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Research Paper

Optimal Sizing of Photovoltaic System for Grid-tied Consumer considering the Economic Perspective: A Case Study of Commercial Load Ilorin, Nigeria

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Abstract: Grid-connected photovoltaic (PV) system is often needed whenever utilities fail to provide consumers with a reliable, sufficient and quality power supply. It provides more effective utilization of power, however, there are technical requirements to ensure the safety of the PV installation and utility grid reliability. In solar systems there is often excessive use of components, resulting in high installation costs. Consequently, appropriate measures must be taken to develop a cost-effective grid-connected PV system. An optimally sized PV system incorporated into an existing unreliable grid-connected commercial load for Mount Olive food processing is presented in this paper. The study focused on providing a reliable electricity supply which is cost-effective and environment-friendly. The techno-economic analysis of grid-connected PV/Diesel/Battery Storage systems was carried out using HOMER Pro software. Results showed that Grid/PV/BSS are technically, economically and environmentally feasible with the cost of energy at 0.136$/kWh and net present cost at $254,469. Also, the excess electricity produced by this combination is 13,264kWh/year, which generates income for the company by selling excess generated energy back to the grid if net metering were to be implemented. Furthermore, the CO2 emissions for these combinations decreased to 10,081.6 kg/year as compared to the existing systems (Grid/Diesel Generator) with emissions of 124,480 kg/year. This is an additional advantage in that it improves the greenhouse effect. A sensitivity analysis was carried out on the variation of load change, grid power price and schedule outages for the optimal system.

Keywords: Solar Photovoltaic, Renewable Energy System, Grid-connected, Scheduled Outages, CO2 Emission.

Nomenclature

COE	Cost of energy
CRF	Cost recovery factor
HOMER	Hybrid optimization model for electric renewables
NASA	National aeronautics and space administration
NPC	Net present cost
PV	Photovoltaic
BSS	Battery storage system
RES	Renewable energy system
CO2	Carbon dioxide
$E_{PV}(t)$	Hourly energy generated by the photovoltaic system [kWh]
A_{PV}	Surface area of the PV modules in [M^2]
η_{PV}	Efficiency of PV generator
$SIR_{PV}(t)$	Solar irradiation at time t [kWh/M^2]

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P_j	Annual energy generated by the PV [kWh]
SOC_{batmin}	Minimum State of Charge of battery
SOC_{batmax}	Maximum State of Charge of battery
SOC_{bat}	State of Charge of battery
DOD	Depth of Discharge
$C_{b,n}$	Nominal capacity or battery rating [Ah]
$V_{b,n}$	Nominal voltage of the battery bank [V].
C_{ann}	Total annual life cycle cost
CRF	Capital recovery factor
x	Life time of the system
r	Interest rate per annum.
$N_{p,grid}$	Number of grid connected
N_{pv}	Number of PV connected
N_{batt}	Number of battery connected
N_{conv}	Number of converters connected
V_{grid}^{a}	Summation of capital cost and O&M cost of operating the grid
W_{PV}^{b}	Summation of capital cost, O&M cost and replacement cost of PV
Y_{de}	Summation of capital cost, O&M cost, and fuel cost of operating diesel generator
AC	Alternating current
$NREL$	National Renewable Energy Laboratory
$SOC_{bat}(t-1)$	Battery's state of charge at time t-1
η_{cha}^{t}	Overall charging efficiency
$E_{grid}(t)$	Energy generated from the grid at time t [kWh],
$E_{de}(t)$	Energy generated by the diesel engine at time t [kWh].
$E_L(t)$	Energy consumed by the load at time *t* [kWh].
η_{INV}	The efficiency of the inverter (%),
$E_{BAT}(t)$	Battery discharge efficiency (%)
$P_{DE}(t)dt$	Energy generated by the battery at time *t* [kWh]
C_{DE}	Fuel cost of the diesel generator
C_{Diesel}	Unit price of diesel
j	Generator fuel curve intercept coefficient
k	Generator curve slope [1/kWh]
P_{DE}^{rated}	Rated power of the diesel generator
P_{DE}^{out}	Output power of the diesel generator
$O\&M$	Operation and Maintenance Cost
C_{CT}	Total Capital Cost
C_{grid}	Capital cost of operating the grid
C_{pv}	Capital cost of operating the photovoltaic
C_{de}	Capital cost of operating the diesel generator
C_{batt}	Capital cost of operating the diesel battery
C_{inv}	Capital cost of operating the inverter
C_f	Fixed cost
N	Number of component connected to the system.
$C_{O\&Mgrid}(t)$	Operation and maintenance cost of grid
$C_{O\&MPV}(t)$	Operation and maintenance cost of PV
$C_{O\&Mbatt}(t)$	Operation and maintenance cost of battery
$C_{O\&Mde}(t)$	Operation and maintenance cost of diesel
$C_{O\&MINV}(t)$	Operation and maintenance cost of grid
$C_{O\&Mf}(t)$	Operation and maintenance cost of other installation charges
X_{batt}^{c}	Summation of capital cost, operation and maintenance cost and replacement cost of battery
Z_{conv}	Summation of capital cost, O&M cost, and replacement cost minus salvage value
DC	Direct current
$SOC_{bat}(t)$	Battery's state of charge at time t

1 Introduction

ELECTRICA energy, which without a doubt contributes significantly to a country's socioeconomic and industrial development [1], [2] should be made accessible at a reasonable cost. However, the rising cost of fossil fuels, which are mostly utilized to produce power internationally, has recently raised concerns about the expense of energy production [3]. Additionally, the emission of CO2, a byproduct, is a problem because it has a harmful effect on the environment. The environmental effects of CO2 emissions have been documented [4], [5]. It's significant to note that millions of people may experience protein and zinc deficits due to CO2 emissions worldwide [6]. Therefore, sufficient efforts should be undertaken to both decrease CO2 emissions from fossil fuels and boost the supply of reliable, reasonably priced power for consumers.

Nigeria ranks among one of the least electrified countries in the world with epileptic power supply and prolonged grid outages. It has been reported that the national grid collapsed for the seventh time within the first seven months of the year 2022 [7]. The cost of manufacturing and conducting business in Nigeria has increased due to the epileptic power supply. Due to this, businesses now extensively rely on diesel generators as a backup and a different source of power supply for their operations. Unfortunately, industrial businesses that rely on diesel generators as a source of power supply have been forced to relocate or shut down entirely due to the unavailability and rise in the price of fossil fuel (diesel oil). The cost of goods and products has skyrocketed as a result of the dependency on generators. Additionally, the expense of fuel is strangling commercial firms, and some may be put out of business if the appropriate steps are not taken to improve the power supply. As a result, the country's current electrical supply crisis calls for the addition of a new source of power.

Solar photovoltaic (PV) systems have been suggested as a potential alternative source of electricity generation in the country among other renewable energy sources [8], [9], [10], and [11]. This is a result of the country's high level of solar radiation, which is the primary determinant of how well solar panels function. The analysis of the potential and financial feasibility of solar photovoltaic power generation in Nigeria for greenhouse gas emissions mitigation has been carried out [12]. The typical sun irradiation in Nigeria is depicted in Fig. 1.

The average daily solar irradiance in Nigeria is about 5.25 kWh/m2/day, with coastal areas receiving 3.5 kW/m2/day and the north receiving 7.0 kWh/m2/day [14]. Moreover, significant advancement in solar energy technologies has drastically improved, and as such, it has been an area of research in the last two decades. To improve the electricity supply in Nigeria, electricity from renewable energy sources was proposed to account for 10% of total energy consumption by 2025 according to Nigeria's renewable master plan (REMP). To achieve this, a total of 1190 MW installed capacity was targeted from renewable sources by 2025 and 42% of this is expected to come from solar PV [15].

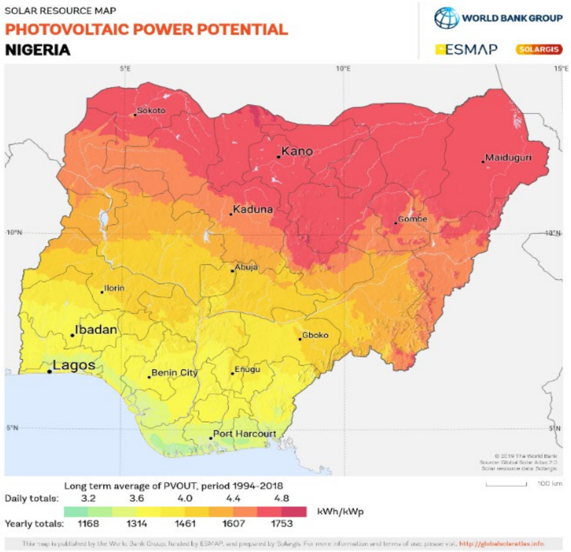


Fig. 1 The average solar irradiance in Nigeria [13]

These factors have encouraged the hybridization of solar PV and other sources of electricity such as diesel generators and the grid, to improve the supply of electricity and consequently reduce the amount of CO2 released into the atmosphere. Electricity generated by hybrid systems would be more dependable, sustainable, and ecologically benign. For instance, in a system where net metering is available, a hybrid of solar PV and the grid could reduce the bill of the solar power customer because the extra solar electricity produced by the PV panels can be sold back to the grid as a return of investment. Here the quantities sold to other consumers during the day via the grid are used at night. Thus, the consumer is billed for the net energy used periodically by the utility.

The first step to achieving a robust hybrid power system is to analyze its technical and economic implications. This has been studied by various scholars over the last decades. Li, et al. [16] conducted a study on the technological and economic performance of grid-connected PV systems in China's five climate zones using HOMER software. The evaluation result shows that grid/PV systems are technically, economically and environmentally feasible for all five climate zones. Kazem, et al. [17] investigate the techno-economic feasibility analysis of a 1 MW photovoltaic grid-connected system in Oman using a simulation carried out in MATLAB environment. The location hourly real-time data, calculated PV instantaneous output power, cell temperature and inverter efficiency are some of the data considered in the simulation. With an annual yield factor of 1875.1 kWh/kWp and an energy cost of roughly 0.2258 USD/kW h, the data demonstrate that the PV system is economically viable.

Furthermore, Bastholm and Fiedler [18] investigated the effect of blackouts on the feasibility of tying an off-grid PV-diesel hybrid system in Tanzania to the national power grid. A grid without blackouts has advantages, including low grid connection costs, low rates, and low income from selling extra electricity to the grid. In [19], the author analysed grid-tied PV systems under a variety of tracking settings, including continuous modifications to the horizontal and vertical axes as well as monthly, weekly, and daily adjustments to the horizontal axis. Using HOMER simulation software, the results showed that, for the location under consideration, the grid-connected vertical axis tracker was more cost-effective than the horizontal axis tracker due to its low energy cost and NPC values.

The possibility of integrating PV/wind power systems into grid/diesel generator systems for supplying the critical loads of industrial parks has been investigated. [20]. The load variation, grid interruption, and weather data of the three case study regions of Ethiopia Park were modelled using HOMER software. With energy costs of 0.044$/kWh, 0.049$/kWh, and 0.048$/kWh, respectively, the techno-economic analysis results demonstrate that grid/diesel/PV/battery systems are technically, economically, and environmentally feasible for all the three climate regions. The optimal sizing of grid-connected photovoltaic systems for a large commercial load has been studied [21]. The ideal size of the PV, converter, and battery system was estimated using HOMER software and the MATLAB environment. To determine the most cost-effective and environmentally benign combination, appropriate consideration was given to NPC, COE, excess electricity, energy savings, and renewable penetration ratio. The findings indicate that 1.60 MW is the ideal capacity of the system for the lowest possible emission and COE. A hybrid PV/wind systems optimization has been proposed based on system cost and the risk of load loss [22]. To choose the ideal capacities of the components that produce the lowest system cost, optimization of the PV array, wind turbine, and battery, optimal PV array tilt angle, and inverter size were carried out. This was achieved using a hybrid iterative and genetic algorithm to generate a set of possible configurations and optimum configurations respectively.

Furthermore, a feasibility analysis of the grid-connected PV power plants in several Saudi Arabian provinces was conducted [23]. The study provides technical, environmental, and economic factors for the selection of workable locations for the building of a grid-connected solar power plant with a 10 MW installed capacity. The study presents technical, environmental and economic characteristics for the selection of viable sites for the construction of a 10 MW installed capacity grid-connected PV power plant. RETScreen software was used and global solar radiation data, sunshine duration data, dry bulb temperature data, and relative humidity data were considered for the feasibility analysis. Analysis of grid-connected PV systems for a household in Pakistan under grid outage consideration using HOMER Pro simulation tool has been proposed [24]. The results pointed out that grid-tied PV systems with battery storage were both economically and technically viable for the case under consideration compared to a stand-alone unreliable grid with battery storage systems.

Other studies focused on the techno-economic analysis of off-grid hybrid power systems utilising various combinations; PV/wind/battery, PV/diesel/battery, PV/wind/battery/diesel, PV/fuel cell/diesel, and PV/wind/diesel systems. For instance, Ariyo, et al. [25] carried out an optimization analysis of a standalone hybrid energy system for the senate building at the University of Ilorin, Nigeria. The average load demand of the building was measured using three phases Fluke 432-II power quality and energy analyzer for different weather conditions; rainy session, dry session and weekend days. PV/Diesel/Battery system configuration yields the optimal results for the building.

Optimization and sensitivity analysis of a stand-alone hybrid energy system for an educational institute has been proposed [26]. The two-hybrid renewable energy sources considered are solar wind and solar biomass systems. The building's hourly, daily, monthly, and yearly energy were estimates. The outcome demonstrated that the solar-biomass hybrid energy system is both cost-effective and environmentally friendly, and it offers a workable solution for satisfying the building's electrical energy needs. Kamran, et al. [27] proposed optimizing a stand-alone hybrid renewable energy system for the rural districts of Punjab, Pakistan. HOMER was used to evaluate the techno-economic viability of the micro hydro/PV/wind energy system based on the load and resource data of the two chosen sites. The outcome demonstrated that the system recovers all costs in 1.7 years.

The analysis of hybrid renewable energy for stand-alone and grid-connected systems taking into account the economic perspective has been established. However, the comparative analysis and the effect of grid outage on a grid-connected PV/Diesel/Battery storage system, considering the techno-economic perspective have not been detailed. Notably, the impact of unscheduled power outages has not received adequate attention. Therefore, this research employs Mount Olive Nigeria Limited, which is based in Ilorin, Kwara State, Nigeria, as a case study, to examine the techno-economic performance of grid-connected PV/Diesel/BSS under unscheduled grid outages. The company uses a diesel generator as a backup to support the unreliable power grid network. In addition, this study investigates the probability of selling the surplus solar PV power generated back to the grid through a net metering scheme. The performance of the designed system is simulated using the HOMER Pro optimization software.

2 Methodology

The methodology adopted in this study is based on HOMER software created by the National Renewable Energy Laboratory. It is the most acceptable and utilized optimization tool in the technical and financial assessments of grid-tied and off-grid renewable hybrid systems. Its operation is reliant on the availability of complete information on the initial investment, operating and maintenance costs, and the costs of replacing system components. Numerous studies have been conducted using the HOMER analytical tool to provide the best possible planning, design, and sizing of renewable energy sources [28], [29], and [30]. To successfully implement this software, the components involved in the system are modelled. Figure 2 shows a screenshot of the schematic diagram of the grid-connected hybrid power system generated from HOMER Pro software.

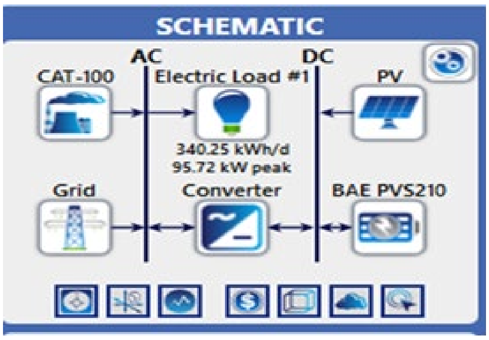


Fig. 2 The schematic diagram of the hybrid system.

2.1 Brief Description of the Site

Mount Olive Nigeria Limited is a leading commercial company in Ilorin, Kwara State, Nigeria. It was established in 1999 and engaged in warehousing, supply and transportation, business and project development, agriculture, real estate management, manufacturing, banking and mining. The company has fifty-five offices and is located on latitude 8.487238°N and longitude 4.537576°E.

2.2 The Hybrid Energy System under consideration

Figure 3 shows the proposed hybrid energy system’s schematic layout. It consists of grid-tied solar photovoltaic and battery energy storage systems as well as diesel generators as a backup.

2.3 Modelling of the Components

2.3.1 Solar Photovoltaic Model

A solar PV module is composed of solar cells which are a type of diode generating electricity when illuminated.

Multiple modules are wired together in series or parallel to provide more energy. The hourly energy generated by the PV system can be expressed as:

$$E_{PV}(t) = A_{PV} \times \eta_{PV} \times S_{IR}(t) \qquad (1)$$

Therefore, the annual energy produced by the PV system can be expressed as:

$$P_J = E_{PV}(t) \times 9\, hrs/day \times 365 \qquad (2)$$

where, $E_{PV}(t)$ hourly energy generated by the photovoltaic system [kWh], A_{PV} Surface area of the PV modules in [m^2], η_{PV} efficiency of PV generator, $S_{IR}(t)$ solar irradiation at time t [kWh/m^2].

2.3.2 Model for Battery Storage

The battery storage system stores energy and starts whenever the PV array is unable to produce enough electricity on its own, such as at night or during extended periods of cloudy or overcast weather. The battery's state is dependent on its prior state of charge as well as the system's energy production and consumption patterns from time "t - 1" to time "t". The amount of energy in the battery during charging and discharging should fall within the range indicated by Eq. (3).

$$SOC_{bat\min} \le SOC_{bat} \le SOC_{bat\max} \qquad (3)$$

where, SOC_{batmin} is the minimum State of charge of battery, SOC_{batmax} maximum State of charge of battery, SOC_{bat} state of charge of battery.

The charging process of the battery bank state is expressed as:

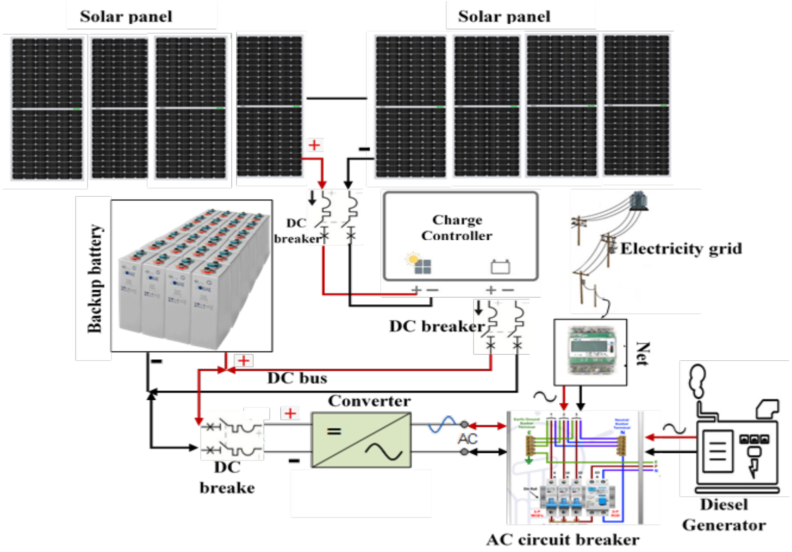


Fig. 3 The proposed block diagram of the hybrid system.

$$E_{PV}(t)+E_{grid}(t)+E_{de}(t)>E_L(t) \quad (4)$$

While the energy stored in the battery during the charging process at time *t* is expressed as:

$$SOC(t)_{bat}=SOC_{bat}(t-1)+ \\ E_{PV}(t)+E_{grid}(t)+E_{de}(t)-E_L(t)\times\eta_{cha}^{t} \quad (5)$$

The batteries discharge rate is expressed as:

$$E_{PV}(t)+E_{grid}(t)+E_{de}(t)<E_L(t) \quad (6)$$

Therefore, battery's bank state of discharge in time t can be expressed as:

$$SOC(t)_{bat}=SOC(t-1)_{bat}+\frac{(E_L(t)-E_{PV}(t))}{(\eta_{INV}\times\eta_{dich})} \quad (7)$$

where, $E_{grid}(t)$ energy generated from the grid at time t $[kWh]$, $E_{de}(t)$energy generated by the diesel engine at time t [kWh]; $E_L(t)$ Energy consumed by the load at time *t* [kWh]; η_{INV} is the efficiency of the inverter (%), η_{dich} battery discharge efficiency (%).

2.3.3 Diesel Generator Model

The diesel generator is used to supplement the renewable energy system's power generation whenever the load demand is not met and the storage system is depleted. The energy generated at year *t* is given as:

$$P_{DE}(t)(dt)=E_L(t)-(E_{PV}(t)+E_{BAT}(t)) \quad (8)$$

where, $P_{DE}(t)dt$ is the energy generated by the diesel generator at year *t*, $E_{BAT}(t)$Energy generated by the battery at time *t* [kWh].

For better performance and higher efficiency, the diesel generator will always operate between 80% and 100% of its rated output. The cost of fueling the diesel generator is determined as:

$$C_{DE}=C_{Diesel}\times\left(jP_{DE}^{rated}+kP_{DE}^{out}\right) \quad (9)$$

where, C_{diesel} is the unit price of diesel, *j* generator fuel curve intercept coefficient, *k* generator curve slope [1/kWh], P_{DE}^{rated}rated power of the diesel generator, P_{DE}^{out} output power of the diesel generator.

2.3.4 Converter Model

The PV delivers the DC power which is converted into AC power by the converter. The other function of the converter is to charge the battery via the rectification process. The inverter model for the PV generator is given as:

$$E_{INV}(t)=E_{PV}(t)\times\eta_{INV} \quad (10)$$

2.4 Grid Modeling

HOMER Pro enables the modelling of an unreliable grid, taking into account both planned and unplanned outages. An unreliable grid model with unplanned grid disruptions was taken into consideration in this study. Mean failure frequency, mean repair time, and variability in repair time are given as inputs to model an unreliable grid with an unplanned outage. The HOMER software creates random outages based on the input and by picking a pseudo-random time step from a full-year simulation period. Figure 4 depicts unscheduled grid outages imported from the software simulation; the green area denotes normal grid performance while the black patch represents sporadic outages throughout the year. The distributed generators are compelled to run during these disruptions.

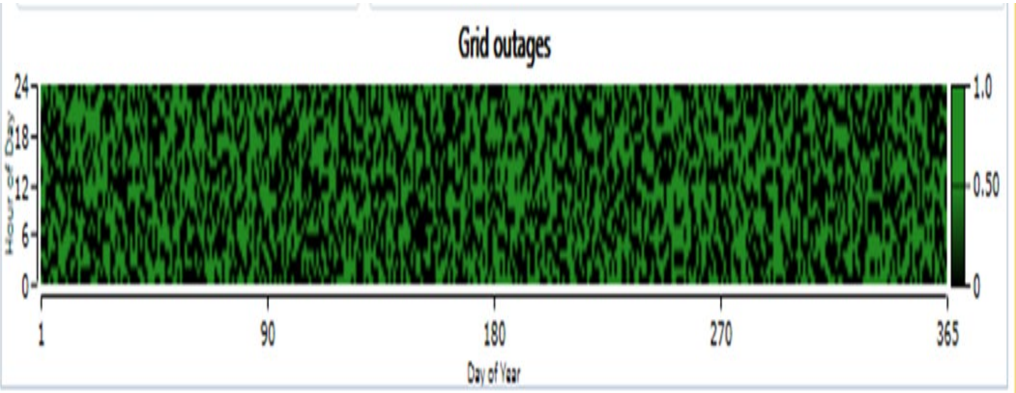


Fig. 4 HOMER random grid outages for the study area

2.5 Cost Function Modelling

The cost-effectiveness of the hybrid PV/battery storage/diesel generator system, connected to a grid, is evaluated by estimating the annual project cost and NPV. The total cost in a year is reliant on the annual maintenance and operation cost and the yearly investment cost.

2.5.1 The Total Capital Cost

Capital cost is the fixed or one-time cost of designing and installing the hybrid system. The total capital cost C_{CT} for the proposed hybrid system is expressed as:

$$C_{CT} = \sum_{grid=1}^{N} C_{grid} + \sum_{PV=1}^{N} C_{PV} + \sum_{de=1}^{N} C_{de} + \sum_{batt=1}^{N} C_{batt} + C_{inv} + C_{f} \tag{11}$$

where, C_{grid} capital cost of operating the grid, C_{PV} capital cost of operating the photovoltaic, C_{de} capital cost of operating the diesel generator, C_{batt} capital cost of operating the battery, C_{inv} capital cost of operating the inverter, C_{f} fixed cost, N Number of component connected to the system.

2.5.2 Annualized Life Cycle Cost

The annualized cost of a component is the cost of a component that yields the same net present value as the actual cash flow sequence associated with that component if it were to occur evenly in each year of the project's lifecycle. The total annualized life cycle cost is expressed as:

$$C_{ann} = (C_{CT} \times CRF(r,x)) \tag{12}$$

While the capital recovery factor (*CRF*) is calculated as:

$$CRF(r,x) = \frac{r(1+r)^{x}}{(1+r)^{x}-1} \tag{13}$$

where, x Life time of the system, r Interest rate per annum.

2.5.3 Annual Operation & Maintenance Cost

The annual operation and maintenance cost of the system is the summation of the operation and maintenance cost of components in the system and it is expressed as:

$$C_{O\&M} = \sum_{t=1}^{365} \left\{ \begin{array}{l} \sum_{t=1}^{24} C_{O\&Mgrid}(t) + \sum_{t=1}^{24} C_{O\&M\,PV}(t) \\ + \sum_{t=1}^{24} C_{O\&M\,de}(t) + \sum_{t=1}^{24} C_{O\&M\,batt}(t) \\ + \sum_{t=1}^{24} C_{O\&M\,INV}(t) + \sum_{t=1}^{24} C_{O\&M\,F}(t) \end{array} \right\} \tag{14}$$

where, $C_{O\&Mgrid\,(t)}$ operation and maintenance cost of grid; $C_{O\&MPV\,(t)}$ operation and maintenance cost of PV; $C_{O\&Mbatt\,(t)}$ operation and maintenance cost of battery; $C_{O\&Mde(t)}$ operation and maintenance cost of diesel; $C_{O\&MINV\,(t)}$ operation and maintenance cost of grid; $C_{O\&Mf\,(t)}$operation and maintenance cost of other installation charges.

2.5.4 The Unit Cost of Electricity by The Hybrid Energy System

The *COE* is the average cost per kWh of useful electrical energy produced by the system and expressed as:

$$COE = \frac{C_{ann}}{E_{L}} \tag{15}$$

The power generated at any time *t* from the proposed system is expressed as

$$NPC = \sum_{a=1}^{N_{pgrid}} N_{pgrid}^{a} \times V_{pgrid}^{a} + \sum_{b=1}^{N_{pv}} N_{pv}^{b} \times W_{pv}^{a} + \sum_{c=1}^{N_{batt}} N_{batt}^{c} \times X_{batt}^{a} + \left(N_{de} \times Y_{de}\right) + \left(N_{conv} \times Z_{conv}\right) \tag{16}$$

where, N_{pgrid} number of grid connected, N_{pv} number of PV connected, N_{batt} number of battery connected, N_{conv} number of converters connected, V_{grid}^{a} summation of capital cost and O&M cost of operating the grid, W_{PV}^{b} summation of capital cost, O&M cost and replacement cost of PV, Y_{de} summation of capital cost, O&M cost, and fuel cost of operating diesel generator, X_{batt}^{c} X_{batt}^{C} summation of capital cost, operation and maintenance cost and replacement cost of battery, Z_{conv} summation of capital cost, O&M cost, and replacement cost minus salvage value.

Eqs. (17) to (21) show the cost associated with each component.

$$V_{grid}^{a} = C_{grid}^{a} + C_{O\&M,grid}^{a} \tag{17}$$

$$W_{PV}^{b} = C_{PV}^{b} + C_{O\&M,PV}^{b} + C_{rep,PV}^{b} \tag{18}$$

$$X^{c}_{batt} = C^{c}_{batt} + C^{c}_{O\&M,batt} + C^{c}_{rep,batt} \tag{19}$$

$$Y_{de} = C_{de} + C_{O\&M,de} + C_{fuel,de} \tag{20}$$

$$Z_{conv} = C_{conv} + C_{O\&M,conv} + C_{rep,conv} - C_{salvage\ \ value} \tag{21}$$

3 Result and Discussion

The system considered in this study consists of load, converter, diesel generator battery storage, and solar panels that are connected to the utility under the arrangement shown in Fig. 2.

3.1 Profile of Mount Olive Company's Daily Loads

Investigations were made into the case study's daily load consumption behavior. The obtained data for the daily load demand was calculated based on the questionnaire and field data. The electrical appliances are listed in alphabetical order, along with their power ratings and daily usage hours. Watt-hours per day are used to calculate the average energy demand. The results of the questionnaire were also compared to the hourly computed data from the energy meter readings. Using this information, an estimate of the case study's daily load energy consumption over 24 hours for the dry season and the wet season was computed. These cases were observed while the company was in operation. Figure 5 shows the daily load profile for the case study after computing the average values for each case.

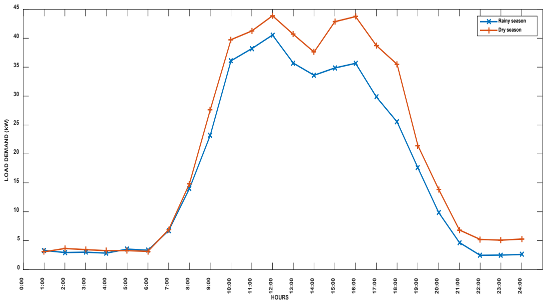


Fig. 5 Daily load profile for the two sessions of the case study.

From Fig. 5, the peak power demand for the dry season increased gradually from 7 hours to reach its peak at about 45 kW around 16 hours and then decreased for the remaining hours. The peak load demand during the rainy season is around 38 kW at around 12 hours, and it then drops sharply to its lowest level at about 22 hours. The HOMER generated main base load is shown in Table 1.

Table 1 The load metrics/baseline.

Metric	Baseline	Scaled
Average (kWh/day)	393.15	340.25
Average (kW)	16.38	14.18
Peak (kW)	110.6	95.72
Load factor	0.15	0.15

3.2 Source of the Data on Solar Irradiance

Figure 6 shows the case study's solar irradiance profile over a year. The weather data were obtained from the Surface Meteorology and Solar Energy database hosted on the National Aeronautics and Space Administration (NASA) website [31]. The site's coordinates of 8.26° latitude and 4.29° longitude were used to create the data**.** According to Fig. 6, the monthly average irradiance value is at its lowest in August (3.90 kWh/m2/day) and at its highest in November (6.05 kWh/m2/day).

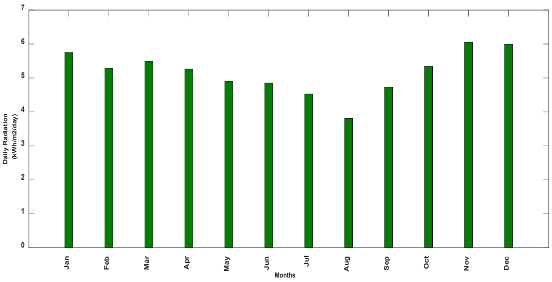


Fig. 6 Daily load profile for the two sessions of the case study.

3.3 Utility System

The grid is expected to meet the load requirements whenever there is a partial absence of electricity produced by the PV/Battery energy storage system. The precise value of interruption data must be known in order to construct a dependable system with the best size of distributed generation. The line interruption duration and interruption frequency for the sites for the year 2021 were collected for the study during this investigation. The collected data are shown in Table 2.

Table 2 Simulation parameters.

Year	2021
Avg. interruption frequency(1/year)	2,560
Avg. duration grid outage (daily)	7h
Grid power price as of (2022)	$/kWh 0.149
Maximum renewable fraction	98%
Maximum annual capacity shortage	2%
Price of diesel/litre (2022)	$1.877
Dollar exchange rate (08/09/2022)	426/$

3.4 System Data Description of the PV, Converter and Battery

The selection of PV array size depends on solar irradiance, demand characteristics and the required renewable energy fraction. The case study is expected to experience an average of 10 hours of sun over a year in Ilorin [31]. The PV converter proposed in this study works with or without batteries connected to the system. This is to reduce the energy drawn from the battery to barest minimum during the day and allow PV to deliver its maximum power to meet the load demand. If batteries are connected, they can be charged and used for lighting during the night. A total number 12V, 220 Ah of 100 tubular batteries was proposed. The batteries are arranged in a series-parallel configuration to meet the targeted output. 10 numbers were connected in series to give an output of 120 V, 220 Ah. While 10 sets of this connection were paralleled to give an output of 120 V, 2,200Ah. This arrangement gives total output energy of 264kWh. The simulation of the components was carried out using Homer Pro software to achieve the best combination of the system; grid/Diesel, grid/Diesel/PV/BSS, and grid/PV/BSS; which is techno-economical and environmentally friendly. Table 3 shows a details description of the data used for the sizing.

Table 3 Description of the data.

Description	Data		
	PV	Converter	Battery storage
Replacement cost	2000 $/kW	300 $/kW	500 $/kW
Investment cost	2,500 $/kW	350 $/kW	600 $/kW
O&M cost	5 $/year	10 $/year	12 $/year
Efficiency		95%	
Lifetime	25 years	12 years	18 years
Declared Voltage			12VDC
Charge state			100%

3.5. Combination 1: Grid/Diesel Generator Systems

A system that combines a grid and a diesel generator was simulated and analysed for comparison. In this case, the building's critical loads will be entirely supplied by the diesel generator during a grid outage. Table 4 shows the average monthly electric production based on the grid/diesel generator system for the case study.

Tables 5 and 6 depict the grid/diesel generation systems' economic and environmental output. The NPC and COE are $1,047,242 and 0.6524$/kWh, respectively, without taking into account the grid's capital and replacement costs. The total gas output from the system is 124,552.1 kg per year emission.

Table 4 Monthly average electric production of Grid/Diesel Gen Systems of the case study.

Month	Grid (kW)	Diesel (kW)
Jan	6.94	11.20
Feb	6.58	11.56
Mar	8.19	11.40
Apr	6.72	12.11
May	6.32	11.65
Jun	6.96	12.19
Jul	7.41	10.68
Aug	6.31	12.04
Sep	8.26	11.75
Oct	7.89	11.57
Nov	7.22	12.50
Dec	6.36	11.44

Table 5 Economic characteristics of optimized grid/diesel generation systems.

System combination	NPC	COE	Initial capital cost
Grid/Diesel Gen systems	$1,047,242	0.6524$/kWh	$4,000

Table 6 Annual emissions from diesel generators during grid/diesel generation in kilograms per year.

System combination	Grid/diesel Gen systems
Carbon dioxide	124,480
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	382
Nitrogen oxide	83.3
Total Emissions (kg/year)	124,948.3

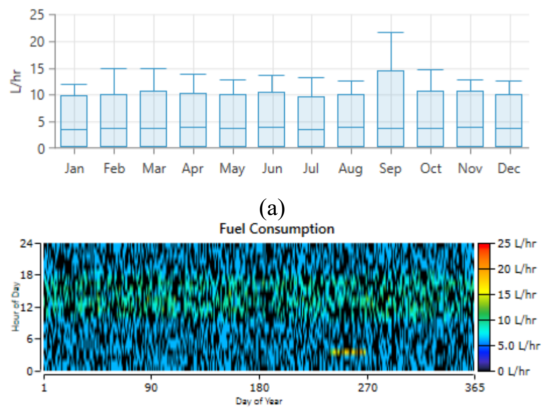
The annual energy production and consumption of the building, the total annual fuel consumed and the annual operating hours of the diesel generator are shown in Table 7. While the total fuel consumed for each month is depicted in Fig. 7.

Table 7 Annual production and consumption of electricity.

System combination	Grid/diesel Gen systems
Grid Purchase (kWh/year)	62,184
Diesel generation (kWh/year)	102,231
Load (kWh/year)	124,173
Fuel consumed (L/year)	32,193
Operating hours (hrs/year)	4,400

3.6 Combination 2: Grid/Diesel/PV/BSS.

The system architecture shows that the battery storage system helps the diesel generator during a grid outage. The monthly average electric production is shown in Table 8. The minimum and maximum monthly power production from the grid and diesel generator are also shown in this table. In general, PV systems produce nearly 75% of the power throughout the year.



(a)

(b)

Fig. 7 (a): Fuel consumed by diesel generator for each month (combination 1), (b): Annual fuel consumed by diesel generator in L/hr. (combination 1).

Table 8 Monthly average electric production of grid/diesel/PV/BSS.

Month	Grid (kW)	PV (kW)	Diesel gen (kW)	BSS (kW)
Jan	3.79	14.84	0.00	2.36
Feb	3.50	15.03	0.03	2.33
Mar	4.57	14.88	0.03	2.74
Apr	3.57	14.27	0.00	2.33
May	3.95	13.15	0.00	2.34
Jun	5.25	11.91	0.00	2.91
Jul	5.83	10.15	0.00	2.79
Aug	5.90	10.35	0.28	3.39
Sep	6.27	11.63	1.86	3.62
Oct	4.83	13.79	0.03	2.75
Nov	4.79	15.82	0.00	2.98
Dec	3.73	15.01	0.00	2.56

Tables 9 and 10 show the financial and annual emission characteristics of the building for optimized grid/ diesel/ PV/BSS systems. The majority of the energy produced by renewable sources is used to meet the load due to the grid outage, which also reduces the need for diesel generators. As a result, the systems' NPC and COE are $262,849 and $0.1494, respectively, with an annual emission cost of 27,288.8kg.

Table 9 Economic characteristics of optimized grid/diesel Gen./PV/BSS.

System combination	NPC	COE	Initial Capital cost
Grid/Diesel Gen/PV/BSS	$262,849	$0.1494	$156,563

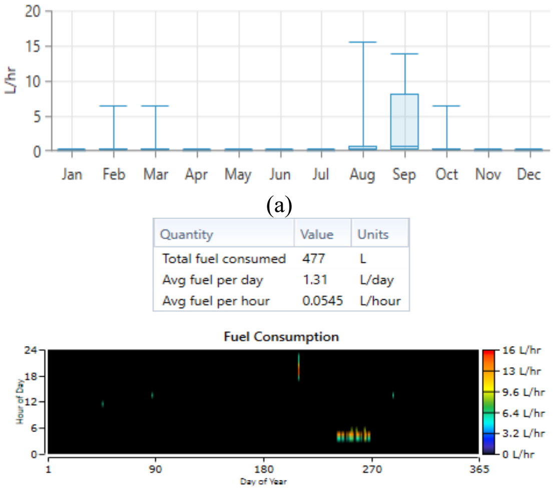
Table10 Annual emissions (kg/year) from diesel generator for grid/diesel Gen/PV/BSS.

System combination	Grid/Diesel Gen./BSS
Carbon dioxide	27, 119
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	115
Nitrogen oxide	54.8
Total Emissions (kg/year)	27, 288.8

The summary of annual energy production from Grid/Diesel/PV/BSS and the annual consumption of the building is shown in Table 11. While the total fuel consumed for each month is depicted in Fig. 8.

Table 11 Annual electric production and consumption of the building.

System combination	Grid/diesel Gen/PV/BSS
Grid Purchase (kWh/year)	40,913
Diesel generation (kWh/year)	1,614
PV Generation (kWh/year)	117,258
Load (kWh/year)	124,191
Excess electricity (kWh/year)	12,815



(a)

Quantity	Value	Units
Total fuel consumed	477	L
Avg fuel per day	1.31	L/day
Avg fuel per hour	0.0545	L/hour

(b)

Fig. 8 (a): Total fuel consumed in each month (combination 2), (b): Annual fuel consumed in L/hr. (combination 2).

3.7 Combination 3: Grid/PV/BSS

In this combination, PV/BSS operates whenever there is a grid outage. The monthly average electric productions for the study are shown in Table 12. In general, it was found that the PV systems could generate enough electricity for the case study throughout the year.

Table 12 Monthly average electric production of grid/PV/battery storage systems.

Month	Grid (kW)	PV (kW)	BSS (kW)
Jan	3.74	15.25	2.32
Feb	3.43	15.44	2.30
Mar	4.43	15.29	2.51
Apr	3.42	14.67	2.29
May	3.85	13.51	2.29
Jun	5.19	12.24	2.85
Jul	5.66	10.44	2.74
Aug	5.99	10.60	3.39
Sep	7.93	11.95	4.13
Oct	4.73	14.18	2.71
Nov	4.72	16.29	2.95
Dec	3.69	15.43	2.53

Tables 13 and 14 display the financial and annual emission characteristics of the building's optimal Grid/PV/Battery Storage Systems. The majority of the energy produced by renewable sources is used to serve the load during the day and battery storage devices are used to serve the load at night due to the grid outage in this area. As a result, the systems' NPC and COE are $254,469 and $0.136, respectively, with an emission cost of 28,288.5kg/year.

Table 13 Economic characteristics of optimized grid/PV/battery systems.

System combination	NPC	COE	Initial Capital cost
Grid/Diesel en/PV/BSS	$254,469	$0.136	$159,524

Table14 Annual emissions (kg/year) from diesel generator for grid /diesel/PV/BSS.

System combination	Grid/diesel Gen./BSS
Carbon dioxide	9,921
Carbon monoxide	0
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide	114
Nitrogen oxide	46.6
Total Emissions (kg/year)	10,081.6

The summary of annual energy production from Grid/PV/BSS and annual consumption for the building is shown in Table 15.

Table 15 Annual electric production and consumption of the building.

System combination	Grid/PV/BSS
Grid Purchase (kWh/year)	41,490
PV Generation (kWh/year)	120,253
Load (kWh/year)	124,131
Excess electricity (kWh/year)	13,264

3.8 Economic and Environmental Performance Analysis

The comparison of the economic and environmental parameters is crucial to choose the optimal supply choice for the study. Table 16 displays the economic and emission variables that serve as feasibility determinant criteria for selecting the ideal combination. The most ideal configuration, which satisfied the case study's load demand at the lowest cost of energy, net present cost, and reduced CO2 emission, is shown in Figs. 9, 10, and 11 based on the results of the simulation combinations of renewable energy sources.

Table 16 A comparison between the three combinations of the hybrid systems.

System combination	NPC ($)	COE ($/kWh)	CO2 Emission (kg/year)
Grid/diesel generator	1,047,242	0.652	124,480
Grid/PV/BSS/diesel generator	262,849	0.149	27,119
PV/BSS/Grid	254,469	0.136	10,081.6

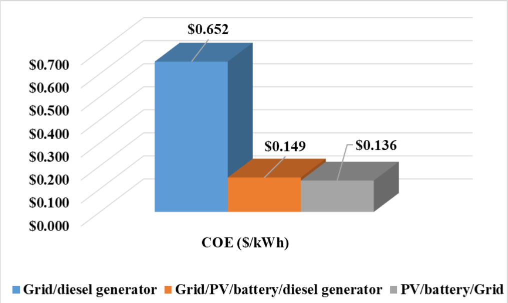


Fig. 9 System configurations versus the cost of energy.

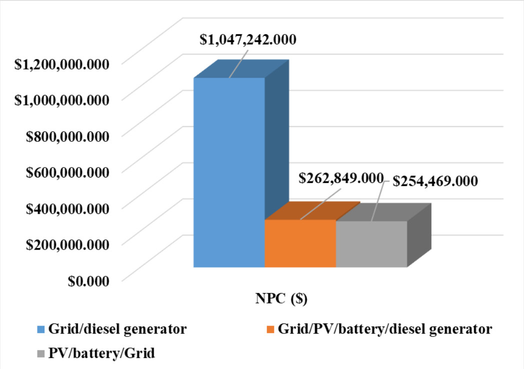


Fig. 10 System configurations versus the net present cost.

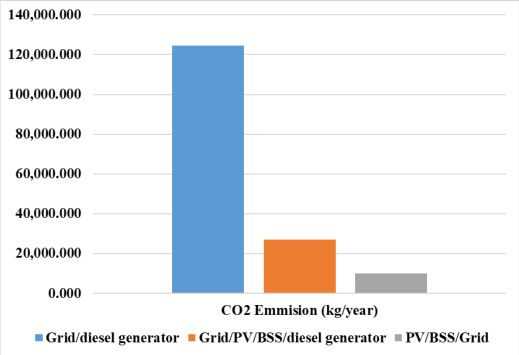
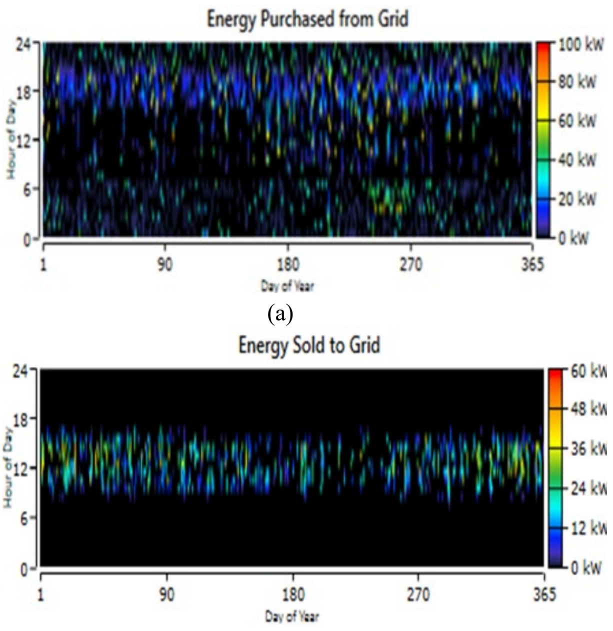


Fig. 11 CO2 emission versus system configuration.

From Fig. 9, Grid/PV/Battery is the most efficient design, with an energy cost of $0.136 as opposed to Grid/Diesel Gen/PV/BSS and Grid/Diesel Gen., which have higher energy costs of $0.652 and $0.149, respectively. For various system configuration possibilities taken into consideration during the simulation, the total NPC is shown in Fig. 10. The lowest net present cost is $254,469.00 for Grid/PV/BSS. When compared to the previous configuration of Grid/Diesel Gen/PV/BSS with NPC of $262,848. Operating the case study only on a grid and diesel generator is quite capital-demanding. Figure 11 shows that using a grid/diesel generator to power the case study will result in the highest CO2 emissions and maintenance expenses when compared to other options. According to the simulation's findings, grid/PV/battery storage has the best configuration, costs the least in terms of NPC and COE, and produces the fewest emissions.

According to Fig. 12 (a), and (b), the extra electrical energy produced by the Grid/PV/BSS selected as the best combination is 13,264 kWh per year. This extra energy can be sold back to the utility grid and produced cash return for the case study**.**



(a)

(b)

Fig. 12 CO2 emission versus system configuration.

3.9 Sensitivity Analysis

The sensitivity analysis was carried out on the suggested optimal design, and the effect of altering multiple values for a given input variable on the optimal system design was carried out. These factors include the capital cost of the PV system, planned and unplanned grid outages, grid tariff, load demand, solar radiation, fuel prices and any other similar elements that could influence the system's economic performance. For the selected ideal system design of Grid/PV/BSS, the impacts of electric load change, grid tariff, and scheduled grid outage on the NPC and COE were investigated.

3.10 Effect of Change in Load

The system design is impacted by load changes because, as was mentioned in the previous section, the study area's daily average load demand is 340.25 kWh/day while its peak load demand is 95.72 kW peak. However, taking into account the dynamic nature of the loads, it was assumed that the case study energy requirements changed by 20%, going from 340.25 kWh per day to 408.03 kWh per day. The performance evaluation for the varying load is presented in Fig. 13. The NPC and COE increased with an increase in load demand.

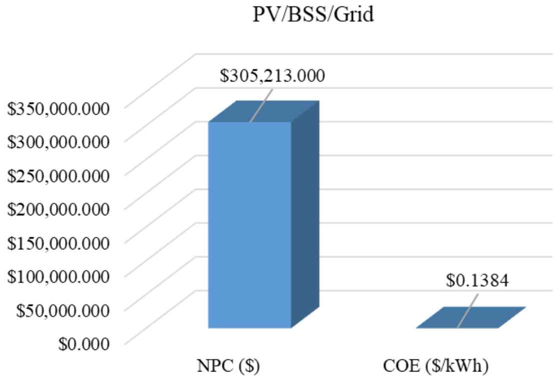


Fig. 13 System net present cost and cost of energy due to an increase in load demand for PV/BSS/grid.

3.11 Effect of Grid Outage and Grid Tariff Power Variations

A schedule of outages between March and May with a total blackout of 95days in a year is assumed for the case study. This outage may occur due to grid collapse or transformer vandalization. By maintaining the 20% increment on the total load demand of the building and the grid power price is set to 0.17$/kWh, the NPC and COE of the case study building increased with an increase in the price of electricity and grid outages as shown in Fig. 14.

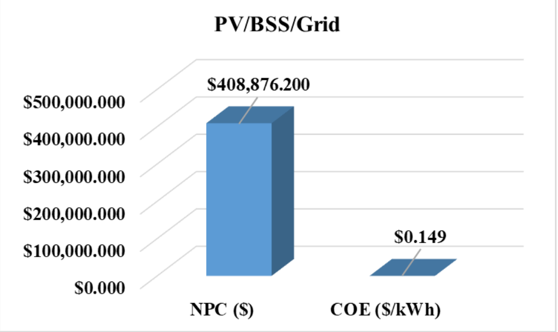


Fig. 14 System net present cost and cost of energy due to scheduled grid outages and increase in the price of electricity for PV/BSS/grid.

4 Conclusion

This study examined the techno-economic viability of grid-connected PV/Diesel/BSS systems for Mount Olive food processing company while taking into account unreliable and unforeseen grid outages. NPC, COE, and emissions were thought of as basic parameters to show whether the designed system is feasible. Taking into account the study's goal, solar energy was potentially viable for the case study. The analyzed yearly average solar radiation for the building is 5.45 kWh/m2 /day, and the annual average temperature for the sites was 28.9°C. In comparison to the other configurations taken into account for the case study, the Grid/Diesel Gen. systems have the highest costs and emissions of CO2. However, the emission was lower in Grid/Diesel/PV/BSS than in the first combination, but Grid/Diesel/PV/BSS had a higher COE than Grid/PV/BSS. Based on technical, economic, and environmental considerations, the Grid/PV/BSS is the best supply option for the case study. The optimal system configuration yielded an energy cost per kilowatt-hour of $0.136 (equivalent to #57.93k), which is more affordable than Nigeria's utility energy cost of $0.149 (#63.47k). If the government institutes a net metering program that allows surplus renewable energy to be sold back to the grid, this might become more alluring. The best Grid/PV/BSS functions fairly with variations in electric load, grid power price, and grid outage variance, according to sensitivity analysis. The NPC and the COE of the optimal systems for the building increased as the electric load and grid power price increased with a scheduled outage on the national grid. According to the findings of this analysis, if grid-integrated solar PV systems were to be implemented in the case study to provide a steady power supply for the building, the results of this study will thus offer a convincing justification for the management of the company to incorporate these systems, and they may also apply to other commercial structures.

Intellectual Property

The authors confirm that they have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing to publication, with respect to intellectual property.

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A. O. Issa: Idea & Conceptualization, Original Draft Preparation. **A. I. Abdullateef:** Idea & Conceptualization, Original Draft Preparation, Revise & Editing. **A. Sulaiman:** Methodology, Original Draft Preparation. **A. Y. Issa:** Original Draft Preparation, Methodology. **M. J. E. Salami:** Revise & Editing. **M. A. Onasanya:** Revise & Editing.

Declaration of Competing Interest

The authors hereby confirm that the submitted manuscript is an original work and has not been published so far, is not under consideration for publication by any other journal and will not be submitted to any other journal until the decision will be made by this journal. All authors have approved the manuscript and agree with its submission to “Iranian Journal of Electrical and Electronic Engineering”.

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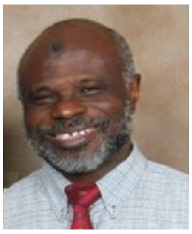

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