = C_g + C_{dg} + C_{pv} + C_b + C_c \ (\$) \tag{2}$$

The goal is to solve for an optimal hybrid mini-grid system with minimum NPC as the objective function, which is given by equation (3).

$$C_{NPC_{minimum}} = \sum\nolimits_i^n C_{(i,P_i)} \ \ (\$) \tag{3}$$

This equation gives the overall cost function of the system where P is the overall power of the optimized system, and i is the number of components that the overall power system is composed of.

The annualized cost of the system, as shown by Gbadamosi *et al.* [11] is given by the expression

$$ACS = \sum_{i=1}^{n} ACC_i + AOMC_i + ARC_i - S_i \ \ (\$/\text{yr}) \tag{4}$$

where

ACC_i = annualized capital cost of each component and is given by

$$ACC = CRF_{(i,proj)} \sum_{i=1}^{n} Cap, i \ \ (\$/\text{yr}) \tag{5}$$

$AOMC_i$ = annualized operation and maintenance cost of each component

$$AOMC = \sum_{i=1}^{n} AOMC_{c,i} \ (\$/\mathrm{yr}) \tag{6}$$

ARC_i = annualized replacement cost of each component

$$ARC = \sum_{i=1}^{n} ARC_{c,i} \ (\$/\mathrm{yr}) \tag{7}$$

S is the salvage value of the system and is obtained using

$$S = C_{repl} \frac{R_{rl}}{R_{cl}} \ (\$/\mathrm{yr}) \tag{8}$$

where C_{repl} is the cost of replacement ($), R_{rl} is the remaining life of the components, and R_{cl} is the lifetime (yr) of the component.

The total (net) power of the entire system is as shown by the expression in equation (9) by Kumar *et al.* [15]

$$P_{net}(t) = P_g(t) + P_{DG}(t) + P_{pv}(t) - P_d(t) \ (\mathrm{kW}) \tag{9}$$

where P_g is the grid power purchased, P_{DG} is the power from the DG, P_{pv} is the output power from the PV, and P_d is the load demand.

1.2 Problem Statement

Inadequate and unreliable electricity supply in educational institutions of developing countries such as Nigeria has been a significant problem for decades. This has impeded proper learning and teaching, hampering such countries' development. On the other hand, most developing countries have abundant renewable energy resources, particularly solar energy. Thus, designing and implementing a hybrid energy system incorporating solar photovoltaic systems can address the problem. The reviewed literature indicates that the use and implementation of a hybrid energy system to guarantee a sufficient and uninterrupted energy supply for an educational institution, ensuring a conducive learning environment, has not been conducted. Considering the need for educational institutions to have an adequate and reliable power supply to ensure proper learning and teaching, lacking in developing countries such as Nigeria, this study became vital. This novel approach focused on an educational institution that will enable adequate electricity from the mini-grid for proper learning and teaching, reduced negative environmental impacts, and lower energy costs. This study aimed to harness the available RE resources, especially solar resources, in conjunction with a mix of DG integrated into the grid to assess the efficiency. The results indicated the feasibility of this approach in the study location, considering the available resources and current economic conditions.

2. Materials and Methods

This section elaborates on the various materials utilized in the study and the methods employed in conducting the research.

2.1 Study Location Description

The study location was the Faculty of Engineering and Technology, Nigerian Defence Academy, Airport Road, Afaka, Kaduna, Nigeria. Chen and Chen [16] reported that the Koppen Climate Classification has five (5) major groups: A-Tropical, B-Dry, C-Mild, D-Snow, and E-Polar. Based on this Classification, Nigeria, specifically Kaduna, the study area, falls under group A, the Tropical region. It is worth noting that the tropical region has abundant sunshine. The location has longitudinal and latitudinal values of 10°36’55.80’’N and 7°21’58.81’’E, respectively. Figure 1 shows the satellite image of the study site.

Figure 1 Satellite Image of the Faculty of Engineering NDA.

The meteorological data of the location of the study were obtained from the National Aeronautics and Space Administration (NASA), which is incorporated into the HOMER Pro software tool used in the study. The Solar Global Horizontal Irradiance and the clearness index were obtained and shown in Figure 2. The average gave 5.65 kWh/m^2/day for the GHI daily radiation and 0.578 as the clearness index across the year, respectively.

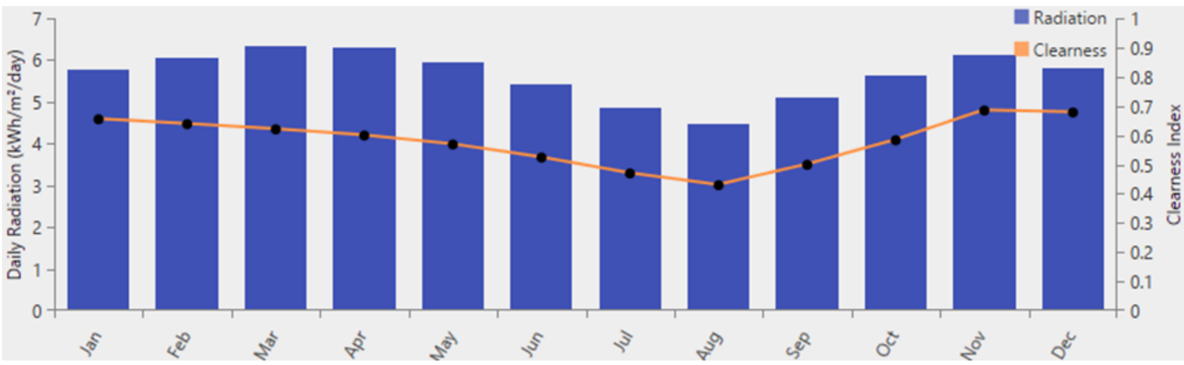

Figure 2 Graph of Monthly Solar Radiation and Clearness Index.

The location's average daily temperature is 23.93°C, obtained from NASA data shown in Figure 3.

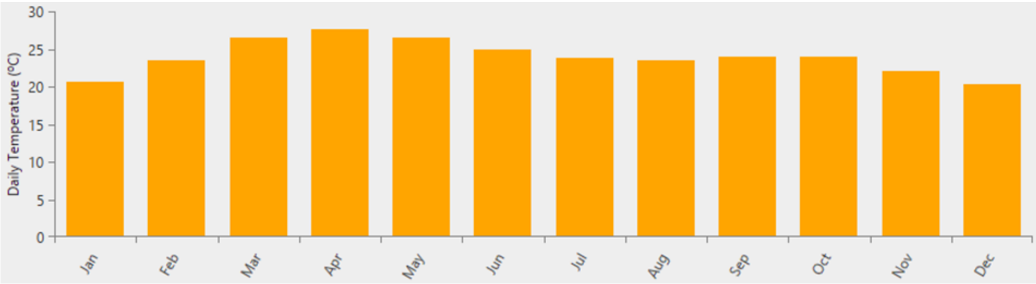

Figure 3 Graph of Monthly Average Temperature Data.

The Faculty building's average daily power consumption was 575.64 kWh. This value was used to calculate the required capacities and sizes of components necessary to design the hybrid mini-grid model. Figure 4 shows the study facility's daily, monthly, and average load profile.

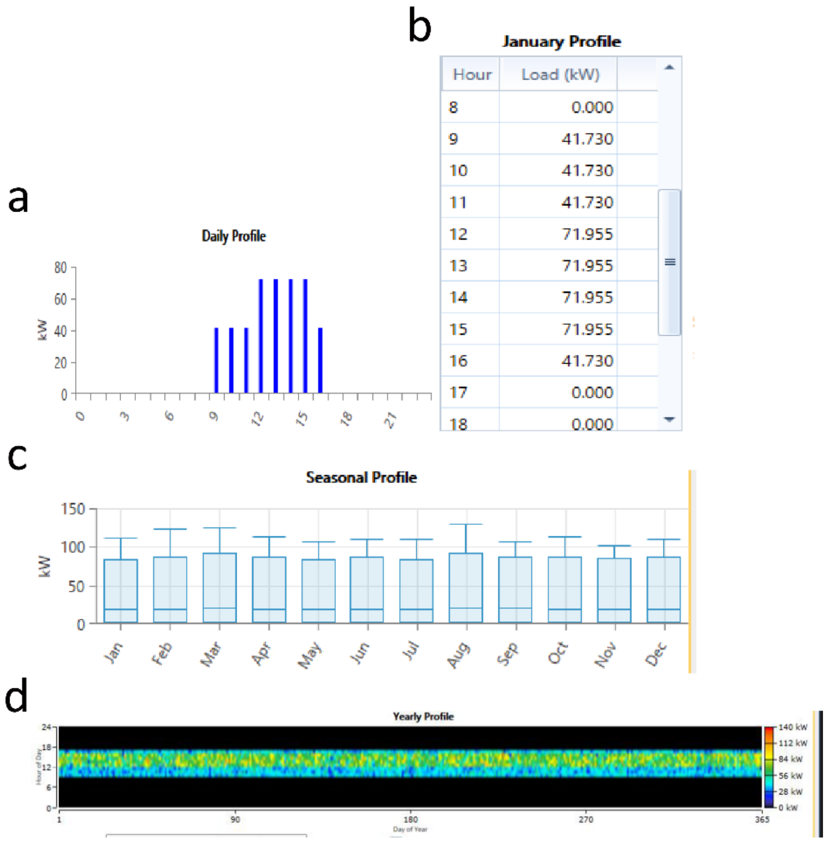

Figure 4 (a) Graphical Daily Load Profile. (b) Numerical Daily Load Profile. (c) Seasonal Load Profile. (d) Yearly Load Profile.

2.2 Methodology

The software platform that was used to simulate the hybrid mini-grid design was HOMER Pro software. Figure 5 illustrates the HOMER Pro optimization framework utilized in this research work. From Figure 5, the daily, monthly, and yearly load data of the study's site location was taken to determine the load data, and the same was used as the load demand used for simulation. The site's daily, monthly, and yearly meteorological data were taken to determine the solar radiation and temperature of the site location used in the simulation. These data were employed to ascertain the economic and electrical characteristics of the components of the mini-grid utilized for simulation. The optimization constraints, such as the technical viability of the system as well as the systems' economics, were also determined using the components and their prevailing market prices at the region of the research. These were all used with the objective function to simulate the designed mini-grid system, which gave the optimal system configuration with the Net Present Cost (NPC), the Levelized Cost of Energy (LCOE), and the sensitivity results of the optimal mini-grid system.

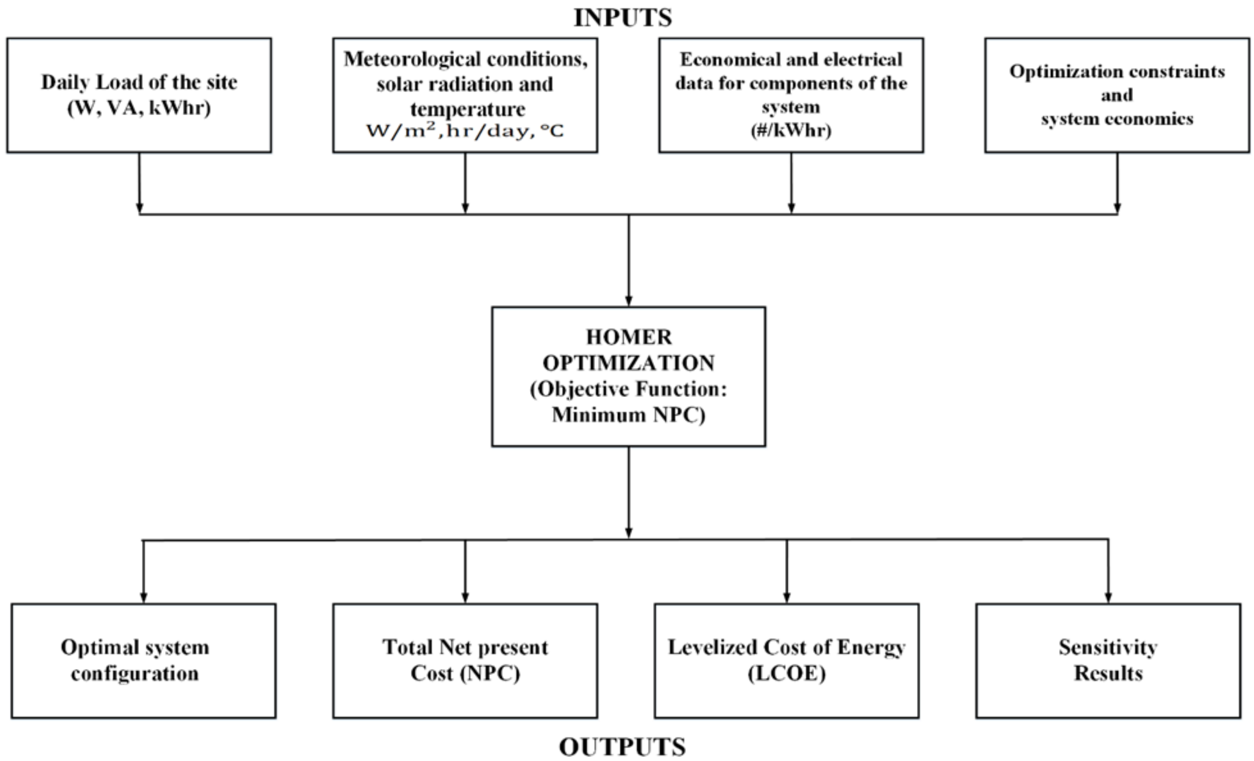

Figure 5 HOMER Pro Optimization Framework.

2.3 Technical Computation of the System

The technical composition of the hybrid mini-grid system are grid, diesel generator, PV, storage system, and converter. The schematic representation of a typical hybrid mini-grid system is depicted in Figure 6, illustrating the connection of the DG, Grid, and AC load to the AC bus. The PV and battery are in DC form, hence their connection to the DC bus. Between the AC bus and DC bus is a converter that converts DC to AC and AC to DC, respectively.

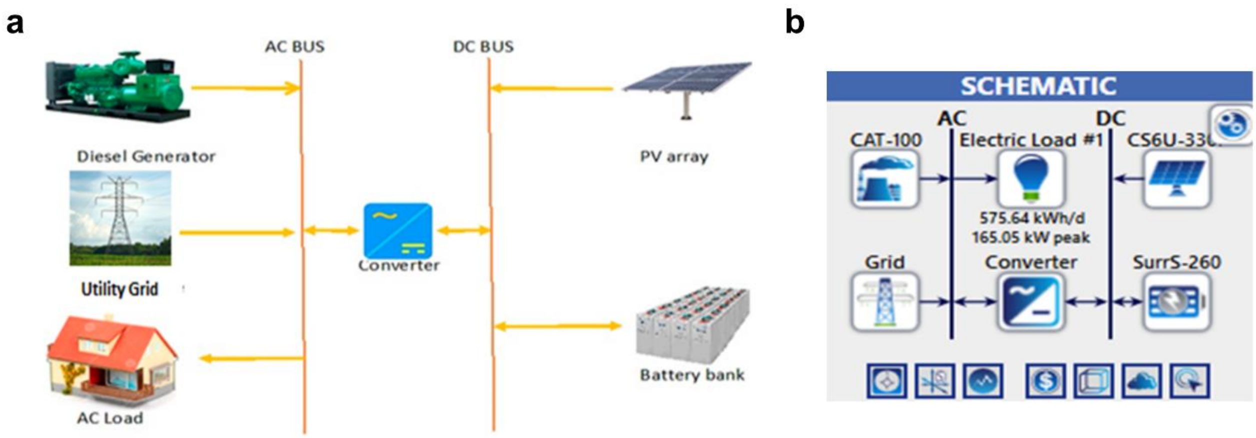

Figure 6 (a) Schematic representation of a Hybrid Mini-grid. (b) Designed Hybrid Mini-grid System Model on HOMER Pro.

Figure 6b shows this same schematic representation in the HOMER Pro environment.

2.3.1 Utility Grid

In this study, the grid served as the base case. Considering the COE provided by the energy providers in the study location, the location falls under Band A, which is expected to get power from the grid for at least 20 hrs/day. This is, however, far from reality, hence the need for this study.

2.3.2 Diesel Generator

Among the systems in this study, diesel generators are the major causes of greenhouse emissions. However, they are one of the most reliable energy-generating sources. They cannot be affected by bad weather, location, or outright outages if they are in a good functional state, even though they are largely responsible for GHG emissions. Considering the nature of unstable weather conditions, which could affect the energy production from the PV modules and curb system failure that could arise from grid outages, DG was included in the hybrid system mini-grid. Hence, in this case, the DG is not only a backup but also an independent power system. This ensures the system is secured and reliable, ensuring continuous power supply by the mini-grid. The DG utilized in the study was CAT-100 kVA. The following equation gives the fuel consumption characteristic of the DG [1].

$$FC_G = (A_G + P_G) + (B_G + P_{R-G}) \tag{10}$$

giving FC_G as the consumption of fuel by the DG, P_G is the DG's output power, P_{R-G} is the DG's rated power, A_G and B_G represent the output of the consumption curve.

2.3.3 Photovoltaic Module

The output power from a PV module depends on some factors. One of the major factors is the location. This is because solar radiation varies across locations. Other factors include module size, load served, and renewable fraction (RF). Canadian Solar MaxPower CS6U-330 PP PV module was used in this study. PV modules are represented mathematically in various literature. Equation (2) gives the power output of a PV module, as noted by [5].

$$P_{pv} = Y_{pv}\left(\frac{G_T}{G_{T,STC}}\right)\left[1+\alpha_p\left(T_C - T_{C,STC}\right)\right] \tag{11}$$

giving P_{pv} as the solar output power, Y_{pv} as the rated capacity of the PV array (which is the power output under standard test conditions, STC), f_{pv} as the derating factor, G_T as the solar radiation incident on the PV array, $G_{T,STC}$ as the incident solar radiation under STC (1 kW/m^2), α_p as the temperature coefficient of power, T_C as the PV cell temperature and $T_{S,STC}$ as the cell temperature at STC of 25°C. When the temperature is neglected, the equation becomes

$$P_{pv} = Y_{pv}\left(\frac{G_T}{G_{T,STC}}\right) \tag{12}$$

To determine the energy that the PV generates, the following expression is used

$$E_{pv} = A \times ŋ_m \times P_f \times ŋ_{PC} \times I \tag{13}$$

giving E_{pv} as the total electrical energy output, A as the total area occupied by the PV system, $ŋ_m$ as the module's efficiency, $ŋ_{PC}$ as the power conditioning efficiency, I as the hourly radiance, and P_f as the parking factor.

2.3.4 Storage System/Battery

Storage systems (batteries) are used for energy storage. They must ensure continuous supply during a system failure or bad weather, which can affect energy generation from the PV, DG, or grid. Surrette S-260 Idealized battery model was used in this study's design of the hybrid mini-grid model. The equation as described by Babatunde *et al.* [17] is used in computing the capacity of the storage system

$$B_{sc} = \frac{DL \times BA_d}{ŋ_{Ba} \times D_oBD \times V_{sm}} \tag{14}$$

giving DL as load demand, Ba_d as days of battery's autonomy, $ŋ_{Ba}$ as the round-trip efficiency of the battery, D_oBD as the depth of discharge, and V_{sn} as the nominal voltage of the hybrid system.

2.3.5 Converter

A converter for energy conversion was employed from AC to DC and from DC to AC. This was necessary because the energy produced from the PV module is DC, and the load served is AC. Thus, when a converter converts energy from AC to DC, it serves as a rectifier, and when converting from DC to AC, it serves as an inverter. In a hybrid system, selecting a converter that can withstand an AC load is vital to serve the intended energy conversion purpose effectively and efficiently. In this study, a generic system converter was used. Thus, the efficiency of the inverter is taken as the ratio of the output power (AC) to the input power (DC) from the PV and is given by the expression [2].

$$\eta_{inv} = \frac{P_{inv,out}}{P_{inv,in}} \quad (15)$$

giving $P_{inv,out}$ as the output of the inverter and $P_{inv,in}$ as the input of the inverter.

A key component for the optimal operation of the inverter is its rating [18], which is given by the expression as

$$I_r = \frac{T_{load} + \left(1 + A_f\right)}{I_e} \quad (16)$$

giving I_r as the inverter's rating, T_{load} as the total load, A_f as the additional load or further expansion, and I_e as the inverter's efficiency. Similarly, the energy generated is given by

$$E_g = P_r + h_a + n_d \quad (17)$$

giving P_r as the rated power, h_a as the availability hours, and n_d as the number of days.

2.3.6 System Control

Two control strategies are used in the HOMER simulation: load following and cycle charging. Load the following strategy, which only charges the battery from RES. In cycle charging, the RES generates power that services the load, and the excess energy is used to charge the storage system (battery). A cycle charging strategy was utilized in this study, and 60 minutes was set as the simulation time.

2.4 Economic Computation of the System

Nigeria's average inflation rate over the last few months was 22.04% [19]. This inflation value was utilized as an input variable for the simulation and analysis of the hybrid system. Other parameters inputted during the design and simulations were the costs of energy from the grid, DG, PV, storage system, converter, and the cost of diesel.

2.5 Sensitivity Analysis

The sensitivity analysis was conducted to determine the optimal configuration with a change in certain parameters. These parameters were set to different values, as shown in Table 1. The sensitivity variables selected for the study are solar radiation, diesel price, and the faculty's load demand. The base case of each sensitivity value was compared with the parameters found in the six regions of Nigeria: South-south (SS), South-west (SW), South-east (SE), North-central (NC), North-west (NW), and North-east (NE), respectively with NW being the base case. The base case for each sensitivity variable of each region was either incremental for global solar irradiation or decremented in terms of diesel price and load demand, respectively. The base case values of global solar irradiation, diesel price, and load demand were 5.65 kWh/m^2/d, 1.82 \$/L, and 575.64 kWh/d, respectively.

Table 1 Sensitivity Parameters.

Parameters	Regional Sensitivity Values					
	SS	SW	SE	NC	NW	NE
Solar Radiation (kWh/m^2/d)	4.53	4.74	4.93	5.36	5.65	5.90
Diesel Price ($/L)	2.00	1.88	1.86	1.84	1.82	1.80
Load Demand (kWh/d)	805.896	748.332	690.76	633.204	575.64	518.076

3. Results and Discussion

The analysis of the system's performance alongside the techno-economic evaluation of the hybrid system is discussed here, as well as the cost implications of the system. HOMER Pro software was used to simulate the hybrid mini-grid system, and the results obtained were from HOMER Pro after designing the system and inputting the required data based on the design requirements as the input data. The results obtained after the design of the system and the simulation carried out are also presented, where the optimal and most economically viable system is identified and presented.

3.1 Power Generation, Consumption, and Economics of the System

After running the simulation, the results obtained gave eight (8) feasible configurations of Grid (G), Diesel Generator (DG), Photovoltaic (PV), Battery (B), and Converter (C) with the grid (G) serving as the base case. Presented in Table 2 are the technical and economic compositions of the system.

Table 2 Technical and Economic Compositions of the Feasible Systems.

S/N	Configuration	Capacity					NPC ($)	LCOE ($/kWh)	RF (%)
		G (kW)	DG (kW)	PV (kW)	B	C (kW)			
1	G+DG+PV+C	999,999	80	479	-	155	182,065.20	0.00198	98.3
2	G+DG+PV+B+C	999,999	80	477	1	152	183,816.73	0.00203	98.3
3	G+PV+C	999,999	-	480	-	157	577,931.07	0.00625	98.3
4	G+PV+B+C	999,999	-	474	1	159	579,768.01	0.00621	98.3
5	G+DG	999,999	80	-	-	-	5,071,023.08	0.137	0
6	G+DG+B+C	999,999	80	-	2	1.29	5,080,163.49	0.137	0
7	G (Base)	999,999	-	-	-	-	5,471,201.30	0.148	0
8	G+B+C	999,999	-	-	2	1.29	5,472,014.70	0.148	0

From Table 2, it is clear that the most optimal and techno-economically viable option is the G+DG+PV+C configuration, which has a combination of grid, DG of 80 kW capacity, PV of 479 kW capacity, and a converter of 155 kW capacity. This system gave an annual energy production of 836,430 kWh/yr, making it the most techno-economically viable option, where the PV produces 827,534 kWh/yr, accounting for 98.94% of the total energy production. The energy purchased from the grid is 8,895 kWh/yr, which is 1.04% of the total energy generated by the system. Also, the system has an integrated generator that generates 0 kWh throughout the year. It is necessary to allow for continuous energy supply, which could result from system failure during the maintenance period and possible outages that could emanate from the grid. This system will allow for continuous power supply to the institution, thereby curbing the erratic supply. In terms of energy consumption, the total energy consumed (load demand) is 522,395 kWh/yr, which 210,109 kWh/yr, which is 40.02%, is used to serve the primary AC load, while the energy sold back to the grid is 312,286 kWh/yr, giving 59.8% of the total energy consumed. The DC primary and deferrable load consumptions are 0 kWh/yr, respectively. Furthermore, this system produces excess electricity of 287,008 kWh/yr, having unmet loads and a capacity shortage of both 0 kWh/yr, respectively. The system has an NPC of $182,065.20, LCOE of 0.00198 $/kWh, a payback of 13.20 years, and a renewable fraction (RF) of 98.3%. The configuration of G+DG+PV+C with the NPC and LCOE of $182,065.20 and 0.00198 $/kWh respectively when compared with other feasible configurations such as G+DG+PV+B+C; G+PV+C; G+PV+B+C; G+DG; G+DG+B+C; G+B+C and the grid which is used as the base case was found to be more robust, viable and techno-economically implementable option. Also, compared with the base case and used (base-grid only), it is cheaper and more reliable.

Table 3 and Table 4 show the energy production and consumption of the system.

Table 3 Summary of Expected Electricity Production.

Component	(Production) kWh/yr	%
CanadianSolar MaxPower CS6U-330P	827,534	98.99
CAT-100kVA-50Hz-PP	0	0
Grid Purchases	8,895	1.01
Total	836,430	100

Table 4 Summary of Expected Electricity Consumption.

Component	Consumption (kWh/yr)	%
AC Primary Load	210,109	40.2
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	312,286	59.8
Total	522,395	100

3.2 Emissions

Table 5 gives a summary of the GHG emissions. The GHG emission is 5,658.3 kg/yr from carbon, sulfur, and nitrogen oxide, respectively. Moreover, it can be observed from the Table that there are no emissions of carbon monoxide, unburned hydrocarbons, or particulate matter. Thus, the GHG emissions result from energy consumed from the grid, not from the DG. Besides, the PV system does not produce any emissions and hence is a clean and renewable energy system.

Table 5 GHG Emissions.

S/N	Quantity	Value	Units
1	Carbon Dioxide	5,622	kg/yr
2	Carbon Monoxide	0	kg/yr

3	Unburned Hydrocarbons	0	kg/yr
4	Particulate Matter	0	kg/yr
5	Sulfur Dioxide	24.4	kg/yr
6	Nitrogen Oxide	11.9	kg/yr
Total		5,658.3	

3.3 Sensitivity Results

In order to observe the impact of change in different independent variables, sensitivity evaluation was carried out on the optimal system running cost, fuel cost, and capital expenditure (CAPEX). Global solar irradiation, diesel price, and load demand of the faculty were the sensitivity parameters selected for the analysis. The base case (actual) for each sensitivity variable was either increased or decreased except for the global solar irradiance, which had real-time values in the country's different regions. The base case values of global solar irradiation, diesel price, and load demand of the faculty were 5.65 kWh/m^2/day, \$1.82/L, and 575.64 kWh/d, respectively. The results of the sensitivity evaluation are presented in Table 6 to determine the operation cost, fuel cost, and CAPEX of the optimal configuration. From the sensitivity results obtained, it was observed that as the sensitivity parameter of the solar irradiance increased, the operating cost reduced by 31.12% compared to the base case. The CAPEX was reduced by approximately 5% from SS, SW, SE, NC, NW, and NE, respectively, due to the increase in solar radiation associated with an increase in initial capital investment in such regions to meet the load demand. This is because the SS region has the lowest solar irradiance while the NE has the highest of 4.53 kWh/m^2/day and 5.90 kWh/m^2/day, respectively. However, the fuel cost over the year remained zero (0). This can be attributed to the time the designed system operates to supply electricity to the faculty, which is during the daytime when there is a substantial solar energy supply converted to usable electricity. By varying the diesel price, the sensitivity scenarios also varied. This was observed in the selected regions of the country in terms of the operating and diesel costs. The decrease in the operating cost was 31.09%, which resulted from decreasing the diesel cost from \$2.00/L in the SS to \$1.80/L in the NE, leading to a corresponding decrease in the operating costs from \$43,452.89 in the SS to \$27,904.82 in the NE respectively. As expected, the CAPEX also decreased with the diesel price, giving the CAPEX of \$508,502.94 and \$361,819.39 in the SS and NE regions, respectively. It was observed that a decrease in load demand resulted in a decrease in operating costs in different regions when other variables were kept constant. Also, the CAPEX decreased with an increase in load demand regionally. This means that the higher the load demand, the higher the CAPEX. The diesel price per year remained zero (0). The overall sensitivity variables affected the performance of the system. Subsequently, the NPC of the system and the LCOE were found to be region-dependent because of the configuration owing to the load demand in a particular region. Furthermore, the system significantly reduced carbon emissions, substantiating that the clean energy system is techno-economically viable.

Table 6 Sensitivity Evaluation to check the Running Cost, Diesel Cost, and Renewable Fraction of the Optimal Configuration.

		Sensitivity Values					
Parameters	Metrics	4.53	4.74	4.93	5.36	5.65	5.90
Solar Radiation (kWh/m^2/day)	Configuration	SS	SW	SE	NC	NW	NE
	Operating Cost ($/yr)	43,465.97	40,353.85	37,241.98	34,127.34	31,014.46	27,901.96
	Fuel Cost ($/yr)	0	0	0	0	0	0
	Capital Expenditure ($)	471,741.41	452,085.52	432,429.63	412,773.74	393,117.85	373,461.96
		Sensitivity Values					
		2.00	1.88	1.86	1.84	1.82	1.80
Diesel Price ($/L)	Configuration	SS	SW	SE	NC	NW	NE
	Operating Cost ($/yr)	43,452.89	40,343.28	37,233.67	34,124.07	31,014.46	27,904.85
	Fuel Cost ($/yr)	0	0	0	0	0	0
	Capital Expenditure ($)	508,502.94	479,166.23	449,829.52	420,492.81	391,156.10	361,819.39
		Sensitivity Values					
		805.896	748.332	690.768	633.204	575.64	518.076
Load Demand (kWh/d)	Configuration	SS	SW	SE	NC	NW	NE
	Operating Cost ($/yr)	31,027.54	31,025.02	31,022.77	31,017.73	31,014.46	31,011.56
	Fuel Cost ($/yr)	0	0	0	0	0	0
	Capital Expenditure ($)	523,495.55	486,103.01	448,710.47	411,317.93	373,925.39	336,532.85

3.4 Results Comparison

Table 7 below shows other research results as compared with the present research.

Table 7 Results Comparison.

Author/Year	Location	Grid (kWh)	DG (kW)	PV (kW)	Converter (kW)	Storage	NPC	LCOE	RF (%)
K. E. Okedu et al. [1]	Port Harcourt, Nigeria	1000	-	60	50	-	$38,215	0.0017 $/kWh	63
T. M. Beza et al. [4]	Lake Tana, Ethiopia	-	-	25	5	40 kWh	$119,139	0.175 $/kWh	86.4
S. L. Gbadamosi et al. [11]	Ekiti, Nigeria	1743	-	357.6	160	24 Nr, 2500 AH	₦281,719,600	31.26 ₦/kWh	52.8
This study	Kaduna, Nigeria	999,999	80	479	155	-	$182,065.20	0.00198 $/kWh	98.3

From Table 7, it can be seen that other researchers have carried out research in hybrid energy systems. However, the results of the optimum configuration obtained in this study differ from those obtained by the researchers in the table.

4. Conclusions

This study was on the design and techno-economic evaluation of a hybrid utility grid-diesel generator-solar photovoltaic mini-grid system at the Faculty of Engineering and Technology, Nigerian Defence Academy, Kaduna, Nigeria. This study prompted the need for educational institutions to have an adequate and reliable power supply to ensure proper learning and teaching in developing countries like Nigeria. This novel approach focused on an educational institution that will enable adequate electricity from the mini-grid for proper learning and teaching, reduced negative environmental impacts, and lower energy costs.

In carrying out this study, the load demand analysis of the faculty building was determined, and the data were used to design a hybrid utility grid-diesel generator-solar PV mini-grid system for the faculty.

The hybrid mini-grid model was simulated for the faculty using HOMER Pro simulation software. Simulation results were obtained, and analysis of the hybrid mini-grid model indicated its techno-economic viability. Optimization of the hybrid utility grid-diesel generator-solar PV mini-grid system was conducted using the HOMER Pro software tool by creating various scenarios of energy demand and energy supply from the various sub-systems of the hybrid mini-grid. This provided the results and the best suitable operating system with the lowest NPC of $182,065.20 as well as the least LCOE, giving the cost of energy as 0.00198 $/kWh of the hybrid mini-grid for the faculty as obtained, which is the hybrid system with the configuration of the grid, diesel generator and solar photovoltaic as the most techno-economical option. The study results reveal that the system provides an optimal hybrid energy system that can be implemented, thereby providing a viable energy supply system for an academic institution in Nigeria, a case study. Thus, this can also be implemented in other parts of Nigeria for continuous energy supply with little modifications depending on the prevailing renewable energy potentials and the terrain at the location and point of implementation.

Nomenclature Table

A	Total area occupied by the PV system,
A_f	Additional load or further expansion
A_G and B_G	Output of the consumption curve
α_p	Temperature coefficient of power
ACC_i	Annualized capital cost of each component
$AOMC_i$	Annualized operation and maintenance cost of each component
ARC_i	Annualized replacement cost of each component
Ba_d	Days of battery's autonomy
C_b	Cost of battery
C_c	Cost of converter
C_{dg}	Cost of diesel generator
C_g	Cost of grid
$C_{i,O\&M}$	Cost of investment, operation, and maintenance

C_{NPC}	The overall net present cost
C_{pv}	Cost of PV system
DG	Diesel generator
C_R	Cost of replacement
DL	Load demand
D_oBD	Depth of discharge
E_{pv}	Total electrical energy output
η_{Ba}	Round-trip efficiency of the battery
η_m	Efficiency of the module
η_{PC}	Power conditioning efficiency
FC_G	Consumption of fuel by the DG
f_{pv}	f_{pv} as the derating factor
G_T	G_T as the solar radiation incident on the PV array
$G_{T,STC}$	$G_{T,STC}$ as the incident solar radiation under STC (1kW/m^2)
h_a	Availability hours
I	Hourly radiance
I_e	Efficiency of the inverter
I_r	Rating of the inverter
kWh	Kilowatt-hour
kWh/m^2/day	kilowatt hour per metre square per day
LCOE	Levelized cost of energy
n_d	Number of days
NPC	Net Present Cost
P_d	Load demand
P_{DG}	Power from the DG
P_f	Parking factor
P_g	Grid power purchased
P_G	DG's output power
$P_{inv,in}$	Input of the inverter
$P_{inv,out}$	Output of the inverter
$P_{net}(t)$	Total (net) power of the entire system
P_{pv}	Output power from the PV
P_{pv}	Solar output power
PV	Photovoltaic
P_r	Rated power giving
P_{R-G}	DG's rated power
RF	Renewable fraction
S	Salvage value
$	Dollars
$/kWh	Dollars per kilowatt hour
T_C	PV cell temperature
T_{load}	Total load
$T_{S,STC}$	Cell temperature at STC of 25°C.
V_{sn}	Nominal voltage of the hybrid system

Y_{pv} Rated capacity of the PV array (which is the power output under standard test conditions, STC)

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Author Contributions

Jesse Tanko Zarmai: Conceptualization, Methodology, Writing - Original Draft, Software, Investigation, Data Curation, Data Analysis. Isaac Ibitoye Alabi: Methodology, Supervision. Ebimene Ezekiel Ebisine: Software, Data Analysis. Musa Tanko Zarmai: Writing - Review and Editing. Ovis D. Irefu: Data Curation, Data Analysis.

Competing Interests

The authors have declared that no competing interests exist.

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