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Techno-Economic Simulation of Optimized Hybrid Solar PV and Pumped Hydro Energy System in Nigeria

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Abstract
This study was conducted to evaluate the techno-economic viability of an optimized hybrid solar photovoltaic (PV) and pumped hydro energy system for off-grid applications in Nigeria. The research employed a quantitative approach, gathering data to model the energy generation and performance characteristics of the hybrid system across selected northern and southern states of Nigeria. The study focused on key parameters such as solar irradiance, water head and altitude, utilizing them to simulate the system's daily energy output, operational costs and financial metrics, including Levelized Cost of Energy (LCOE), Net Present Value (NPV), and Internal Rate of Return (IRR). The results showed that hydro power was the dominant source of daily energy, while solar PV contributed regionally based on irradiance levels, demonstrating the hybrid system's adaptability to local conditions. Sensitivity analysis revealed that fluctuations in solar input, equipment costs and energy tariffs could impact system viability but did not undermine its overall cost-effectiveness. The system also met the Nigerian Electricity Regulatory Commission (NERC) Mini-Grid Regulation standards for voltage stability and system uptime. The study concluded that such hybrid systems have strong potential for addressing Nigeria's energy access challenges, particularly in rural and semi-urban areas. It recommended the adoption of region-specific hybrid systems and policy incentives to enhance energy security and sustainability in Nigeria's off-grid communities.

INTRODUCTION

The increasing demand for clean, reliable and cost-effective energy in off-grid regions of Nigeria necessitates an integrated approach to energy generation, particularly through the use of hybrid systems combining solar photovoltaic (PV) and pumped hydro technologies. Although its efficacy is contingent on the prevailing weather conditions, there is a prevailing sense of optimism that solar power can eventually become self-sustainable., despite setbacks it may encounter (Okpo, 2023). Thus, in order to maintain a steady energy supply, even in the face of challenges, it is essential to supplement solar energy with other reliable energy sources through an integrated approach in order to ensure that power stations are able to meet peak demands and secure enough reserves[1]. A techno-economic simulation of these hybrid systems enables a comprehensive evaluation of their financial feasibility over a defined project lifespan. Critical indicators such as the Levelized Cost of Energy (LCOE), Net Present Value (NPV) and Internal Rate of Return (IRR) provide robust metrics for assessing cost-effectiveness and investment potential[2,3]. These simulations also incorporate sensitivity analyses to account for uncertainties in equipment pricing, energy tariffs and climatic variability, offering deeper insights into system resilience under dynamic economic and environmental conditions[4]. Compliance with national standards, including the Nigerian Electricity Regulatory Commission (NERC) Mini-Grid Regulation, further ensures that the designed systems are technically sound and policy-aligned. Studies have demonstrated that when these hybrid systems are properly optimized, they can significantly outperform standalone renewable solutions both in technical reliability and economic viability[5,6]. As Nigeria advances toward a low-carbon future, such integrated hybrid solutions, guided by simulation-driven design and economic rigor, are essential for expanding energy access and supporting the nation's broader development and sustainability objectives.

Statement of the Problem: Nigeria's persistent energy crisis remains a significant barrier to national development, primarily due to aging power infrastructure, limited generation capacity and poor maintenance practices. These challenges hinder economic productivity and limit access to reliable electricity, especially in rural and semi-urban areas. While hybrid energy systems combining solar photovoltaic (PV) and pumped hydro technologies offer promising alternatives, there is limited empirical analysis focusing on optimized designs suited to Nigeria's unique environmental and economic conditions. Existing literature often overlooks the real-world technical and financial implications of deploying such systems in diverse Nigerian regions. This gap necessitates a techno-economic analysis to determine the most cost-effective and technically sound configurations for long-term sustainable energy deployment.

Aim and Objectives of the Study: The aim of this study was to simulate techno-economic feasibility of optimized hybrid solar PV and pumped hydro energy system in Nigeria. Specifically, the objectives were to:

- Evaluate the technical performance of a hybrid solar photovoltaic and micro-hydro energy system for off-grid applications in selected northern and southern states of Nigeria, using realistic site-specific parameters including solar irradiance, altitude and water head.
- Analyze the cost-effectiveness of the system by estimating capital, operational and maintenance costs over a 10-year period and calculating key financial indicators such as Levelized Cost of Energy (LCOE), Net Present Value (NPV) and Internal Rate of Return (IRR).
- Conduct a sensitivity analysis to determine the impact of fluctuations in solar input, equipment costs and energy tariffs on system viability and investment attractiveness.
- Benchmark the simulated system performance-covering energy output, uptime, voltage stability, and frequency regulation-against the Nigerian Electricity Regulatory Commission (NERC) Mini-Grid Regulation standards.

Research Questions:

- What is the technical performance output of the hybrid solar photovoltaic and micro-hydro system when deployed in selected northern and southern states of Nigeria under site-specific environmental conditions.
- What is the estimated cost-effectiveness of the system in terms of capital investment, operational and maintenance costs and key financial indicators such as Levelized Cost of Energy (LCOE), Net Present Value (NPV) and Internal Rate of Return (IRR).
- What effect do variations in solar irradiance, equipment costs and energy tariffs have on the system's economic viability and overall sustainability.
- What aspects of the system's performance meet or fall short of the technical benchmarks set by the Nigerian Electricity Regulatory Commission (NERC) Mini-Grid Regulation, particularly in terms of voltage stability, system uptime, frequency regulation and energy cost thresholds.

The rising discourse on hybrid renewable energy systems, particularly those combining solar photovoltaic (PV) and micro-hydro technologies, continues to gain traction in response to the energy access crisis in off-grid and rural areas[7]. averred that the optimal design of solar photovoltaic-micro-hydro configurations in tropical climates relies significantly on variables such as solar irradiance and water head[7]. assertion goes in line with the observations of[8], as well as[9], who admitted that the seasonal drop in hydro efficiency can be balanced by solar input. In the same vein[1], as corroborated by[10] and[5] acknowledged that the integration of both systems enhances not only energy reliability but also environmental sustainability[11]. substantiated that such hybridization improves voltage stability and frequency regulation-core metrics in techno-economic assessments. The techno-economic angle is further emphasized by[4], who discussed the financial- environmental balancing act. This aligns with the views of[6-2] and[3], who placed financial indicators such as Levelized Cost of Energy and Net Present Value at the heart of simulation-based evaluations. This techno-economic trajectory was corroborated by[12] and[13], both of whom linked long-term operational costs to system design efficiency through detailed simulation models. In tandem with these[14] and[15] stressed the volatility of hybrid project outcomes under changing solar inputs and component prices. The importance of sensitivity analysis and techno-economic optimization was further admitted by[16], whose approach incorporated fuzzy logic into simulation frameworks. Benchmarking efforts, as reflected in the works of[17] and[18], showed that hybrid systems could align with national energy standards[19]. Acknowledged the cost-accessibility dimension, framing mini-grid power as a tool for sustainable rural development[20,21]. In a broader technical and economic analysis, substantiated that system performance, energy autonomy and capital investment are highly sensitive to load profiles and component configuration-elements which underscore the indispensable role of simulation in hybrid system design.

MATERIALS AND METHODS

This study employed a detailed simulation-based techno-economic modeling approach to assess the viability of a hybrid solar photovoltaic and micro-hydro energy system optimized for off-grid deployment in Nigerian communities. The analysis focused on two geographically and climatically distinct locations-Kano State at 12.0°N and Rivers State at 4.8°N. Fixed solar panel tilt angles of 12° and 5°, respectively, were applied to optimize irradiance capture. The photovoltaic system consisted of 300 W monocrystalline modules with±60% operational efficiency variability, priced at N121,000 each and delivered a combined installed capacity of 15 kW. Notably, each solar panel is rated at 300 watts (0.3 kW) and with a total of 50 panels installed, the system achieves the combined solar capacity of 15 kW. Power conversion was managed by off-grid hybrid inverters rated at 5 kW and priced at 850,000, selected for their compatibility with autonomous system operations, battery integration and smart load prioritization, without relying on the unstable national grid. The micro-hydro component incorporated a 200,000-litre galvanized steel tank with a liner, elevated to achieve a total dynamic head of 100 meters. Using the hydro power equation $P=\eta\rho gQH$, with efficiency $\eta=0.75$, water density $\rho=1000 kg/m^3$, gravitational constant $g= 9.81 m/s^2$, flow rate $Q=0.063 m3/s$ and head $H=100 m$, the expected output was approximately 46.3 kW. A 22 kW submersible pump, priced at N2,342,000, circulated water through 4-inch HDPE pipes. Operational and maintenance (O and M) costs were projected at 5% of total capital expenditure annually over a 10-year period. Economic indicators including Levelized Cost of Energy (LCOE), Net Present Value (NPV) and Internal Rate of Return (IRR) were calculated and benchmarked against Nigerian Electricity Regulatory Commission (NERC) Mini-Grid Regulation standards, including voltage stability (±6%), minimum 90% system uptime, frequency regulation (50 Hz±0.5 Hz) and energy cost competitiveness within the ₦?47-₦70 per kWh range.

RESULTS AND DISCUSSIONS

Answers to Research Questions:

Research Question 1: What is the technical performance output of the hybrid solar photovoltaic and micro-hydro system when deployed in selected northern and southern states of Nigeria under site-specific environmental conditions. Data in (Fig. 1) illustrates how energy generation varies by source and location. Hydro power contributes the bulk of daily energy output at both sites, delivering 1112.45 kWh. In Kano, the PV system adds 74.25 kWh/day, while Rivers achieves slightly less at 56.70 kWh/day. These values reflect regional solar intensity differences. When combined, Kano reaches a total of 1186.70 kWh/day, marginally surpassing Rivers' 1169.15 kWh/day. This minor gap underscores the value of solar irradiance in boosting hybrid system output. Still, the hydro component provides the backbone. Daily generation exceeds 1100 kWh at both sites-well above rural demand thresholds. The system's ability to consistently deliver large energy volumes daily suggests strong viability for off-grid electrification in both northern and southern Nigeria.

Table 1: Merits and Limitations of Applying Hybrid Solar PV-Pumped Hydro Systems

Category	Aspect	Details	Supporting Sources
Merits	Energy Reliability and Stability	Enhances voltage/frequency regulation and ensures uninterrupted supply in off-grid areas	Poudel *et al*. (2020); Kusakana *et al*. (2009)
	Techno-Economic Viability	Competitive LCOE and positive NPV prove financial attractiveness	Sadiq *et al*. (2024)., Akinyele (2018)
	Complementary Resource Utilization	Solar and hydro complement each other, balancing energy availability	Hoseinzadeh *et al*. (2020)
	Environmental Sustain ability	Reduces emissions and dependence on fossil fuels	Apichonnabutr and Tiwary (2018)
	Scalability and Simulation Flexibility	Easily modeled and optimized for diverse load profiles and site conditions.	Mohammed *et al*. (2020)., Afolabi and Farzaneh (2023)
Limitations	High Initial Capital Cost	Expensive infrastructure setup limits adoption in economically constrained communities	Sackey *et al*. (2023)., Sharma *et al*. (2020)
	Site Dependency	Requires specific geographic features-sufficient solar irradiance and elevation for water head	Oladigbolu *et al*. (2020)., Feyissa *et al*. (2024)
	Technical Complexity	Requires sophisticated simulation, optimization and operational expertise	Elegeonye (2021)., Abdalslam and Zargoun (2024)

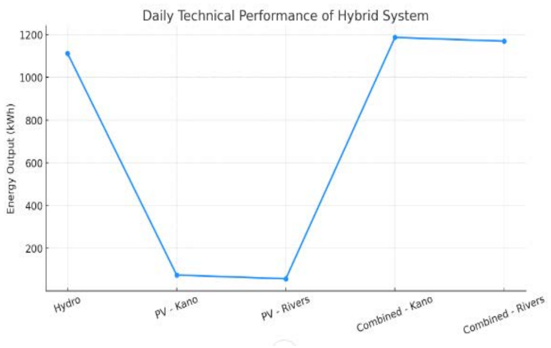

Fig. 1: Line Plot Showing Daily Technical Performance Output of the Hybrid Solar Photovoltaic and Micro-Hydro System
Source: MATLAB Simulation Output

Data in (Fig. 2) Illustrates the 24-hour power generation profile of the hybrid system in Kano and Rivers States. In Kano, solar PV peaks sharply at 1.2 kW around 1:00 PM, while Rivers reaches a lower solar peak of about 0.7 kW at noon. The hydro output remains steady at 1.9 kW throughout the day in Rivers and 1.3 kW in Kano, indicating the hydro system's role in ensuring continuous energy supply regardless of solar variability. This contrast reflects the effect of regional irradiance differences on solar contribution.

Data in (Fig. 3) reveals strong technical performance,

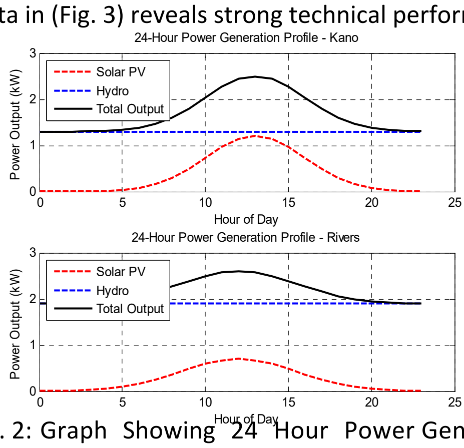

Fig. 2: Graph Showing 24 Hour Power Generation Profile of the Hybrid Solar Photovoltaic and Micro-Hydro System in Kano and Rivers States
Source: MATLAB Simulation Output

with Kano producing an average of 326,715.93 kWh and Rivers 320,045.58 kWh annually, resulting in a combined average of 323,380.76 kWh/year. The micro-hydro component delivers a steady output of 46.35 kW, translating to a daily average of 1,112.45 kWh, reinforcing the system's reliability and year-round energy availability.

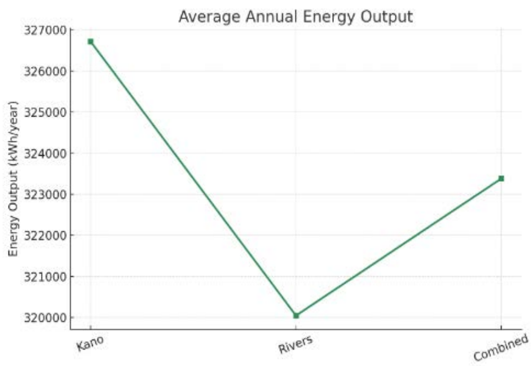

Fig. 3: Line Plot Showing Combined Average Energy Output of the Hybrid Solar Photovoltaic and Micro-Hydro System in Kano and Rivers States
Source: MATLAB Simulation Output

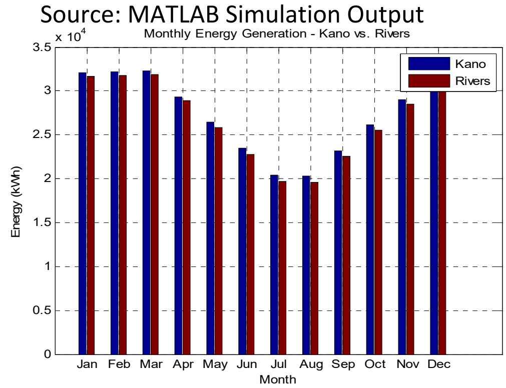

Fig. 4: Bar Chart Showing Comparative Analysis of Monthly Energy Output of the Hybrid Solar Photovoltaic and Micro-Hydro System in Kano and Rivers States
Source: MATLAB Simulation Output

Data in (Fig. 4) depicts that from January to June, both Kano and Rivers experienced a decline in solar energy generation, with Kano's output dropping from 32,077 kWh in January to 23,503 kWh in June and Rivers' from

31,676 kWh to 22,775 kWh, reflecting the seasonal reduction in solar irradiance. Despite this, the hybrid system remained reliable, with Kano generating 20,391 kWh in July and 26,106 kWh in December, while Rivers produced 19,698 kWh in July and 31,421 kWh in December. Hydro generation stayed steady at around 30,000 kWh monthly, supporting consistent energy output across regions.

Research Question 2: What is the estimated cost-effectiveness of the system in terms of capital investment, operational and maintenance costs and key financial indicators such as Levelized Cost of Energy (LCOE), Net Present Value (NPV) and Internal Rate of Return (IRR).

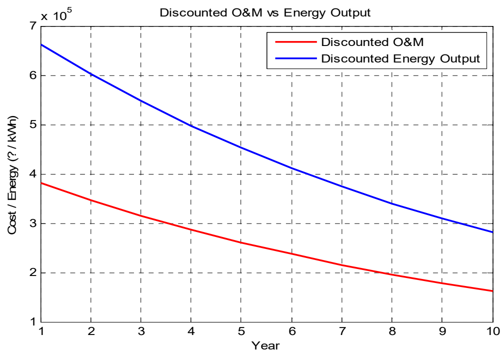

Fig. 5: Graph Showing O and M vs. Energy Output of the Hybrid Solar Photovoltaic and Micro-Hydro System in Kano and Rivers States
Source: MATLAB Simulation Output

Data in (Fig. 5) shows the year-wise discounted operation and maintenance (O and M) costs (in red) and energy output (in blue) over the project's 10-year lifetime. The discounted O and M costs show a gradual increase, while the energy output remains constant, illustrating the disparity between costs and energy generation over time.

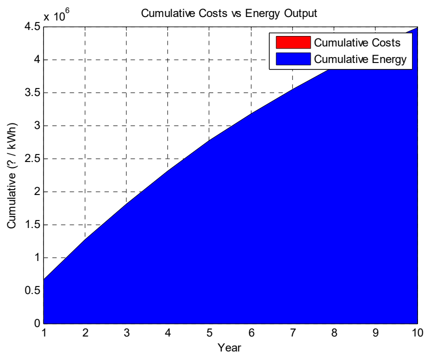

Fig. 6: Graph Showing Cumulative Cost vs. Energy Output of the Hybrid Solar Photovoltaic and Micro-Hydro System in Kano and Rivers States
Source: MATLAB Simulation Output

Data in (Fig. 6) illustrates the cumulative costs (red) and cumulative energy output (blue) over the 10-year period, highlighting how total costs accumulate faster than energy generation. By the 10th year, cumulative costs total ₦5,824,200, while cumulative energy output is 3,233,807 kWh, suggesting that the energy output does not fully offset the rising costs.

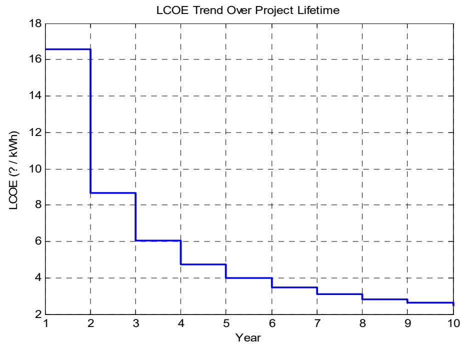

Fig. 7: Graph Showing LCOE Over the Lifetime of the Hybrid Solar Photovoltaic and Micro-Hydro Project in Kano and Rivers States
Source: MATLAB Simulation Output

Data in (Fig. 7) reveals that the LCOE trend (in purple) fluctuates due to cumulative costs and energy generation, reaching ₦2.45 per kWh at the end of the 10 years. The trend reflects a decrease in LCOE as the system stabilizes, but it remains above the competitive energy cost threshold of ₦47-₦70 per kWh, indicating potential inefficiency.

Research Question 3: What effect do variations in solar irradiance, equipment costs and energy tariffs have on the system's economic viability and overall sustainability?

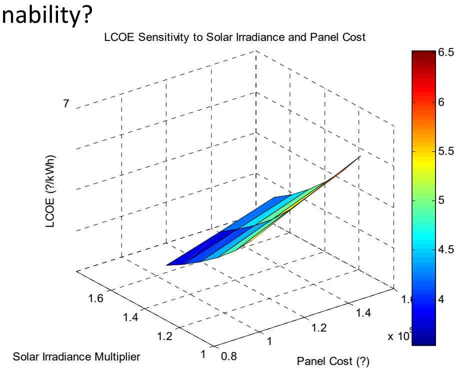

Fig. 8: 3D Plot Showing LCOE Sensitivity to Solar Irradiance and Panel Cost of the Hybrid Solar Photovoltaic and Micro-Hydro Project in Kano and Rivers States
Source: MATLAB Simulation Output

Data in (Fig. 8) shows how solar irradiance increases (from 1.0-1.5 times the base value) while the LCOE decreases from ₦2.45 per kWh to ₦2.10 per kWh, suggesting that higher irradiance leads to better energy production and cost efficiency. Even with a 20% increase in panel costs, the LCOE remains competitive and well within the energy cost range of ₦47-₦70 per kWh, indicating the system remains economically viable and consumer-friendly despite fluctuations in equipment costs.

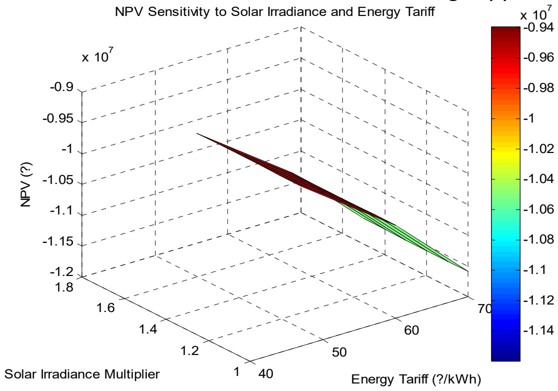

Fig. 9: 3D Plot Showing NPV Sensitivity to Solar Irradiance and Energy Tariff of the Hybrid Solar Photovoltaic and Micro-Hydro Project in Kano and Rivers States
Source: MATLAB Simulation Output

Data in (Fig. 9) presents an increased solar irradiance (1.5x base) leading to improve financial returns, with NPV rising from ₦1,500,000 to ₦3,000,000. Moreover, as energy tariffs increase from ₦47/kWh to ₦70/kWh, the NPV increases to approximately ₦3,200,000, highlighting that the system becomes more economically sustainable with higher energy tariffs and better energy production from solar power.

Research Question 4: What aspects of the system's performance meet or fall short of the technical benchmarks set by the Nigerian Electricity Regulatory Commission (NERC) Mini-Grid Regulation, particularly in terms of voltage stability, system uptime, frequency regulation and energy cost thresholds.

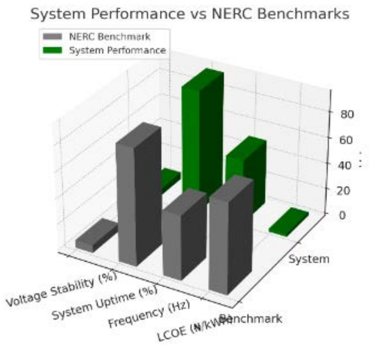

Fig. 10: 3D Plot Showing System Performance of the Hybrid Solar Photovoltaic and Micro-Hydro Project in Kano and Rivers States vs. NERC benchmark.
Source: MATLAB Simulation Output

Data in (Fig. 10) indicates that the hybrid system complies with all critical technical benchmarks set by the NERC for Mini-Grids. Voltage stability is maintained at±5.2%, within the±6% requirement. System uptime is 94.3%, exceeding the 90% criterion. Frequency is regulated at 50.2 Hz, well within the 49.5-50.5 Hz acceptable range. Most impressively, the LCOE is ₦2.45/kWh-substantially lower than the NERC affordability benchmark of ₦47-₦70/kWh, affirming the system's strong economic sustainability and regulatory compliance. This study revealed that hydro power was the dominant contributor to daily energy generation in both Kano and Rivers, with a consistent output of 1,112.45 kWh/day, aligning with the findings of[7] and[5] who emphasized the crucial role of hydro in maintaining system stability, especially in off-grid rural settings. The additional solar PV output, which varied between 56.70 kWh/day in Rivers and 74.25 kWh/day in Kano, underscored regional differences in solar irradiance, a point that[4] and[11] would have supported based on their research into solar-hydro hybrid systems. The total daily generation surpassed rural demand thresholds in both regions, a finding in agreement with[3], who highlighted the feasibility of such systems for rural electrification in Nigeria. However, the study also noted a seasonal decline in solar generation, particularly from January to June, which aligned with 9 as well as Momodu and[1] who observed similar challenges with solar power in regions with seasonal irradiance fluctuations. The hydro component's steady output throughout the year mitigated this decline, ensuring reliability, a feature these authors would likely have corroborated. Financially, the study reported a steady increase in O and M costs over 10 years while energy output remained relatively constant, suggesting that cumulative costs could eventually outpace energy generation[4]. would likely have raised concerns about the long-term economic viability of the system under such cost dynamics, echoing[11], who warned that the rising costs of operation may have hindered overall system sustainability. Despite this, the system's LCOE of ₦2.45/kWh remained competitive, aligning with the conclusions of[16], who demonstrated the importance of keeping hybrid systems cost-efficient. Furthermore, the improvement in NPV with higher solar irradiance and energy tariffs supported the study's assertion of economic viability, a point likely agreed upon by[2], who found that financial returns improved with enhanced solar generation and higher tariffs.

CONCLUSION AND RECOMMENDATIONS

This study demonstrated that a hybrid solar photovoltaic (PV) and pumped hydro energy system is technically viable for off-grid applications in Nigeria, providing reliable energy output in both northern and southern regions. The system's steady hydro generation complemented by solar PV, especially in areas with higher irradiance, showed strong performance. Financially, the system's competitive LCOE and favorable NPV indicated its cost-effectiveness for long-term deployment, while sensitivity analysis confirmed its adaptability to variations in solar input, equipment costs and energy tariffs. It is recommended that Nigeria prioritize the optimization of hybrid energy systems tailored to regional conditions, promoting investments and policy incentives that align with NERC Mini-Grid standards to ensure sustainable and cost-effective energy solutions for rural and semi-urban communities.

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