Optimization of an Autonomous Hybrid Power System for an Academic Institution

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***Abstract* — The epileptic power supply in Nigeria is enormously impeding universities' administrative, academic, and research activities. The diesel generators on which most of these institutions rely as alternative power sources during grid failures are not viable solutions as the grid outage is incessant and the duration usually lasts for hours, at times for days. The effects of these are high running costs and increased environmental pollution. If normal activities in the universities are to continue unhindered and to reduce the health risks associated with the fossil-based generators, there is the need to explore other alternatives such as utilizing the environmentally-friendly, free and abundant renewable resources to meet their electricity demands. The present study uses Hybrid Optimization of Multiple Energy Resources (HOMER) to evaluate two different configurations of a stand-alone diesel generator (DG) system and a hybrid solar photovoltaic(PV)-diesel generator(DG)-battery energy storage (BES) system for sustainable power supply to the Baze University Abuja, Nigeria. The net present cost and levelized cost of energy, operating cost, and carbon dioxide emission of the hybrid PV-DG-BES system are lower by 50%, 30.93%, and 90% respectively when compared to the stand-alone DG system. Therefore, a hybrid solar PV-DG-BES system is a suitable technology to sustainably power the University.**

***Index Terms* — Hybrid Power System, Optimization, Photovoltaic, Simulation.**

I. INTRODUCTION

Nigeria is the most populous country and the largest economy in Africa [1], [2]. By 2050, Indonesia, Nigeria, China, India, Pakistan, and the USA, are the six nations expected to have a population exceeding 300 million [3]. Furthermore, with the current population of 206 million people and an annual growth rate of 2.58% [4], according to the United Nations, Nigeria is set to occupy the third position in the global ranking of the most populated country by 2050 [2]. The increase in population always leads to an increase in power demands. Unfortunately, more than half of Nigeria's populations do not have access to electricity, and the largest proportion resides in rural areas [5]. The present power generation capacity is 7,652.6 MW, with an average peak generation of 5,000 MW [6], and the demand was envisaged to have hit 52,000 MW by mid 2020 [7]. Nigeria's electricity consumption per capita (i.e. 144 kWh) is far below that of South Africa (4,229 kWh), Egypt (1,699 kWh), Libya (1,841 kWh), and Namibia (1,564 kWh) [8]. Apart from the severe power generation deficit, the country's electricity supply industry is faced with numerous challenges such as overstressed transmission and distribution networks, energy theft, poor maintenance, regular destruction of equipment by vandals, and lack of modern control systems [1]. Because of these, there are high rates of power failure, and system collapse incidences have continued to be a frequent phenomenon. For instance, the country's electricity supply industry witnessed 647 system collapses between 1987 and 2014 [9], and 36 collapses between 2014 and 2017 [10]. In 2019, the system collapsed twelve times and had collapsed three times in 2020 as of September [11]. The radial nature of its feeders and long extensions especially in the distribution networks practically make them susceptible to faults. Thus, even where the central grid exists, the power supply is unreliable, and its incessant outage has posed an enormous challenge on the educational, social, industrial, and economic activities of the country. The frustration experienced during power outages is of high consequences. Imagine sudden seizure of power to elevators in high rise structures, life-saving healthcare facilities in the hospitals, or critical industrial or military equipment. This could lead to injuries, damages, and sometimes deaths.

One of the most affected spheres of life by this epileptic power supply is the education sector. It is a common practice in Nigerian academic institutions for classes to be taught without electricity. Many classes that require the use of electrical appliances such as computers, smartboards, projectors, simulators, machines in workshops, etc are usually impeded by an irregular power supply from the central grid. The effects of these are ineffective teaching, learning, and administrative activities, and poor cutting-edge research outputs. The fossil-based generators on which most of these institutions rely as a substitute or alternative power source is not a sustainable solution since the grid outage is persistent and the duration usually lasts for hours, at times for days. More so, the cost of operation and maintenance of these generators are high and they also cause environmental pollution [12], [13]. To proffer a solution to this challenge, the government of Nigeria came up with the energizing education programme (EEP) with the mandate to look into the integration of renewable resources for sustainable power supply to the seven university teaching hospitals and the thirty-seven federal universities in the country [14], [15]. Under this EEP, 2.8 MW and 7.1 MW off-grid hybrid solar power systems have been accomplished for Alex Ekwueme

Published on October 8, 2020.
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Federal University and Bayero University Kano respectively [15]. Ogbonnaya *et al* [3] surveyed different literature that places Nigeria as having enormous renewable resources such as solar, wind, geothermal, water, and biomass that can be harnessed for power generation.

The major drawbacks of renewable technologies are their intermittency nature and dependence on certain weather and seasonal conditions [16], [17]. For instance, water in river changes flow according to the seasons, the solar irradiation is lesser in winter than in summer and unavailable at night, and similarly higher wind speed is recorded in summer, etc.

The prices of renewable energy systems, especially solar photovoltaic (PV), and battery energy storage (BES) system have significantly reduced in the recent time, and from the techno-economic point of view, their operation in hybrid form is becoming more attractive [18]. A hybrid renewable energy system (HRES) can be described as an electricity production system in which energy supply consists of a combination of two or more types of electricity generating sources such as pico or microhydro plants, solar photovoltaic (PV) panels, wind turbine (WT) generators, and/or fossil-based generators [17]. An HRES can be efficiently deployed to supply reliable electricity to the end-users, unlike a single renewable source [19].

Numerous studies have been reported on the techno-economic evaluation of hybrid energy systems (HES), and the preferred systems usually prove to be the most cost-effective system that can reliably satisfy the electricity demands. Khan *et al* [13] conducted an assessment of off-grid hybrid energy systems (HES) for a university campus. The study considered four different scenarios of configurations that included stand-alone diesel generator (DG), PV-BES system, wind turbine (WT)-BES, and PV-WT-BES system respectively. The optimization performed in Hybrid Optimization of Multiple Energy Resources (HOMER) revealed the most feasible system to be the PV-WT-BES system having presented the least NPC (US$3,054,109) and LCOE (US$0.258). Rinaldi *et al* [20] focused on determining the optimal configuration of hybrid PV-Wind-diesel systems for three small communities without access to the grid in the remote Peruvian villages. The systems were modeled in seven scenarios of single component system (solar, wind, and diesel) and the hybrid component systems. HOMER software was used to establish the optimal sizing of the system considering the lowest NPC, initial capital cost, total annual operating cost, cost of energy, the generation fractions, and the resulting CO_2 emissions. The obtained results revealed that, for all of the investigated communities, the hybrid solar-wind-diesel system is the most sustainable configuration. Ariyo *et al.* [21] explored the viability of providing alternative power supply from a hybrid PV-DG-BES system to the administrative building of the University of Ilorin, Nigeria. The renewable resources data (wind speed and solar irradiance) of the case study over one year were extracted from the National Aeronautics and Space Administration (NASA) database. The various system configurations analyzed to meet the demand at the minimum cost of energy favoured the hybrid PV-DG-BES architecture with the cost of energy being US$0.283/kWh. Khare *et al* [22] used particle swarm optimization (PSO) and chaotic particle swarm optimization (CPSO) algorithms, and HOMER for optimization of the renewable energy system for a police control room. A hybrid solar-wind energy system proved to be the most feasible solution for a stand-alone application. The fuel cost reduction was about 70-80% higher compared to that of the DG. Timilehin *et al* [12] examined the possibility of combining PV array, DG, and BES systems for efficient energy management and to minimize dependence on DG. The university campus chosen as a case study had 6 MW power plants comprising a stand-alone gas turbine and thirteen diesel generators as backups which gulp up a huge amount of money in terms of fueling and maintenance. The results of simulation using HOMER revealed that the proposed system can guarantee sustainable electricity, with lesser carbon footprints. Zia and Shaikh [23] used Net Present Cost (NPC) as the parameter for the optimum solution of a hybrid PV-WT-DG. The idea was to design a microgrid from a limited budget of US$200,000.00 for 18 houses with a peak demand of 6.59 kW. The optimal configuration modeled, simulated, and optimized in HOMER proved a significant decrease of carbon dioxide and carbon monoxide by 80.76% and 80.56% respectively, and the optimum system had an NPC of USD$15,089.00 Babatunde *et al* [24] proposed a multicriteria approach for the selection of the most suitable HRES for a typical low income household. The analysis was based on two energy demand scenarios; consumer demand based on energy efficient equipment and consumer energy demand without energy efficiency. Results showed that the optimal HRES based on both energy demand scenarios is a hybrid PV-DG-BES architecture. Jahangiri *et al* [25] conducted a techno-environ-economic feasibility study comparing a hybrid system consisting of the grid/wind turbine/solar cells and hydrogen. The analysis was done using four vertical axis wind turbines(VAWT). The results of the simulation in HOMER indicated that the lowest price of the electricity was US$1.55/kWh which was obtained by using EOLO VAWT in the main grid/wind turbine/solar cell scenario. Amer *et al* [26] used Particle Swarm Optimization (PSO) techniques as an optimization searching algorithm for reducing the Levelized Cost of Energy (LCOE) while maximizing the quality of services of wind and photovoltaic hybrid system for an average demand of 1 kW. The wind power generated by the system was 1.0185 kW and that of the PV was 0.23153 kW. Yeshalem and Khan [27] presented a study on the viability deployment of a hybrid renewable energy system that will provide reliable electricity for a specific remote mobile base station in Ethiopia using HOMER. The scaled energy consumption used in the analysis was 41.4 kWh/day. The PV/battery and PV/wind/battery hybrid systems were compared with the conventional stand-alone diesel generator system. The configuration of the PV array and battery was the most economically viable option with the total Net Present Cost (NPC) of US$57,508 and per-unit cost of electricity [COE] of US$0.355/kWh. Das *et al* [28] presented a study that focused on a model of a small hybrid power generation unit with storage and a micro-hydro generation unit and a diesel generator to mitigate the rising energy demand and to reduce dependence on the DG. In terms of the NPC, the hybrid system was 27% cheaper compared to only diesel-driven system. The cost of energy was US$0.206/kWh which is 28% cheaper than only diesel system.

Baze University Abuja, Nigeria which is the focus of this study is a private university and is, therefore, not captured by the EEP. During the usual power failure from the central grid, the university has six functional backup diesel generators of different capacities (820 kVA, 150 kVA, 25 kVA, 5 kVA, and 2-number 500 kVA) that supply the required electricity to ensure that the normal activities are not halted. Meanwhile, this is not a sustainable solution due to the high costs of operation and maintenance and the negative environmental impact of the diesel generator. Therefore, this research aims to conduct a techno-economic analysis of two different scenarios; stand-alone diesel generator and standalone hybrid solar PV-DG-BES system for sustainable power supply to the university. The results of the simulation and optimization using the Hybrid Optimization of Multiple Energy Resources (HOMER) software for the two cases will be analyzed and preference will be given to the system that presents the least net present cost (NPC), levelized cost of energy (LCOE), and the lowest carbon footprints.

II. MATERIALS AND METHODS

A. Study Location

The Baze University is located on latitude 9^0 0.4’N and longitude 7^0 24.3’E in Nigeria’s Federal Capital Territory, Abuja. The university began full operation in 2011 with three faculties and a foundation class and has now expanded to six faculties and a school of postgraduate studies. The satellite view and the generator yard of the university are shown in Fig. 1 and Fig. 2 respectively.

Fig. 1. Aerial view of Baze University Abuja, Nigeria [11].

Fig. 2. Generator yard of the university.

B. The Proposed Power System

The first case proposes a hybrid power system (HPS) comprising a solar PV array, battery energy storage (BES) system, converter, backup diesel generator (DG), and an electrical load as shown in Fig. 3(a). The diesel generator will come on board when there is insufficient or no power generation from the PV and the state of charge of the BES is low. The bidirectional converter allows the synchronization of DC to AC and vice versa. Fig. 3(b) represents the second case in which only DG is used to power the university loads.

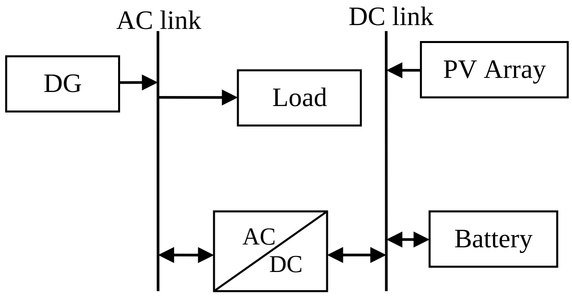

Fig. 3 (a). CASE I: Hybrid Solar PV-DG-BES system architecture.

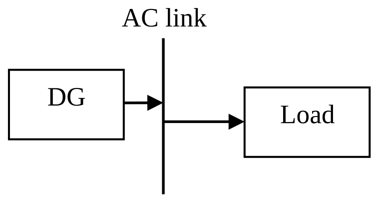

Fig. 3 (b). CASE II: Stand-alone diesel generator architecture.

C. Hybrid Optimization of Multiple Energy Resources

The computer model utilized to explore the various design options is the Hybrid Optimization of Multiple Energy Resources (HOMER) developed by National Electric Renewable Laboratory (NERL) in the USA. HOMER performs three main tasks; simulation, optimization, and sensitivity analysis. The simulation process establishes whether the hybrid system is viable. HOMER estimates the system’s life cycle costs and also ranks the system to be optimal if found to adequately and sufficiently meet the thermal and electric loads after satisfying all constraints imposed by the designer. The sensitivity analysis guides the user to understand and make necessary planning to take care of the effects of uncertainties such as unpredictable weather conditions, fluctuating fuel prices, interest rates, etc.

D. Electrical Load Assessment of the University

Four maximum demand energy meters measure energy delivered to the university from the central grid. According to these meters, the university consumes approximately 3,804.12 kWh/day. And this is the synthetic load that was fed into the HOMER software. The scaled peak demand is 636.06 kW, baseline peak demand is 405 kW at the load factor of 0.25, day-to-day random variability, and a time step of 20% and 10% respectively. The daily load and seasonal load profiles of the university are shown in Fig. 4 and Fig. 5 respectively.

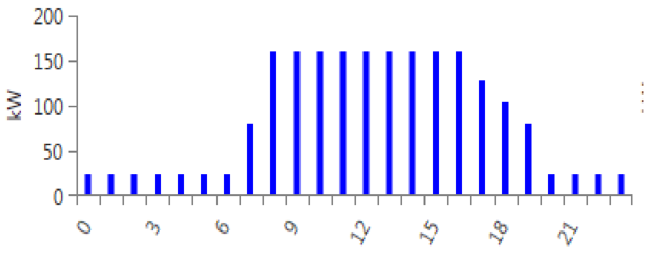

Fig. 4. Daily load profile of the university.

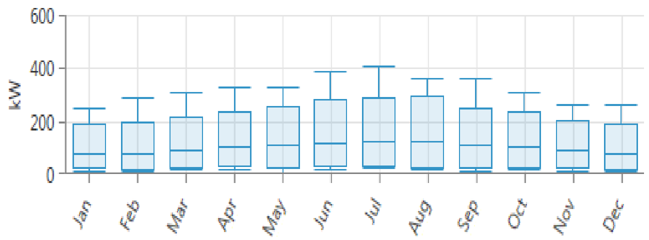

Fig. 5. Seasonal load profile of the university

E. Hybrid Energy System Modeling

The modeling of the proposed HPS is described in the following subsections.

1. Solar Photovoltaic Panel

Solar Photovoltaic (PV) panel is the main building block of any PV system, while the main building block of the PV panel is the solar cell. The power supplied in kW by the PV panels can be expressed as [29]:

$$P_{pv} = G(t) \times \eta_{pv} \times A_{pv} \times 0.01 \tag{1}$$

where, A_{pv} is the total area covered by the PV panels at the project site, G(t) is the hourly irradiation (W/m^2), η_{pv} is the efficiency of the PV module.

2. Storage Battery

Storage battery commonly referred to as one or more electrochemical cells converts electrical energy into chemical energy during a charging process and converts stored chemical energy into electrical energy during a discharge process. On autonomous days, the storage capacity of the battery can be computed as [29]:

$$C_{Bat} = \frac{E_L AD}{\eta_{inv} DOD \eta_{bat}} \tag{2}$$

E_L, AD, DOD, η_{inv}, and η_{bat} represent average load demand in kWh per day, the number of autonomous days, depth of discharge of the battery, inverter efficiency, and battery efficiency respectively.

3. Diesel Generator

Diesel generators have been widely employed along with renewable sources to increase the reliability of such systems. The fuel consumption of a diesel generator is determined by using (3) [29]:

$$F_c = C_g P_o + K_g P_r \tag{3}$$

P_o, P_r, K_g, and C_g represent the nominal power of the diesel generator, operating power output of the diesel generator, fuel curve slope in liter/kWh and the fuel curve intercept coefficient in liter/kWh.

4. Converter

To maintain the flow of energy between the DC and AC buses, a power converter is needed. It is a device that converts electrical power from AC to DC in a process called rectification and from DC to AC in a process called inversion.

F. Economic Analysis

Each component that made up an HPS has some cost data such as capital, replacement, operation and maintenance costs, fuel/diesel price, interest, and inflation rates, project lifetime, and so on. These costs are considered in the simulation and optimization stages and based on them, the Net Present Cost (NPC) of each plan is calculated [30]. The optimum system can be found by reducing the cost of the whole system and providing adequate energy supply to the load. The NPC, Levelized Cost of Energy (LCOE), and payback period are useful economic indicators that help to measure and evaluate the best HRES costs. The NPC is the sum of all costs and revenues throughout the project lifetime as given in (4) [31].

$$NPC = \frac{T_{AC}}{CRF(\alpha, T_P)} \tag{4}$$

where T_{AC} is the total annualized cost, α is the annual real interest rate (%), T_p is the project lifetime (year) and CRF is the capital recovery factor given by [20], [30]:

$$CRF(\alpha, i) = \frac{\alpha(1+\alpha)^i}{(1+\alpha)^i - 1} \tag{5}$$

where i is the number of years. The real interest rate (α) is determined using the nominal interest rate (α') and the annual inflation rate (β) given by [31]:

$$\alpha = \frac{\alpha' - \beta}{1+\beta} \tag{6}$$

In HOMER, the rate of inflation is the same for all types of costs (fuel cost, maintenance cost, labor cost, etc.) occurring throughout the lifetime of the project.

The Levelized cost of energy (LCOE) is the ratio of the total annualized cost (T_{AC}) of the system to the annual load served in kWh per year (E_{tot}) as given in (7) [13]. In other words, it is the average cost per kWh of producing electricity from the HRES [31].

$$LCOE = \frac{T_{AC}}{E_{tot}} \tag{7}$$

G. Solar Resources Data

The average solar global horizontal irradiance monthly data of the university was extracted from the National Renewable Energy Laboratory Database in HOMER. The monthly average solar Global Horizontal Irradiance (GHI) data showing the clearness index and the daily radiation in

KWh/m^2/day are shown in Table I and represented graphically in Fig. 6. The highest and lowest solar radiation occurs in March and July respectively. The annual average is 5.55 kWh/m^2/day.

Fig. 6. Solar Global horizontal irradiance data of the university.

TABLE I: MONTHLY SOLAR GLOBAL HORIZONTAL IRRADIANCE DATA OF BAZE UNIVERSITY ABUJA

Month	Clearness Index	Daily Radiation (kWh/m^2/day)
January	0.621	5.598
February	0.596	5.769
March	0.600	6.172
April	0.586	6.152
May	0.563	5.282
June	0.520	5.291
July	0.459	4.697
August	0.454	4.714
September	0.496	5.101
October	0.601	5.871
November	0.648	5.899
December	0.633	5.550

H. Summary of Components Parts and Characteristics

The technical and economic characteristics of the components modeled and simulated in HOMER are summarized in Table II.

TABLE II: SYSTEM COMPONENTS AND CHARACTERISTICS THE ARRANGEMENT OF CHANNELS

Components	Specifications	Description
Diesel Generator	Size	1 kW
	Capital Cost	US$500
	Replacement Cost	US$500
	Operations and Maintenance cost	US$0.030/hr
	Lifetime	25 years
	Fuel Cost	US$0.40/litre
PV Panel	Size	1 kW
	Capital Cost	US$2,000
	Replacement Cost	US$2,000
	Operations and Maintenance cost	US$10/year
	Lifetime	25 years
Battery	Type	Lead Acid
	Nominal voltage	12 V
	Nominal Capacity	1 kWh
	Maximum Capacity	83.4 Ah
	Round trip efficiency	80%
	Capital Cost	US$300
	Replacement Cost	US$300
	Operations and Maintenance cost	US$10/year
Converter	Size	1 kW
	Capital Cost	US$350
	Replacement Cost	US$350
	Operations and Maintenance cost	US$0.00
	Efficiency	95%
	Lifetime	15 years
Project lifetime		25 years

The inflation rate is 12.05% [32], the real interest rate is 11% [33] and the diesel fuel price is taken as US$0.59 per liter according to the current exchange rate (US$1 = ₦386.53).

I. HOMER Search Space

HOMER usually considers several combinations and capacities of components in its search space to arrive at the optimal solution. In this study, the search space comprises a total of 7×2×7×9=882 configurations, and the capacities and sizes of the components specified are shown in Table III.

TABLE III: THE SEARCH SPACE

Converter (kW)	Generator (kW)	PV Panel (kW)	Battery (strings)
0	0	0	0
24	700	10	50
60		100	100
120		200	150
300		500	200
500		1000	500
1000		2000	1000
			5000
			8000

III. RESULTS AND DISCUSSION

A. Case I: Hybrid Solar PV-DG-BES System

In all, 1,394 cases were simulated; 746 cases were found to be feasible and 648 cases were infeasible due to capacity shortage constraints. Table IV presents a summary of the most feasible system. That is, the optimum system configuration ranked according to the least total NPC and LCOE. The results indicate that the PV panel of 1000 kW is capable of supplying the university electricity demand of 3,804.12 kWh/day with mean annual solar insolation of 5.55 kWh/m^2/day. The generator size is 700 kW and is expected to supply the university whenever the energy output from the solar PV is low or the battery bank is drained such that it cannot sufficiently supply the load.

TABLE IV: OPTIMUM HYBRID SYSTEM ARCHITECTURE

Generator Capacity	700 kW
Photovoltaic System Capacity	1000 kW
Battery storage system	5000 strings
Dispatch strategy	Load following
Renewable Fraction	89.9%
Converter capacity	500 kW

The size of the converter is 500 kW, whereas the dispatch strategy is "load following". HOMER uses two types of dispatch strategies; "load following" and "cycle charging". In the "cycle charging" strategy, the diesel generator starts when necessary and runs at its rated capacity. Its excess energy is then sent to the battery storage system to charge the batteries. In the "load following" strategy, however, the diesel generator starts when necessary and generates only the amount of power that cannot be produced using the solar PV or battery system to supply the load. The fraction of the energy delivered to the load through the solar PV, otherwise known as the renewable fraction is 89.9%.

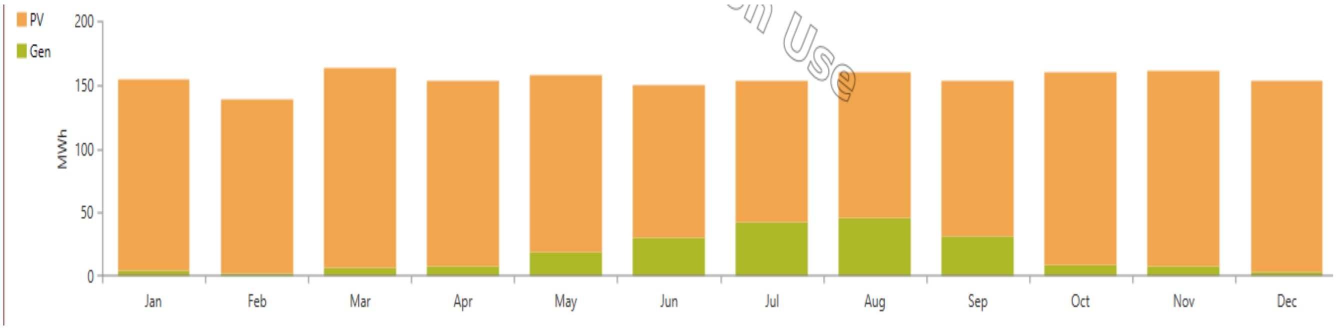

Fig. 7. Monthly electric production from the hybrid system.

As presented graphically in Fig. 7, the total electrical energy production from the hybrid system (Solar PV-DG-BES) is 1,856,434 kWh/year. The DG is expected to produce about 11.3% (210,036 kWh/year) of the electrical energy with peak contribution occurring in August, whereas the remaining 88.7% (1,646,398 kWh/year) will come from the solar PV.

The excess electricity of 324,999 kWh (i.e. 17.5%) is being generated per year, with no capacity shortage and no unmet loads. This excess generation can be channeled to power some uncritical loads in the university.

Furthermore, the DG emissions to the atmosphere are carbon dioxide (160,507 kg/year), carbon monoxide (1,012 kg/year), unburned hydrocarbons (44.1 kg/year), particulate matters (6.13 kg/year), sulfur dioxide (393 kg/year), and nitrogen oxides (950 kg/year). The rate of fuel consumption of the generator is 7 liters/hour. The graph of the generator fuel consumption is shown in Fig. 8.

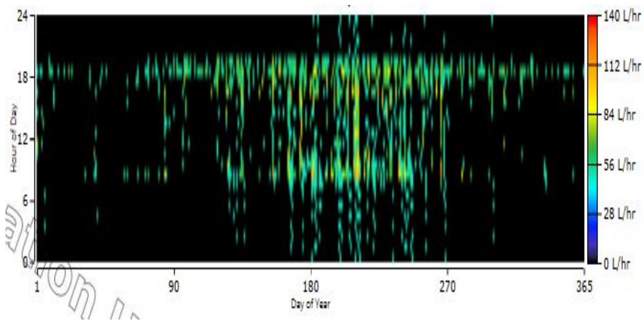

Fig. 8. Diesel generator fuel consumption.

In terms of the economics of the system, the optimum system architecture has a total NPC of US$10,213,580.00, an operating cost of US$218,521.90, and the LCOE is US$0.2597 per kWh. As defined earlier, NPC is the sum of all costs and revenues throughout the project lifetime. The LCOE, however, is the average cost per kWh of producing electricity from the HRES. The cost of electricity per kWh from the proposed hybrid system is expensive compared to if electricity were to be supplied from the national grid whose LCOE is US$0.18/kWh (US$1 = ₦386.53) in line with the recent Nigerian Electricity Regulatory Commission (NERC) approved service reflective tariff for Abuja Electricity Distribution Company Plc, Nigeria.

B. Case II: Standalone Diesel Generating System

When only a DG is to be used to power the whole university, the total NPC, the LCOE, and the operating cost are US$20,360,370.00, US$0.5178 per kWh, and US$706,576.40 respectively.

The total electrical production of the DG is 1,948,876 kWh per year with a mean electrical output of 222 kW. The university requires 564,746 liters of fuel to power its loads per year. About 1,478,287 kg of carbon dioxide will be emitted to the environment every year. Other hazardous particles to be emitted to the environment by the DG are; carbon monoxide (9,318 kg/year), unburned hydrocarbon (407 kg/year), particulate matters (56.5 kg/year), sulfur dioxide (3,620 kg/year), and nitrogen oxides (8,754 kg/year). Table V provides a quick comparison of the two cases in terms of the NPC, LCOE, and CO_2 emission.

TABLE V: SUMMARY OF NPC, LCOE, AND CO_2 EMISSION

Parameter	Case I	Case II
NPC	US$10,213,580.00	US$20,360,370.00
LCOE	US$0.2597	US$0.5178
CO_2	160,507 kg/year	1,478,287 kg/year

The NPC and LCOE of Case II (stand-alone DG system) are 50% higher than those of Case I (hybrid solar PV-DG-BES system). More so, the environment will be saved of about 90% of CO_2 if the Case I is considered.

IV. Conclusion

This work investigated two different cases of stand-alone DG system and autonomous hybrid solar PV-DG-BES system for Baze University Abuja respectively. The university consumes approximately 3,804.12 kWh/day, and the annual mean solar radiation extracted from the NASA database is 5.55kWh/m^2/day. The results of the simulation using HOMER revealed that an optimum hybrid system comprising solar PV, converter, battery bank, and a diesel generator can guarantee year-round electricity for the university at the net present cost of US$10,213,580.00, operating cost, and per kWh cost of energy of US$218,521.90 and US$0.2597 respectively. It was also established that it is more expensive and environmentally harmful if the university decides to entirely rely on a diesel generator to power its loads. Although where the central grid exists like the Baze University, a renewable energy system is not the utmost solution except for the grid's incessant failure which has always made the university falls back to the expensive and environmentally harmful diesel generator. Key findings of this assessment are summarized below:

(i) In the PV-DG-BES system, PV array is responsible for the production of 88.7% of electricity. Thus, the university receives sufficient solar radiation that can be harnessed for sustainable power supply.

(ii) PV-DG-BES system has lower NPC and LCOE and provides a reliable power supply with no capacity shortage and no unmet loads. The NPC and LCOE for solar PV-DG-BES system are 50% lower compared to the stand-alone DG system.

(iii) PV-DG-BES is environmentally friendly compared to the stand-alone DG system. The CO_2 emission represents only 10% of a DG system as a result of high renewable energy penetration of 90%.

(iv) The operating cost of PV-DG-BES is US$218,521.90, and that of the stand-alone DG system is US$706,576.40, which is 30.93% higher.

Given the above findings, an autonomous hybrid solar PV-DG-BES system is a suitable technology to sustainably power Baze University Abuja in contrast to the stand-alone DG system. Further studies can consider integrating wind resources into the energy mix to improve the system reliability and to significantly reduce reliance on the DG.

Acknowledgment

The authors are grateful to those whose collaboration led to the success of this work.

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