SELECTION, TECHNO-ECONOMIC AND ENVIRONMENTAL ANALYSIS OF OFF-GRID POWER SYSTEM FOR APPLICATION IN A NIGERIAN UNIVERSITY BUILDING

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Abstract: The electricity mix and access duration in Nigerian educational institutions is poor. This paper presents analysis of the off-grid optimal energy systems (OES) for serving a Nigerian university building load. The feasible system for serving the demand load of 250kWh/day for the building is a hybrid power system consisting of a 75kW rated solar PV, 40kW biogas engine and a 30 number 1kWh battery bank storage operating with a 33.6kW converter. The OES's COE and NPC are 0.253\$/kWh and \$175219.7 respectively. Scenario analysis outcomes indicate that the building OES varies with load and resource potential.

Keywords: hybrid energy system, wind energy, solar energy, net present cost, microgrid

1. INTRODUCTION

The delivery of reliable electricity supply is vital to the Sustainable development of a society. It has important domestic applications in lighting, heating, cooling, refrigeration and for operating appliances, computers, electronics, machinery, and public transportation systems [1]. Also, access to electricity brings a positive impact on income, expenditure, health, education and research. However, the provision of electricity in Nigeria continues to be plagued by unreliable services. Most homes, industries and health institutions receive electric service that is about 50 % far less than their demand [2]. The universities hold the key to the future development of the nation. This key sector also suffers from unstable and unreliable energy supply, which hinders learning, research and community development. When available, the electricity supplies often constitute a danger to the highly delicate teaching, medical and research equipment manufactured in compliance with the present electronic age. Multi-million Naira equipment bought locally or donated by foreign collaborators is damaged on daily basis due to irregular electricity and fluctuations in voltage [3].

The lack of reliable electricity has pushed many end users to self-generation using diesel generating sets which are primarily fuelled by petrol and diesel [2]. Diesel generating sets create noise pollution and also present both environmental and health hazards because they emit various types of harmful pollutants. A report on emissions from the use of diesel engine generators in Nigeria by the World Bank estimates that about 0.16 million tons of diesel engine-based Carbon Dioxide (CO_2), emissions came from the residential sector in 2010. Table 1 shows the other harmful emissions for the residential and commercial sectors [4]. CO_2 is the main pollutant responsible for climate change followed by black carbon. In 2019, energy consumption in buildings accounted for over 30% of global energy consumption and 10 $GtCO_2$ or 28 % of greenhouse gas emissions [5]. Due to the requirement of the Kyoto protocol, implementing actions to increase energy efficiency and alleviate building emissions is no more a choice but rather an obligation. An effective strategy that permits attaining both economic, energy, and air quality

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goals is to grow the share of the renewable energy power system (REPS) in the building sector. Precisely, a shift to RE-based micro-grids with distributed generation systems (DGS) represents an effective strategy. This will help to aggressively lessen energy use while decarbonising the power sector. Also, use of RE based distributed generation systems in Nigeria will result to: 1) a reductions of lifecycle greenhouse gas emissions from our built environment and 2) the mitigation and adaptation of Nigerian society to climate change

Table 1. Diesel Gensets Emissions in the Nigerian residential and commercial sector in 2010 [4].

Pollutants	Emissions		units
	residential	commercial	
CO_2	0.16	0.07-0.12	$MtCO_2/yr$
SO_2	0.15	0.07-0.11	$ktSO_2/yr$
NO_X	4.1	1.8-2.8	$ktNO_x/yr$
Black Carbon (BC)	0.11	0.05-0.08	ktBC/yr
Organic Carbon (OC)	0.13	70-108	ktOC/yr

Distributed generation systems refers to a diversity of generation technologies interconnected with an electric load that generates electricity at or close to an area of use and can operate in grid-connected (on-grid) or isolated (off-grid) mode [6]. Renewable-based Distributed generation is emerging as an important option for the future development and restructuring of electricity infrastructure [7]. Possible benefits of distributed generation include lower electricity costs, higher flexibility, improved power quality, higher system efficiency and greater reliability [8]. The performance of a renewable-based distributed energy system depends on the building load profile, resource availability potential and geographical location. Also, the building's demand load depends on size, main activity, and geographical zone. Furthermore, the Nigerian government encourages the installation of RE-based power systems in the nation's institutions of learning. So it is vital to conduct a performance assessment of the distributed generation system options and the potential economic value of their investments to advise their optimal combination and operating mode. This will will hel to to guarantee their sustainability technically and financially. Many researchers in Nigeria and across the globe have focused on the modelling and optimisation of hybrid renewable power systems (HRPS) for both grid and off-grid applications [2, 9–15]. Their overall findings conclude that HRPS are a sustainable, reliable and cost-effective route for powering communities and institutional buildings with substantial environmental benefits.

The goal of the current research is to access and select the optimal distributed generation system based on the available resources that can serve the electric demand load of a university building reliably and sustainably. In addition, the impact of future load growth and different geographical contexts on the optimal system is studied to explore their impact on optimal system type and cost. The analysis will help in making informed decisions concerning the choice of power systems to de deployed to enable the much needed transition to sustainable energy systems in the building and other similar buildings.

2. METHODOLOGY

HOMER (Hybrid Optimization of Multiple Energy Resources) Pro software was used to model and select the best optimal system based on a minimal net present cost (NPC). The steps followed consist of the following:

- Energy audit of the building to determine demand load;
- Resource assessment to determine occurring RE with exploitable potential in the site;
- Candidate distributed energy system screening and selection;
- Costing of the various components;
- Design, and optimisation of the distributed energy system for the site in HOMER Pro;
- Sensitivity analysis;
- Analysis and discussion of the results.

2.1. Study location and energy resource potentials

The case study building is a faculty of engineering university departmental building of Enugu State University of Science and Technology (ESUT)) located in Agbani Town, Enugu ($6^{\circ}18.3^{'}N, 7^{\circ}33.8^{'}E$) in *Nkanu west* local government area of Enugu State in the southeastern region of Nigeria, (see Figure 1). This building has two floors, with a hip roof area of about $700m^2$, ideal for mouting roof-top PV modues. A fossil-based utility grid under the Enugu Electricity Distribution Company (EEDC) feeds the building electricty supply. The site has a modest wind and solar resource potential. For solar radiation, ESUT has a modest resource potential. The solar radiation for the site as shown in Figure 2, is obtained from NASA surface meteorology data in HOMER Software spanning over 22 years (1983 to 2005). During the year, the daily occurring solar radiation in the site varies from the lowest value of 3.91kWh/m^2/day in August to a high of 5.74kWh/m^2/day in February with a year average of 4.93kWh/m^2/day. The temperature characteristically varies from 23.92℃ in December to 26.62℃ in April and with a mean of 25.21℃ [16]. Figure 2 also displays the plot of the monthly average wind resource availability at this site taken from the NASA database in HOMER measured over 30 years (1984-2013). The wind speed fluctuates from 3 to 5 m/s at an annual average of about 4.09 m/s at 10 m hub height which is within the cut-in speed of most WTs.

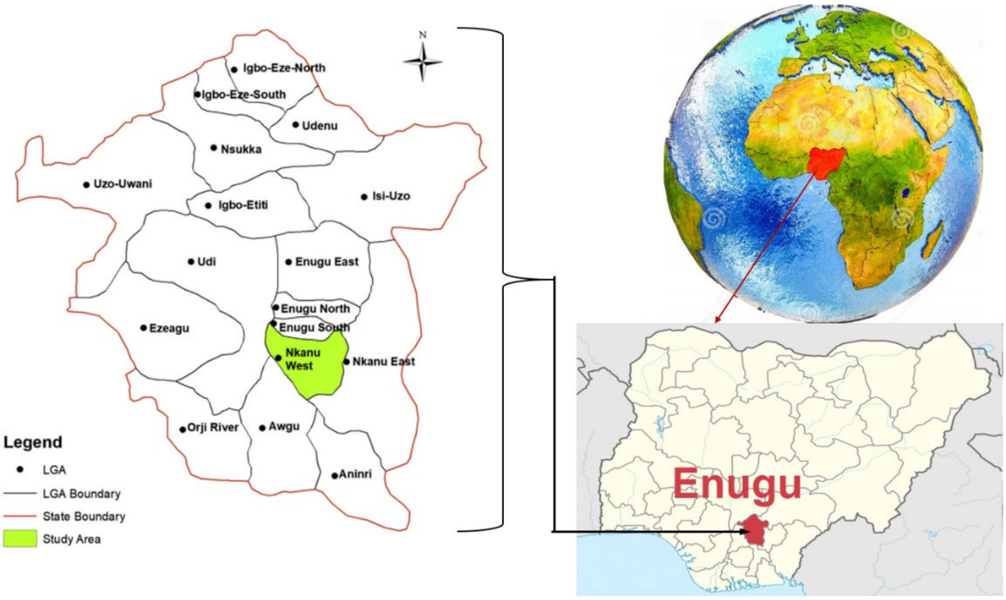

Fig. 1. The location of the understudy educational building on the map of Nigeria.

Biomass is another RE source that has high potential availability in this study location. Enugu has a present population of 882,178 and the amount of municipal solid waste being generated in Enugu municipality has been estimated to be 420 tonnes daily and this results in the waste generation of 0.48kg/capita/day [17]. The area of study has some farms around it; therefore, agricultural residues are the assumed feedstock. An average monthly biomass resource availability of about 8 tonnes per day is assumed for the location. By assuming a month-to-month variability of ±10%, the monthly biomass availability in the study region is shown in Figure 3.

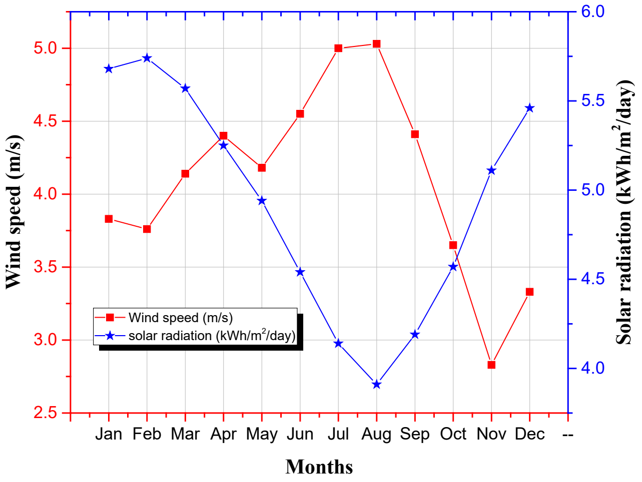

Fig. 2. Daily radiation in ESUT, Agbani-Enugu Nigeria.

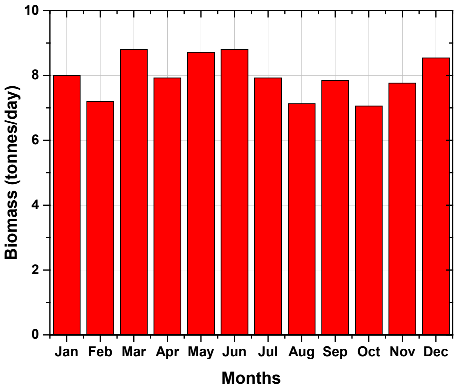

Fig. 3. Monthly biomass availability.

2.2. Load profile of the university building

The daily electrical load of the building is determined by an energy audit of the wattage ratings and usage duration of all the appliances in the building. Reference [16] contains the estimated load demand of the building. For the hourly, daily and yearly load variation, HOMER Pro was used. To account for hourly and day-to-day variations that may accompany the energy demand, day-to-day random variability of 10 % is assumed, while for the time-step-to-time-step, a random variability of 20 % is assumed. Based on these and a 30 % allowance for safety load, the building requires an annual average load of 254.24kWh/day and a peak of 32kW at a load factor of 0.33. Figure 4 shows the hourly variation of the building load while Figure 5 shows its yearly variation. The load is maximum (18.42kW) between 10 am and 3 pm, when office activities are at peak. The load declines and remains at a minimum value of 4.92kW between the hours of 9 pm and 4 am when all the staff have gone home or asleep and the appliances have been turned off except the external security lightings

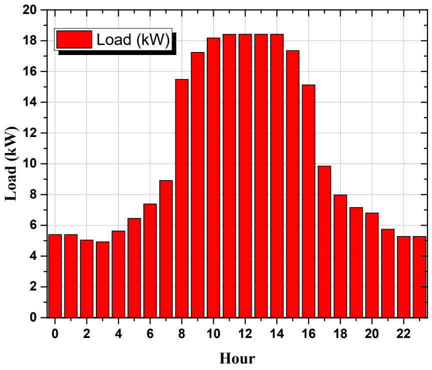

Fig. 4. Hourly load variation of the building.

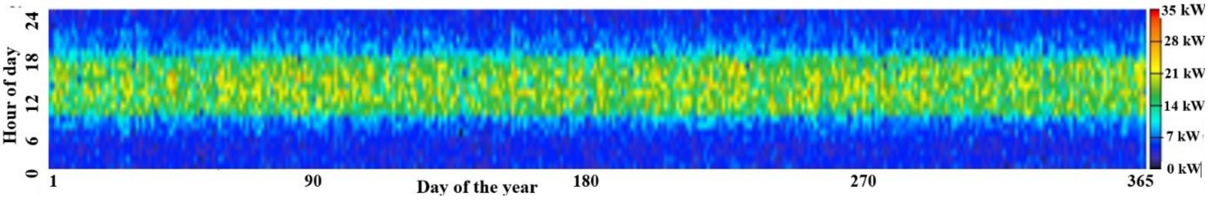

Fig. 5. Yearly load demand profile.

2.3. Selection of candidate DES

The distributed energy systems (DES) for the site were screened based on cost, fuel availability and maturity of the technology. The selected systems are wind turbine (WT), solar photovoltaic (PV), biomass engine generator (BDG), diesel generator and a hybrid renewable power system (HRPS) involving all or any of the selected single source disributed energy systems (DES). The schematic of the HRPS is shown in Figure 6. A diesel generator has been added to the hybrid system to serve as backup power for cases of low power output from the RE power sources [18].

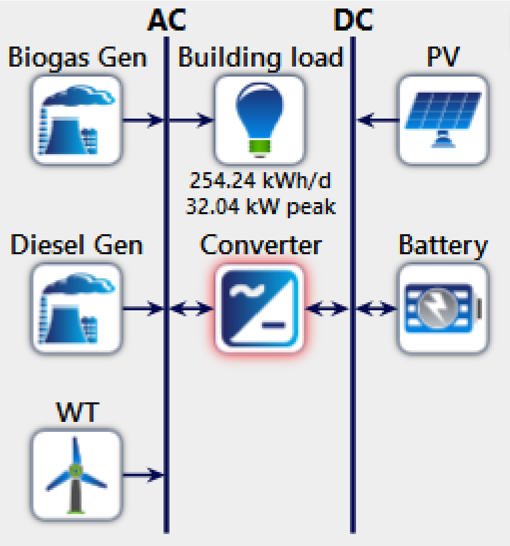

Fig. 6. Hybrid power system model schematic in HOMER Pro.

2.4. Modelling and optimisation in HOMER Pro

HOMER's economic simulation process, operates the system in a way that minimizes total NPC, and in its optimization process, it searches for the system configuration with the lowest NPC. In the project, the economic performances of the distributed generation system (DGS) are compared using the total net present cost (NPC), cost of electricity (COE) and internal rate of return (IRR) as metrics. In HOMER the total NPC is calculated by summing the total discounted cash flows in each year of the project lifetime using equation (1) [19]:

$$NPC = \frac{TAC}{CRF(i,t)} \tag{1}$$

$$CRF(\$) = \frac{i\times(1+i)^N}{(1+i)^N-1} \tag{2}$$

$$i = \frac{r-e}{r+e} \tag{3}$$

where *TAC* is the total annualized cost ($), *CRF* is the capital recovery factor, *t* is the annual project lifetime, *N* is the number of years, *i* is the annual real interest rate (%), *r* is the nominal interest rate w, *e* is the annual inflation rate.

The cost of electricity (COE) is the average cost per kilowatt-hour of useful electrical energy that the system produces. The COE is used to compare the economics of electricity generation from each of the considered DG options. The COE is estimated using equation (4) [20]:

$$COE = \frac{C_{ann,tot}}{E_{prim}+E_{def}+E_{grid.sales}} \tag{4}$$

where $C_{ann,tot}$ is the total annualised cost, $E_{prim} and\ E_{def}$ are the total amount of primary and deferrable load, respectively that the systems served per year and $E_{grid.sales}$ is the amount of electricity the system sells to the grid per year (for grid-connected systems).

The economic parameters of the systems are shown in Table 2.

A real discount rate of 12.75%, an inflation rate of 2%, and a project lifetime of 25 years have been assumed.

Table 2. Cost specifications of the main components.

Component	Capital cost	Replacement cost	O&M cost	Lifetime	Source
PV array	\$ 1500 kW^{-1}	\$ 1000 kW^{-1}	\$ 10 \$yr^{-1}	25 yr	-
Inverter	\$ 200 kW^{-1}	\$ 200 kW^{-1}	–	10 yr	[21]
Diesel generator	\$ 200 kW^{-1}	\$ 200 kW^{-1}	\$ 0.12 kWh^{-1}	25,000 h	[21]
Bio-generator	\$ 112 kW^{-1}	\$ 112 kW^{-1}	\$ 0.16 kW^{-1}	9125 h	[21]
Battery	\$176 kWh^{-1}	\$ 176 kWh^{-1}	\$ 8yr^{-1}	15 yr	[21]

3. RESULTS AND DISCUSSION

The result of the simulations reveals that out of the analysed distributed generation system considered for the building, only 11 are feasible for meeting the load of the building under the design conditions and constraints stated in the HOMER Pro software. The ranking of the feasible power generation sources in terms of their NPC and COE is shown in Figure 7. As can be seen, the best system for meeting the load of the building in terms of the lowest NPC is a hybrid system consisting of solar PV, biogas engine (BDG) and a battery bank (BB) for storage.

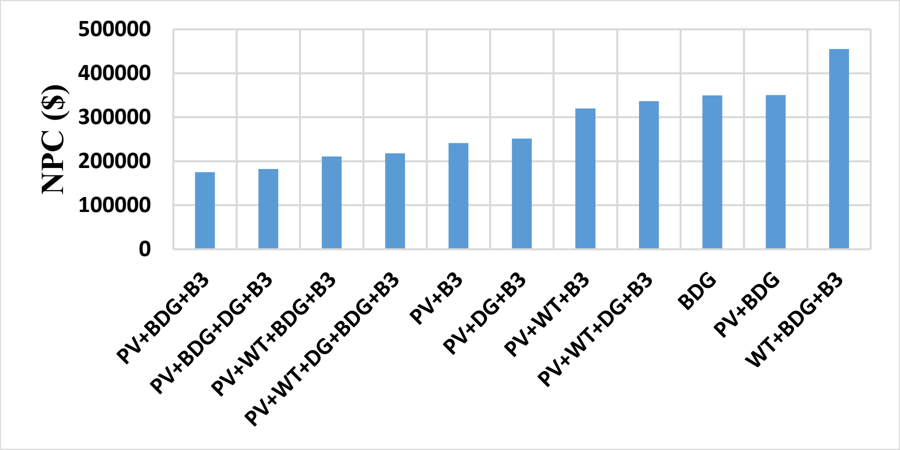

Fig. 7. Ranking of feasible DG systems for the site.

The summary of the rating of the components of all the feasible distributed generation system, including their technical and economic performance results is presented in Table 3. It can be seen that HRPS generally performs better than the stand-alone RES considered (WT, PV and BDG) because HRPS harnesses the advantages of the single energy systems making it up to produce more power during any cycle than would have been possible with a single energy source.

Table 3. Summary of optimisation results of the DG systems.

Architecture	Components ratings (kW)	NPC (\$)	COE (\$/kWh)	BDG output (kWh/yr)	PV Output (kWh/yr)	WT output kWh/yr)
PV/BDG/B3^{a}/Inv	75.6/40/30/33.6	175,220	0.253	11,106	88,266	-
PV/BDG/DG/B3^{a}/Inv	74.1/40/40/32/33.7	182,746	0.264	11,560	87,586	-
PV/WT/BDG/B3^{a}/Inv	42.5/25/40/30/40.8	210,735	0.305	5,207	65,263	39,352
PV/WT/BDG/DG/B3^{a}/Inv	42.5/25/40/40/30/40.8	218,347	0.316	5,207	65,263	39,352
PV/B3^{a}/Inv	144/52/39.6	241,351	0.349	-	105,928	-
PV/DG/B3^{a}/Inv	146/40/50/42.7	251,835	0.364	-	106,197	-
PV/WT/B3^{a}/Inv	127/25/48/39.2	320,120	0.463	-	103,011	39,352
PV/WT/DG/B3^{a}/Inv	127/25/40/50/48.2	336,732	0.487	-	103,011	39,352
BDG	40	349,723	0.506	112,665	-	-
PV/BDG/Inv	0.34/40/0.25	350,304	0.506	112,184	542	-
BDG/B3^{a}/Inv	40/2/0.329	350,337	0.506	112,665	-	-
BDG/DG/B3^{a}/Inv	40/40/2/1.65	358,313	0.518	112,665	-	-
PV/BDG/DG/Inv	21.5/40/40/2.23	390,318	0.564	105,632	34,367	-

WT/BDG/DG/B3[a]/Inv	25/40/40/16/9.64	428,780	0.620	89,869	-	39,352
WT/BDG	25/40	454,503	0.657	99,999	-	39,352
WT/BDG/B3[a]/Inv	25/40/2/0.0835	455,010	0.658	99,989	-	39,352
PV/WT/BDG/DG/Inv	15.4/25/40/40/6.26	486,857	0.704	91,808	24,504	39,352
PV/WT/BDG/Inv	9.3/50/40/3.32	557,399	0.806	88,820	14,807	78,705
WT/BDG/DG	25/40/40	685,780	0.991	99,989	-	39352

[a] stated value for battery bank (B3) is quantity, not power rating.

As shown in Table 3, optimization output is categorized into three parts including the architecture, costs and system, whilst each rank is the lowest NPC representative of each system architecture. The optimal PV/ BDG/Battery system has the least COE and NPC of 0.253$/kWh and $175,219.7 respectively among the system architectures. This system encompasses a PV of 75.6kW, BDG of 40kW, 30 Batteries of Generic 1 kWh Lead Acid and a 33.6 kW converter. The annual power output by the system is 99,373kWh out of which 36.4 % (36,170kWh) represents excess electricity produced. Solar PV contributes 88.2 % of the yearly energy production of the system with the biogas generator supplying the remaining 11 %. The breakdown of the contribution of each power source to the system's monthly power generation is shown in Figure 8.

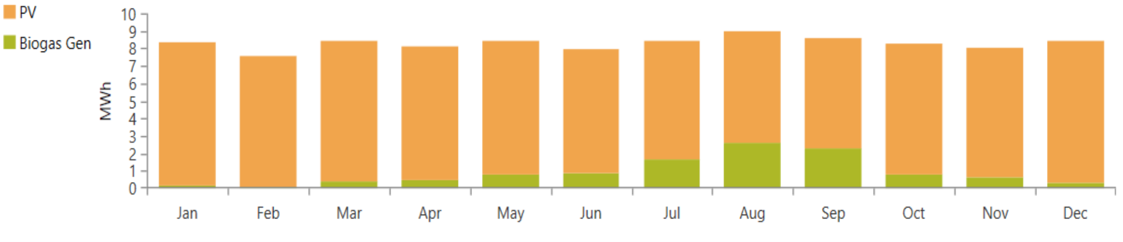

Fig. 8. Breakdown of power contribution from power sources.

The BDG consumes a total feedstock of 22.8 tons averaging 0.0626 tons per day or 0.00261 tons per hour. The monthly and yearly biomass consumption by the BDG system is depicted in Figure 9. Table 4 displays the comparison of the cost summary of the optimal PV/BDG/BB system with a base case standalone BDG of 40kW capacity. Based on the base case system, the optimal system retunes an IRR of 32 % and an ROI of 28 % with a simple payback of 3.2 years.

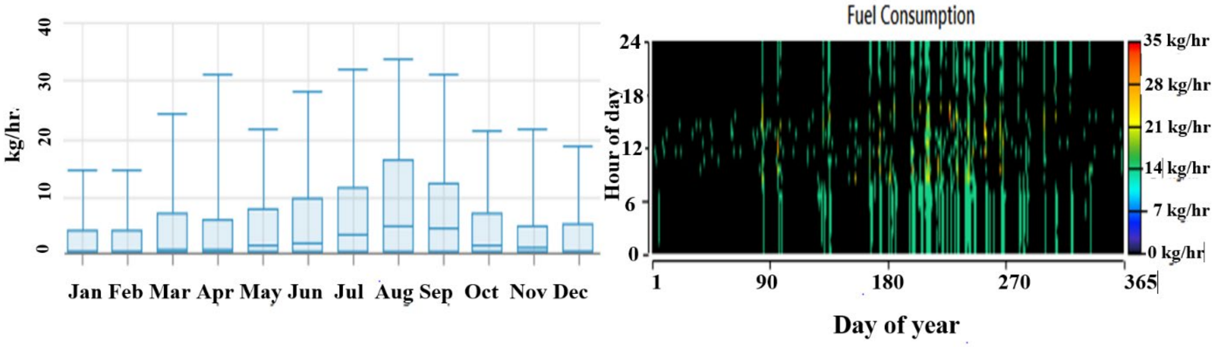

Fig. 9. Biomass consumption of the biogas system.

Table 4. Comparison of cost of the optimal system with base case BDG system.

Cost parameter	Base case system	Lowest cost system
NPC ($)	349,723	175,220
Initial capital ($)	4,480	129,997
O&M ($/yr)	46,310	6,066
LCOE ($/kWh)	0.506	0.253

Also, a comparison of the system with the existing grid in the building is shown in Table 5. It can be seen that to meet the AC primary load of 92,798kWh/year in the building, the optimal DG system (PV/BDG/BB) for the building emits only 4.19 kg/year of CO_2 emissions. This translates to savings of 40,905 and 121,890kg/yr of GHG emission for the use of the existing fossil-based grid and 40kW diesel engine system respectively.

Table 5. Comparison of emission of optimal system with grid and DG system.

Pollutants	Existing Grid system	40 kW Diesel system	Best Off grid system
	Emissions (kg/yr)		
Carbon Dioxide	40,910	121,895	4.19
Carbon Monoxide	29.7	768	-
Particulate matter	9.3	4.66	-
Sulphur Dioxide	696.7	298	-
Nitrogen Oxides	74.2	722	-

3.1. Sensitivity analysis

The mean wind speed in Nigeria ranges from about 4.0–7.5m/s in the northern region and 3.0 - 3.5m/s in the southern region. Also, the solar radiation potential in the Nothern and Southern region varies from 5.62 - 7.01 and 3.54 - 5.43kWh/m^2 respectively.

To measure the performance and applicability of the system to different geographical locations, a sensitivity analysis of the impact of varying resource potential (wind and solar radiation) and the demand load of the building on optimal system type were evaluated.

The wind speed, v (m/s) and solar Global Horizontal Radiation, GHR (kWh/m^2) potentials were varied from 3 to 7.5 while a future load (L) growth of about 40 % is considered. Figures 10, 11 and 12 depict the optimal systems graph with COE superimposed for the: variation of wind speed with load at mean solar radiation of 4.93kWh/m^2; variation of solar radiation and wind speed at a load of 350kWh/day; and variation of load and solar radiation at a mean wind speed of 4.09m/s.

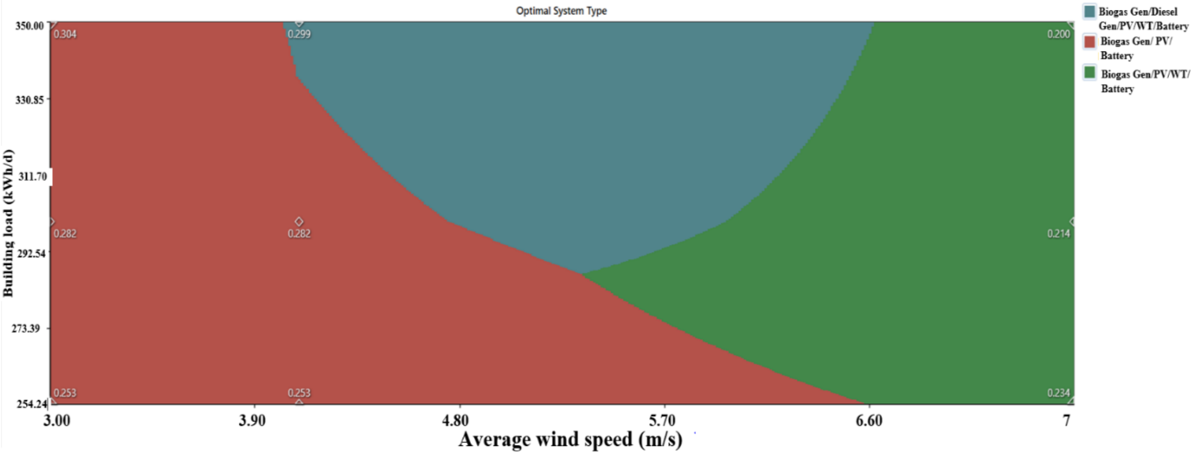

Fig. 10. Optimal system plot for variation of load and wind speed.

The optimal systems graphs show that the different optimal system types are possible at different combinations of the assessed variables. This means that the optimal system type is not constant but varies according to geographical locations and demand load.

From Figure 11, it can be seen that if the building load should increase from 254kWh/day by about 40 % to 350kWh/day at a mean wind speed and annual solar radiation of 4.09m/s and 4.93kWh/m^2 respectively, the usage of the backup diesel generator system cannot be avoided in the optimal system.

In this case the cost effective system for the building changes to Biogas-Gen/Diesel-Gen/PV/WT/Battery system. However ass mean wind speed reaches a high of 7.1m/s, the cost effective system becomes Biogas-

Gen/PV/WT/Battery system irrespective of the level of solar radiation. Mean wind speeds below 3.90m/s resulted to a hybrid Biogas-Gen/PV/battery system as the cost effective system.

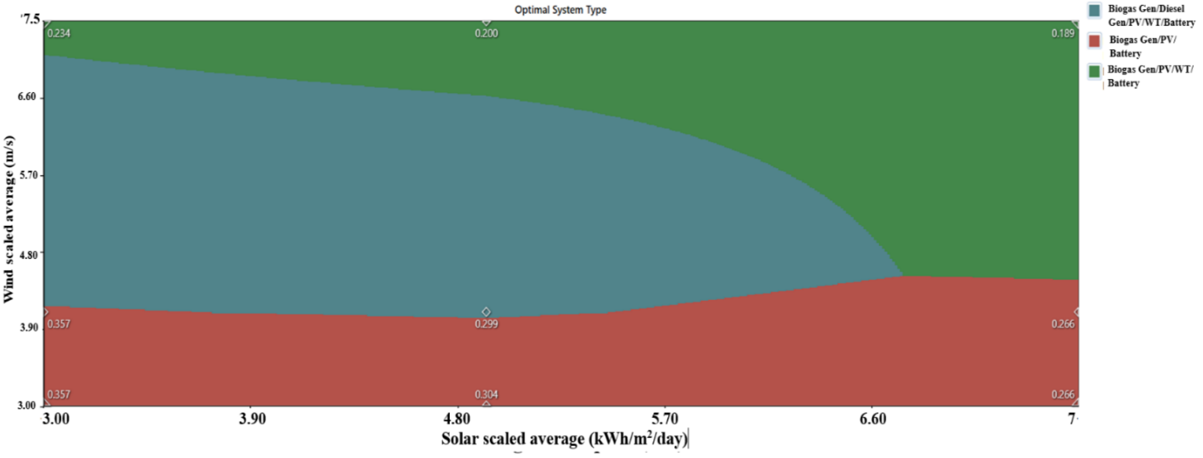

Fig. 11. Optimal system plot for variation of solar radiation and wind speed.

Also, Figure 12 shows that Biogas Gen/PV/battery systems is the most cost-effective system at solar radiation and loads ranging from 3.9 –7 kWh/m^2/day and 254 -330 respectively depending on the wind resource, and diesel fuel price. Site with solar radiation below this threshold is best served by a system consisting of either a hybrid Biogas-Gen/PV/WT/battery system or Biogas-Gen/Diesel-Gen/PV/WT/battery system depending on the load.

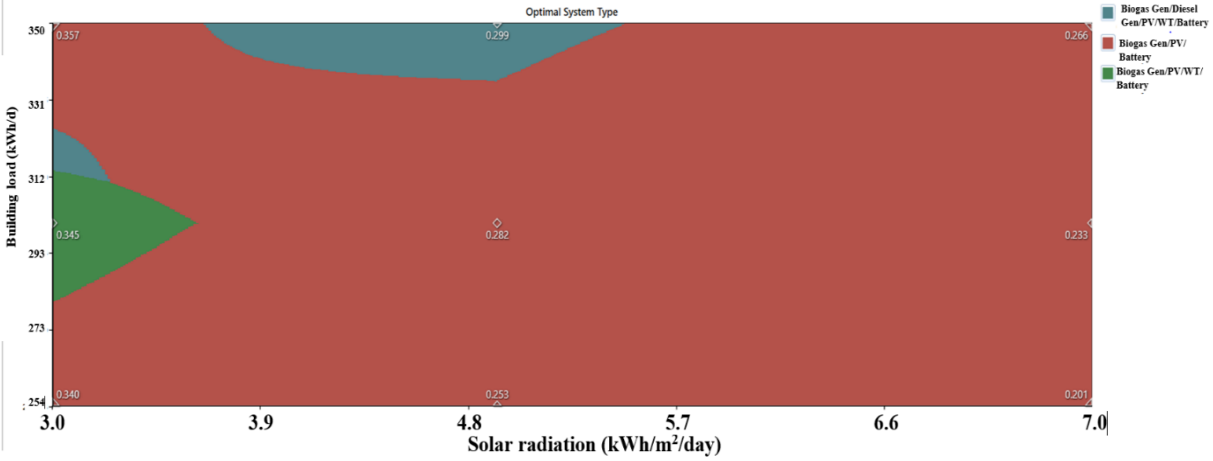

Fig. 12. Optimal system plot for variation of load and solar radiation.

4. CONCLUSIONS

This paper has presented the selection and analysis of an optimal standalone distributed energy system (DES) for an educational building application at Enugu State University of Science and Technology (ESUT) using HOMER Pro software.

The operational performance of the selected optimal system was investigated considering its net present cost (NPC), cost of electricity (COE) and emission reduction. In the proposed distributed energy systems, to ensure a very high renewable fraction (RF), it was pre-assumed that a renewable power system (RPS) is the primary energy supplier, while a battery bank (BB) with a diesel engine generator (DG) acted as a backup system to deal with the intermittency associated with RE sources.

Results obtained show that the optimal off-grid distributed generation system for meeting the daily demand load of 255kWh of the building in terms of 100 % RF, lowest net present cost (NPC) and minimal cost of electricity (COE) is a standalone hybrid system consisting of a 75kW rated solar PV, 40kW biogas engine (BDG) and a 30

number battery bank storage. The COE of the system is 0.253$/kWh while its NPC is $175,219.7. Other findings are as follows:
- Based on the base case system made up of BDG of 40 kW capacity, the optimal system retunes a 32 % internal rate of return and a 28% return on investment at a simple payback of 3.2 years;
- The optimal DG system (PV/BDG/BB) for the building returns annual GHG emission savings of 40, 905 and 121,890kg respectively when compared with the existing fossil-based grid and 40 kW diesel engine system respectively.

Based on the study's findings, it is recommended that integrating the selected standalone hybrid power system into the building is a beneficial option to improve power supply and energy mix in an environmentally friendly way albeit, at a cost higher than the prevailing grid tariff in the building. Sensitivity analysis shows that if the building load should increase by about 40%, the usage of the backup DG system in the optimal system cannot be avoided.

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