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DESIGN AND ANALYSIS OF GRID-CONNECTED ENERGY SYSTEMS FOR COMMERCIAL BUILDINGS

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ABSTRACT

This paper presents the design of energy generation based on the national grid, solar photovoltaic (PV), and diesel-based supply systems for a commercial building in Obanikoro, Lagos with a total demand and peak load of ~56,000 kWh/yr and 13.5 kW, respectively. The grid is simulated based on the average daily supply of 6 hours being experienced in the study location, indicating that the building is not served for an average of 18 hours/day. The paper considers three design configurations: grid, grid + PV, and grid + PV + generator systems in HOMER Microgrid tool and their performances are compared in terms of the annual generation, load not served, and the emissions. A load demand of ~14,000 kWh/yr meaning that 75 % of total demand is not met. A 35.2 kW PV was added to the grid, with both supplying 49,687 and 13,826 kWh/yr, respectively. However, a 6.98% of the load is not served. A 15 kW generator is then added to form the grid + PV+ diesel generator configuration, and the participating energy sources supply 15,818, 49,723 and 4,834 kWh/yr, respectively. This configuration is able to meet the demand without any deficit. The CO_2, CO, unburned hydrocarbons, particulate matter and SO_2 and nitrogen oxides emissions for the three configurations are 8.824, 0, 0, 0, 0.0383 and 0.0187 tonnes/yr; 8.192, 0, 0, 0, 0.0355 and 0.0174 tonnes/yr, and 11.833, 0.0259, 0.00113, 0.000157, 0.0435 and 0.0407 tonnes/yr, respectively. The study can help to mitigate the energy shortage in commercial buildings.

Keywords: Distributed generation, diesel, energy demand, eco-friendly system, photovoltaic, demand not served

INTRODUCTION

Energy is one of the essential factors for social and economic development and modernization (Usman *et al.*, 2018). The processing of goods from natural resources, for example, and many other sectors of the economy and services require energy. On the global level, the challenges of climate change and global warming justify the quest for alternative energy sources such as solar, wind, biomass, hydropower, geothermal, tidal and wave. These sources attract a growing attention to address the traditional fossil fuel challenges (Mubaarak *et al.*, 2020).

The limitation of a single-source energy system is the issue of reliability. However, having more than one source of energy supply is expected to achieve reliable supply A hybrid system may incorporate different resources such as renewable energy systems, natural-gas based system, combined heat and power (CHP) system, grid, etc., (Atef *et al.*, 2020).

This paper reviewed related studies in the literature; the study by Abdul-Wahab *et al.*, 2020 is on the simulation of a hybrid power system (HPS) for Masirah Island location in Oman. Sharif *et al*., 2014 also presented the design of an energy hub based on the natural gas, wind and solar resources. Charabi and Abdul-Wahab, 2020 discussed the optimal sizing and performance evaluation of a hybrid renewable electricity for a mini-grid in Oman. Harajli *et al.*, 2020 presented the hybrid solar/diesel power system. Adesanya and Schelly (2019) studied the viability of PV-diesel system for private companies. Akinyele *et al.*, 2015 discussed renewable energy system solutions for an offgrid house. A study by Salameh *et al.*, 2021 discussed the analysis and performance of solar PV/fuel cells/diesel power system for Khorfakkan city, Sharjah, United Arab Emirates. Rehman *et al*., 2020 investigated an optimal wind/PV/diesel/ battert-based HPS for Muhavoor village in India.

Energy shortage is one of the problems militating against commercial businesses in several parts of the country. This study is motivated by the need to provide reliable energy supply for commercial buildings in Lagos, Nigeria, as a means to reduce noise and air pollution and also provide alternative energy for businesses. Therefore, this study considers the design of energy supply system based on grid, solar PV, and diesel systems for a commercial building in Obanikoro Lagos.

The study considered the simulation of energy supply system for a total demand and peak load of ~ 56,000 kWh/yr and 13.5 kW, respectively. The grid configuration is set as the baseline and is based on the average daily supply of 6 hours being experienced in the study location, i.e., the building is not served for an average of 18 hours/day. The actual appliances and the consumption in a typical commercial building in Lagos were used to obtain a practical load profile for the systems design. The paper presents three design configurations: grid, grid + PV, and grid + PV + generator systems in HOMER Microgrid tool environment and their performances are compared in terms of the annual generation, load not served, and the emissions. Furthermore, the work compared the emissions by the hybrid grid + PV + diesel design configuration with that produced when the building is being powered entirely by a diesel generating system. The results can help to plan energy for commercial buildings.

MATERIALS AND METHODS

A commercial building in Obanikoro Lagos is used as case study in this work. The appliances used in this building include the lighting fittings, computers, rechargeable fans, printers, pumping machine, etc. This work is interested in proposing an energy system based on grid/PV/diesel supply system for the building. The paper uses the Hybrid Optimization Model for Electric Renewables (HOMER) Pro Microgrid tool to simulate the energy system for the building.

Demand profile

The commercial building's load demand is shown in Table 1, which has been obtained through energy audit/survey carried-out on the appliances, their ratings and hours of operation. Also, Figure 1 is the load profile obtained through an analytical approach. The analytical approach involves the authors' experience and familiarization with the daily operation of the appliances. The total daily demand of the building is 153.372 kWh/d, which is 55,980.78 kWh/yr on a yearly basis. This demand was used as input in HOMER software before simulating the power generating sources.

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Table 1. Load demand of the commercial building

S/No.	Loads	Unit	Rating of Load (W)	Total Load (W)	Total Load in (kW)	Hours of operation (hr)	Daily load demand (kWh/day)
1	Surrounding LED bulbs	12	18	216	0.216	12	2.592
2	LED bulbs in the room	14	10	140	0.14	10	1.4
3	Bulbs in the stores/toilets	10	6	60	0.06	5	0.3
4	Bulbs in the kitchen	4	10	40	0.04	10	0.4
5	Bulbs at the sitting room	4	18	72	0.072	10	0.72
6	Bulbs at the meeting room	4	18	72	0.072	10	0.72
7	Bulbs for Penthouse	5	18	90	0.09	8	0.72
8	Bulbs for meeting room	4	18	72	0.072	10	0.72
9	Television set	4	100	400	0.4	10	4.0
10	DSTV/GOTV decoder	4	45	180	0.18	10	1.8
11	Home Theater	2	200	400	0.4	8	3.2
12	Desktop computer	2	180	360	0.36	10	3.6
14	Laptop	8	100	800	0.8	8	6.4
15	Printer 1	3	150	450	0.45	4	1.8
16	Printer 2	1	550	550	0.55	4	2.2
17	WIFI	1	30	30	0.03	24	0.72
18	Mobile charger	12	5	60	0.06	24	1.44
19	Rechargeable fan	11	60	660	0.66	8	5.28
20	Horse fan	4	150	600	0.6	8	4.8
21	Air conditioning unit	8	1120	8,960	8.96	10	89.6
22	Pumping machines	2	1120	2,240	2.24	4	8.96
23	Flood lights	4	250	1000	1	12	12
	Total energy needed per day (kWh/day)						**153.372**
	Total energy needed per year (kWh/yr)						**55,980.78**

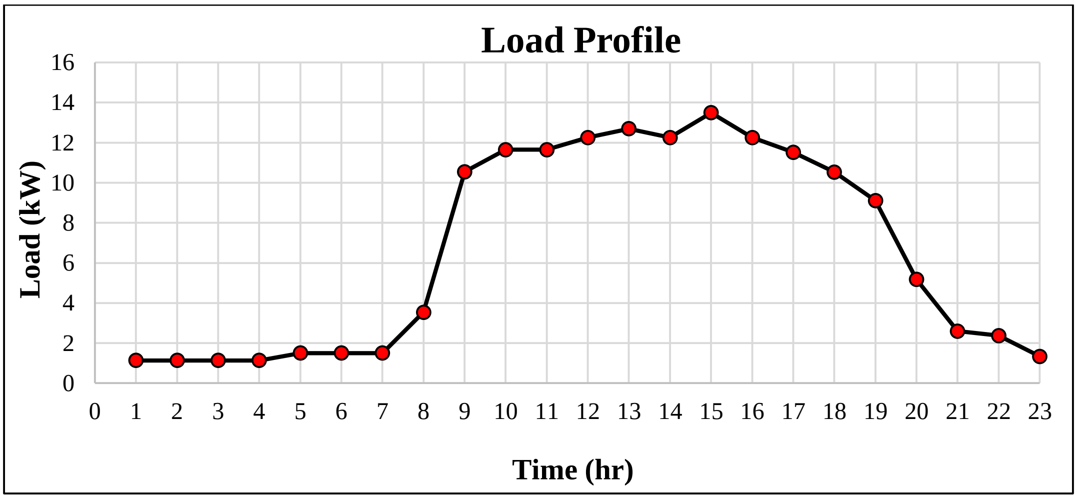

Fig. 1. Load profile of the building

Solar energy resource

The solar radiation and the ambient temperature used for the study location are based on data provided in (Weather-and-climate, 2022; Meteoblue, 2022). These include the total monthly average peak sun-hours, the average daily peak sun hours and the average monthly ambient temperature used for the analysis. The ambient temperatures are obtained from the source (Meteoblue, 2022) by adding the maximum and minimum values and then dividing them by 2. The values of peak-sun hours and ambient temperature estimated from (Weather-and-climate, 2022; Meteoblue, 2022) for January to December are 6.45, 7.07, 6.42, 5.83, 6.29, 5.33, 3.23, 2.42, 3.33, 5.32, 6.83 and 7.10, respectively; and 28.5, 29, 28.5, 29, 28, 26, 25.5, 25, 25.5, 26.5, 28, and 28.5 (°C).

Sizing of solar PV array

The size of the PV power output is calculated using Equations (1) and (2) (Eriksson and Gray, 2018; HOMER):

$$P_G = n \cdot P_{NPV} \cdot D_{RF} \cdot \frac{G_S}{G_{STC}} \cdot [1 + K_T(C_T - C_{T,STC})] \quad (1)$$

$$C_T = A_T + \frac{(NOCT - 20°C)}{G_{REF}} \cdot G_S \quad (2)$$

where P_{NPV}, n, D_{RF}, G_S, G_{STC}, K_T, C_T, $C_{T,STC}$, A_T, NOCT, and G_{REF} represent solar module's nominal rated power (W), number of solar modules, derating factor, solar irradiance for the location (Wm^{-2}), solar irradiance at STC (1000 Wm^{-2}), temperature coefficient of power (%/°C), Cell temperature (°C), Cell temperature at standard test condition, i.e., 25°C, ambient temperature (°C), nominal operating cell temperature (°C), and the solar irradiance a reference level of 800 Wm^{-2}. In this work, the values used for *NOCT*, K_T, solar PV module's efficiency and D_{RF} are 47°C , 13 %, -0.5 (%/°C) and 80 %, respectively in the system's model in HOMER.

Charge controller sizing

The size of the voltage regulator can be obtained by Equation (3): (Al-Shamani *et al.*, 2015; Okakwu *et al.*, 2022).

$$I = I_{SC} \cdot N_P \cdot S_F \quad (3)$$

where I, I_{SC}, and N_p represent rated current of the charge controller (A); short-circuit current of module (A), and the number of modules configured in parallel. The safety factor, S_F is introduced to ensure that the charge regulator is able to accommodate the maximum current of the array and a load current that is more than that the planned value. Values of S_F ranging

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from 1.25 to 1.3 have been used in some implementations.

Battery sizing

The size of the battery can be calculated according to Equation (4) (Bajpai and Dash, 2012; Okakwu *et al*., 2020):

$$B_{SIZE} = \frac{E_L \times A_d}{V_B \times DOD_{max} \times \eta_b} \quad (4)$$

where E_L, A_d, V_B, DOD_{max}, and η_b are the total load demand in Watt-hr, days of autonomy, nominal voltage (V), maximum depth of discharge and the battery efficiency. The state of charge (SOC) of the battery can be estimated by Equation (5) (Eriksson and Gray, 2019):

$$SOC = \frac{B_{AC}}{B_{RC}} = 100 - DOD_{max}\,(\%) \quad (5)$$

where B_{AC} and B_{RC} represent the available battery capacity (Ah) and the rated battery capacity (Ah).

Inverter sizing

The power inverter power rating may be calculated using Equation (6) (Akinyele *et al*., 2015).

$$INVERTER_{RATING} = 3\,(I_L) + (O_L) \quad (6)$$

where $INVERTER_{RATING}$, I_L and O_L are inverter rating (kVA), inductive loads (kW) and the other loads (kW).

Generator sizing and fuel consumption estimation

The generator has to be able to meet the peak load requirement, implying that the generator set must maintain a capacity above the peak load. The hourly fuel consumption of the generator can be approximated according to Equation (7) (HOMER; Sadeghi and Ameri, 2014):

$$F_C = \mu P_N + \alpha P \quad (7)$$

P_N is the nominal or rated power of the generator, while P is the electrical power generated at time t. μ is a constant called the fuel curve intercept, while α is a constant known as the fuel curve slope.

Emissions evaluation

The emissions associated with the three energy design configurations, i.e., grid, grid + PV, and the grid + PV and generator systems are compared in terms of the CO_2, CO, unburned hydrocarbon (HC), particulate matter, SO_2 and NO_x from HOMER. The default emissions for the grid configuration is first set as the baseline and then the grid + PV and grid + PV+ generator configurations are compared with a situation whereby the building is served entirely by a diesel generating system.

RESULTS AND DISCUSSION

Grid supply and performance

Figure 2 represents the grid and the load model in HOMER software. The grid situation is that the average power supply to the study location is about 6 hours per day over the year. This supply is then translated to 25 % of the total hours in the day, which is a total of 2190 hours supply for 365 days (i.e., 25 % of the total of 8760 hours in the year). This way, the grid only supplies 25 % of the entire load demand of the commercial building in the year (i.e., ~ 14,000 kWh/year). This is around one-quarter of the building's load demand of about 55, 981 kWh/yr (i.e. 153.372 kWh/yr multiplied by 365). Therefore, the unmet load demand obtained from the simulation is 75 %, meaning that the shortage is the difference between the load demand of ~ 56,000 kWh/yr and 14,000 kWh/yr, which is ~ 42,000 kWh/yr. The results demonstrate that the building's demand is not met for 75 % of the time in the year. The grid supply for January to December is shown in Figure 3.

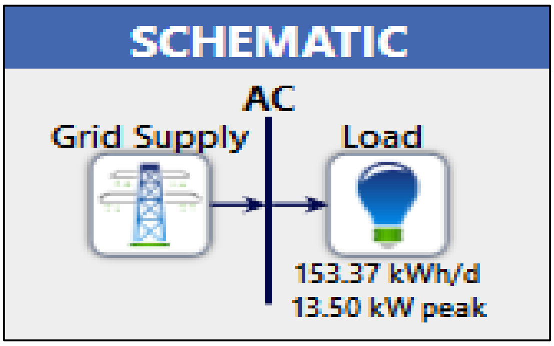

Fig. 2. Grid supply and load model in HOMER

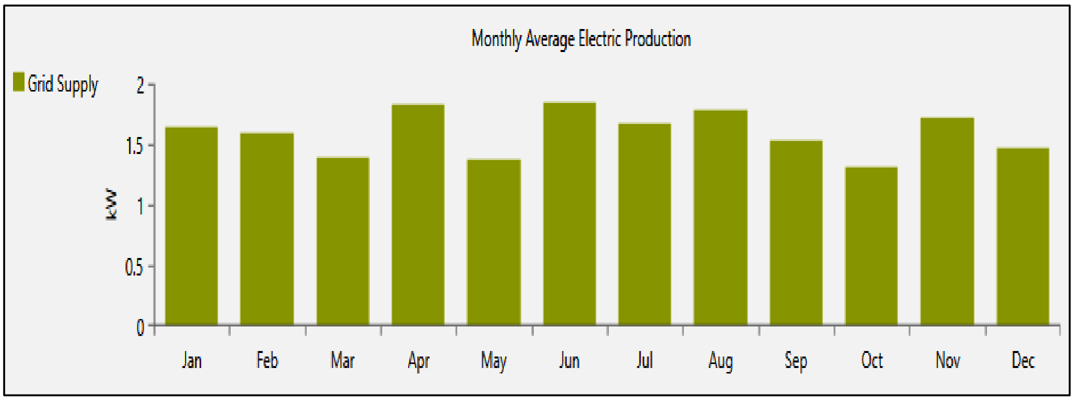

Fig. 3. Grid supply from January to December

Grid and PV supply and performance

Figure 4 represents the combined supply from the grid and the PV system, including battery and inverter. The size of the PV modules is 35.2 kW that is added to the existing grid configuration. The energy supplied by the PV and the grid are 49,687 and 13, 826 kWh/yr, i.e., 78.2 and 21.8 %, respectively. Figure 5 shows the supply by the grid and PV from January to December.

Also, the result indicates that the PV supply has complemented the grid and the total energy generation is now being able to meet a larger portion of the building's demand. An unmet electric load demand of 3, 907 kWh/yr per year was obtained from the simulation, which is 6.98 %. This means that the building will not be supplied for about 7 % of the time in the year.

The battery size is 13,310 Ah, which has been obtained from the DOD, autonomy, battery efficiency and system voltage of 60 %, 2, 80 % and 48 V, respectively. Figure 6 presents the SOC result. The profile shows that lowest battery SOC values were closer to the lowest SOC baseline of 40 % in July and August.

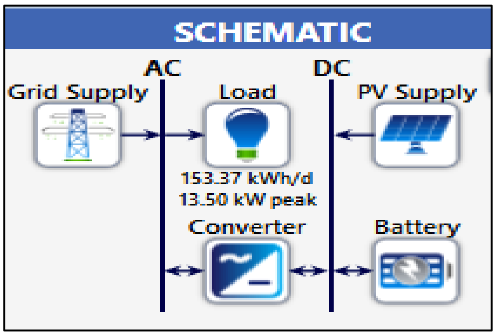

Fig. 4. Grid and PV supply model in HOMER

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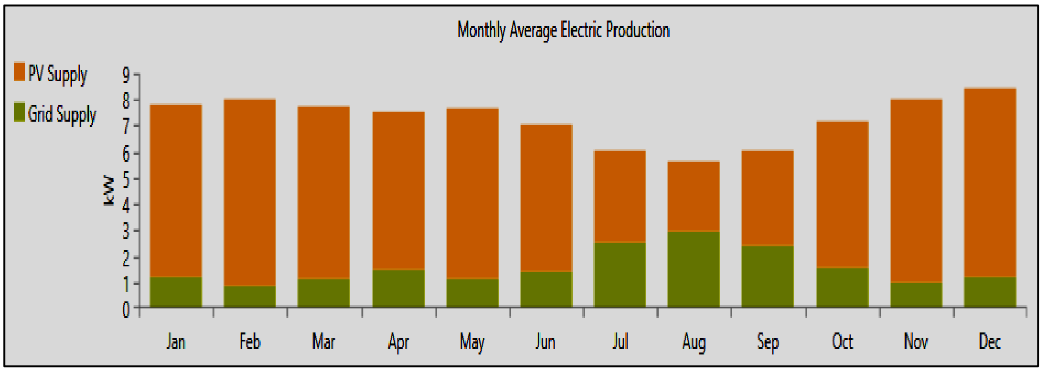

Fig. 5. Grid and PV supply for the months

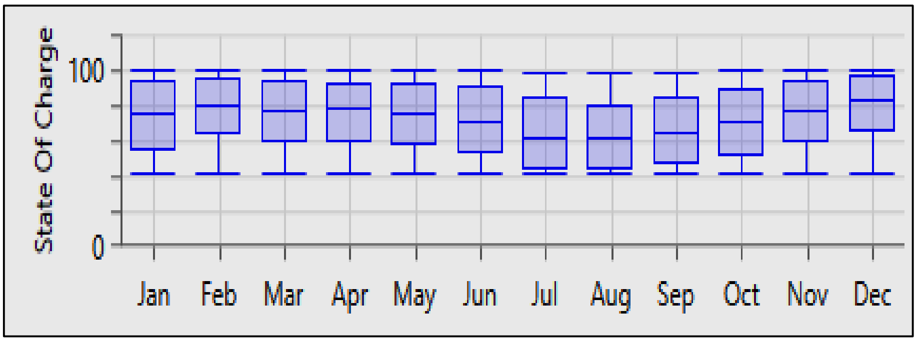

Fig. 6. SOC for the grid and PV supply

Grid, PV and diesel generator supply and performance

Figure 7 represents the combined supply from the grid/PV/diesel generating system, including the battery and inverter. The size of the PV modules still remains 35.2 kW but a 15 kW generator is now included to the configuration. The energy supplied by the grid, PV and the generator sources are 15,818, 49,723, and 4,834 kWh/yr, which is 22.5, 70.7, and 6.87 % energy mix contributions, respectively. The total electricity produced in this case is 70, 374 kWh/yr. The supply by the grid/PV/grid/diesel generator from January to December is shown in Figure 8.

There is no electricity shortage in this energy system scenario. Therefore, the unmet electric load demand is zero, meaning that the building's demand will be met all year round. This demonstrates one of the benefits of the hybrid energy system in terms of the realizing high reliability of energy supply (Olabode *et al*., 2021). The battery state of charge for this option is shown in Figure 9, which has experienced appreciable increment compared to Figure 6.

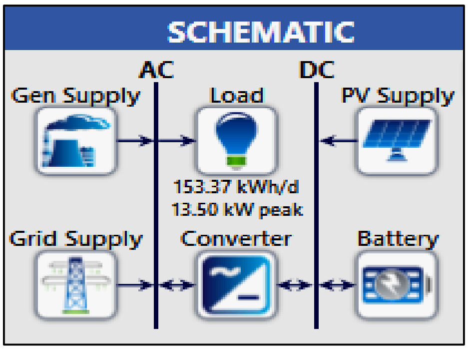

Fig. 7. Grid, PV and generator system supply model in HOMER

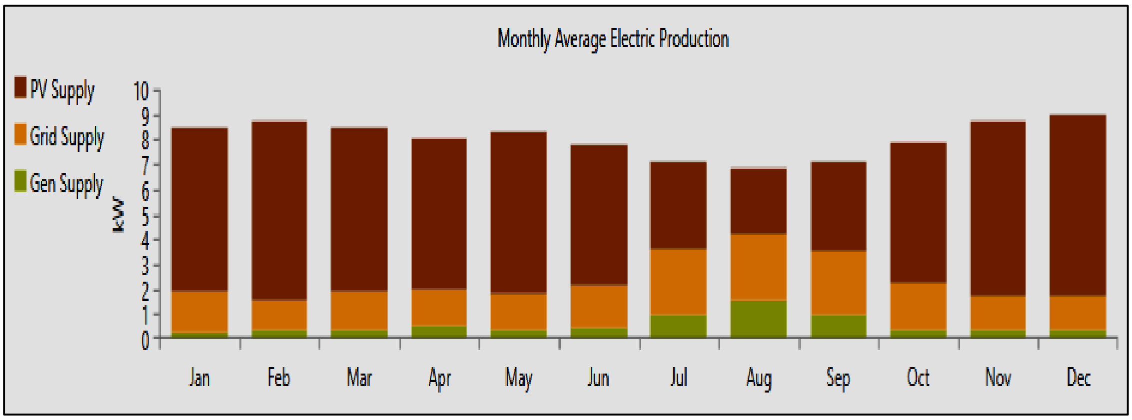

Fig. 8. Grid, PV and generator supply from January to December

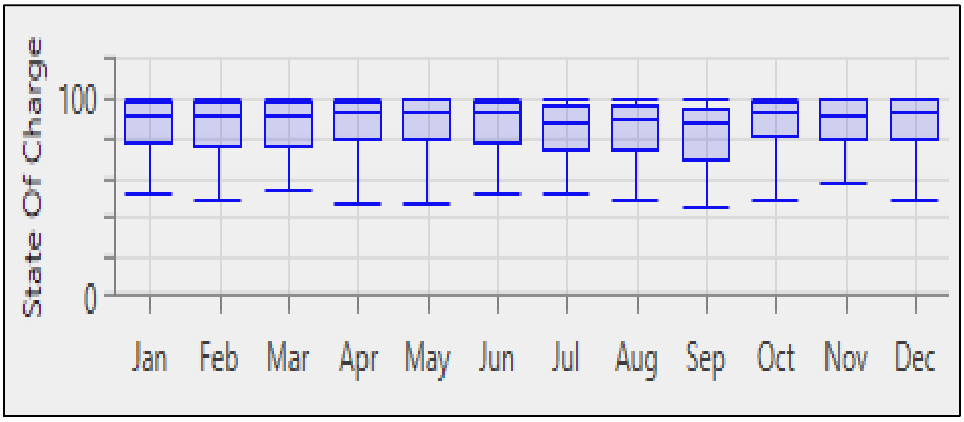

Fig. 9. SOC for the grid, PV and generator system

Comparison of the Emissions Produced by the Systems

Table 2 presents the emissions by the grid, grid + PV, and the grid + PV + diesel generating systems, compared with a diesel generating system. It also presents the amount of emissions saved by employing the grid + PV + diesel generator.

The CO_2, CO, unburned HC, PM, SO and NO_x emissions obtained from the grid, grid + PV, and the grid + PV + generator contributions are 8.824, 0, 0, 0, 0.0383 and 0.0187 tonnes/yr; 8.192, 0, 0, 0, 0.0355 and 0.0174 tonnes/yr, and 11.833, 0.0259, 0.00113, 0.000157, 0.0435 and 0.0407 tonnes/yr, respectively. However, the corresponding emissions obtained supposed the building is entirely powered by a diesel generator are 58.9, 0.371, 0.0162, 0.00225, 0.144 and 0.349 tonnes/yr. The diesel design configuration that produced these results is shown in Figure 10, and the values of μ and α are 0.704 L/hr/kW_{rated} and 0.25 L/hr/$kW_{o/p}$, respectively.

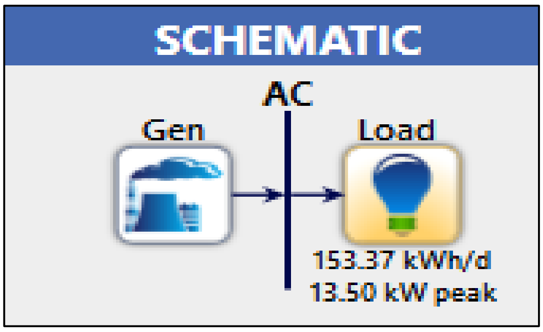

Figure 10. Diesel design configuration in HOMER

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The amount of emissions saved by employing the grid + PV + diesel generator are 47.067, 0.3451, 0.01507, 0.002093, 0.1005 and 0.3083 tonnes per year, respectively. These translate to 79.91, 93.01, 93.02, 93.02, 69.79 and 88.34 % emission reduction. The results obtained by this study also demonstrate that the grid + PV + diesel system configuration is a suitable energy option as it completely meets the building demand requirements. Although it produces higher emissions compared to the grid configuration, it generates much lower emissions compared to the diesel configuration.

Table 2: Emissions by the systems

Emissions (tonnes/yr)	Grid Supply	Grid + PV Supply	Grid + PV + Diesel Gen Supply	Diesel Gen Supply	Emissions saved by Grid + PV + Diesel Gen Supply
CO_2	8.824	8.192	11.833	58.9	47.067
CO	0	0	0.0259	0.371	0.3451
Unburned HC	0	0	0.00113	0.0162	0.01507
Particulate	0	0	0.000157	0.00225	0.002093
SO_2	0.0383	0.0355	0.0435	0.144	0.1005
NO_x	0.0187	0.0174	0.00407	0.349	0.3083

CONCLUSION

This research work has presented the design and analysis of electrical power generation based on the supply from the national grid, solar photovoltaic, and diesel-based systems for a commercial building in Obanikoro, Lagos. The paper's simulation and evaluation were based on a total demand and peak load of ~56,000 kWh/yr and 13.5 kW, respectively. The grid design configuration was simulated using the prevailing energy situation at the study location, specifically on the average daily supply of 6 hours, which led to a situation whereby the building is not served for an average of 18 hours/day. The study has examined three design configurations such as the grid, grid + PV, and grid + PV + generator systems using the HOMER Microgrid tool. It evaluates the systems' performances and comparisons in terms of the annual electricity generation, load not served, and emissions generated and avoided. The paper simulated a 35.2 kW PV, which was added to the grid, with both supplying 49,687 and 13,826 kWh/yr, respectively. However, the grid + PV configuration incurred an energy deficit of 6.98 %. A 15 kW generator was then incorporated to form the grid + PV+ diesel generator design configuration with the electricity supply of 15,818, 49,723 and 4,834 kWh/yr, respectively. The results showed that this configuration served all the load without any unmet electric demand. The CO_2, CO, unburned hydrocarbons, particulate matter and SO_2 and nitrogen oxides emissions obtained for the three design configurations are 8.824, 0, 0, 0, 0.0383 and 0.0187 tonnes/yr; 8.192, 0, 0, 0, 0.0355 and 0.0174 tonnes/yr, and 11.833, 0.0259, 0.00113, 0.000157, 0.0435 and 0.0407 tonnes/yr, respectively, which are lower compared to when the commercial building is being served by a diesel generator producing corresponding emissions of 58.9, 0.371, 0.0162, 0.00225, 0.144 and 0.349 tonnes per year. Therefore, the results demonstrated emissions reduction of 79.91, 93.01, 93.02, 93.02, 69.79, and 88.34 %, respectively when the grid + PV + diesel generator configuration is being run for the building. The study can help to mitigate the energy shortage in commercial buildings.

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