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A Review of Hybrid Off-Grid Power Systems for Electrification in Oil-Producing Rural Areas: A Case Study Focus on Uzere, Nigeria

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ABSTRACT: The aim of this paper is to review of the analysis and simulation of integrating an off-grid hybrid power system to a distribution network in oil producing rural area of Nigeria. The study analyzes existing literature on the integration of gas generators, solar photovoltaic (PV) systems, and energy storage technologies for rural electrification. By examining the specific case of Uzere, an oil-producing rural community in Delta State, Nigeria, this review highlights the technical and economic challenges involved in hybrid system deployment. It also explores recent advancements in energy management and optimization tools, such as HOMER Pro, to simulate hybrid solutions tailored to rural needs. This review offers insights into sustainable and cost-effective solutions for rural electrification in similar regions.

KEYWORDS: Hybrid power system, rural electrification, gas generator, solar PV, HOMER Pro, Nigeria, off-grid, renewable energy, review

1. INTRODUCTION

In many rural regions of sub-Saharan Africa, access to reliable and affordable electricity remains a significant challenge. Despite substantial efforts to expand grid infrastructure, off-grid and hybrid energy systems have emerged as viable alternatives to meet energy demand in isolated areas. The hybridization of renewable energy sources, such as solar PV, with traditional power generation technologies like gas generators, has the potential to address intermittency issues associated with renewables while reducing reliance on fossil fuels. Oil-producing regions in the Niger Delta are rich in natural resources but often lack access to reliable grid power. To address these challenges, hybrid power systems, which combine traditional energy sources like gas generators and diesel generators with renewable energy technologies such as solar PV, have gained attention as a potential solution for off-grid rural communities. This review focuses on the specific case of Uzere, a rural oil-producing community in Delta State, Nigeria, where energy needs are primarily met by a 500 kW gas generator. The aim is to explore the broader implications of hybrid system integration and how it can be optimized using modern energy simulation tools like HOMER Pro.

This review covers the following:

- Current state of rural electrification in Nigeria.
- Key technologies used in hybrid off-grid systems.
- Methodologies for integrating hybrid systems with distribution networks.
- Techno-economic assessments of hybrid systems.
- Recent developments in simulation tools for system design and optimization.

1.1. Current State of Rural Electrification in Nigeria

1.1.1 Energy Access and Challenges

Nigeria is situated between latitudes 4° and 14°N and longitudes 2° and 15°E on the west central African axis. Nigeria has been classified as a lower middle-income nation by the UN and World Bank, Fantom, N. (2016). The nation is bordered with four other countries and the Atlantic Ocean. It is the largest and most populated country in the African continent, with an estimated population of 220 million people living there as of 2023 with a land area of roughly 924,000 km^2. The sluggish growth in the electricity industry can be linked to the fact that eighty percent of Nigerians are impoverished. Salmon, and C. Tanguy, J. (2016) and Salisu, S. et al., (2019). Most people are under-electrified in general, while the vast bulk of the unelectrified population is concentrated in the rural areas because they are not connected to the national grid.

Even though Nigeria is one of the largest producers of petroleum in Africa, the country's rural populace still has a difficult time getting electricity. Compared to urban regions, rural regions have a far lower electrification rate, and many of these communities have either nonexistent or unreliable electricity availability. The International Energy Agency (IEA) estimates that 40% of Nigeria's rural areas are electrified, and many of these communities rely on petrol or diesel generators for electricity.

1.1.2 Government Initiatives

The Nigerian government has put in place a number of programs designed to enhance rural electrification and expand access to energy in areas that are currently underserved. These are a few major projects:

1.1.2.1 Rural Electrification Agency (REA)

The national policy on rural electrification is implemented by the REA, which was established in 2013. It focusses on increasing rural communities' access to power through a number of initiatives, such as the installation of off-grid and mini-grid systems.

1.1.2.2 National Electrification Project (NEP)

The NEP, which was started in partnership with the World Bank, intends to give energy to more than 25 million people in Nigeria. Its main goal is to use solar and hybrid energy systems to provide underprivileged and unserved areas with electricity.

1.1.2.3 Solar Power Naija Program

By 2023, five million Nigerian families should have solar-powered home systems according to this project, which was first announced in 2021. The goal of the program is to increase rural communities' access to energy and to off-grid solar solutions.

1.1.2.4 Mini-Grid Policy

To promote private sector involvement in mini-grid projects, the Nigerian government created the Mini-Grid Regulation. This policy facilitates community-driven electrification by outlining the structure for mini-grid licensing, implementation, and operation.

1.1.2.5 Partnership with International Organizations

Partnerships with institutions such as the World Bank, African Development Bank, and United Nations Development Programme (UNDP) have resulted in financial support and technical guidance for electrification initiatives in rural areas.

Nigeria is committed to providing universal access to electricity by 2030, and these and other measures support the development of renewable energy technology, especially solar PV systems.

2. RELATED LITERATURE

Over the past few years, hybrid power systems have drawn a lot of attention, especially for rural electrification in developing nations. The variable nature of renewable energy. The variable nature of renewable energy sources is addressed and a more dependable energy solution is offered by combining solar PV, battery storage, and conventional generators. An assessment of hybrid mini-grid systems' contribution to rural areas' sustainable energy supply is provided by Akinyele & Rayudu (2016). According to their research, appropriately sized hybrid systems can lessen reliance on petrol and diesel, which can save money and have a positive impact on the environment. The opportunities and difficulties of integrating renewable energy sources into Nigeria's electrical system are examined by Babatunde et al. (2019). In order to fulfil the targets for rural electrification, they underscore the importance of distributed generation, particularly in off-grid areas, and the possibilities of hybrid systems to meet rural electrification targets.

The incorporation of solar photovoltaic and storage batteries into hybrid systems has become the subject of numerous studies. In his 2015 study, Kusakana examines the feasibility of integrating solar photovoltaics with battery storage in off-grid systems throughout Africa, pointing out that these systems are now more financially appealing due to falling battery costs. In order to maximize performance, Oshiro et al. (2018) address the technical difficulties associated with integrating batteries for energy storage in off-grid systems, such as battery sizing and charge/discharge cycles.

Research on hybrid systems linked to 11kV or 33kV networks—or any other higher voltage network—is equally pertinent. The integration of wind and solar electricity into 33kV networks in East Africa is discussed by Hansen et al. (2019), with an emphasis on the systems' technical and financial difficulties. An overview of linked hybrid power systems is provided by GIZ (2020), noting the importance of grid stability and power quality.

To meet electrical needs in a sustainable manner, renewable energy sources including wind, hydroelectricity, solar power, and biomass must be included into the mix of energy sources. Concerns about climate change, energy security, and the desire to transition to low-carbon energy systems have given this integration international traction (Jacobson, 2021). Recent research has shown that incorporating renewable energy is both financially sustainable and practically possible, especially in off-grid and decentralized energy installations. Recent studies by Hu et al. (2023) concentrated on incorporating energy from renewable sources into microgrids. The study underlined how crucial energy storage technology and sophisticated control tactics are to enhancing grid stability and dependability. Additionally, Gupta et al. (2022) conducted a thorough analysis of off-grid renewable energy options, emphasizing the role hybrid mini-grid systems play in providing rural populations with dependable access to electricity. In order to analyze the techno-economics of hybrid energy from renewable sources systems for off-grid electrification in Nigeria, Ayodele and Olatomiwa (2021) carried out a study. The study highlighted the nation's potential for affordable and environmentally friendly energy options. Similarly, Chendo and Udo (2020) investigated how mini-grid systems in rural African villages might include solar PV systems. The study emphasized how crucial decentralized energy solutions are to improving socioeconomic development and energy access. Adaramola et al.'s research from 2019 looked at the techno-economic viability of hybrid renewable energy systems for Nigerian rural electrification in addition to the previously mentioned studies. The study emphasized how combining various renewable energy sources might improve energy accessibility and dependability.

A study was carried out in Ethiopia by Beza TM, Wu CH, and Kuo CC in 2021 to address the problem of island access to energy. The research location's basic case for electricity generation was a diesel generator (DG). In order to offer a load of 76.94 kWh/day, it has been compared with a hybrid that included solar PV, wind, and battery systems sources. The suggested hybrid system was simulated using HOMER ProThe most efficient hybrid mini-grid system, based on the results, has 40 batteries, every weighing 1 kW, 10 kW of DG, and 25 kW of PV. When compared to a DG standalone system, it reduced GHG emissions by 33,102 kg yearly. Its LCOE, NPC, and RF were $0.175/kWh, $119,139, and 86.4%, respectively. This hybrid configuration was found to be the least expensive when compared to the base case and other hybrid configurations that were examined in the study. In a similar vein, a sensitivity study that varied the diesel price, load demand, and global horizontal irradiation (GHI) produced an LCOE of $0.179/kWh, NPC of $151,468, and RF of 69.1%. This provided additional evidence that the system was the most practical and effective setup.

Adefarati et al. (2020) conducted a study that examined the integration of energy from renewable sources into mini-grids systems in rural African communities. The study emphasized capacity building and community engagement as critical elements in supporting sustainable energy transitions.

2.1. Case Studies of Hybrid System Integration

2.1.1 Global Perspectives

Energy sources that can be produced naturally without diminishing the resources of the world are referred to as renewable energies. Solar, wind, hydro, geothermal energy, biomass, and biofuels are some of these sources. Renewable energy sources are more sustainable and cleaner than non-renewable ones, which are limited and release a lot of greenhouse gases. Examples of non-renewable energies are coal, oil, and gas. Furthermore, these energies can now be captured and used more economically because to advancements in technology in recent years. One of the most important ways to fight climate change and lessen reliance on fossil fuels is to use renewable energy. León Gómez and colleagues (2023) and Kharrich and colleagues (2021). Investments in these energy sources have the potential to boost sustainable economic development and create jobs. In conclusion, using renewable energy sources is essential to securing a safer and greener future for coming generations.

Global research on the incorporation of hybrid electrical systems for electricity in rural areas has been done in a number of studies. Mwangi, P. et al. (2023) showed that hybrid PV-diesel systems dramatically lower operating costs in rural parts of sub-Saharan Africa. Similarly, Kumar et al.'s (2023) study on hybrid system use in South America demonstrated that, especially in areas with plenty of solar energy, these systems provide a dependable substitute for diesel generators alone.

Renewable energy systems classified as hybrids are ones that produce power by combining two or more renewable sources. In locations where access to the traditional electrical grid is either unavailable or the connection is inconsistent or restricted, these devices are quite helpful. In 2018, Dipti, D. Solar and wind energy are combined in a particular instance of a hybrid system. Batteries are used to store the electricity produced by solar panels during the day while the sun is shining. In order to create additional electricity and charge the batteries during the night, wind energy conversion systems, or WECS, harness the wind.

A hybrid alternative energy source, or HRES, is made up of a minimum of two renewable energy sources, including photovoltaic systems and wind turbines, that are used in tandem to enhance system efficiency and, to some extent, stability in the energy supply. This study's goal is to provide a thorough analysis of wind-solar HRES from the standpoints of design optimization techniques, power architectures, mathematical modelling, and power electronic converter topologies. The inclusion of an energy storage system can further minimize the uncertainty of HRES, hence this research offers various hybrid energy source and storage system coupling methods and highlights their main benefits and drawbacks. The state-of-the-art HRES converters for power and control schemes have been shown and discussed. This paper aims to provide a thorough reference for academics, professionals, and policymakers in this subject by reviewing various energy source combinations, modelling, power converter topologies, sizing, and optimization approaches employed in the current HRES. The scope of upcoming developments as well as studies on HRES is also covered in this article, along with the technological difficulties related to HRES. P. Roy and associates (2022). A hybrid system that integrates hydro and solar energy is another example. Solar panels produce electricity during the day, which is then utilized to pump water to a dam from a lake or river. The water in the dam is released through a hydro turbine at night when the sun doesn't shine in order to produce more energy. According to Singh, R., and Bansal, R. C. (2018), renewable energy hybrids have the potential to be more dependable and efficient than single-source systems. They also lower the cost of generated energy and enable better use of the resources that are available. Due to these factors, hybrid systems are growing in popularity across the globe, particularly in isolated or rural locations.

Renewable power seems like a sensible solution because there isn't a transmission or distribution grid for electricity in remote or inaccessible regions due to the high cost of building a transmission line, unsuitable geographical conditions, and other factors affecting the production of sustainable energy. Therefore, the combined solar-wind-diesel generating system with battery bank and grid-independence was examined in this research taking into account the solar and wind energy potential of Turkalan village in East Azerbaijan Province. HOMER software was used to analyze the system under study and determine its best measurement. Three parameters were subjected to sensitivity analysis: wind speed, environmental light reflection, and solar radiation. The target energy supply was 22 kWh/d with a 2.5 kW maximum load demand. The four hybrid systems that the software suggested based on total net present cost (NPC) were solar-wind-generator-battery, solar-battery, solar-battery, and solar-wind-battery, in that order. The purpose of the studies was to identify the system that is most suited for the region. N. Ganjei et al. (2022).

Owing to seasonal variations in wind speed and solar radiation, the reliability of renewable energy sources, like solar and wind, is subject to significant fluctuations Zheng S., et al., (2024). One solution used to address this issue is the incorporation of Hybrid Renewable Energy Systems (HRES). By utilizing the best hours and seasons for energy generation, HRES reduces reliability issues and offers cost savings when compared to depending only on a single renewable energy source Luo J. et al., (2024). On the other hand, determining the optimal system size to meet particular load demands at a particular site is complicated due to the unpredictable nature of energy sources, the complexities of efficient cost modeling, and the time-consuming nature of optimization computational methods inherent to the context of optimal design Shirkhani, M. et al., (2023)

Software solutions are necessary to overcome this obstacle, and the literature outlines several software programs that facilitate the optimization process World Energy Outlook 2017 (2023). The National Renewable Energy Laboratory (NREL)'s Hybrid Optimization Model for Electric Renewable (HOMER) is a well-liked option among them. It makes it possible to evaluate various combinations quickly and accurately, which speeds up the complex optimization process. Gao, J., and associates (2024). The integration of two solar thermal collector technologies was examined by Rosales-Perez et al. (2024) in an effort to increase the solar systems' economic viability for district heating applications. They assessed the energy and cost-effectiveness of hybrid systems that combine parabolic trough and flat plate collectors at various radiation levels and industrial process temperatures. When compared to solo parabolic trough collector systems with smaller solar field sizes, the hybrid system achieved considerable solar percentages with a lower levelized cost of heat. Khan and colleagues (2005) conducted a study in Newfoundland, Canada, to investigate the feasibility of using hydrogen as a power source in a combined energy system. Using simulation and optimization approaches, the study evaluated a range of conventional and renewable energy sources as well as several energy storage options. The HOMER software was utilized for this purpose. The study's conclusions suggested that, given current cost dynamics, a wind-diesel storage system might be feasible. Nevertheless, an intriguing idea surfaced: if fuel cell costs were cut by about 15%, a wind-fuel cell system might become more appealing.

Further research was carried out by Indonesian scientists with the goal of creating an independent power system to meet the energy needs for community and administrative functions in three different regions of Maluku, Indonesia. In this regard, Putra et al. (2016) focused on the analysis of three particular locations: Wairtan, Klishatu, and Leiting Village. Using software like HOMER Pro, PVsys, and PVsol, the study examined the impact of community and administrative energy demands. The findings of this study could be utilized to improve both the rural electrification initiative and the Bright Indonesia campaign, according to the authors. With an emphasis on the Italian and Iberian day-ahead power markets, Gomez et al. (2023) developed an optimization model to manage operational revenue in liberalized power markets. According to the study, compared to operating each component independently, the hybrid PV-wind-storage power plant may have an annual net income increase of 4%. Research on the potential for hydrogen generation at the Shagaya renewable power station using a hybrid energy system was conducted by Hussam et al. in 2024. The most economical designs that would increase the renewable component and lower greenhouse gas emissions were found using techno-economic and optimization analyses. The upgraded system cut carbon dioxide emissions by 14,819 kg annually and produced 111,877 kg of green hydrogen annually. The results of the sensitivity research showed that, in comparison to wind turbines and electrolysers, the cost of energy (COE) is more susceptible to fluctuations in PV costs. Using various solar PV tracking techniques, Dekkiche et al. (2023) evaluated the techno-economic feasibility of hybrid energy systems (HES) that include photovoltaic (PV) and reformer fuel-cell (RF-FC) components and are grid-connected. Throughout the assessment, HOMER Pro software was used to simulate and assess the costs and viability of various system configurations over the course of their operational lifetimes. The best financial results seem to be attainable with careful design of a grid-tied hybrid PV/RF-FC energy system, especially when using a Vertical Single Axis Tracker (VSAT).

Salem et al. (2024) proposed a polygeneration system that incorporates storage to lessen the effects of erratic weather and uses renewable energy to create many energy forms. The system was dynamically analyzed, modelled, optimized, and simulated under Gujrat, Pakistan weather conditions using the transient simulation software TRNSYS®. Air conditioning, heating, electric power supply for electric cars, building load and national grid, hydrogen for internal combustion engines, fuel cell electric vehicles, and industrial use are just a few of the uses that the system makes possible. Six different hybrid system scenarios were examined in a separate experiment conducted by Chisale et al., (2023), all of which were intended to increase electrical reliability, decrease reliance on the grid, and lower costs for a school environment. HOMER Pro was used to optimize the system configuration, and CRITIC-PROMETHEE II techniques were used for the analysis that followed. Combining grid power with solar photovoltaic (PV) and biogas-generated electricity was the most beneficial setup. Compared to Malawi's grid electricity, which now costs 0.11 $/kWh, the levelized cost of electricity for this proposed system is determined to be 0.095 $/kWh, indicating a cost benefit. The report suggests that in order to reduce greenhouse gas emissions, governments and academic institutions should fund the development of alternative energy sources.

Located in the Al Wasta Governorate of Oman, the city of Duqm is powered by a combination of 10 diesel generators that can produce 76 MW of power when combined with other leased power sources that can provide 18 MW. Al-Badi and colleagues (2022) present a novel approach that proposes a whole conversion of the city's electric power supply from diesel to hydrogen, thereby adopting renewable energy sources. The HOMER Pro program was used to evaluate the technical and financial performance of the microgrid. The results show that combining fuel cell, solar, and wind energy is the most sensible and economical course of action. Interestingly, hydrogen turns out to be a more financially viable solution than batteries for longer-term energy storage needs.

2.2.2 African Context

In the years to come, solar energy, which is praised for having a very little carbon footprint, has the potential to completely transform the energy industry. An increasingly important part of the global transition to more ecologically friendly energy sources is this renewable energy source, which maximizes the sun's enormous potential. Still, there are relevant obstacles that need to be overcome, as noted by Deng et al. (2019). In particular, there are still many obstacles to overcome, including the difficulties of efficiently expanding solar energy installations to meet rising demand and the difficulties of transferring this energy over long distances. In order for solar power to reach its full potential and make a significant contribution to a sustainable energy future, it will be imperative that these issues are resolved, according to Zhenchen et al. (2019) and Rajesh G. et al. (2020).

According to a study by Molu et al. (2022), Cameroon's lack of readily available and dependable energy is impeding the country's development. On Manoka Island, Douala, Cameroon, they investigated the viability of putting Hybrid Renewable Energy Systems (HRES) in place to cover the energy needs of three small villages. They evaluated the viability of combining solar panels, wind turbines, battery cells, fuel cell generators, biogas, and an electrolyser in an off-grid HRES system using technical, environmental, and economic analysis. The analysis proved the arrangement's cost-effectiveness by presenting low unit energy costs and a strong net present value. Their work essentially amounts to a ground breaking case study in sustainable electricity provision, making a substantial contribution to our understanding of renewable energy and its potential for both energy security and sustainable development in Cameroon.

The viability of combining three different electrochemical energy storage technologies—lead acid, lithium-ion, and vanadium redox flow—into separate hybrid energy systems was investigated in a different study conducted by Das et al. in 2022. The results showed that, in comparison to load-following strategies, using a hybrid system with a cyclic charging strategy resulted in lower energy costs, albeit with somewhat higher lifecycle emissions. The cheapest energy solution was provided by hybrid alternatives using vanadium redox flow technology; these alternatives ranged in price from 0.126 to 0.187 dollars per kilowatt-hour. These choices also showed positive environmental effects over the course of their lifetime, with annual emissions ranging from 46,258 to 104,664 kg of CO2-equivalent. The findings of the sensitivity analysis showed that lower energy prices were associated with lower lifetime emissions and dependability. This research provides vital information that energy planners may use to choose the best battery technology and dispatch plans possible, resulting in better technical, financial, environmental, and social consequences.

In the Faculty of Engineering and Technology, Nigerian Defense Academy, Kaduna, Nigeria, Zarmai J.T. et al. (2024) conducted a study on the design and techno-economic evaluation of a hybrid utility grid-diesel generator-solar photovoltaic mini-grid system. This study made clear that, in developing nations like Nigeria, educational institutions must have a sufficient and dependable power source in order to guarantee effective instruction and learning. This innovative method concentrated on a school setting that will provide sufficient electricity from the mini-grid for appropriate instruction and learning, lessen adverse effects on the environment, and save energy expenses. In order to create a hybrid utility grid-diesel generator-solar PV mini-grid system for the faculty, this study assessed the load demand analysis of the faculty building. The faculty was given access to a simulation of the hybrid mini-grid model using HOMER Pro. After simulations were run, the hybrid mini-grid model's techno-economic viability was determined through analysis. By generating several scenarios of energy demand and supply from the various sub-systems of the hybrid mini-grid, the HOMER Pro software tool was used to optimize the hybrid utility grid, diesel generator, and solar PV mini-grid system. This produced the results and the optimal operating system, which has the lowest NPC of $182,065.20 and the lowest LCOE. The hybrid mini-grid for the faculty, which has the grid, diesel generator, and solar photovoltaic system configured as the most techno-economic option, has an energy cost of 0.00198 $/kWh. According to the study's findings, the system offers the best hybrid energy system that is feasible to put into place, giving a case study of a Nigerian academic institution access to a workable energy supply system. Therefore, with few adjustments, this can also be applied in other regions of Nigeria for a constant supply of electricity, contingent upon the existing renewable energy resources and the topography at the implementation site.

Grid synchronization technologies, legislative incentives, and regulatory frameworks have all been studied recently in an effort to encourage the linking of off-grid mini-grids to the distribution network. Two remote Gambia communities without grid electricity are Chewel and Fugal. Mbinkar E.N., Asoh D.A. et al., (2021) used the two nearby communities as case studies to assess the efficacy of energy generation utilizing PV technology. According to the study, the average temperature in the area is 31°C, and the average solar irradiation is 6.16 kWh/m2/day. The load estimations for Fuga and Chewel are 49.15 kWh/day with a peak load of 8.1 kW and 27.375 kWh/day with a peak load of 4.725 kW, respectively. Based on the simulation findings generated with HOMER software, a 15 kW PV system and 96 × 12 V batteries (four batteries per string) plus an inverter are needed to generate and supply electricity to these communities. This showed that the system operation costs, LCOE, and NPC are $4,303, $1,060, and $164,192 annually, respectively. This resulted in replacement costs totaling $122,337, $12,889, and $29,946, in addition to operating and maintenance expenses for a ten-year period.

The goal of a study by Aliyu A. et al. (2019) was to provide a framework for identifying the many technologies that might be implemented and employed in various contexts to satisfy energy demand. Three configurations were taken into consideration in the Nigerian research: all-off-grid, on-grid, and off-grid. Optimization using linear programming techniques in the MATLAB environment showed which parts of the nation would make good sites for solar and wind PV projects. The potential for installing solar and wind PV systems in Kaduna was determined to be 53.49% and 46.5%, respectively. The southern portion of the nation did not have wind as a feasible RE source. In addition, the best option for Nigeria was an off-grid/on-grid mix, especially considering that the overall installation cost was $211.49 billion, compared to $244.33 billion for an all-off-grid arrangement.

2.2.3 Uzere Community: A Case Study

An intriguing scenario is shown in the case study of Uzere, where the community lacks a dependable electrical system but has access to natural gas due to nearby oil extraction. At the moment, the main power source is a 500 kW gas generator. In order to create a hybrid system, this study investigates the possibility of including a second 500 kW gas generator, solar PV, and battery storage.

3. HYBRID OFF-GRID POWER SYSTEMS

3.1 Definition and Components

To supply a community's power demands without relying on the national grid, a hybrid off-grid power system integrates different energy sources. These systems' main constituents are:

- **Gas Generators**: Reliable and scalable, gas generators provide a consistent source of power but are subject to fuel price fluctuations and environmental concerns.
- **Solar Photovoltaics (PV)**: Solar PV is a clean, renewable energy source that can complement gas generators by supplying power during the day, reducing reliance on fossil fuels.
- **Battery Storage**: Energy storage systems help balance load fluctuations and store excess energy from solar PV for later use.
- **Converter**: converter is an electronic device that changes electrical energy from one form to another. Converters are essential in hybrid power systems, especially those integrating different energy sources, such as gas generators, solar photovoltaic (PV) systems, and batteries.

These components work together to form a hybrid system that offers increased reliability and potential cost savings compared to standalone systems.

3.2 Advantages of Hybrid Systems

- **Fuel Savings**: By integrating renewable energy, hybrid systems reduce the need for fuel, which is particularly important in oil-producing areas where fuel price volatility is common.
- **Increased Reliability**: Battery storage and renewable energy sources ensure that power is available even during peak demand or generator outages.
- **Environmental Benefits**: Hybrid systems, particularly those with a significant renewable energy component, help reduce greenhouse gas emissions.

4. METHODOLOGIES FOR HYBRID SYSTEM DESIGN AND INTEGRATION

4.1 Load Demand Estimation

A critical first step in hybrid system design is understanding the load demand of the target community. In the case of Uzere, the energy demand is around 8,606 kWh/day, with a peak power requirement of 734.20 kW.

Table 3.1 Load Metrics

METRIC	BASELOAD	SCALOED
Average Power (kW/day)	8606	8606
Average Power (kW)	358.54	358.54
Estimated Peak Power (kW)	734.20	734.20
Load Factor	0.49	0.49

4.2 System Design Using HOMER Pro

The **HOMER Pro** software is widely used for the design and simulation of hybrid energy systems. It allows for the evaluation of different system configurations based on performance and cost-effectiveness. In the Uzere case, the hybrid system configuration includes:

- A second 500 kW gas generator.
- 500 kW of solar PV.
- Battery storage for balancing and reliability.
- Converter

Figure 4.1 schematic diagram of the Hybrid System which shows the integration of the gas generators, solar PV, and battery storage into the Uzere community's existing distribution network.

SCHEMATICS

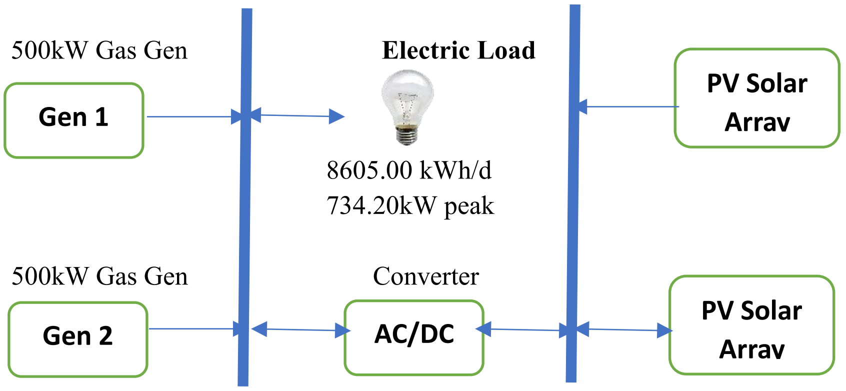

Figure 4.1: Schematic diagram of the HOMER Model

The figure 4.2 shows the Single Line Diagram (SLD) of the design of Gas Generator-Solar-Battery hybrid off-grid power system and its components.

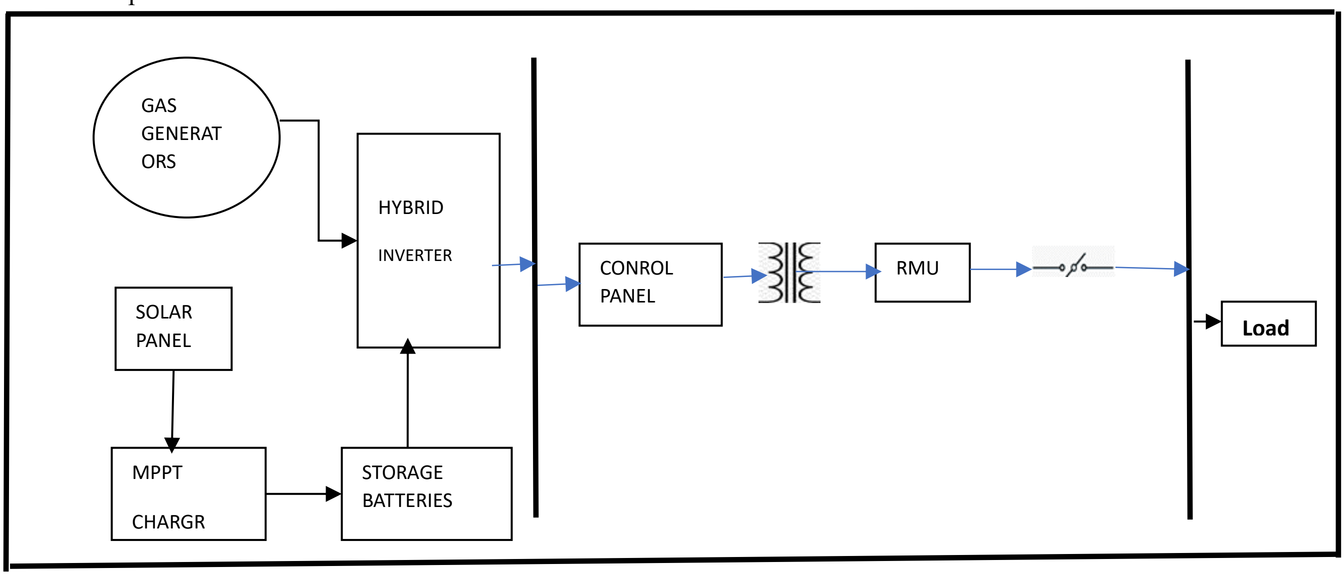

Figure 4.2 Single Line Diagram of the design of Hybrid Power Solution

5. TECHNO-ECONOMIC ANALYSIS

5.1 Effect of Fuel Prices on System Viability

Fuel prices play a significant role in determining the cost-effectiveness of hybrid systems. In the case of Uzere, the LCOE (levelized cost of energy) varies significantly depending on the price of gas. The following table presents the results based on different gas price scenarios.

Table 5.1: Effect of Gas Price on Hybrid System

Gas Price (Naira/SCM)	LCOE (Naira/kWh)	NPC (Billion Naira)	RE Fraction
250	65.63	127	100%
450	71.54	235	100%
564	73.48	294	100%

At lower gas prices (N250/SCM), the system achieves an LCOE of N65.63/kWh, making it highly cost-competitive compared to conventional grid power.

5.2 Comparison to Other Hybrid Systems

When compared to other rural electrification projects in Nigeria and sub-Saharan Africa, the hybrid system designed for Uzere proves to be cost-effective, especially when local gas resources are available.

6. CHALLENGES

6.1 Technical Challenges

Integrating hybrid systems into rural off-grid communities like Uzere presents several technical challenges:

- **Grid Stability**: Ensuring that the hybrid system can handle load variations without destabilizing the network.
- **Energy Storage**: The cost and capacity of battery storage remain barriers to widespread adoption of hybrid systems.

6.2 Economic and Policy Barriers

Hybrid system adoption in rural communities is frequently hindered by their high initial capital expenditure (CAPEX) in the absence of government subsidies or private investment. The promotion of hybrid power systems by policymakers is necessary as a means of addressing rural electrification.

7. CONCLUSIONS, RECOMMENDATIONS AND FUTURE DIRECTIONS

7.1 Conclusions

An extensive overview of hybrid off-grid power systems has been given by this review, with a focus on rural electrification in Nigeria's oil-producing regions like Uzere. Key findings that can be made are as follows:

1. **Urgent Need for Electrification**: Nigerian rural communities, however endowed with abundant natural resources, confront formidable obstacles when it comes to consistent access to energy. Many towns still rely on costly, environmentally harmful diesel generators, and the rate of electrification is still low.
2. **Potential of Hybrid Systems**: A viable option for electrifying remote areas is to use hybrid power systems, which include energy storage, solar photovoltaic cells, and gas generators. These systems can minimize greenhouse gas emissions, employ nearby resources, and deliver dependable, affordable power.
3. **Economic Viability**: The integration of renewable energy sources can result in significant cost savings in terms of levelized cost of energy (LCOE), according to the techno-economic study. Especially when local gas resources are used, the optimized hybrid system for Uzere shows potential LCOEs that can rival traditional grid generation.
4. **Simulation Tools for Design**: For the purpose of developing and perfecting hybrid systems, sophisticated simulation tools such as HOMER Pro are indispensable. With the use of these instruments, engineers are able to assess several setups and determine which solutions are most economical for particular community requirements.
5. **Challenges and Barriers**: Hybrid system deployment presents a number of obstacles despite its advantages, such as high initial capital costs, regulatory obstacles, and the requirement for specialized staff for both operation and maintenance. For hybrid system deployment in rural areas to be successful, several issues must be resolved.

7.2 Recommendations

The review's conclusions lead to the following suggestions to improve the incorporation of hybrid off-grid power systems in Nigeria's rural electrification initiatives:

1. **Policy Support and Incentives**: Incentives and well-defined policy frameworks are needed from the Nigerian government to encourage the adoption of hybrid power systems. In order to draw in private investment, this includes tax breaks, financial assistance, and subsidies for renewable energy technologies.
2. **Capacity Building and Training**: Investing in local technicians' and engineers' training programs and capacity building is vital. By doing this, communities will be better equipped to manage and keep up hybrid power systems, which will increase their sustainability.
3. **Community Engagement**: Planning and executing hybrid systems should require the active participation of local communities. Projects that take into account their energy preferences and needs will be more well-received and successful.
4. **Research and Development**: It is important to support ongoing research and development to advance hybrid system technology, such as improved integration techniques and more effective energy storage options. Innovation in this subject

can be stimulated by collaboration with research and academic institutes.

5. **Monitoring and Evaluation**: It will be essential to put in place strong frameworks for monitoring and evaluating hybrid systems in order to evaluate their effectiveness and effects on rural areas. This can guide future initiatives and assist identify best practices.
6. **Scaling Up Successful Models**: Effective pilot programs, like the Uzere case study, ought to be expanded upon and repeated in comparable locations throughout Nigeria. Other rural electrification programs can benefit from using these success stories as a model by being documented and disseminated.

7.3. Future Directions

In order to facilitate the implementation of hybrid systems in rural areas, future research should concentrate on investigating novel finance strategies, such as community-based financing or public-private partnerships. Further research into the integration of other renewable energy sources, such biomass or wind, could improve the dependability and sustainability of Nigeria's rural electrification initiatives.

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