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Design and simulation of an effective backup power supply for academic institutions in Nigeria: A case study of NDA postgraduate school

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ABSTRACT

This research work is aimed to mitigate the adverse effect of numerous portable generators used in academic environments due to the unstable power supply experienced in Nigeria. Data for the study on the existing backup, availability hours from the national grid, and load demand for the area of study were obtained from the residents of the campus, facility managers, and Kaduna Distribution Company as the grid supplier from August 2017 to December 2020. The average load of the campus was obtained to be 80kW. These were used as a baseline to obtain the required size and quantity of material to generate the backup power needed. A total ampere-hour requirement of the battery to be used was obtained to be 4,278.07Ah considering the average battery depth of discharge of 80%. This resulted in a total number of cells required to be 134 considering a battery with a 200 Ah rating and a nominal voltage rating of 48V. A solar photovoltaic (PV) system rating of 166.4 kW is required to sufficiently charge the battery bank and also serve the load. This amounts to a minimum of 5 panels per string connected in series and 34 number panels per string connected in parallel based on which the total number of panels required summed up to 666. The inverter rating for the load was obtained to be 150 kVA with a total load of 100 kVA, an efficiency of 80%, and an average future expansion of 20 %. A diesel generator rating of 100 kVA with a starting kVA rating of 113.64kVA is required to efficiently serve the load considering future expansion of 1.1 and operating efficiency of 80 %. These obtained parameters were simulated using MATLAB/Simulink to test the feasibility of the backup systems. The generation cost of each backup was calculated based on which solar PV with battery bank has an initial energy generation cost of 81.9 ₦/kWh and a future energy generation cost of 0.27 ₦/kWh while diesel generator has an initial energy generation cost of 1602.04 ₦/kWh and a future energy generation cost of 8.07 ₦/kWh as such, PV has the least energy cost and more economical for the academic environment.

1. Introduction

Nigerian power sector faces numerous challenges in terms of electricity generation to transmission down to the distribution system [1]. The country has an estimated population of over 204 million people [2] with a total installed generation capacity of 12,522 MW and an available install capacity of 4500 MW against a total projected demand of 17GW by 2020 [3 – 5]. As such, a lot of problems of system collapses, load shedding, insufficient voltage, and system instability occur. For any developed academic institution, stable electricity has been one of the major indices to facilitate E-learning, research development, and a conducive learning environment.

The backup power supply is an alternative method to provide alternate electricity when there is no supply from the national grid [6]. These backup supplies are engine generators, battery banks, solar systems, wind generators, etc. Most of these off-grid backup supply is

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mostly applicable to low-demand areas because their application in high-demand areas require large hectares of land and the cost of implementation and maintenance is very high [7 – 10]. These emissions are hazardous to the inhabitants of such an environment which is why the central pollution control board (CPCB) laid down emission regulation for generator sets [11–13]. According to this board, the permissible emission for a petrol generator is set according to their classes as shown in Table 1. While the permissible emission from diesel generators (DGs) is illustrated in Table 2.

From Tables 1 and 2, it can be deduced that diesel generators have a lower emission effect than petrol generators, and also the higher the capacity rating of the generator the lower the emission effect [11]. In a report published by the consumer product safety commission (CPSC), more than 900 people lost their lives due to carbon monoxide poisoning from domestic generators and also estimated about 15,400 were treated in an emergency room for carbon-monoxide (CO) poisoning from domestic generators between 2005 to 2017 [12].

The backup power supply is an alternative means to provide electricity when there is no supply from the national grid. These backup supplies are engine generators, battery banks, solar systems, wind generators, etc. Most of these off-grid backup supply is mostly applicable to low-demand areas because their application in high-demand areas require large hectares of land and the cost of implementation and maintenance is very high [8, 9]. According to the literature [7], a 1 kW capacity solar power system requires 10 square meters of space.

Table 1 Petrol generator emission [12].

Class	Displacement (cm^3)	CO (g/kWh)	NOX + HC (g/kWh)
1	Up to 99	250	12
2	99 - 225	250	10
3	225	250	8

Table 2 Diesel generator emission [14].

Power of Motor	CO (g/kWh)	NOX + HC (g/kWh)	Particulate Matter
Up to 19 kW	3.5	7.5	0.3
19 kW to 75 kW	3.5	4.7	0.3
75 kW to 800 kW	3.5	4.0	0.2

HC: Hydrocarbon; NOX: Nitrogen oxide.

2. Review of Literature

In Nigeria, system voltage from 33 kV downwards is categorized as distribution. In distribution networks, the sending and receiving end power are not the same due to load centres along the distribution lines. At each load centre, a node is created and the power at different junctions of the node are not the same hence power flow and power losses are different in each branch [15]. Distribution networks also have different topologies which are the ring and the radial topology and also each has its merits and demerits. It can also be an overhead line system with bare aluminium conductors or Arial bundled cables (ABC) of an underground distribution system with insulated cables. The underground distribution systems are mostly used where there is very high wind or a crowded area where there are so many rights of way issues [16, 17].

In [18], an analysis was presented on the techno-economic viability of a hybrid off-grid renewable power system for sustainable rural electrification in Benin. It was described that one of the major challenges in the African continent is non-access to energy as such, more than 55% of the human population experience that challenge. A hybrid optimization model for electric renewables (HOMER) was used to carry out optimization, simulation, and sensitivity analysis of the hybrid model. From this analysis, it was found that PV/DG/battery system has the lowest net present cost and renders sufficient power supply with 0% unmet load. 000It reduces battery storage cost as it requires only 30% of that of a PV/battery standalone system. This is economically more feasible than a grid extension project over a considered project lifetime and the system has a cost of electricity of 0.207/kWh which is lower than the current national grid tariff. From an economic point of view, taking DG as a typical case system, a hybrid system consisting of PV/DG/battery has a shorter payback period of 3.45 years with an internal rate of return of 33.3%. The major drawback of this research is its limitation to small rural areas with small loads. The use of batteries in much larger loads cannot be sustainable and will require a very high cost of implementation.

In [19], a presentation was made on the performance assessment of institutional photovoltaic based energy systems for operating as micro-grid. In this research work, it was addressed that an electrical micro-grid system must be compatible with the existing grid network infrastructure and enough days of autonomy must also be considered during grid outage conditions to ensure an uninterruptible power supply. The load and PV profile analysis as well as energy contributions from each distributed energy resource were carried out. An energy management strategy was proposed and an evaluation of the performance of the upgraded system was made. The energy management technique had a notable impact on the performance of both the PV and battery storage. Integration of DG into the system enhanced the battery throughput from 37 % to 72 %. In this research, the cost of energy generated from the DG is not evaluated to ascertain if it is economical compared to other energy sources.

In [20], an optimized alternative backup power supply with a wind generator to supply isolated loads was presented. It was stated that the energy output of a wind generator is variable as a result of variation in wind speed at the location where it is installed through the day-hours and year-months. As such, a backup power supply is required for operating wind generators to supply isolated loads. The alternative backup power supply system used were DG/PV/battery system (BS) and PV/DG systems to supply these isolated loads of a tourist village in Egypt. A hybrid model was presented that incorporating added features of dynamic modelling and graphical user interface in the set of power system block and MATLAB coded program to assess the capacity of the backup power supply (BUPS) for operating a wind generator (WG) to supply isolated loads. An economic model was initiated to optimize from an economic point of view the considered BUPS. From this model, it was found that for WG/DG generation system 2×300 kW-WG with 2×150 kW DG is more economical to supply the studied load while for WG/BS generation system, two WG of 300 kW rating with 140 MWh BS capacity were the optimal hybrid generation system and for Photovoltaic power source (PVPS)/WG/BS generation system, 2×300 kW wind generating machine (WGM) rate, PVPS has a peak power of 17.27 kW and 33.38 MWh BS capacity is the optimal hybrid generating system. The WG/PVPS/DG generation system 2×300 WGM with 17.27kWp-PVPS and 1×50kW DG is the most economical one of the BUPS with WG to supply the isolated load. To implement 17.27 kW solar power requires a very big space of land which makes the research less applicable to areas with limited land.

In [21], a paper was presented on optimal grid-connected PV systems for a campus micro-grid. This model was simulated with HOMER software using an actual load profile of Kuala Lumpur University in Malaysia and renewable resources as the input parameters. Based on the techno-economic analysis carried out on the HOMER software, it was found that grid-connected PV systems with battery storage are the most optimal systems. This result was limited to a load of 50 kW which is just one section of the university. Considering an entire academic institution with much higher loads will require more inputs which may lead to a better and wider scope for cheaper generation costs.

3. Methodology

To design an effective backup system that will sufficiently power a given facility, a systematic approach is required in the sizing and selection of the equipment required (Fig. 1). In this case, solar energy systems and diesel generators are employed as backup sources. It is necessary to ascertain the current power infrastructure, as well as load demand of the area under consideration hence the transformers within the Nigerian Defence Academy (NDA) postgraduate school, were assessed to ascertain their loading capacity and install capacity to determine the size of backup that will appropriately serve the load.

3.1. Solar Panel

The solar PV is sized based on the amount of battery discharge. This is computed using equation (1).

$$PV_r = \frac{\text{Battery discharge}}{\text{Worst month peak sun hour (PSH)}} \times 1.2 \quad (1)$$

Where, PV_r is the photovoltaic rating.

3.2. Battery

A key to sizing the capacity of the battery is to obtain the total energy demand of the area under consideration. The battery discharge (BD), battery rating (BR) or capacity, and the total energy demand in volt×ampere×hour (VAh) is expressed as follow:

$$\text{Battery discharge} = \frac{\text{Total VAh}}{\text{System Voltage}} \quad (2)$$

$$\text{Battery rating} = \frac{\text{BD}}{\text{DOD}} \times \text{Autonomy days} \quad (3)$$

$$\text{Total energy demand VAh} = \frac{\text{Total Wh}}{\text{Power factor}} \quad (4)$$

Where, DOD is the depth of discharge of the battery, and Wh is Watt×hour.

3.3. Charge Controller

To regulate the charging of the battery, maintain it at high voltage, and prevent charge from going back to the PV panel at night, a charge controller is required [22]. Charge controllers are rated in amperes (i.e., the safe current they can withstand during normal operation). The charge controller rating (CC_r) is deduced as:

$$CC_r = I_{PV,max} + 20\% \quad (5)$$

Where, $I_{pv,max}$ is the short circuit current of the PV panel.

3.4. Inverter

The inverter is sized appropriately as follow:

$$I_r = \frac{T_{load} + (1 + A_f)}{I_e} \quad (6)$$

Where, I_r is the inverter rating (VA), T_{load} is the total load, A_f is the additional/further expansion, and I_e is the inverter efficiency.

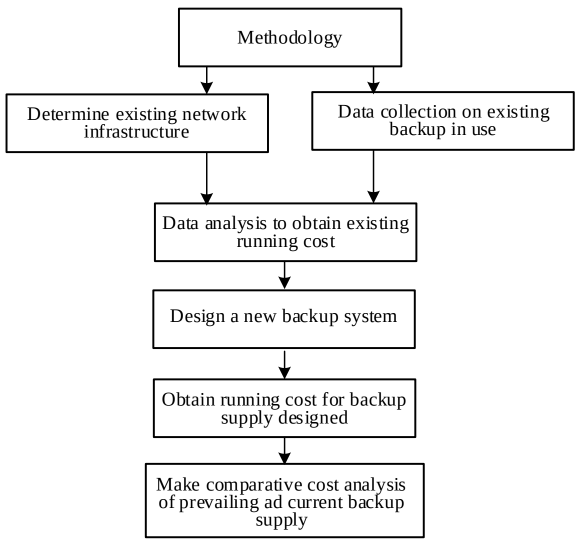

Fig. 1 Methodology process flow.

Table 3 List of distribution transformers and their details.

Transformer Name	Rated capacity (kVA)	Loaded capacity (kVA)	Maximum load attained (A)	Percentage loading (%)
PowerHouse	500	90	125.21	18
Weapon Tc	200	96	133.56	48
WO 2 Quarters	300	129	179.47	43
Officers' Quarters	300	168	233.73	56
NDA Mosque	200	3	4.17	1.5
St. Martins	500	15	20.87	3
Block 39	500	527	733.19	105.4
Postgraduate school	300	10	12.52	3

Source: Kaduna Electricity Distribution Company.

3.5. Energy Generated

The total energy (kWh) generated can be calculated using equation (7).

$$\text{Energy generated} = P_r \times h_a \times n_d \qquad (7)$$

Where, P_r is the rated power (kW), h_a is the availability hour (h) and n_d is the number of days. A list of distribution transforms on the existing network is described in Table 3.

4. Results and Discussion

From data obtained on the existing network (Table 3), the PG school has two distribution transformers (PG school and powerhouse). These transformers have a maximum load of 100 kVA which is equivalent to almost 80 kW. This was obtained from the load assessment report obtained from Table 3 which was used to calculate required materials that will serve the required demand (Table 4). A total ampere-hour requirement of the battery to be used was obtained to be 4,278.07Ah while based in equation 3 coded in the m file considering average battery depth of discharge of 80%. This resulted in a total number of cells required to be 134 considering a battery with a 200Ah rating and a nominal voltage rating of 48V. All results stated in this paragraph are tabulated in Table 4. The size of the charge controller is selected based on the maximum short circuit current expected for the circuit. These batteries are expected to be replaced every four years.

With a load of 80 kW, a PV system rating of 166.4 kW is required to sufficiently charge the battery bank and also serve the load. This amounts to a minimum of 5 panels per string connected in series and 34 number panels per string connected in parallel based on which the total number of panels required summed up to 666 (Table 5). These were calculated using equation (1).

Using the battery specification and size requirement in Table 6 as input for the simulation, a nominal charging current of 49,188.91A was obtained with a maximum charging current of 86,492.37A and a maximum discharging current of 43,246.18A. Also, a maximum charging power of 6,746.4kW and a maximum discharging power of 3,373.2W were obtained.

The inverter rating for the load was obtained to be 150 kVA with a total load of 100 kVA, the anciency of 80%, and the average future expansion of 20% (Table 7). This was obtained using equation (6).

A DG rating of 100 kVA with a starting kVA rating of 113.64kVA is required to efficiently serve the load considering future expansion of 1.1 and operating efficiency of 80% (Table 8).

Table 4 Battery sizing parameters for PG school.

Parameters	Value
Obtained amp hour for the battery	4,278.07 Ah
Nominal voltage of the battery	48 V
Nominal current of the battery	200Ah
Number of battery cells required	134
Battery depth of discharge	80%

Table 5 Table for the designed Solar Panel (PV Plant Parameters) output for the PG school

Parameters	Value
Power rating required for the PV panel	250W
Total number of required strings	4
Maximum number of panels per string to be connected without exceeding maximum voltage required.	170
Minimum required power rating for the solar PV plant (minimum)	166.4kW
Number of panels per string connected in series	5
Number of panels per string connected in parallel	34
Total number of panels used	666
Total solar power generated by plant	166.4 kW

Table 6 PG school battery charging and discharging.

Parameters	Value
Nominal charging current of the battery	49,188.91 A
Maximum charging current for the battery	86,492.37 A
Battery discharging current (max)	43,246.18A
Battery charging Power (max)	6,746.4 kW
Battery discharging Power (max)	3,373.2 kW

Table 7 PG school inverter rating/sizing parameters.

Parameters	Value
T_{load}	100 kVA
A_f	0.2
I_e	0.8
Inverter rating	150 kVA

Table 8 PG school diesel generator rating/sizing parameters.

Parameters	Value
KVA_s	113.64 kVA
F_e	1.1
AU_e	0.8
DG rating	100 kVA

4.1. Estimated Bill of Quantity for Backup Systems

To ascertain the cost of energy for each backup source, one must establish the cost of labour, materials required to generate the energy, and also the maintenance cost of the overall system throughout its life span [23]. The estimated bill of quantity (BOQ) for solar PV system with backup batteries and for the diesel generator including fuel cost is shown in Table 9 and Table 10, respectively. The cost of energy generated against the total energy generated is plotted from these data as illustrated in Fig. 2 which shows a clear indication of cost reduction in the future. The cost profile was generated from the total energy generated by the solar plant 24 hours a day for 25 years. This includes the cost of maintenance and replacement of relevant parts when needed.

Fig. 3 was generated from the amount of energy supplied by the generator and the cost of energy generated. The cost of energy generation includes the initial material cost, the fuel cost, and the maintenance cost. The running hours were selected to be 8 based on the grid feeder banding which the campus falls under a BAND C feeder with a maximum of 16 hours per day. Also, as an academic environment, the generator is considered to run for four months per semester which makes it eight months per year. This results in a total of 200 months in 25 years. As observed (Fig. 3), the generation cost is much higher compared to the energy generated which implies that it will be less economical for the environment.

Comparative cost analysis between solar and diesel generators showed that solar has a much lower cost compared to the generator with almost 54.2%. This implies that the cost of unit energy per kilowatt-hour produced by the generator is almost twice the cost of unit energy generated by the solar PV system as such, the solar PV system is most recommended for the NDA postgraduate school.

Table 9 BOQ for solar PV system with backup batteries.

Items	Quantity	Unit Cost (₦)	Total Cost (₦)
Photovoltaic panel (250W)	666	65,000	43,290,000
Deep cycle battery (200Ah)	134	140,000	18,760,000
Charge controller (100A)	1	200,000	200,000
Inverter (300 kVA)	1	10,700,000	10,700,000
Automatic changeover with timer	2	250,000	500,000
Deep cycle battery replacement	670	140,000	93,800,000
Charge controller replacement	2	200,000	400,000
Inverter replacement	1	10,700,000	10,700,000
Subtotal			178,350,000
Labour = 15% of subtotal			26,752,500
Maintenance= 5% of (subtotal + labour)			10,255,125
Miscellaneous = 5% of (subtotal+labour+maintenance)			11,280,637.5
Total			**226,638,262.5**

Table 10 BOQ for diesel generator including fuel cost.

Items	**Quantity**	**Unit Cost (₦)**	**Total Cost (₦)**
Diesel Generator (C100)	1 no	10,000,000.00	10,000,000.00
Switchgear for essential load	1 no	4,500,000	4,500,000
Automatic changeover switch	2 no	250,000	500,000
150 sqmm*4 core cable	50 m	48,000.00	2,400,000
Subtotal			17,000,000
Labor = 15% of subtotal			8,500,000
Maintenance cost = 15% of subtotal			3,825,000
Miscellaneous = 5% of (subtotal + labour)			1,466,250
Total			**30,791,250**

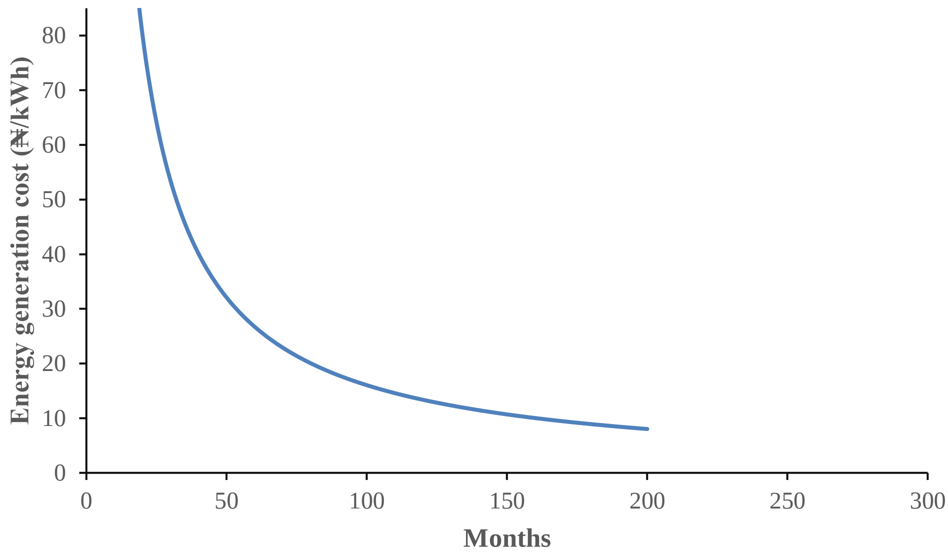

Fig. 2 Graph of solar energy generation cost against generation month.

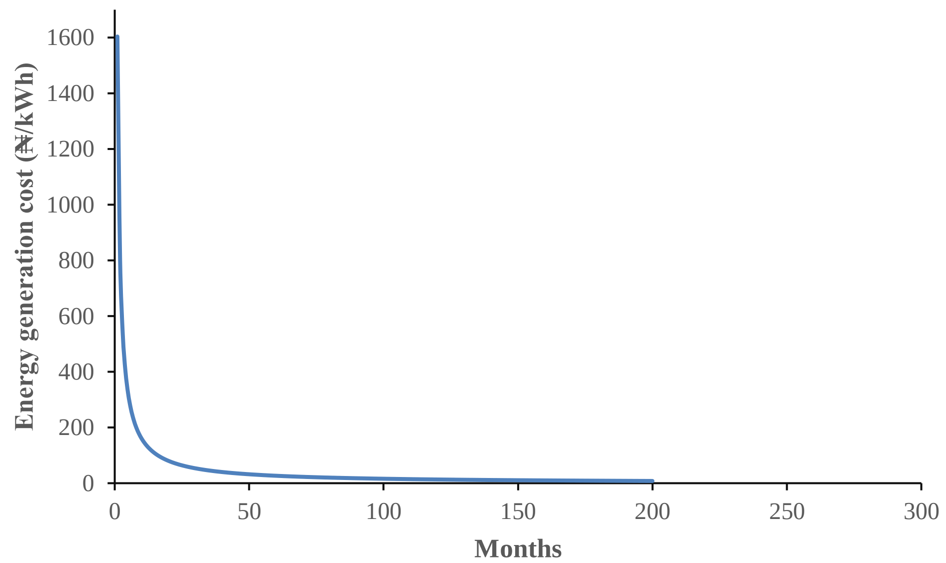

Fig. 3 Graph of energy generation cost from diesel generator against generation month.

4.2. Summary of Findings

After this research, it was found out that:

1. Steady power supply can be achieved in the NDA postgraduate school by use of either diesel generator or solar PV system to compensate outage durations from the national grid.
2. The PG School has a total load of 80 kW, hence, requires an inverter rating of 126.5 kVA or a diesel generator of 100 kVA with 113.64 starting kVA.
3. The solar PV system has an initial energy generation cost of 81.9 ₦/kWh and future cost of 0.27 ₦/kWh while the diesel generator has an initial cost of 1603.7 ₦/kWh and a future cost of 8.01 ₦/kWh considering an operational lifespan of 25 years.

5. Conclusion

The design and simulation of an effective power system backup for NDA postgraduate school were done using MATLAB version 2020b. Two most commonly used backup systems were considered (i.e., solar PV and diesel generators). The diesel generator has an initial power generation cost of 151.04 ₦/kWh which later dropped to as low as 0.75 ₦/kWh while the solar PV system with battery has an initial generation cost of 81.9 ₦/kWh and 0.27 ₦/kWh on the long run as such, it was deduced that the solar PV system with a battery bank is more cost-effective and efficient to the environment. This backup cost was obtained based on 25 years of energy production.

6. Recommendations

NDA postgraduate school as an academic institution requires a steady power supply for a conducive academic environment and modern educational process that necessitates the use of power supply. As such, a reliable and cost-effective backup system is needed to compensate for the shortfall from the national grid. In this research, solar PV with battery bank has lower generation cost than the diesel generator as such it is recommended that

1. Solar PV with a battery should be used as a backup source for the institution.
2. The transformers within the institution require proper load balancing as some are overloaded while some are underutilized. These will increase the efficiency and lifespan of the transformers and also reduce technical losses.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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