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Techno-Economic Assessment of Distributed Generation in Nigeria's Low Voltage Distribution Network

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The availability of a good power supply is said to be essential for achieving sustainable development in the majority of developing countries. Huge capital expenditures are necessary to achieve a consistent electricity supply, mostly for grid development. In order to achieve a reliable power supply, this research, titled "Techno-Economic Assessment of Distributed Generation (DG) in Nigeria's Low-Voltage Distribution Network," aims to integrate a flexible energy mix at the household level. This was achieved by the development of an energy assessment template through computation using ratings of typical electrical devices contained in a three-bedroom flat in Nigeria. The information obtained was aggregated with field data obtained from household energy audit as well as energy band data collected from the power utility company. The optimal energy mix based on formulated algorithm comprised of photovoltaic (PV) system with capacity of 12.7 kW, a petrol generator with capacity of 15 kW, a converter with capacity of 12 kW, and 16 units of batteries (eight connected in series and two connected in parallel) with a nominal optimal hybrid capacity of 15.89 kWh. However, the HOMER Pro software's optimization results revealed that the planned size of PV panels, batteries, and the supply from the public power utility company were adequate for the load. The net present cost, cost of electricity, and operating costs of the proposed hybrid

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system obtained was $23,714, $0.308 kWh, and $700 per year, respectively. The proposed template is suitable and adaptable to any desired grid size.

Keywords: Distributed generation; techno-economic assessment; PV system; HOMER Pro; optimization.

1. INTRODUCTION

Most developing countries largely depend on centralized generating plants for their electricity generation [1]. A notable characteristic of these plants is their remote location from the load centres. According to [2] although these centralized plants are able to meet the energy demand of the consumers, in some cases, during peak hours, generation from the centralized power plants become insufficient to compensate for the increased energy demand. The shortfall in the energy demanded as stated by [3] is serviced by distributed generation (DG) system mainly to compensate the additional demand during peak hours and periods of power outages due to unprecedented faults from the centralized power stations.

Distributed generation (DG) as defined by [4], is the production of electrical energy through diverse alternative energy producing sources at locations in close proximity to the load or sites of consumption. Typically, DGs are small modular electrical energy sources ranging in capacity from few kilowatts to few megawatts. Unconventional energy resources such as solar, wind, biomass, tidal and geothermal are the core components of DG [5]. These renewable power sources have been harnessed and utilized for industrial, commercial, water and medical applications [6]. Solar photovoltaic (PV), wind turbines, micro-hydro, biomass, diesel generators, and fuel cells are a few examples of the various DG technologies. Ref [7] noted that, regarding price, effectiveness, environmental impact, and availability, each of these technologies has pros and cons. As a result, it's critical to choose the best DG unit type, size, and position for a specific network depending on a number of factors and limitations.

Utilizing software modelling tools that can simulate network operation and determine pertinent metrics like power losses, voltage profile, power factor, reliability indices, net present value, levelized cost of energy, payback period, and carbon footprint is one method for conducting a techno-economic assessment of DG in Nigeria's low voltage distribution network as was done by [8-12]. ERACS, ETAP, PSS/E, and MATLAB are a few examples of such tools. Another strategy for doing a techno-economic analysis of the DG in Nigeria's low voltage distribution system is to employ analytical techniques that can define the issue as an optimization problem and resolve it using mathematical procedures or meta-heuristic algorithms [13], [14].

The current study looks into a grid-connected hybrid system's potential as a microgrid in Nigeria from a techno-economic-environmental perspective. This is the done with the aim of providing a blueprint for assessing the relationship between public electricity supply outage hours and the required microgrid capacity to bridge the energy gap and bring about efficient power delivery. In order to accomplish this, current electricity supply data from the Port Harcourt Electricity Distribution (PHED) power utility company in the study location, as well as household energy demand to determine the energy lapse, will be used. The information gathered will then be used to analyse the cost of deploying scaled-down DG to households in the study area to close the energy gap.

2. REVIEW OF RELATED LITERATURE

A considerable deal of concepts have been offered by many researchers on various methods for managing and analysing microgrid and DGs. Some of these earlier works that are connected to the one in this study has been examined and summarised.

Ref [15] provided a critical review of the most relevant challenges currently facing electrical distribution networks, with an explicit focus on the massive interconnection of electrical microgrids and the future with relevant renewable energy source integration. No case study was undertaken by the authors to ascertain energy demand disparity with respect to consumers load profile and energy band.

Ref [11] analysed 33/11KV RSU injection substations to improve performance using Distributed Generation (DG) Units to reduce power losses and low voltage profile. The analysis confirmed that DG was properly sized and placed, and injection substation transformers were improved for power flow without overloading. The authors used ETAP 7.0 to model the distribution network under consideration using load flow. The base-case and priority list for power loss and voltage profile without DG were analysed, as was the integration of DGs at each bus. Total branch power losses were 2824KW and 3575.3KVar without DG, 4265.2KW and 412.7KVar with DG at each bus, and 195.8kW and 240.7KVar with DG at optimal position. The entirety of their proposal was based on simulation on ETAP. Practical household energy demand data factored into their consideration for DG deployment.

Bashir *et al*. [16] suggested a proactive and reactive energy management methodology to efficiently address generation and demand uncertainty in islanded and interconnected residential microgrid system operation (MG). Renewable energy sources (RES), a diesel generator (DG), and a storage device with grid power exchange were evaluated by the MG. Their stochastic mixed-integer linear programming (MILP) model with 24-hour rolling horizon was simulated periodically by updating input data and advancing hourly for a year. The authors sought to reduce MG costs while respecting household comfort. The energy balance was improved by a clever central management system for HVAC and electric water heater loads and well-insulated buildings' thermal inertia. The reactive technique approximated random MG component outages using a two-state Markov chain mechanism. Numerical results showed the benefits of synchronising demand response and supply sources in Helsinki, Finland. The research case study was Helsinki, Finland, with predictable energy demand. The case study for this research uses energy differently from the authors.\

In another study, Olaniyan et al. (2018) employed statistical analysis of field survey and online sales records of household equipment to estimate Nigeria's current and future residential electricity demand and generation capacity to attain 100% energy availability under various scenarios. The North East and South West had excessive home electricity consumption, whereas the median was 18–27 kWh per capita. The authors used disaggregated, zone-by-zone and urban/rural data rather than a whole-of-country approach to better analyse infrastructure investment and rural/urban approaches. They used the data to identify sub-national transitions that minimise investment and maximise home energy access. The research focused on statistical analysis of field survey and other data. Household energy mix was not studied in the study.

3. MATERIALS AND METHODS

Integrating Distributed Generation (DG) into power networks, particularly at the distribution end, has been shown to reduce power loss, increase electricity dependability, and promote environmental sustainability by reducing GHG emissions. This study proposes an optimal DG allocation method for Nigeria's distribution network using Uyo as a case study to maximise the grid's financial Techno-Economic and Environmental Benefits (TEEBs). Dataset including average cost of electricity (per kW), average number of appliances per household, average number of hours of electricity supply (per day), energy consumed (kW) per household, and home appliance rating as used by different band of customers (A, B, C, D, E) at the distribution end as categorised by Nigerian Electricity Regulatory Commission (NERC) was obtained (field data and data from power utility company). This information was used to calculate (using a simple model) the required energy from alternative sources (PV source in this case) to supplement energy supply during outages. The model will be implemented in HOMER Pro software and examined to improve energy planning. Fig. 1 shows the research methodology flowchart.

3.1 Study Area and Data Sampling

Power distribution in Akwa Ibom State capital, Uyo, was studied. Samples were taken from Osongama Estate, Ewet Housing, Oron Road, and Aka Road. On Ewet Housing D-Line, 30 dwellings, three hotels, and a church were assessed. In Osongoma Estate, 25 residences, including a church, were surveyed on Apostolic Road and Edem Akai streets. 30 Obio Imo homes were assessed on Oron Road. In Aka Road, 25 residences and a school were assessed near Akpa Ube Street. Finally, 25 Ifa Ikot Akpabio dwellings were surveyed. An energy consumption study was conducted at each sampled location, taking into consideration light fixtures, electrical, and electronic appliances and registering them against their rated capacity.

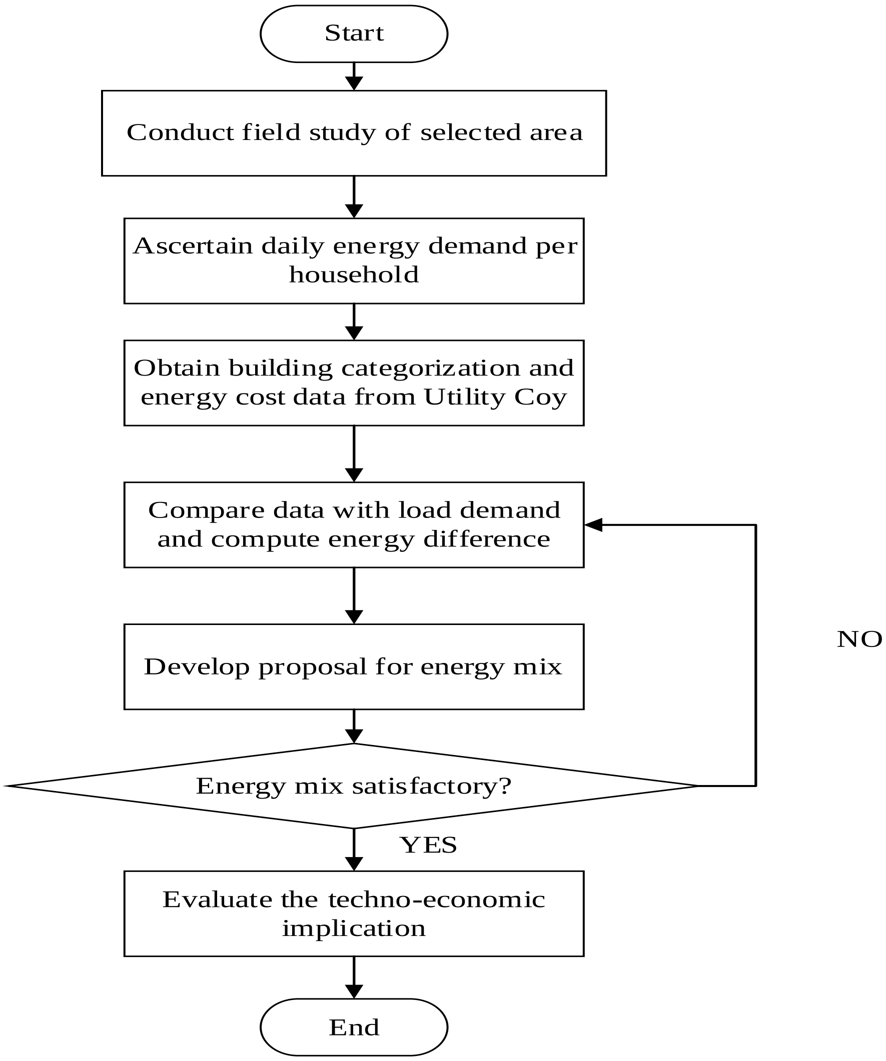

Fig. 1. Proposed research methodology

3.2 Household Energy Demand

Survey results were sorted residential energy usage data. A solar power installation design is needed after the energy audit to determine the number of solar panels, battery capacity, inverter type, cable sizes, and charge controller type. Four stages are required:

i. Load estimation (energy audit).
ii. Estimate battery bank.
iii. PV panel, charge controller, and cable size estimation.
iv. System cost estimation.

3.2.1 Energy Audit

The energy requirement (load capacity) of a typical Nigerian household (middle class) is estimated by aggregating the total load connected (plus anticipated load in most cases) to the PV source. Olaniyan et al. [17] reported that many homes are not metered and when metered, that many metres do not function efficiently. Power consumption of home appliances was measured using Equation 1 from [17].

$$E_{ha} = \sum_{i=1}^{n} \frac{(R_i H_i Q_i)}{1000} \quad (1)$$

where E_{ha} is total electricity consumed by a household (kWh), R is appliance power rating (W), H is appliance operation duration (h) and Q is the unit quantity of appliance, i.

For analysis, a three-bedroom apartment with a family from the lower middle class is taken into account. Table 1 lists the electrical load for the apartment. It is important to note that grid-tied systems are scaled based on the PV array's power output rather than the building's load requirements. This is due to the fact that any power needs in excess of what a grid-connected PV system can provide are immediately met by the grid.

3.2.2 Sizing of solar array

As shown in Equation 2, the DC power produced by a PV array depends on a variety of factors, including the PV peak power at standard test conditions (STC), solar radiation, and cell temperature.

$$P_{PV_{out}} = P_{PV_{peak}} \times \left(\frac{G}{G_{ref}}\right) \times \left[1 + K_T\left(T_c - T_{ref}\right)\right] \quad (2)$$

where $P_{PV_{out}}$ is the output power of the PV array, $P_{PV_{peak}}$ is the power of the PV array at STC, G is solar radiation in W/m^2, G_{ref} is solar radiation at STC usually taken to be 1000 W/m^2, K_T is the temperature coefficient of mono and polycrystalline Silicon (S_i) cells taken to be $3.7 \times 10^{-3}(1/C)$, T_{ref} is the reference temperature at STC taken as $25\ ^0C$ and T_C is the cell temperature computed using Equation 3.

$$T_C = T_{amb} + (0.0256 \times G) \quad (3)$$

where T_{amb} is the ambient temperature.

For grid-tied PV system, AC voltage is used to initialise component design. In Nigerian power system, approved voltage for appliances is 230 V AC (phase-to-phase) and 415 V AC (Line-to-line). Therefore, the equivalent DC phase voltage is calculated using Equation 4.

$$\begin{aligned} V_{DC}^{phase} &= \sqrt{2} \times V_{AC}^{phase} \\ &= \sqrt{2} \times 230 \\ &= 325.27\ V \end{aligned} \quad (4)$$

The specifications of the selected PV module are given in Table 2.

To account for voltage ripples, 10 % of $V_{DC}^{phase}$is added to the computed value. Hence,

$$\begin{aligned} V_{DC}^{phase} &= 325.27 + 10\ \%\ \text{of}\ 325.27 \\ &= 357.80\ V \end{aligned}$$

Number of modules in series (N_s^{PV}) is determined from Equation 5.

$$\begin{aligned} N_s^{PV} &= \frac{V_{DC}^{phase}}{V_{mp}} \\ &= \frac{357.80}{58} \\ &= 6.17 \end{aligned} \quad (5)$$

To allow for some headroom, N_s^{PV} is taken to be seven (7). The seven modules output maximum point voltage and open circuit voltage at STC of 406 V DC $(7 \times V_{mp})$ and 487.9 V DC $(7 \times V_{OC})$, respectively. The additional voltage designed into the system is aimed at making up for anticipated 4% voltage drop, losses along the cable, voltage variation from the PV generator due to temperature rise above 25^oC and other variations in the environmental condition (irradiance).

Table 1. Energy audit of a typical Nigerian household

Appliance	Qty	Power rating (W)	×Use (hr/day)	×Use (day/wk)	÷ 7 days	Wh rating (Wh)
Ceiling fans	4	340	8	7	7	2720
Light bulbs	8	120	5	7	7	600
Television (43”)	2	200	6	7	7	1200
Laptop	1	65	4	7	7	260
Pressing iron	1	1200	0.8	3	7	411.43
Electric kettle	1	1500	0.3	7	7	450
Blender	1	450	0.5	3	7	96.43
Microwave	1	900	2	4	7	1028.57
Cooker	1	1500	3	2	7	1285.71
Washing Machine	1	600	1	3	7	257.14
Water Pump	1	746	0.8	3	7	319.71
Air conditioner	1	1120	3	4	7	1920
Refrigerator	1	170	12	7	7	2040
Phone chargers	5	30	4	7	7	120
Total rating		**8941**	**Average daily load:**			**12708.99**

Table 2. Technical specifications of selected PV module

Panasonic HIT N330 VBHN330SA16 Solar Panel	
Parameter	**Specification**
Cell Type	Monocrystalline Silicon
STC Power Rating (Pmax)	330 W
Open Circuit Voltage (V_{OC})	69.7 V
Short Circuit Current (I_{SC})	6.07 A
Max. Voltage $\left(V_{mp}\right)$	58.0 V
Max. Current $\left(I_{mp}\right)$	5.70 A
Pmax Temperature Coefficient	$-0.30\%/^oC$
V_{OC} Temperature Coefficient	$-0.174\ V/^oC$
I_{SC} Temperature Coefficient	$1.82\ mA$
NOCT	42.2^oC
CEC PTS Rating	306 W
Cell Efficiency	22.09%
Module Efficiency	19.7%
Watt per Ft^2	18.3 W
Maximum System Voltage	600 V
Series Fuse Rating	15 A
Dimensions $L \times W \times H$	$159 \times 1053 \times 35\ mm$
Module Area	$1.67\ m^2$
Weight	18.5 kg
Operating Temperature	-40^oC to 85^oC
Warranted Tolerance ($\pm$)	$\pm 10\%$

In order to avoid under sizing of system components, the estimated average daily power demand is divided by the product of efficiencies ($\eta_{overall}$) of all components that make up the power unit which gives the required daily energy, E_r as presented in Equation 6 [18].

$$E_r = \frac{Daily\ average\ power\ demand}{\eta_{overall}} \tag{6}$$

where daily average power demand obtained from Table 1 is 12708.99 Wh and $\eta_{overall}$ is rated at 80% for all connected devices. Daily energy requirement from solar array is determined thus:

$$E_r = \frac{12{,}708.99}{0.8}$$
$$= 15{,}886.24\ Wh$$
$$= 15.89\ kWh$$

Peak power of the PV, P_{pv} is computed from Equation 7 expressed as follows:

$$P_{pv} = \frac{E_r}{T_{min}} \tag{7}$$

where T_{min} is the average sun hours per day which for Nigeria is estimated to be five (5) hours.

$$P_{pv} = \frac{15{,}886.24}{5}$$
$$= 3{,}177.25\ W$$
$$= 3.18\ kW$$

The number of modules in parallel (N_p^{PV}) is computed from Equation 8.

$$N_p^{PV} = \frac{P_{pv}}{N_s^{PV} \times P_{max}} \tag{8}$$
$$= \frac{3{,}177.25}{7 \times 330}$$
$$= 1.38$$

N_p^{PV} is rounded up to be 2 so as to meet the load requirement with maximum power current of 12.14 A $\left(2 \times I_{mp}\right)$. Total number of PV modules (N_m) required is computed by taking the product of series and parallel connected modules, mathematically expressed in Equation 9:

$$N_m = N_p^{PV} \times N_s^{PV} \tag{9}$$
$$= 2 \times 7$$
$$= 14$$

A total of 14 PV panels are to be connected in series and parallel to achieve the desired power rating. For confirmation, computed rating of PV modules becomes 4620 W ($2 \times 7 \times 330\ W$).

3.2.3 Estimation of Required Battery Capacity

Equation 10 is used to estimate the anticipated battery capacity:

$$\text{Bat. Capacity. (Ah)} = \frac{\text{Total Watt-hr per day used by applicances}}{\left(\text{DOD}\times\eta_{B_{Ah}}\times\text{nominal battery voltage}\right)} \times \text{days of autonomy} \quad (10)$$

where DOD is the permissible dept of discharge; $\eta_{B_{Ah}}$ is the ampere hour efficiency.

Total average energy demand as computed from Table 2 is 12708.99 Wh, since the system proposed is to be interconnected with the grid, there is little or no need of incorporating days of autonomy in the design and this in turn drastically reduces the overall cost of installation. The selected battery for the proposed study is LiFePO4 48 V 240 Ah battery. Thus, the required rough estimate of the storage $\left(E_{rough}\right)$ is 12.71 kWh and for consistent energy availability, a threshold of energy safety $\left(E_{safe}\right)$ is incorporated into the design by taking into account the depth of discharge (DOD) which in this case is taken to be 80% expressed mathematically in Equation 11.

$$\begin{aligned} E_{safe} &= \frac{E_{rough}}{DOD} \\ &= \frac{12708.99}{0.8} \\ &= 15{,}886.23\ Wh \\ &= 15.89\ kWh \end{aligned} \quad (11)$$

Required battery capacity (C) is computed from Equation 12 as follows:

$$C = \frac{E_{safe}}{V_b} \quad (12)$$

where V_b is the rated battery voltage which in this case is 48 V.

Therefore,

$$C = \frac{15{,}886.23}{48} \qquad = 330.96\ Ah$$

Ideally, 2 V 1500 Ah rated battery bank would have provided a perfect setup for the proposed study, low rated voltage batteries are however known to be far more expensive than its contemporaries. Hence, to realise the designed system capacity, combination of series and parallel battery configuration is recommended for reduced cost.

Total number of batteries in series $(N_s^{batteries})$ required to meet the rated capacity is obtained dividing the total battery capacity (C) by the capacity of one battery (C_b) as given in Equation 13.

$$\begin{aligned} N_s^{batteries} &= \frac{C}{C_b} \\ &= \frac{330.96}{240} \\ &\approx 2 \text{ batteries} \end{aligned} \quad (13)$$

The number of batteries to be connected in parallel $\left(N_p^{batteries}\right)$ is computed using Equation 14.

$$\begin{aligned} N_p^{batteries} &= \frac{V_{DC}^{phase}}{V_b} \\ &= \frac{357.80}{48} \\ &\approx 8 \end{aligned} \quad (14)$$

The total number of batteries required is 16 in total with 8 branches and two series batteries.

3.2.4 Estimation of Required Battery Capacity

The current rating I_{CC} of the solar charge controller to be used is determined mathematically from Equation 15 as follows:

$$I_{CC} = I_{SC} \times N_p^{batteries} \times F_{safe} \quad (15)$$

where F_{safe} is a safety factor $\left(F_{safe} = 1.25\right)$ for oversizing current rating of PV-connected devices being used for more than three (3) hours while safety factor for voltage is 1.15 multiplied by open circuit voltage [19].

From market survey, one of the commonly available quality charge controllers is the Must MPPT Solar Charge Controller (PC1800A Series 60/80A). Therefore,

$$\begin{aligned} I_{CC} &= 6.07 \times 8 \times 1.25 \\ &= 60.7\ A \end{aligned}$$

In situations where the computed current is higher than the rating of available charge controller, the number of controllers to be connected in parallel $(N_{controller})$ is calculated from Equation 16.

$$N_{controller} = \frac{I_{CC}}{I_{cr}} \quad (16)$$

where I_{cr} is the charge controller current rating.

Thus;

$$N_{controller} = \frac{60.7}{60} \approx 1$$

One controller is sufficient for the proposed setup.

3.2.5 Inverter selection

Among specifications given by Leonics [20], it is stated that the inverters for grid-tied systems are to be of the same rating as that of the PV array and this informed the selection of MUST High Frequency On Grid Solar Inverter PH5000 Series (2.5-6KW). From Table 3, devices that are likely to run at the same time have a combined power rating of approximately 9000 W (9 kW) at 230 V. Recommended hybrid inverters to meet the load demand is the MUST PV3500 PRO Solar Inverter (4 - 12 kW).

3.2.6 Cable sizing

The safety factor (F_{safe}) for current and voltage is the major component in estimating wire size for electrical systems. In this case for example, main DC cable with M numbers of parallel connection of stings linked to N modules, Equations 17 and 18 give the current and voltage rating of wires to be used.

$$\text{Current: } I_{sc} \times N \times 1.25 \qquad (17)$$

$$\text{Voltage: } V_{OC} \times M \times 1.15 \qquad (18)$$

3.2.7 Building categorization and energy cost

Data was collected from the energy utility company in charge of the case study area (PHED) as presented in Table 3. The data collected was to obtain information on the cost of energy per kWh.

3.2.8 Proposed energy mix

The energy mix proposed in this study which is a variant of the model presented by [21] includes fossil fuel generators, battery storage, public power delivery, and renewable energy sources (PV system). A schematic representation of this energy mix is shown in Fig. 2, while Fig. 3 shows the same model in HOMER Pro interface. An algorithm using pre-established conditions governs the entire system.

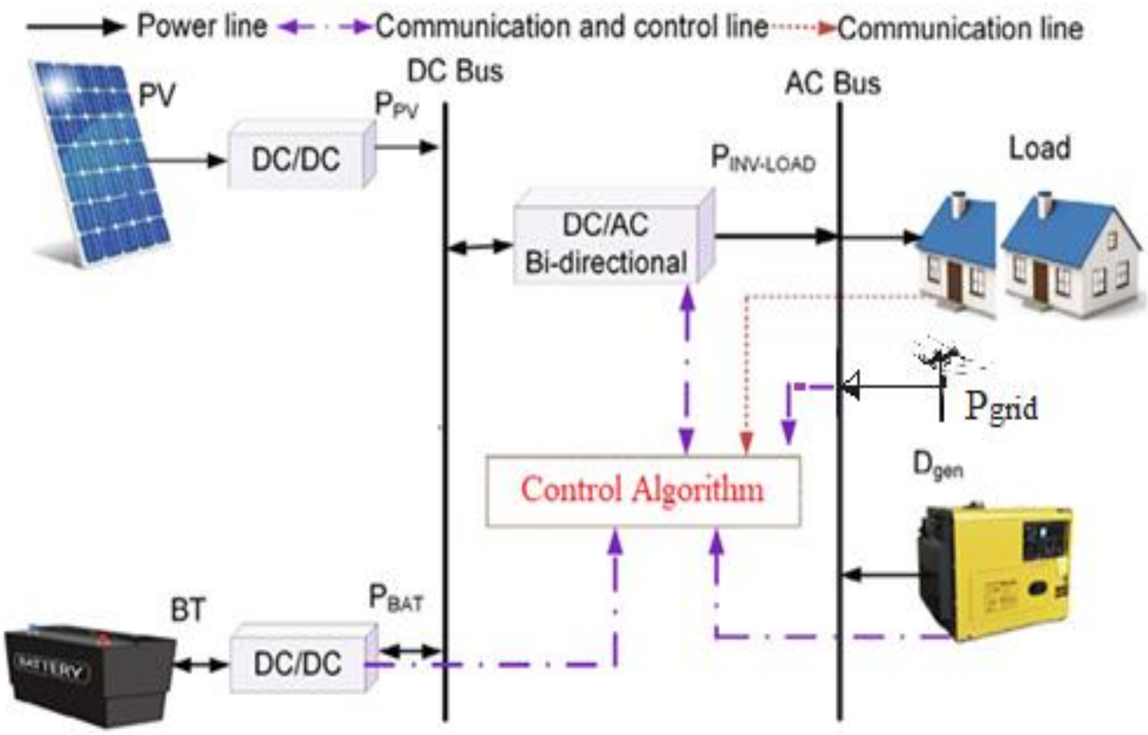

Fig. 2. Proposed energy mix schematics

Table 3. Cost of electricity per band

Category	July-Nov 2022	Dec - 2022
A – Non-MD	62.02	72.67
A – MD1	60.96	71.62
A – MD2	59.23	69.88
B – Non-MD	60.96	68.98
B – MD1	59.18	67.18
B – MD2	59.12	67.12
C – Non-MD	56.38	56.38
C – MD1	54.64	54.64
C – MD2	54.64	54.64
D – Non-MD	39.67	39.67
D – MD1	55.43	55.43
D – MD2	55.43	55.43
E – Non-MD	39.44	39.44
E – MD1	55.43	55.43
E – MD2	55.43	55.43

MD1 – Consumers with independent transformers
MD2 – Consumers connected to public transformers but with independent feeder pillar
Non-MD – Consumers connected to public transformers

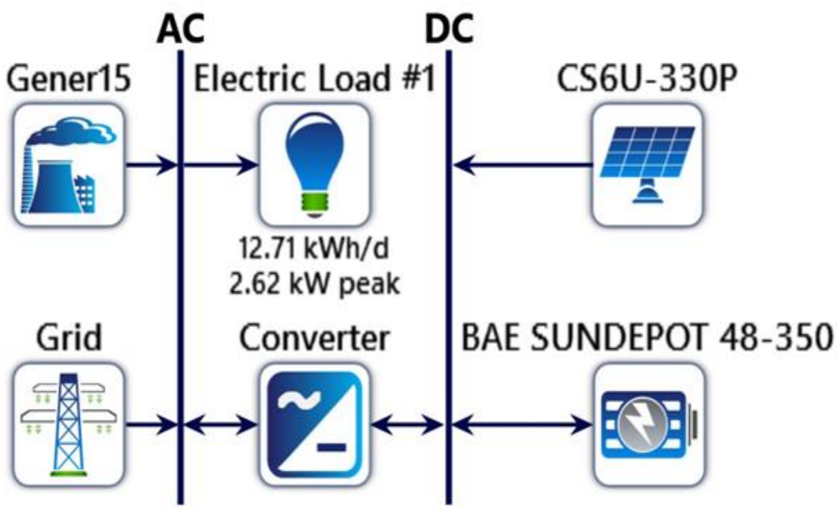

Fig. 3. Proposed energy mix in HOMER Pro

3.2.9 PV output power

By design, DC power is the predominant output of PV array whose intensity is dependent on a number of factors ranging from PV peak power at STC, cell temperature and solar radiation. [22], [23]. These measurements were akin to those presented by [24], [25] given their study site similarity to the one presented in this report.

4. RESULTS AND DISCUSSION

The outcome of the design in the previous section is presented in this section.

4.1 Technoeconomic Analysis of Proposed Energy Mix

The Schematic diagram of hybrid system proposed is given in Fig. 2. Details of the cost implication of constituent elements is given in this section. The cost detailing was done in HOMER Pro software in US Dollar ($) denomination with official Naira conversion.

PV system: The solar PV component in HOMER was modelled based on Equation 19.

$$P_{pv} = Y_{pv} f_{pv} \left(\frac{G_T}{G_{T,STS}}\right) \left[1 + \alpha_p \left(T_c - T_{c,STS}\right)\right] \quad (19)$$

where f_{pv} represents the derating factor of the PV, Y_{pv} Ypv represents the PV rated capacity in kW, $G_{T,STS}$ represents the incident radiation at standard test conditions $(1\ kW/m^2)$ and GT represents the insolation on the PV array in kW/m^2 , α_p represents the temperature coefficient of power $(\%/°C)$, T_c is the PV cell temperature in $°C$, and $T_{c,STS}$ is the PV cell temperature under standard test conditions $(25^0 C)$.

From a market survey of the prices of solar modules in Nigeria, and taking a conversion rate of 466 Naira to 1 USD, the capital cost per kW for a Panasonic HIT solar panel was taken as ₦309,424 ($664), and comprised both purchase and installation costs. In terms of future projections based on increased adoption of renewable energy sources, the costs of solar PVs expected to reduce, therefore a replacement cost of ₦270,280 ($580) was used. The operating and maintenance costs for the solar PV were fixed at ₦4,700/year ($10/year).

Petrol Generator: In designing the proposed hybrid MG system, a petrol generator was selected as back-up in scenarios where the energy obtained from the solar PV's or batteries (rainy days) are not sufficient to cater for the residential loads and also with public power grid outage within the same period. HOMER uses Equation 20 in modelling the power output of a petrol generator as a result of the pattern of its fuel consumption (F_G).

$$F_G = B_G P_{G-rated} + A_G P_{G-out} \tag{20}$$

where P_{G-out} represents the power output of the generator, A_G represents one coefficient of consumption of fuel based on the consumption curve, B_G also represents another coefficient of consumption of fuel and $P_{G-rated}$ represents the nominal power of the diesel generator.

It should be noted that oftentimes A_G and B_G are typically chosen as $1/kWh$ but could be changed as desired. From online market survey of the costs of petrol generators, the capital cost for a 15 kVA Fireman petrol generator was taken as ₦2,600,000 ($5,579) and this capacity was selected based on the surveyed load capacity of 12.7 kW. Hence a total cost of ₦2,600,000 ($5,579) per 15 kVA or ₦173,333 ($372) per kVA was used. The cost of the generator's replacement was set at ₦2,800,000 ($6,009), while an operations and maintenance cost of ₦10,200 ($22/hr) which takes into consideration the component part repairs and replacement costs.

Battery: From an online market retail store, each unit of the battery had a cost price of approximately ₦250,000 ($536), and this was inputted as the capital cost per quantity in HOMER. The replacement cost of the battery was taken as ₦251,640 ($540), with an operations and maintenance cost taken as ₦4,660/year ($10/year).

Inverter: From an online market retail store, total cost price of the two inverters was approximately ₦850,000 ($1825), and this was inputted as the capital cost per quantity in HOMER.

The optimization results obtained from the hybrid energy system modelled in HOMER Pro is presented in Tables 4 to 7. The net present cost of the components of the system proposed are summarised in Table 4. For ease of setup, United States Dollars ($) was used as basis of pricing of all components envisaged in the design.

Table 4. Net present costs of system components

Name	Capital	Operating	Replacement	Salvage	Total
BAE SUNDEPOT 48-350	$5,000	$129.28	$1,072	-$439.19	$5,762
CanadianSolar MaxPower CS6U-330P	$3,250	$840.29	$0.00	$0.00	$4,090
Generac 15kW Protector	$2,950	$0.00	$0.00	-$689.03	$2,261
Grid	$0.00	-$5,915	$0.00	$0.00	-$5,915
System Converter	$722.96	$0.00	$306.73	-$57.73	$971.97
System	$11,923	-$4,945	$1,379	-$1,186	$7,171

Annual costs of various components are presented in Table 5.

Table 5. Annual operating costs of system components

Name	Capital	Operating	Replacement	Salvage	Total
BAE SUNDEPOT 48-350	$386.77	$10.00	$82.94	-$33.97	$445.74
CanadianSolar MaxPower CS6U-330P	$251.40	$65.00	$0.00	$0.00	$316.40
Generac 15kW Protector	$228.20	$0.00	$0.00	-$53.30	$174.90
Grid	$0.00	-$457.54	$0.00	$0.00	-$457.54
System Converter	$55.92	$0.00	$23.73	-$4.47	$75.19
System	$922.29	-$382.54	$106.67	-$91.74	$554.69

Also, the production per component as analysed in HOMER Pro is also presented in Table 6

Table 6. Annual energy production per component

Component	Production (kWh/yr)	Percent
CanadianSolar MaxPower CS6U-330P	18,438	89.0
Generac 15kW Protector	0	0
Grid Purchases	2,269	11.0
Total	20,708	100

Table 7. Comparative economics of proposed system

	Base System	Proposed System
Net Present Cost	$7,796	$7,171
CAPEX	$0.00	$11,923
OPEX	$603.09	-$367.60
LCOE (per kWh)	$0.130	$0.0282
CO2 Emitted (kg/yr)	2,932	1,434
Fuel Consumption (L/yr)	0	0

Based on results obtained from HOMER Pro as presented in Tables 4 to 6, 20 PV panels is suggested to be sufficient for the setup of the proposed system to output 89% of the total energy need of the household in conjunction with the integrated energy storage while the energy deficit totalling 11% is purchased from the grid annually.

In terms of cost comparison, Table 7 presents a breakdown of cost of system installation and required years of payback (in case of lease). From analysis of Table 7, 6.40% internal rate of return (IRR) was recorded from simulation at approximately 25 years of discounted payback period and 12 years of simple payback duration.

5. CONCLUSION

This study examined the techno-economic impact of DG on Nigeria's low voltage distribution network and proposed a concept for a grid-connected microgrid that might be replicated. The PV system was created manually, with components chosen to meet the recorded household load. There were some discrepancies between the computed and optimised results in HOMER Pro. The difference between the computed number of PV panels (seven series and two parallel connections) and the optimal number was very noticeable (10 series and two parallel connections). Comparative economic analysis of the proposed system revealed an 8 percent Net Present Cost difference between it and the base system, as well as a capital expenditure (CAPEX) requirement of $11,923 for the proposed system setup as opposed to zero for the basic system. According to operating expenditure (OPEX), $603.09 was spent on system operation over the course of a year in the base case, while $367.60 was made thanks to net metering policy, which allowed for the sale of excess generated power to the grid. The proposed configuration also had the lowest lifetime cost ($0.0282) of producing power during the two systems' combined lifetimes (base and proposed systems). This was true across all indicated generation technologies.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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