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Techno-Economics Analysis of an Off-Grid Hybrid Power System for Rural Areas in Nigeria

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Abstract

This research aims to analyze the techno-economic viability of an off-grid hybrid power system for rural areas in Nigeria, specifically in the Uzere community of Delta State, where access to reliable and sustainable power supply from the national grid remains a significant challenge. This study employed both survey and simulation modeling methodologies using HOMER Pro software application. The existing 500kW Independent thermal station was evaluated alongside solar and power storage sources. The results revealed that relying solely on thermal generation, without incorporating alternative energy sources, resulted in a Levelized Cost of Energy (LCOE) of ₦63.65/kWh and a Net Present Cost (NPC) of ₦54.9 billion. This outcome was primarily attributed to the low-priced gas incentives offered by oil and gas-producing companies and operators. The optimized hybrid system yielded an LCOE of ₦120.48/kWh and NPC of ₦30.9 billion, reducing gas emissions by 30%. The national grid tariff of ₦225.00/kWh was significantly higher. The study recommends collaborative policy frameworks, adequate funding, and gas incentives between government agencies and oil-producing companies to promote off-grid hybrid power systems in rural communities, ensuring uninterrupted and sustainable power supply for social and economic growth.

Keywords: Rural electrification; Solar PV; HOMER Pro; Techno-economic analysis

1. Introduction

Nigeria, Africa's largest economy, is plagued by a persistent electricity crisis that has hindered economic growth and development (Eberhard et al., 2016). The country's power sector is characterized by inadequate generation, transmission, and distribution infrastructure, resulting in widespread power outages and unreliable electricity supply (IEA, 2020). Globally, electricity generation capacity stands at approximately 6,800 GW, with transmission and distribution capacities of around 4,200 GW and 2,600 GW, respectively (IEA, 2020). In Africa, these capacities are significantly lower, at around 700 GW for generation, 400 GW for transmission, and 250 GW for distribution (IEA, 2020). Nigeria's electricity sector fares even worse, with a generation capacity of about 13 GW, transmission capacity of around 8 GW, and distribution capacity of approximately 5 GW (NERC, 2020). Rural areas, in particular, are disproportionately affected, with millions of Nigerians lacking access to electricity (World Bank, 2020). This has affected the Nigerian government's ability to provide sustainable and reliable power to Nigerians. Utilization of available power sources is hindered by many factors, such as technological experience, corruption and uneven allocation of resources, non-availability of multiple energy sources, ineffective maintenance practices, non-utilization of gas resources for power, and reliance on obsolete equipment. This study investigates the techno-economic viability of an off-grid hybrid power system as a potential solution to Nigeria's electricity crisis, focusing on the Uzere community in Delta State.

Access to reliable and affordable electricity is a fundamental driver of economic development, social well-being, and human progress. Be that as it may, regardless of significant advancements in investment endeavors, electricity has remained scarce and inaccessible. For many years, a significant piece of the total populace has needed access to power, especially in remote and rustic districts (Ayua et al., 2024). In many of these regions that do not have adequate electricity, extending the central grid infrastructure to reach remote rural areas and communities is always very expensive, time-wasting, and technically difficult. This makes millions of people worldwide continue to depend on inefficient, local, and environmentally hazardous energy sources such as kerosene lamps, biomass, fossil fuel, and diesel generators for their energy needs. This affects and hinders socio-economic development and also poses serious health and environmental risks, such as deforestation, indoor air pollution, and carbon emissions (World Bank, 2020).

The significance of electricity in driving economic growth and development cannot be overstated, as it plays a vital role in the progress of nations worldwide. Traditionally, centralized power generating stations reliant on fossil fuels have been the primary source of electricity, supplying the maximum capacity. However, the finite nature of fossil fuels and their detrimental environmental impacts have necessitated a paradigm shift towards exploring alternative energy sources. As a result, research has increasingly focused on harnessing renewable energy sources to mitigate the environmental concerns associated with traditional fossil fuel-based power generation (Kumar et al., 2018).

Off-grid and mini-grid systems have become obvious as an alternative solution to address the energy unavailability in remote and rural areas where the extension of grid networks is not achievable and expensive. These mini-grids are locally generalized systems for generating and distributing electricity that serve autonomously from the central grid infrastructure. The off-grid and mini-grid system consists of small units of power generation units, such as micro-hydro turbines, wind turbines, solar power, or biomass generators, added with energy storage systems and distribution networks (Abdul et al., 2020). These off-grids are often owned and operated by individual owners or independent power producers (IPPs).

Technology has made renewable energy sources, which include solar and wind, increasingly suitable for integration into off-grid mini-grids due to their sustainability, abundance, and decreasing costs. This drive towards sustainable renewable energy not only enhances energy production, access, and reliability but also contributes to the fight against climate change efforts by reducing greenhouse gas emissions (IEA, 2021). Despite the significant potential of off-grid mini-grids powered by renewable energy, there are still obstacles and challenges to their widespread deployment and adoption. These challenges include technical complicatedness, financing constraints, regulatory challenges, institutional capacity constraints, and community engagement issues (UNDP, 2020). Additionally, the unrivaled nature of off-grid mini-grids raises questions about their long-term scalability, sustainability, and integration into the broader energy landscape.

The integration of renewable energy entails incorporating sources like solar, wind, hydro, and biomass into the energy mix to sustainably fulfill electricity needs. This integration has garnered worldwide momentum in response to climate change worries, energy security issues, and the imperative to shift towards low-carbon energy systems (Jacobson, 2020). Recent studies have highlighted the practical possibility and financial sustainability of integrating renewable energy, particularly in off-grid and decentralized energy setups. Gunmi et al. (2024) conducted recent research focusing on integrating renewable energy sources into microgrids. The study emphasized the importance of advanced control strategies and energy storage technologies in improving grid stability and reliability. Furthermore, Sharma et al. (2020) did an extensive review of off-grid renewable energy solutions, highlighting the significance of hybrid mini-grid systems in delivering dependable electricity access to remote communities. Ayodele et al. (2021) conducted a study examining the techno-economic analysis of hybrid renewable energy systems for off-grid electrification in Nigeria. The study emphasized the potential for cost-effective and sustainable energy solutions in the country. Likewise, Cyril et al. (2024) explored the integration of solar photovoltaic systems into mini-grid networks in rural African communities. The study highlighted the importance of decentralized energy solutions in enhancing energy access and fostering socio-economic development. In addition to the aforementioned studies, research conducted by Adaramola et al. (2014) examined the techno-economic feasibility of hybrid renewable energy systems for rural electrification in Nigeria. The study underscored the potential of integrating multiple renewable energy sources to enhance energy access and reliability. Beza et al. (2021), conducted a study in Ethiopia to address the challenge facing electricity access on an island. A diesel generator (DG) was used as the base case for power generation in the study location. It was compared with a hybrid of renewable PV, wind, and battery systems sources to supply a load of 76.94 kWh/day. The HOMER Pro software was used to simulate the proposed hybrid system. The results revealed that the most optimal hybrid mini-grid system was a PV/DG/battery system of 25 kW of PV, 10 kW of DG, and 40 batteries of 1 kW each, which gave LCOE, NPC, and RF of $0.175/kWh, $119,139 and 86.4% respectively and also reduced GHG emissions by 33,102 kg/year as compared with the DG standalone. This hybrid configuration was found to be the least expensive compared to the base case and other hybrid configurations considered in the study. Similarly, a sensitivity analysis was carried out with a variation of global horizontal irradiation (GHI), diesel price, and load demand and gave LCOE of $0.179/kWh, NPC of $151,468, and RF of 69.1%. This further confirmed the system as the most viable and optimal configuration.

To deliver dependable electrical services to isolated and off-grid populations, off-grid hybrid mini-grid systems include several renewable energy sources, energy storage devices, and backup generators. These systems provide a decentralized method of energy access, allowing communities to generate and consume electricity independently (Kumar et al., 2018). Recent developments in off-grid hybrid mini-grid technologies have concentrated on using creative design and control techniques to increase system efficiency, lower costs, and improve dependability.

Zarmai et al., (2024), carried out a study on the design and techno-economic evaluation of a hybrid utility grid-diesel generator-solar photovoltaic mini-grid system at the Faculty of Engineering and Technology, Nigerian Defense Academy, Kaduna, Nigeria. This study prompted the need for educational institutions to have an adequate and reliable power supply to ensure proper learning and teaching in developing countries like Nigeria. This novel approach focused on an educational institution that will enable adequate electricity from the mini-grid for proper learning and teaching, reduced negative environmental impacts, and lower energy costs. This study analyzed the load demand of the faculty building and designed a hybrid utility grid-diesel generator-solar PV mini-grid system using HOMER Pro simulation software. The simulation results showed that the hybrid system is techno-economically viable. Optimization of the system was conducted, and the results indicated that the most suitable operating system has a Net Present Cost (NPC) of $182,065.20 and a Levelized Cost of Energy (LCOE) of 0.00198 $/kWh.

Off-grid renewable energy power systems generate electricity from renewable sources without connecting to the main electrical grid. These systems are crucial for providing energy access in isolated and rural areas where grid extension is impractical or costly. Jumare et al., (2020) assessed the feasibility of a hybrid grid-connected PV, wind, and biogas system in northern Nigeria. Their proposed model considered various input parameters, including solar PV, wind turbine, and biogas system models, as well as economic characteristics. The authors utilized GaBi tools, Microsoft Excel, and HOMER software for data collection, system design, and optimization. The study's results showed that the most practical off-grid setup consisted of a 1500 kW PV system, a 1000 kW converter, 150 batteries, 30 wind turbines, and a 3500 kW biogas generator set. In contrast, the grid-connected system proved more feasible, with a 2000 kW PV system, a 1000 kW converter, 30 wind turbines, and a 2500 kW biogas genset. The grid-connected model was found to be more technically and economically viable, serving an annual load of 14,978 MW while reducing component size and emissions.

When modeling a PV system, two crucial current flows must be considered: recombination and diffusion currents, which arise from the movement of charge carriers within the PV cell. Recombination currents occur when a hole-pair and an electron recombine in the p-n junction, (Servaites et al., 2021). Diffusion current flow, on the other hand, occurs across the p-n junction due to variations in charge carrier concentration (Nolasco et al., 2019).

Research has shown that the lumped parameter equivalent circuit (LPEC) model accurately replicates the characteristics of a photovoltaic cell under various operating conditions (Coetzer et al., 2023). The LPEC model represents the effects of recombination and diffusion currents using traditional diodes. This approach is more convenient than other modeling methods, as it simplifies the estimation of model parameters based on manufacturer datasheets (Ishaque and Salam, 2011). Figure 1 illustrates the circuit diagram of the Single-Diode Model (SDM), a widely used PV cell model that balances accuracy and simplicity (Chaibi, 2019). The SDM's performance is determined by various parameters, including Currents: diode saturation (I_D), photo-generated (I_{ph}), Ideality factor (F), Resistance: series (Rs), parallel (Rp), PV manufacturers typically provide indirect values for these parameters through three distinct point features: Short-circuit current (0, Isc), Open-circuit voltage (Voc, 0) and Maximum power point (V_{MPP}, I_{MPP}) (Ogiari, 2019).

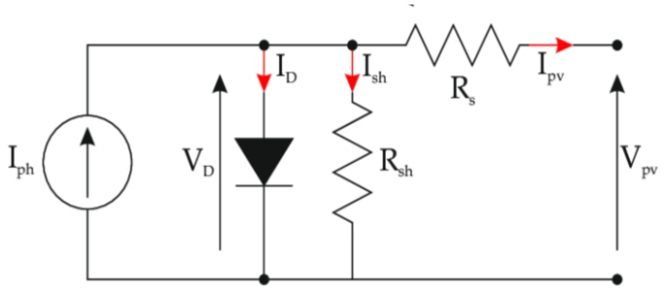

Figure 1: A typical illustration of the Circuit Diagram of the SDM

The SDM characteristics equation relating the output voltage and the current of a photovoltaic cell is given in Equation 1.

$$I = I_{ph} - I_o \left(e^{\frac{q(v-IR_S)}{nkT}} - 1 \right) - \frac{(v-IR_S)}{R_{sh}} \qquad (1)$$

where I is the output current of the PV cell, Iph is the photo-generated current which is proportional to sunlight, and Io is the diode saturation current. The parameter q represents the electron charge (1.602×10^{-19} C), while V is the output voltage of the PV cell. Rs and Rp denote the series and parallel (shunt) resistances of the PV cell, respectively. The diode ideality factor is represented by n, typically ranging between 1 and 2. K is the Boltzmann constant (1.38×10^{-23} J/K), and T is the absolute temperature of the cell measured in Kelvin.

Due to the essential need for electricity for rural communities in developing countries for agricultural productivity and socio-economic development, this research is of great importance. This research is aimed at providing solutions and strategies to provide a reliable and sustainable power supply for rural communities through the integration of hybrid off-grid power solutions of smart gas generators, solar PV, and energy storage systems. This will facilitate socio-economic development, and agricultural productivity, and reduce environmental hazards. The findings underscore the viability of this approach within the study area, considering the enormous availability of gas resources in the study area.

2. Methodology

2.1 Description of Study Area

The study area is Uzere Community (Figure 2), a rural settlement in Isoko South Local Government Area of Delta State, Nigeria (5°20.6'N, 6°13.8'E), with a population of approximately 15,948 people. The main occupations of the residents are farming and fishing, while the local economy is also driven by petroleum exploration and agriculture. Uzere lies within the tropical rainforest belt, characterized by luxuriant vegetation. The community experiences a tropical wet and dry climate, with relatively constant temperatures throughout the year.

2.2 Materials and Software

Google Earth Pro was used to obtain high-resolution satellite imagery of Uzere Community, aiding in identifying geographical features and infrastructure for site assessment. Microsoft Spreadsheet facilitated data analysis, visualization, and calculations. Meteorological data, including temperature and solar radiation, was collected to inform the design and simulation of the hybrid energy system. Additionally, a digital electrical data recorder from the SCHMITT Energo Smart Gas Generator captured electrical parameters such as voltage, current, and power output, providing insights into daily energy demand and system performance.

2.3 Hybrid Optimization Model for Electric Renewables (HOMER) Pro Software

HOMER Pro is a widely used tool for designing and analyzing hybrid energy systems, facilitating system optimization, feasibility studies, and sensitivity analyses based on Net Present Cost (NPC). It helps determine the optimal system size, assess various configurations, and evaluate techno-economic performance. While HOMER excels in optimizing systems with known variables and constraints, it has limitations, including the inability to model environmental factors, voltage, and frequency stability. The software requires input data such as component specifications, load profiles, meteorological data, and economic parameters. Its output includes key performance metrics like Renewable Fraction (RF), NPC, and Levelized Cost of Energy (LCOE), aiding in cost-effective system design. The NPC calculation methodology follows Equations 2 and 3, as detailed by researchers like Sanni et al. (2018).

$$C_{NPC} = \frac{C_{ann.tot}}{CRF_{(i,Rproj)}} \qquad (2)$$

Where C_{NPC} is the net present cost, $C_{ann.tot}$ is the total annual cost of the system, i is the real discount rate, R_{proj} is the duration of the project, and $CRF_{(i,N)}$ is the capital recovery factor (Equation 3)

$$CRF_{(i,N)} = \frac{i(1+i)^N}{(1+i)^{N-1}} \qquad (3)$$

The cost of energy is expressed as calculated using Equation 4.

$$COE = \frac{C_{ann.tot}}{E_{served}} \tag{4}$$

where E_{served} is calculated using Equation 5.

$$E_{served} = E_{pri} + E_{def} + E_{grid,sales} \tag{5}$$

where E_{served} is the total energy served by the system. The output power of the PV system is calculated using Equation 6.

$$P_{pv} = P_{pv\text{-}rated} f_{pv} \left[1 + k_c \left(T_c - T_{ref}\right)\right] \tag{6}$$

Where $P_{pv\text{-}rated}$ is the PV system's rated power under standard test conditions, f_{pv} is the derating factor of the PV array, It represents the global solar irradiation incident on the PV array surface per unit area, and I_s is the solar irradiation per unit area of the PV array surface under standard temperature conditions (25°C). I_s is given as *1 kW/m²*, where *Kc* represents the PV array temperature coefficient, *Tc* is the temperature of the PV cell, and *Tref* is the temperature of the PV cell under standard test conditions. If the temperature effect is neglected *(Kc = 0)*, Equation 6 simplifies accordingly.

$$P_{pv} = P_{pv} = P_{pv\text{-}rated} f_{pv} \frac{I_T}{I_s} \tag{7}$$

HOMER Pro calculates the Levelized Cost of Energy (LCOE), which represents the average cost of the useful energy produced by the plant, expressed in naira per kilowatt-hour (kWh. Equation 8 illustrates the relationship, as described by, Hassane et al.(2022)

$$LCOE = \frac{C_{total}}{E_{total}} = \frac{\text{Total Lifecycle Cost}}{\text{Total Energy Generated over its lifetime}}$$

$$LCOE = \frac{I_o + \sum_{t=1}^{n} \left(\frac{At}{(1+i)^t}\right)}{\sum_{t=1}^{n} \left(\frac{M_{t,el}}{(1+i)^t}\right)} \tag{8}$$

where LCOE is the levelized cost of electricity in N/kWh, Io is the initial investment, At is the total cost for year t, Mt, el is the quantity of electricity produced in kWh/year, n is the project life in years, and t is the number of years (1, 2, 3, …….. n).

2.4 Markovian state of operation

The Markovian state of operation typically refers to a situation in which the future state of a system depends only on its present state, not on the sequence of states that preceded it. In the context of power systems or hybrid energy systems, this concept can be applied to model the behavior of different operational states within a system, such as generator, battery, or renewable power availability. Markov chain transition matrix helps to quantify the likelihood of moving from one state to another. The hypothetical matrix for this setup, where each value represents the probability of moving from one state to another in the next time-period is represented in Table 1

Table 1: Markovian State of Operation

Current state				
	S	SB	BG	G
S	0.7	0.2	0.1	0
SB	0.3	0.4	0.2	0.1
BG	0.1	0.3	0.4	0.2
G	0	0.1	0.2	0.7

The system can be in one of five states: Solar State (S), Solar to Battery state (SB), Battery to Generator state (BG), and Generator State (G).

The transition from Solar State (S) to Battery state (SB) occurs when the system requires battery support while solar energy is still available. This can happen due to cloudy conditions or sudden demand spikes, and there is a 20% chance of this transition occurring. When the system is in a Solar to Battery state (SB), there is a 20% probability that it will transition from Battery to Generator state (BG). This typically happens when the battery is depleted or the solar power is reduced. In the Battery to Generator state (BG), the system relies on both battery and generator support. However, during periods of high demand and low solar power, there is a 20% chance that the system will transition to Generator State (G), relying solely on the generator for support. Finally, when the system is in Generator State (G), there is a 10% chance that it will transition from Solar to Battery state (SB) as solar power becomes available.

3. Results and Discussion

3.1 Solar Irradiance and Clearness

Table 2 and Figure 2 present the monthly variations in the clearness index and daily solar radiation for the study location. The table provides exact numerical values, while the figure visually illustrates the trends, highlighting seasonal fluctuations in solar energy availability.

Table 2: Solar Irradiance and Clearness of Study Location

Month	Clearness Index	Daily Radiation (kWh/m2/day)
January	0.654	5.76
February	0.637	6.06
March	0.62	6.32
April	0.598	6.3
May	0.568	5.94
June	0.523	5.4
July	0.469	4.85
August	0.428	4.47
September	0.498	5.11
October	0.582	5.63
November	0.684	6.11
December	0.677	5.79
Average		5.645

As revealed in Table 2 and Figure 2, solar radiation data obtained from the National Renewable Energy Laboratory (NREL) database show that the study location receives an average global radiation of 5.65 kWh/m²/day. The lowest radiation was recorded in August, with 4.47 kWh/m²/day and a clearness index of 0.428, which corresponds to the peak of the rainy season.

3.2 Monthly Average Temperature

Table 3 and Figure 3 present the monthly variations in daily ambient temperature for the study location.

Month	Daily Ambient Temperature (°C)
January	20.62
February	23.46
March	26.43
April	27.57
May	26.43
June	24.95
July	23.87
August	23.48
September	23.95
October	24.03
November	22.05
December	20.31
Average	23.93

As revealed in Table 3 and Figure 3, the highest monthly average temperature of 27.57°C occurs in April, coinciding with the peak of the dry season, while the lowest temperature of 20.31°C is recorded in December, likely due to the influence of the harmattan season.

3.3 Design of Hybrid Power Solution

Figure 4 presents the Single Line Diagram (SLD) of the designed Gas Generator-Solar-Battery hybrid off-grid power system.

The system integrates with the existing 11kV distribution network via a 400V/11kV step-up transformer. Key components include a totalization control panel with 4x500A input and 2000A output circuit breakers, ensuring balanced power distribution and system protection. An 11kV RMU with one incomer and two output breakers manages power flow and provides fault protection. This design ensures seamless integration of the hybrid power system into the off-grid 11kV distribution network in the study area.

3.4 Energy Demand Metrix

Table 4 summarizes the energy profile results generated from the digital electric data dashboard of the base system for weekdays, weekends, and holidays respectively. Figure 5 illustrates the load demand profile.

Figure 2: Graph of Monthly Solar Radiation and Clearness Index

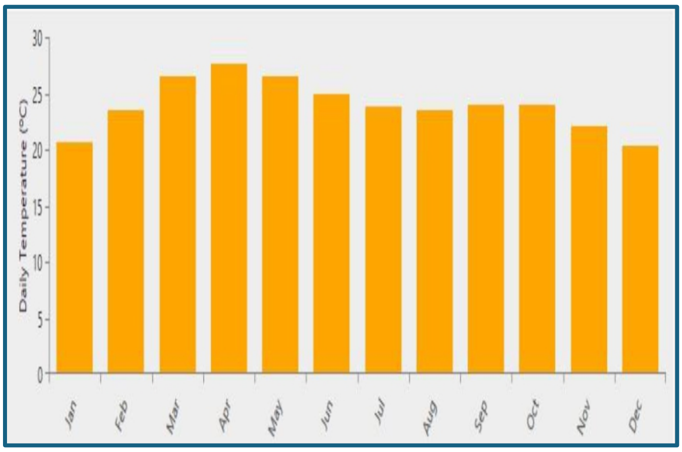

Figure 3: Monthly Average Temperature Data

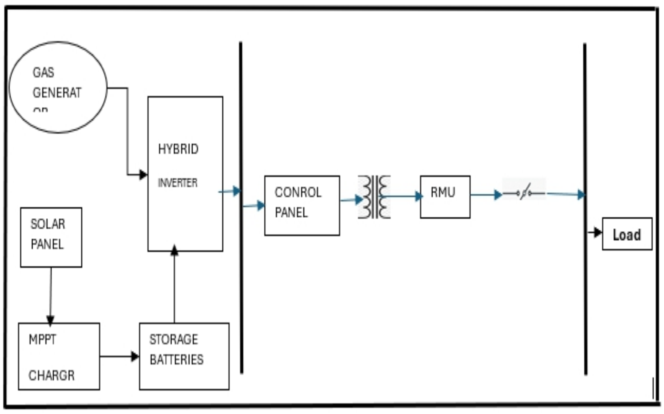

Figure 4: Single Line Diagram of the design of the Hybrid Power Solution

Table 4: Energy Audit (Load Demand)

Metrics	Off Peak (kWh)	Peak Load (kWh)	Average Load (kWh)
Weekdays	359	420	389.5
Week-Ends	385	450	417.5
Holidays	375	445	410

As shown in Table 4, the energy audit reveals variations in load demand across different periods. On weekends, the off-peak load demand reaches 385 kWh, while the peak load demand rises to 450 kWh. The average load demand during weekends is 417.5 kWh, indicating a higher energy requirement compared to weekdays and holidays.

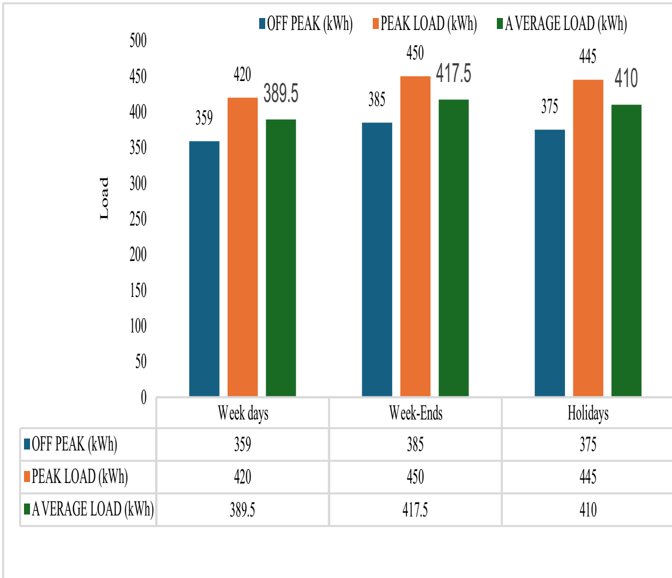

Figure 5: Graphical presentation of Energy Audit (Load Demand)

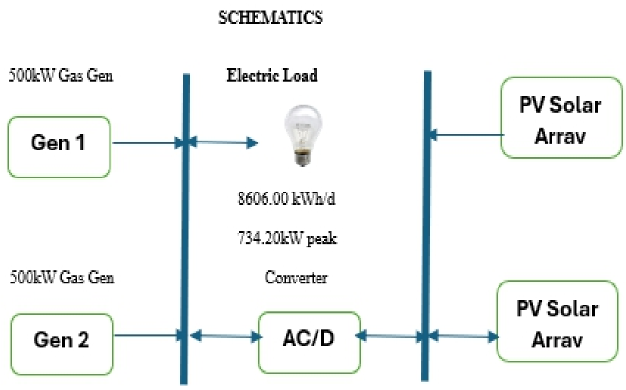

Figure 6: Schematic Representation of the Hybrid Off-grid System

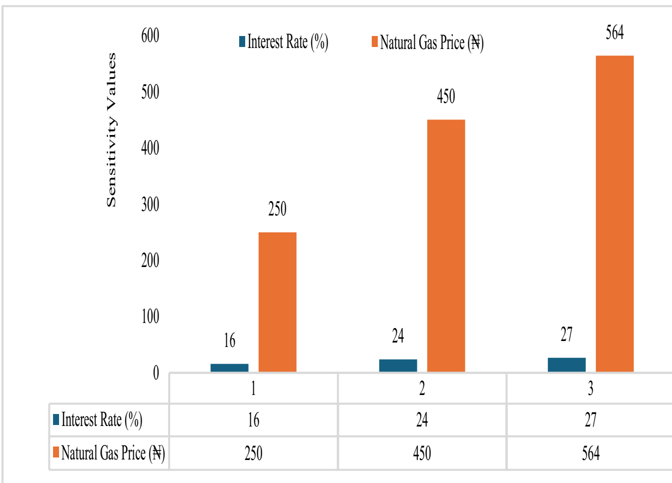

Figure 7: Graphical presentation Sensitivity Criteria

Table 7: Optimization Result with Sensitivity Criteria

Sensitivity		Architecture					Cost			
Interest Rate (%)	Natural Gas Price	CS6X-325P (KW)	500KWGen1 (KW)	500KWGen2 (KW)	SENEC V3 10 (#)	Converter (KW)	NPC (₦)	LCOE (₦)	Operating Cost (₦)	CAPEX (₦)
16	250		500	500	1	3,306	₦54.9B	₦63.65	₦195M	₦1.24B
24	250		500	500	1	5.74	₦18.4B	₦71.53	₦220M	₦397M
27	250		500	500	1	5.74	₦12.8B	₦73.48	₦224M	₦397M
16	450	900	500	500	800	3,306	₦91.9B	₦106.63	₦328M	₦1.80B
24	450	900	500	500	800	574	₦30.9B	₦120.48	₦365M	₦1.10B
27	450	900	500	500	800	574	₦21.7B	₦124.99	₦373M	₦1.10B
16	564	900	500	500	800	3,306	₦109B	₦126.69	₦391M	₦1.80B
24	564	900	500	500	800	574	₦36.1B	₦140.45	₦428M	₦1.10B
27	564	900	500	500	800	574	₦25.2B	₦144.97	₦435M	₦1.10B

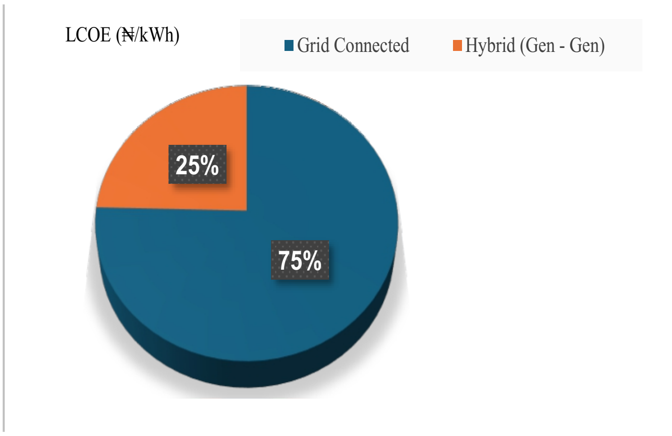

Figure 8: Comparison of Base of Generators with Grid Power

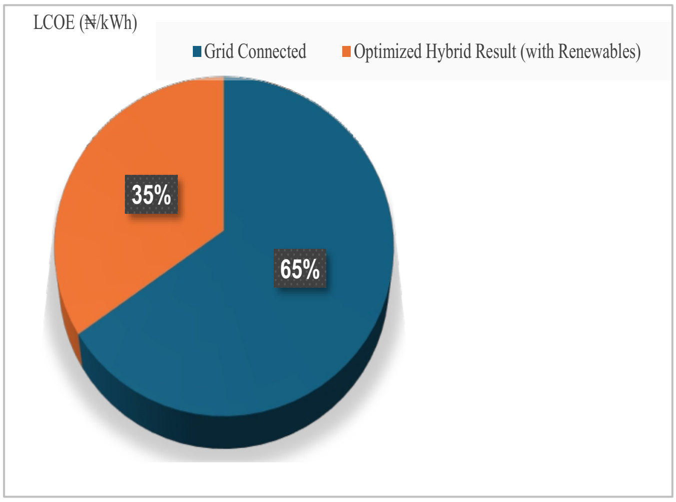

Figure 9: Comparison of LCOE of grid and Hybrid Connected

Table 9: Optimization Results with Hybrid System

Architecture						Cost			
CSX325P (KW)	500KW (GEN1) (KW)	500KW (GEN2) (KW)	SENEC V3 10 (#)	CONVERTER (KW)	Dispatch	NPC (₦)	LCOE (₦)	Operating (₦)	CAPEX (₦)
900	500	500	800	574	CC	₦30.9B	₦120.48	₦365M	₦1.10B
900	500	500	800	551	CC	₦31.0B	₦120.55	₦365M	₦1.10B
	500	500	1	27.6	CC	₦32.0B	₦124.78	₦387M	₦402M
	500	500	1	41.3	CC	₦32.1B	₦124.81	₦387M	₦406M
900	500		800	551	CC	₦32.3B	₦125.60	₦384M	₦872M
900	500		800	597	CC	₦32.3B	₦125.69	₦384M	₦884M
900		500	800	551	CC	₦32.3B	₦125.69	₦383M	₦927M
900		500	800	597	CC	₦32.3B	₦125.79	₦384M	₦939M
	500		800	379	CC	₦37.2B	₦144.97	₦449M	₦522M
		500	800	367	CC	₦37.3B	₦145.25	₦449M	₦574M

3.5 Load Matrix of Hybrid Power System

Table 5 and Figure 6 illustrate the load metrics and provide a schematic representation of the hybrid power system, respectively.

Table 5: Load Metrics of the hybrid solution

Metric	Base load	Scaled
Average Power (Kw/Day)	8606	8606
Average Power (Kw)	358.54	358.54
Estimated Peak Power (Kw)	734.2	734.2
Load Factor	0.49	0.49

The hybrid power system consists of 2x500 kW gas generators, (expandable to 2 MW), a solar photovoltaic (PV) system, battery storage, and a converter system. The results show that the average daily energy output of the system is 8606 kWh/day, with an average hourly power output of 359 kW. The peak power demand is 734 kW, and the load factor of 0.49, indicating a significant requirement for reliable power supply.

3.5 Gas Supply

The IPP receives a direct piped gas supply, with reduced gas prices serving as an incentive for the study location. Transportation, haulage, and associated costs are eliminated. For simulation purposes, nominal gas prices of ₦250.00/m³, ₦450.00/m³, and ₦564.00/m³ were used.

3.6 Sensitivity Criteria

The sensitivity criteria used in this analysis, highlighting the impact of interest rates and natural gas prices, are summarized in Table 6.

Table 6: Sensitivity Criteria

Interest Rate (%)	Natural Gas Price (₦)
16	250
24	450
27	564

Table 6 and Figure 7 show the sensitivity criteria. The inflation rate was held constant at 32.4%, while different interest rates and gas prices were used as sensitivity cases. This analysis allows for the assessment of the project's viability under varying economic scenarios.

3.7 Techo-Economic Analysis

Table 7 shows the optimization result with sensitivity criteria

The optimal solution, as indicated by the lowest Levelized Cost of Energy (LCOE), is the conventional thermal power system with 500 kW of generation, at an interest rate of 16%. This configuration yields an LCOE of ₦63.65/kWh, with a Net Present Cost (NPC) of ₦54.9 billion, an operating cost of ₦195 million, and a capital expenditure (CAPEX) of ₦1.24 billion. This optimal solution provides the most cost-effective power generation option, leveraging the low-cost natural gas incentives.

3.7.1 Comparison with Non-Grid Power Solutions

Table 8 and Figure 8 present the comparison analysis of the Levelized Costs of Energy (LCOE) for the off-grid thermal solution and grid-connected power systems.

Table 8: Comparison of Base of Generators with Grid Power Solution

Hybrid option	LCOE (₦/kWh)	Hours served
Hybrid (Gen - Gen)	63.65	24 hr
Grid Connected	225.00	24 hr

The result reveals a significant cost difference. The off-grid thermal power system has an LCOE of ₦63.65/kWh, while the grid-connected system has an LCOE of ₦225.00/kWh. This represents a substantial cost savings of approximately 71.7% for the off-grid thermal system.

Table 9 presents the optimization results for the hybrid power system.

The optimal solution, as indicated by the lowest Net Present Cost (NPC) and Levelized Cost of Energy (LCOE), is the hybrid power system configuration with 900 kW of thermal generation, 800 kW of solar power, and a converter size of 574 kW.This configuration, which employs a cycle charging dispatch strategy, yields an NPC of ₦30.9 billion, an LCOE of ₦120.48/kWh, an operating cost of ₦365 million, and a capital expenditure of ₦1.10 billion.As shown in Table 9, this optimal solution provides the most cost-effective and efficient power generation mix, considering the trade-offs between thermal and solar power sources.

3.7.2 Comparison with Non-Grid Power Solutions

To evaluate the economic benefits of integrating renewable energy sources, the Levelized Cost of Energy (LCOE) for different power system configurations was analyzed, comparing the optimized hybrid system with renewables to the conventional grid-connected system.

Table 10: Comparison of Grid-Connected and Optimized Hybrid

Hybrid option	LCOE (₦/kWh)	Hours served
Grid Connected	225	24hours
Optimized Hybrid Result (with Renewables)	120.48	24hours

The results highlight the substantial cost advantage of the optimized hybrid system incorporating renewables. With an LCOE of ₦120.48/kWh, the hybrid system achieves a 46.5% reduction in energy costs compared to the grid-connected system, which has an LCOE of ₦225.00/kWh. This significant cost savings underscores the economic viability of renewable energy integration, making it a more affordable and sustainable alternative for power generation.

3.8 Environmental Impact

The incorporation of solar photovoltaic (PV) technology into the gas-based power system yields significant environmental benefits. A comparative analysis of carbon dioxide (CO_2) emissions between the hybrid system and the gas-only system reveals a substantial reduction of 30% in emissions. This reduction makes the hybrid system a more environmentally sustainable option, contributing to a decrease in greenhouse gas emissions and mitigating the adverse impacts of climate change.

4. Conclusion

This study analyzed the techno-economics of two power generation modes: Gas-to-Power (thermal) and harnessing the energy mix (hybrid/renewable). The findings suggest that harnessing the energy mix offers a more economically viable option, with significant cost savings and improved efficiency compared to traditional Gas-to-Power thermal generation. The optimal solution for thermal generation had an LCOE of 63.65/kWh, while the hybrid solution combining thermal and solar power had an LCOE of 120.48/kWh. The low cost of energy from thermal generation was attributed to the nearness of raw materials. The study's findings have significant implications for Nigeria's energy sector. To fully harness the renewable energy potential of Nigeria, it is recommended that, Government and regulatory bodies should focus on formulating policies and providing funding to produce cheap and sustainable off-grid electricity for oil-producing communities. Gas supply and nominal gas pricing incentives should be provided for these communities. Community renewable energy projects should be encouraged to enable decentralized electricity generation from environmentally friendly technologies. Integration of micro-off-grid hybrid power systems to the 11kV or 33kV distribution network should be explored to distribute off-grid power to rural communities.

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