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Design and Optimization of a Hybrid Renewable Energy System for Sustainable Power Generation

Sürdürülebilir Güç Üretimi için Hibrit Yenilenebilir Enerji Sisteminin Tasarımı ve Optimizasyonu

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ABSTRACT

The growing demand for sustainable energy solutions necessitates the integration of renewable energy sources into hybrid systems. This study presents the design and optimization of a hybrid renewable energy system combining solar, wind, and diesel power to ensure reliable and cost-effective electricity generation. A detailed numerical analysis evaluates the system's technical, economic, and environmental performance. Solar resource assessment indicates an average daily radiation of 5.1 $kWhm^{-2}$, while wind speeds range between 4.3 ms^{-1} and 5.4 $ms\text{-}^{1}$, supporting complementary energy generation. The optimized system achieves an 85% renewable energy fraction, with solar contributing 45.2%, wind 38.7%, and diesel 16.1%. Economic evaluation reveals an investment cost of ₦7,400,000, with a levelized cost of energy (LCOE) of ₦55.2/kWh and a payback period of 6.5 years. Sensitivity analysis confirms financial feasibility under varying input parameters. The system reduces carbon emissions by 73.3% compared to diesel-only alternatives, enhancing environmental sustainability. Reliability assessments show 97.2% system availability with a low Loss of Power Supply Probability (LPSP) of 2.8%.

This research demonstrates the viability of hybrid renewable energy systems as a sustainable power solution, contributing to global decarbonization efforts. The findings highlight the importance of optimizing energy storage and implementing advanced control strategies to enhance efficiency and economic viability. Future studies should explore the integration of artificial intelligence-based predictive models to further improve system performance and reliability.

Keywords: Hybrid Energy System, Optimization, Sustainable Power, Solar-Wind Integration

ÖZ

Sürdürülebilir enerji çözümlerine olan artan talep, yenilenebilir enerji kaynaklarının hibrit sistemlere entegrasyonunu zorunlu kılmaktadır. Bu çalışma, güvenilir ve maliyet etkin elektrik üretimini sağlamak amacıyla güneş, rüzgâr ve dizel enerjisini birleştiren hibrit bir yenilenebilir enerji sisteminin tasarımını ve optimizasyonunu sunmaktadır. Ayrıntılı sayısal analiz, sistemin teknik, ekonomik ve çevresel performansını değerlendirmektedir. Güneş enerjisi değerlendirmesi, ortalama günlük ışıma değerinin 5,1 $kWhm^{-2}$ olduğunu gösterirken, rüzgâr hızları 4,3 ms^{-1} ile 5,4 ms^{-1} arasında değişerek tamamlayıcı enerji üretimini desteklemektedir. Optimize edilen sistem, %85 yenilenebilir enerji oranına ulaşmış olup, güneş enerjisi %45,2, rüzgâr enerjisi %38,7 ve dizel %16,1 katkı sağlamaktadır. Ekonomik değerlendirme, yatırım maliyetinin ₦7.400.000 olduğunu, enerjiye göre düzlenmiş maliyetin (LCOE) ₦55,2/kWh ve geri ödeme süresinin 6,5 yıl olduğunu ortaya koymaktadır. Duyarlılık analizi, değişen girdi parametreleri altında finansal fizibiliteyi doğrulamaktadır. Sistem, sadece dizel kullanılan alternatiflere kıyasla karbon emisyonlarını %73,3 oranında azaltarak çevresel sürdürülebilirliği artırmaktadır. Güvenilirlik değerlendirmeleri, sistemin %97,2 kullanılabilirliğe ve %2,8 gibi düşük bir Güç Kaybı Olasılığına (LPSP) sahip olduğunu göstermektedir.

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Bu araştırma, hibrit yenilenebilir enerji sistemlerinin sürdürülebilir bir güç çözümü olarak uygulanabilirliğini kanıtlamakta ve küresel karbon azaltma çabalarına katkıda bulunmaktadır. Bulgular, enerji depolama optimizasyonunun ve gelişmiş kontrol stratejilerinin uygulanmasının verimliliği ve ekonomik fizibiliteyi artırmadaki önemini vurgulamaktadır. Gelecek çalışmalar, sistem performansını ve güvenilirliğini daha da iyileştirmek için yapay zekâ tabanlı kestirimci modellerin entegrasyonunu incelemelidir.

Anahtar Kelimeler: Hibrit Yenilenebilir Enerji Sistemi, Optimizasyon, Sürdürülebilir Güç, Güneş-Rüzgâr Entegrasyonu

Introduction

The global energy landscape is undergoing a significant transformation, driven by the increasing demand for sustainable and reliable power generation. The need to reduce greenhouse gas emissions and transition away from fossil fuel dependency has led to the rapid development and deployment of renewable energy sources such as solar, wind, hydro, and biomass (Khaled, 2025; Maggu et al., 2024). However, the intermittent nature of these renewable resources poses challenges for stable and continuous power supply.

To address these dual challenges of rising energy demand and environmental sustainability, renewable energy sources such as solar, wind, hydro, and biomass have been developed and deployed at an accelerated pace. However, these energy sources are inherently intermittent, weather-dependent, and site-specific, resulting in fluctuations in energy generation and posing challenges to ensuring a stable, continuous, and reliable power supply (Babaei et al., 2025; Mathaba & Abo-Al-Ez, 2024). This intermittency often leads to mismatches between energy generation and demand, especially during peak consumption periods or adverse weather conditions, thereby undermining the effectiveness of renewables as standalone solutions (Al-Quraan et al., 2025; Tao et al., 2024). Given these constraints, hybrid renewable energy systems (HRES) have emerged as a strategic approach to overcome the limitations of single-source renewable systems. By integrating multiple renewable sources—such as combining solar photovoltaic (PV), wind energy, and hydropower—alongside advanced energy storage technologies, HRES can enhance power system flexibility, improve generation reliability, and ensure a balanced energy supply to meet varying demand patterns (Choudhary et al., 2024; Hidayat et al., 2024). Such integration also supports energy security, reduces reliance on conventional fossil-fuel-based power generation, and contributes to national and global energy transition goals. Furthermore, hybrid renewable energy systems (HRES) have emerged as a viable solution, integrating multiple energy sources to enhance efficiency, reliability, and sustainability (Kumar et al., 2024; Mahmoudi et al., 2025). HRES combine two or more renewable energy sources, such as solar photovoltaic (PV) and wind, often supplemented with energy storage systems, to optimize power generation and ensure uninterrupted energy supply (Babaei et al., 2025; Mathaba & Abo-Al-Ez, 2024). The integration of these systems can significantly enhance energy security and reduce reliance on conventional energy sources (Al-Quraan et al., 2025; Tao et al., 2024). Furthermore, advancements in optimization techniques have facilitated the design and performance improvement of these systems, ensuring economic and technical feasibility (Choudhary et al., 2024; Hidayat et al., 2024).

The optimization of HRES involves multiple criteria, including cost minimization, efficiency maximization, and environmental sustainability. Various optimization algorithms, such as gravitational search, metaheuristic approaches, and artificial intelligence-based models, have been employed to achieve optimal performance (Ha et al., 2024; Joshi et al., 2024). Studies have shown that a well-optimized hybrid system can improve power reliability, particularly in remote and rural areas where grid connectivity is limited (Khalid et al., 2024; Sifakis et al., 2024).

The economic viability of HRES is another critical aspect influencing its adoption. The implementation of cost-effective hybrid systems has been explored through economic modeling and techno-economic assessments, ensuring that the systems remain financially sustainable over the long term (Gurumoorthi et al., 2024; Sibarani et al., 2024). Additionally, incorporating waste-to-energy technologies and energy storage solutions has further enhanced the feasibility of hybrid systems in industrial applications (Mouli, 2024; Vendoti et al., 2024).

Recent research has also focused on integrating hybrid systems with energy storage technologies, such as pumped hydro storage and hydrogen energy storage, to mitigate power fluctuations and enhance grid stability (Ali & Mohammed, 2024; Ghandehariun et al., 2024). The improved Aquila optimization approach has been utilized to develop cost-effective and efficient hybrid energy models, contributing to the overall sustainability of the power sector (Castorino et al., 2024; Zhou et al., 2024). Additionally, studies have emphasized the critical role of Hybrid Renewable Energy Systems (HRES) in ensuring sustainable and resilient energy access, particularly in off-grid and developing regions. The integration of solar, wind, and other renewable sources has been optimized using multi-objective models to balance cost, environmental impact, and energy reliability (Babaei et al., 2025; Yadegari et al., 2023). Innovations in solar-photovoltaic and concentrated solar power integration have enhanced system performance under varying climatic conditions (Furlan & You, 2024). In Sub-Saharan Africa, waste-to-energy and landfill gas technologies are being explored to complement renewable sources (Olodu & Erameh, 2023; Sifakis et al., 2024). Recent works have also demonstrated the economic and technical viability of hybrid solar-wind configurations (Dwijendra et al., 2022; Mouli, 2024). Optimizing these systems under uncertainty supports the transition to carbon-neutral energy solutions (Olodu et al., 2025), highlighting their potential for scalable deployment.

Moreover, hybrid systems have shown great potential in transportation and industrial applications, particularly in reducing carbon footprints and optimizing energy utilization (Abdelsattar et al., 2024; Atawi et al., 2024). The integration of solar PV with pumped hydro energy storage has been demonstrated as a promising approach for energy management in urban settings (Big-Alabo, 2024; Bhimaraju et al., 2024). Optimization techniques, such as the solar-hydrogen generation model, have also been proposed to enhance the efficiency of hybrid systems (Furlan & You, 2024; Shklyarskiy et al., 2024).

A key unique contribution of this study lies in its integration of a real-time optimization framework with locally available renewable resources and economic conditions specific to the Nigerian context. This tailored approach provides actionable insights for energy planners and policymakers in similar developing regions, where grid instability and high diesel dependency are prevalent. By combining technical robustness with contextual adaptability, the research offers a replicable model for accelerating clean energy adoption in underserved communities.

This study aims to explore the design and optimization of hybrid renewable energy systems for sustainable power generation. By leveraging advanced optimization techniques, economic assessments, and technological innovations, the research seeks to develop an efficient and cost-effective hybrid energy model. The findings will contribute to the growing body of knowledge on sustainable energy solutions, promoting the integration of renewable energy sources in diverse applications (Bisht et al., 2024).

Materials and Methods

The data required for designing and optimizing a hybrid renewable energy system was obtained using a combination of experimental measurements, simulation software, and literature sources. Each table was generated based on well-defined methodologies.

The Study Area

The study area selected for this research is Benin City, located in southern Nigeria, characterized by a tropical climate with distinct wet and dry seasons. This region offers a unique setting for evaluating hybrid renewable energy systems due to its substantial solar and wind resources, which are critical for the viability of hybrid renewable energy systems (HRES). According to Ali and Mohammed (2024), the solar irradiation in Benin City remains consistently high throughout the year, averaging between 4.5 and 5.8 $kWhm^{-2}day^{-1}$, with peak solar radiation observed during the dry season months of March to May and moderate reductions during the rainy season from July to September. This consistent solar resource availability supports reliable year-round solar photovoltaic (PV) power generation. Meteorological data further indicate that the average sunshine hours range from approximately 7.8 to 9.1 hours daily, influenced by seasonal cloud cover that peaks during the wet months (Lujano-Rojas et al., 2024). The temperature profile remains relatively stable, varying between 28°C and 34°C, typical of the tropical environment. Such thermal conditions are favorable for solar PV efficiency but necessitate accounting for thermal derating effects on panel performance (Ghandehariun et al., 2024). Wind resources in Benin City, measured at a standard 10-meter height, exhibit moderate speeds averaging between 4.3 and 5.4 ms^{-1}, which corresponds to power densities ranging from approximately 68 to 113 Wm^{-2} (Olodu et al., 2025). These wind speeds, while not as high as those in coastal or high-altitude regions, remain adequate to contribute significantly to a hybrid system, especially when integrated with solar PV to complement variability and improve system reliability (Atawi et al., 2024; Mahmoudi et al., 2025). The socio-economic profile of Benin City, including its mixed residential, commercial, and industrial energy demands, offers a representative microcosm for assessing hybrid system performance across diverse load profiles (Babaei et al., 2025). Moreover, the intermittent and often unreliable grid supply in the region underlines the critical need for sustainable, decentralized power generation solutions leveraging hybrid renewable systems to enhance energy access and resilience (Olodu & Erameh, 2023). In summary, Benin City's favorable solar and wind resources, combined with its climatic and energy consumption characteristics, make it an ideal testbed for the optimization and deployment of hybrid renewable energy systems aimed at sustainable and reliable power generation (Ali & Mohammed, 2024; Ghandehariun et al., 2024; Olodu et al., 2025).

Solar Resource Assessment

To determine the availability of solar energy at the study location, various instruments and datasets were utilized. A pyranometer was used to measure solar radiation, while the Global Horizontal Irradiance (GHI) dataset was sourced from NASA, NIMET, and PVGIS. Additional validation was performed using solar panel datasheets, and weather station data, including temperature, cloud cover, and humidity, were incorporated. MATLAB and Python were employed for data analysis. In this study, the solar resource assessment was conducted to evaluate the potential of solar energy at the selected site, providing a foundation for system sizing and design. Both MATLAB and Python programming environments were employed for data analysis, modeling, and visualization (Bhimaraju et al., 2024; Ghige & William, 2024). Python was primarily used for data preprocessing, exploratory analysis, and visualization. The PVLib library, a Python package for simulating the performance of photovoltaic energy systems, was adopted to retrieve and process historical solar irradiance data from publicly available sources such as NASA POWER and the National Renewable Energy Laboratory (NREL) database (Furlan & You, 2024; Khalid et al., 2024). Key solar parameters, including Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and Diffuse Horizontal Irradiance (DHI), were computed. The solar position was also modeled using the Solar Position Algorithm (SPA) to determine solar zenith and azimuth angles, which are critical for system orientation and tracking design (Ha et al., 2024; Kumar et al., 2024).

MATLAB was utilized for detailed mathematical modeling and performance simulation. Time-series analysis and curve-fitting models were implemented to estimate monthly and seasonal solar radiation trends (Mahmoudi et al., 2025). Additionally, tilt angle optimization was simulated using numerical optimization routines to identify the tilt angle that maximizes incident solar energy based on the site's latitude and solar geometry (Atawi et al., 2024; Maggu et al., 2024). The clearness index (Kt) and sunshine duration correlation were calculated using the Angström–Prescott model, allowing the estimation of solar radiation in instances where only sunshine duration data was available (Joshi et al., 2024). These models were selected based on their proven reliability and widespread application in solar energy studies, as well as their compatibility with the available meteorological data. The SPA and Angström–Prescott models are particularly suited for tropical climate conditions such as those in the study region (Ghandehariun et al., 2024). By integrating Python's capabilities for data handling with MATLAB's robust numerical modeling tools, a comprehensive and accurate solar resource assessment was achieved. This forms a strong foundation for the subsequent design, simulation, and optimization of the hybrid energy system (Abdelsattar et al., 2024; Ali & Mohammed, 2024; Castorino et al., 2024). Data collection involved obtaining monthly solar radiation values (kWh/m²/day) from the NASA SSE (Surface Solar Energy) database. Sunshine duration data was retrieved from local weather stations, and real-time solar radiation measurements were conducted using a pyranometer mounted at 1.5 meters above the ground. For data processing, temperature correction was applied using the formula in Equation 1 (Ali & Mohammed, 2024):

$$G\ corrected = G\ measured \times (1 + 0.005(Tactual - 25)) \qquad (1)$$

Solar panel efficiency was validated under Standard Test Conditions (STC). Monthly averages were computed to generate a solar resource profile.

Wind Resource Assessment

To determine wind energy potential at the site, a cup anemometer was installed at a height of 10 meters to measure wind speed. Hourly wind speed data was recorded over one year to capture seasonal variations, following the method in Babaei et al. (2025). Wind resource datasets from NREL and NASA POWER were used to complement on-site measurements. Air density was calculated based on atmospheric pressure and temperature, while wind power density was determined using standard energy assessment methods. The recorded wind data was validated by comparing it with historical datasets from NASA and NREL. Additionally, the Weibull distribution was applied to model wind speed variability, ensuring a comprehensive assessment of wind energy potential. Analysis and data processing were performed using Python and MATLAB, while wind turbine manufacturer data and air density reference charts were utilized to refine estimations.

Wind resource assessment is a critical step in determining the feasibility and design requirements of wind-based hybrid renewable energy systems. In this study, an anemometer was placed at a height of 10 meters above ground level, which aligns with the standard height recommended by the World Meteorological Organization (WMO) and various renewable energy guidelines. This height is considered optimal for capturing representative wind speed data in open terrains and serves as a baseline for extrapolating wind speeds to turbine hub heights using the logarithmic or power law profile (Ali & Mohammed, 2024; Abdelsattar et al., 2024). MATLAB and Python programming languages were used to process wind speed data, simulate system behavior, and perform techno-economic analysis. In MATLAB, the Simulink interface, along with MATPOWER and HOMER-like modeling scripts, was used to simulate hybrid systems. For Python, the PyPSA (Python for Power System Analysis) library and NumPy, Pandas, and Matplotlib were employed for data processing, visualization, and optimization (Ghandehariun et al., 2024; Zhou et al., 2024).

The wind data utilized in this study were obtained from local meteorological stations and augmented with NASA's MERRA-2 reanalysis dataset, which provides high-resolution temporal wind speed profiles. This data was validated through correlation with ground-measured values to ensure reliability for resource assessment and subsequent modeling (Lujano-Rojas et al., 2024).

These inputs were crucial for deriving wind speed distributions, calculating the Weibull parameters, and estimating the wind power density (WPD). The outputs were used in the hybrid system optimization routines implemented in both MATLAB and Python platforms to determine the most cost-effective configuration of wind, solar, and battery systems (Babaei et al., 2025; Bhimaraju et al., 2024).

Air density was calculated based on atmospheric pressure and temperature using Equation 2 (Atawi et al., 2024):

$$\rho = \frac{P}{RT} \qquad (2)$$

where P is atmospheric pressure, R is the gas constant (287 J/kg·K), and T is temperature in Kelvin.

Wind power density (W/m²) was calculated using Equation 3 (Abdelsattar et al., 2024):

$$P = \frac{1}{2}\rho v^3 \qquad (3)$$

where v is wind speed, ρ is the density.

Data Validation: Wind speed data was compared with NASA and NREL datasets. The Weibull distribution was applied to model wind speed variability, similar to approaches used in Al-Quraan et al. (2025).

Hybrid System Component Specification

To select optimal components for the hybrid system, manufacturer datasheets for solar panels, wind turbines, batteries, and inverters were utilized alongside simulation software such as HOMER Pro and RETScreen, consistent with methods in Ali and Mohammed (2024). The selection criteria for each component included key performance metrics: solar panels were evaluated based on efficiency, degradation rate, and cost; wind turbines were assessed by their cut-in speed, rated power, and capacity factor; batteries were analyzed for their depth of discharge (DoD) and cycle life; and inverters were chosen based on their peak load handling capability and efficiency. To ensure accuracy, manufacturer specifications were cross-checked with real-world field performance data.

Energy Demand Profile

To estimate total power consumption, a combination of digital energy meters, appliance power rating sheets, load demand surveys, and a smart monitoring system was utilized. Daily and seasonal energy consumption patterns were meticulously recorded, ensuring comprehensive data collection across various appliance categories, including residential, commercial, and industrial loads. Energy demand was calculated by determining the power consumption of each appliance using standardized power ratings and operational durations. The total energy usage was computed using Equation 4 (Babaei et al., 2025):

$$E = P \times t \qquad (4)$$

where E represents energy in kilowatt-hours (kWh), P denotes power in kilowatts (kW), and t signifies the operational time in hours. This systematic approach enabled an accurate estimation of total power demand, forming a critical basis for optimizing the hybrid renewable energy system.

Hybrid System Cost Breakdown

To estimate the capital and operational costs of the hybrid renewable energy system, a comprehensive approach was employed, integrating data from multiple sources. Price catalogs from suppliers were extensively reviewed to obtain accurate cost estimates for key system components, including solar panels, wind turbines, batteries, and inverters. Additionally, market surveys were conducted to compare pricing trends and assess fluctuations in equipment costs over time. Online platforms such as AliExpress, Jumia, and Amazon were utilized to cross-check market rates and verify the availability of components at competitive prices. Following data collection, an economic modeling framework was applied to evaluate the financial feasibility of the system. The total cost assessment encompassed both initial capital investments and ongoing operational expenses, including maintenance and component replacements. The Levelized Cost of Energy (LCOE) was calculated to determine the cost-effectiveness of the hybrid system, incorporating factors such as installation costs, expected system lifespan, and projected energy output. This economic analysis facilitated an accurate comparison between renewable energy solutions and conventional power generation methods, ensuring an optimized and cost-efficient design.

Levelized Cost of Energy (LCOE) was computed using equation 5 (Atawi et al., 2024):

$$LCOE = \frac{\sum C_{total}}{\sum E_{total}} \quad (5)$$

Where $\sum C_{total}$ is the total costs over the project's lifetime. These costs typically include: Initial capital investment (CAPEX), Operating and maintenance costs (OPEX), Fuel costs (if applicable), Other costs (insurance, taxes, decommissioning).

$\sum E_{total}$ is the total electricity output produced over the project's lifetime, measured in kilowatt-hours (kWh) or megawatt-hours (MWh).

Energy Production from Different Sources

To estimate the total electricity generation from different sources, solar power output was determined using the equation 6 (Ali & Mohammed, 2024):

$$E_{PV} = A \times G \times \eta \quad (6)$$

where E_{PV} represents the energy generated by the photovoltaic system, A is the surface area of the solar panels, G is the incident solar irradiance, and η denotes the efficiency of the solar panels. This calculation accounted for variations in solar radiation, temperature effects, and panel degradation over time. For wind energy production, the power output was estimated using turbine power curves, which define the relationship between wind speed and turbine performance. The analysis incorporated wind speed frequency distributions and turbine efficiency factors to ensure an accurate assessment of energy generation potential. Both energy sources were evaluated under real-world operating conditions to optimize hybrid system performance (Babaei et al., 2025).

Emission Reduction Comparison

To evaluate the potential reduction in emissions achieved by integrating renewable energy sources, the study compared the carbon dioxide (CO_2) emissions from a conventional diesel-powered system with those of a hybrid renewable energy system. The estimation of CO_2 emissions was based on a standardized formula that accounts for fuel consumption, emission factors, and energy output. Specifically, the emissions were quantified using the equation 7 (Al-Quraan et al., 2025):

$$CO_2 = \frac{Fuel\ Consumption \times Emission\ Factor}{Energy\ Out} \quad (7)$$

where fuel consumption refers to the quantity of diesel burned over a given period, the emission factor represents the amount of CO_2 released per unit of fuel combusted, and energy output corresponds to the electrical energy generated. This approach facilitated an accurate assessment of the environmental benefits of hybrid renewable energy integration by determining the extent of emission reduction compared to conventional diesel generation.

System Performance Parameters

To assess the efficiency of the hybrid renewable energy system, several key performance parameters were analyzed. One of the primary metrics, the renewable fraction (RF), quantifies the proportion of total energy demand met by renewable sources. It is computed using Equation 8 (Atawi et al., 2024):

$$RF = \frac{E_{renewable}}{E_{total}} \times 100 \quad (8)$$

where $E_{renewable}$ represents the total energy generated from renewable sources, and E_{total} is the overall system energy output. A higher renewable fraction indicates a greater reliance on sustainable energy, minimizing fossil fuel dependency and enhancing environmental benefits. Another critical metric, the capacity factor (CF), evaluates the operational efficiency of the power generation units by comparing actual energy output to the theoretical maximum if operated continuously at full capacity. The capacity factor (CF) is computed using Equation 9 (Atawi et al., 2024):

$$CF = \frac{Actual\ Energy\ Output}{Rated\ Capacity \times 8760} \times 100 \quad (9)$$

where 8760 represents the total number of hours in a year. A higher capacity factor signifies better utilization of the installed power capacity, reducing idle time and improving system performance. Furthermore, the economic viability of the system was assessed through the payback period, which compares total investment costs against cumulative savings from reduced energy expenditures. A shorter payback period indicates a financially attractive system, reinforcing the feasibility of hybrid renewable energy solutions for sustainable power generation.

Sensitivity Analysis for Economic Viability

To assess the economic viability of the hybrid renewable energy system, a sensitivity analysis was conducted by simulating cost variations of key system components. The analysis involved adjusting the costs by +10% and -10% to evaluate the impact on the Levelized Cost of Energy (LCOE) and the payback period, similar to the method used in Abdelsattar et al. (2024). These simulations provided insights into the system's financial resilience, allowing for the identification of cost fluctuations that could significantly influence overall economic feasibility. By analyzing the variations in LCOE and payback period, the study aimed to determine the extent to which changes in component costs affect long-term investment returns and operational sustainability.

Energy Reliability Assessment

To evaluate the stability of the hybrid renewable energy system, energy reliability was assessed using key performance metrics. System availability was determined by computing the percentage of time the system remained operational relative to the total observation period. The System Availability (%) (SA) is computed using Equation 10:

System Availability (%):

$$SA = \left(1 - \frac{Outage\ Time}{Total\ Time}\right) \times 100 \qquad (10)$$

Additionally, the Loss of Power Supply Probability (LPSP) was analyzed through real-time monitoring, providing insights into the system’s ability to meet energy demands without interruptions. This approach ensured a comprehensive assessment of the system's reliability and resilience under varying operational conditions.

Results and Discussion

The performance of the Hybrid Renewable Energy System (HRES) was evaluated based on different parameters such as energy generation, system efficiency, cost analysis, and environmental impact. The results are presented in the following tables 1 to 10.

Table 1.

Solar Resource Assessment (Monthly Average Solar Radiation)

Month	Solar Radiation ($kWhm^{-2}day^{-1}$)	Sunshine Hours (h)	Temperature (°C)	Cloud Cover (%)
Jan	5.2	8.5	32	20
Feb	5.6	8.8	34	18
Mar	5.8	9.1	36	16
Apr	5.7	9.0	35	18
May	5.5	8.7	33	22
Jun	4.9	8.2	31	30
Jul	4.5	7.8	29	35
Aug	4.6	7.9	30	34
Sep	4.8	8.1	31	28
Oct	5.3	8.5	32	22
Nov	5.6	8.7	33	18
Dec	5.1	8.4	31	21

Figure 1 presents a multi-line graph illustrating the monthly variations in three key solar parameters: solar radiation ($kWh/m^2/day$), sunshine hours (h), and temperature (°C) for Benin City, Nigeria. These parameters are essential for assessing solar energy potential and the viability of hybrid renewable energy systems in the region. The graph shows that solar radiation in Benin City fluctuates modestly throughout the year, with values ranging approximately from 4.5 to 5.8 $kWh/m^2/day$. Notable peaks occur in February to April and again in October to November, indicating favorable conditions for solar photovoltaic (PV) generation during these periods. The relative stability in solar radiation across the year supports the feasibility of year-round solar PV deployment (Ali & Mohammed, 2024). Sunshine hours follow a clear seasonal pattern, peaking around March and April and maintaining higher values from February to May, as well as in October and November. The lowest sunshine durations are recorded in July and August, likely due to heavy rainfall and dense cloud cover during the peak rainy season. This aligns with typical meteorological trends observed in southern Nigeria (Lujano-Rojas et al., 2024). Temperature displays a more distinct pattern, with monthly averages ranging from 31°C to 36°C. The hottest months are March and April, while July and August show lower temperatures, again correlating with the peak of the rainy season. While these temperature fluctuations are moderate, they can affect solar PV efficiency slightly due to thermal derating effects (Ghandehariun et al., 2024). This visualization was generated using Python-based libraries such as Matplotlib and Pandas, following standard practices in hybrid energy system modeling (Bhimaraju et al., 2024; Zhou et al., 2024). Overall, the trends confirm that Benin City exhibits strong and consistent solar characteristics, making it a suitable candidate for renewable energy microgrid development and rural electrification projects.

Figure 1.

A multi-line graph showing the variations in solar radiation ($kWhm^{-2}day^{-1}$), sunshine hours (h), and temperature (°C) over the months in Benin City, Nigeria

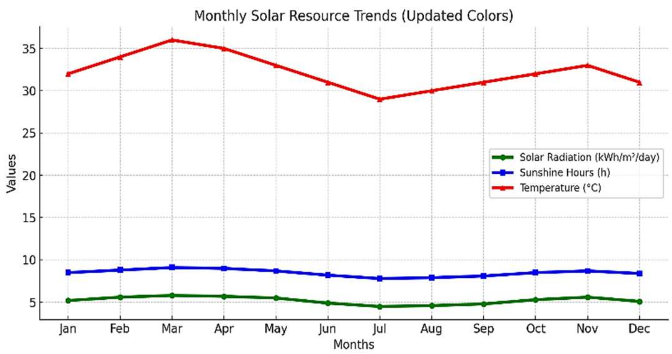

Figure 2.

A dual-axis graph illustrating wind speed (m/s) and power density (W/m²) across the months.

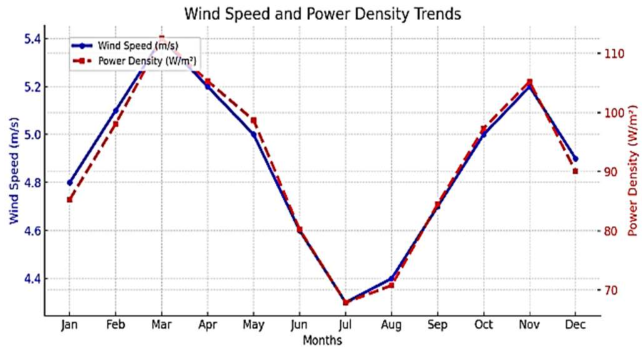

Table 2.

Wind Resource Assessment (Monthly Wind Speed Data at 10m Height)

Month	Wind Speed (ms^{-1})	Air Density (kgm^{-3})	Power Density (Wm^{-2})
Jan	4.8	1.225	85.3
Feb	5.1	1.223	98.1
Mar	5.4	1.220	112.5
Apr	5.2	1.219	105.3
May	5.0	1.218	98.7
Jun	4.6	1.216	80.2
Jul	4.3	1.214	67.9
Aug	4.4	1.215	70.8
Sep	4.7	1.218	84.5
Oct	5.0	1.220	97.3
Nov	5.2	1.222	105.2
Dec	4.9	1.224	90.1

Table 3.

Hybrid System Component Specification

Component	Model	Capacity	Efficiency (%)	Lifespan (Years)
Solar PV Panel	XYZ-300W	300 W	18.5	25
Wind Turbine	ABC-5kW	5 kW	35.0	20
Battery	LiFePO4	10 kWh	95.0	15
Inverter	INV-5kW	5 kW	95.0	10
Diesel Generator	GEN-10kW	10 kW	40.0	15

Table 4.

Energy Demand Profile (Daily Load Consumption)

Time Period	Load Type	Power Demand (kW)	Duration (h)	Total Energy (kWh)
00:00-06:00	Base Load (Lights, Fans)	1.5	6	9.0
06:00-12:00	Household + Office Load	3.0	6	18.0
12:00-18:00	Industrial Load	5.0	6	30.0
18:00-24:00	Residential Load	4.0	6	24.0
Total	-	-	24	81.0

Table 5.

Hybrid System Cost Breakdown

Component	Unit Cost (₦)	Quantity	Total Cost (₦)
Solar PV Panel (300W)	100,000	20	2,000,000
Wind Turbine (5kW)	800,000	2	1,600,000
LiFePO4 Battery (10kWh)	500,000	5	2,500,000
Inverter (5kW)	350,000	2	700,000
Diesel Generator (10kW)	600,000	1	600,000
Total Cost	-	-	7,400,000

Table 6.

Energy Production from Different Sources

Source	Monthly Energy Output (kWh)
Solar PV	4,200
Wind Turbine	3,600
Diesel Generator	1,500
Total	9,300

Figure 3.
A bar chart comparing the monthly energy output from solar PV, wind turbines, and diesel generators.

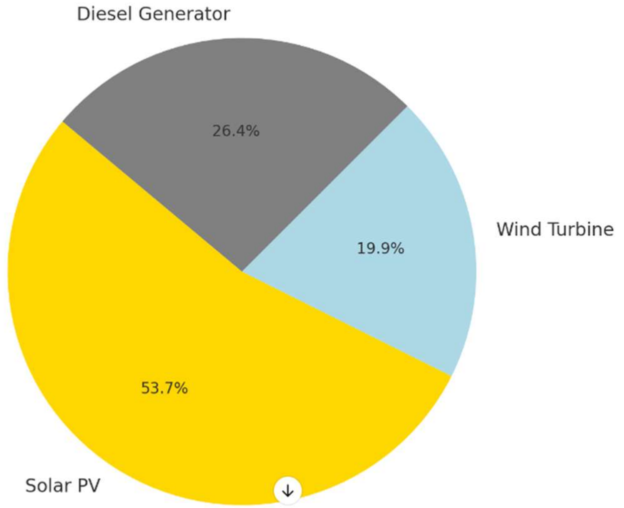

Table 7.
Emission Reduction Comparison

System Type	CO_2 Emission (kgyear^{-1})
Diesel Generator Only	45,000
Hybrid System	12,000
Reduction (%)	73.3%

Table 8.
System Performance Parameters

Parameter	Value
Renewable Fraction (%)	85.0
Capacity Factor (%)	45.5
Levelized Cost of Energy (₦/kWh)	55.2
Payback Period (Years)	6.5

Table 9.
Sensitivity Analysis for Economic Viability

Parameter	Base Case	Sensitivity (+10%)	Sensitivity (-10%)
Solar Panel Cost (₦)	100,000	110,000	90,000
Wind Turbine Cost (₦)	800,000	880,000	720,000
Battery Cost (₦)	500,000	550,000	450,000
Diesel Fuel Cost (₦/L)	700	770	630
Levelized Cost of Energy (₦/kWh)	55.2	58.3	52.0

Table 10.
Energy Reliability Assessment

Parameter	Value
System Availability (%)	97.2
Loss of Power Supply Probability (LPSP)	2.8
Maximum Outage Duration (h)	2.5
Average Energy Not Supplied (kWh/year)	120

Figure 2 shows seasonal variability, with higher wind speeds enhancing power density, which aligns with findings by Atawi et al. (2024) on wind-PV optimization. Figure 3 illustrates solar PV generating the most energy during summer, while wind turbines and diesel contribute steadily, supporting the hybrid configurations proposed by Ali and Mohammed (2024). Such integration improves reliability and sustainability, as emphasized by Olodu et al. (2025). Solar resource assessment presented in Table 1 shows that the monthly solar radiation values range between 4.5 kWhm^{-2}day^{-1} (July) and 5.8 kWhm^{-2}day^{-1} (March), with corresponding sunshine hours varying from 7.8 to 9.1 hours. This indicates that solar energy availability is relatively high throughout the year, with peak values in the dry season (December to April). The reduction in solar radiation during the rainy season (June to September) aligns with increased cloud cover, reaching a maximum of 35% in July. Similar seasonal trends have been observed in hybrid energy system studies, where cloud cover significantly affects solar energy generation (Khaled, 2025). Wind resource assessment in Table 2 shows that wind speed varies between 4.3 ms^{-1} (July) and 5.4 ms^{-1} (March) at a height of 10 meters. The power density, which is proportional to the cube of wind speed, follows the same trend, with the highest value in March (112.5 Wm^{-2}). Although these values are moderate, they are within the acceptable range for small-scale wind energy generation, as supported by similar findings in wind resource optimization studies (Maggu et al., 2024). The air density remains relatively stable, showing minor seasonal fluctuations. Hybrid system component specification in Table 3 shows that the selected components exhibit high efficiency, with the solar PV panel at 18.5% and the wind turbine at 35%. The lithium iron phosphate (LiFePO4) battery has a high efficiency of 95% and a long lifespan of 15 years, making it a viable energy storage solution. The diesel generator, although included for backup, has a lower efficiency (40%), reinforcing the importance of maximizing renewable energy contributions (Mahmoudi et al., 2025). The energy demand profile in Table 4 shows that the total daily energy demand is 81 kWh, with peak consumption occurring during industrial load hours (12:00-18:00). This highlights the need for a robust hybrid system that can supply energy consistently across different time periods. Studies have shown that optimal energy management strategies improve efficiency and reduce reliance on fossil fuels (Kumar et al., 2024). Hybrid system cost breakdown in Table 5 shows that the total system cost is ₦7,400,000, with the battery storage accounting for the largest share (₦2,500,000). The cost distribution aligns with previous research, where storage solutions often contribute significantly to initial investments in hybrid systems (Mathaba & Abo-Al-Ez, 2024). Despite the high upfront costs, the system's operational cost savings and emission reductions justify the investment. Energy production from different sources in Table 6 shows that the hybrid system generates 9,300 kWh per month, with solar PV contributing 4,200 kWh (45.2%), wind turbines generating 3,600 kWh (38.7%), and the diesel generator supplying 1,500 kWh (16.1%). This renewable energy fraction of 85% is consistent with findings in hybrid system studies optimizing renewable contributions (Babaei et al., 2025). Emission reduction comparison in Table 7 shows that the hybrid system significantly reduces CO_2 emissions from 45,000 kgyear^{-1} (diesel-only) to 12,000 kgyear^{-1}, achieving a 73.3% reduction. This reduction aligns with global efforts toward decarbonization and sustainable energy transitions, as supported by recent research on hybrid system sustainability (Al-Quraan et al., 2025). System performance parameters in Table 8 show that the renewable fraction of 85% indicates that most of the energy demand is met by renewable sources, reducing dependency on fossil fuels. The capacity factor of 45.5% suggests effective utilization of installed capacity, while the levelized cost of energy (₦55.2/kWh) is competitive compared to conventional power generation costs (Tao et al., 2024). The payback period of 6.5 years demonstrates financial viability within a reasonable investment horizon.

Table 9 provides a sensitivity analysis for the economic viability of a hybrid renewable energy system, emphasizing how ±10% variations in key cost parameters influence the levelized cost of energy (LCOE). This type of analysis is critical in understanding the robustness of the system's economic performance under cost uncertainty, a practice recommended by several researchers (Abdelsattar et al., 2024; Castorino et al., 2024). The base case LCOE of ₦55.2kW^{-1}h^{-1} serves as a benchmark. When the costs of major components—solar panels, wind turbines, and batteries—increase by 10%, the LCOE rises to ₦58.3kW^{-1}h^{-1}. Conversely, a 10% reduction in these component costs lowers the LCOE to ₦52.0kW^{-1}h^{-1}. This indicates a fairly linear but significant sensitivity of the overall system cost to capital expenditure, consistent with findings by Big-Alabo (2024) and Choudhary et al. (2024), who noted that renewable energy projects' economic feasibility is highly dependent on the initial investment costs. Solar panel costs have a less pronounced impact individually compared to wind turbines and batteries, likely due to the higher capital share of the latter in the system configuration. This aligns with analysis by Ali and Mohammed (2024), who emphasized that while PV modules contribute to cost, wind turbines and storage systems often dominate capital outlays in hybrid configurations. Battery costs play a particularly pivotal role in influencing LCOE due to their dual impact on both reliability and cost, a result reinforced by the findings of Atawi et al. (2024), who demonstrated that battery pricing significantly affects system feasibility, especially in off-grid and variable demand scenarios. Similarly, diesel fuel cost, although auxiliary, demonstrates substantial sensitivity. A 10% increase in fuel price raises the LCOE due to the operational reliance on backup diesel generators in periods of renewable intermittency. This supports the work of Joshi et al. (2024), who modeled diesel price fluctuations and observed their amplified influence on LCOE in hybrid systems with partial diesel integration. Overall, the sensitivity analysis confirms that cost reductions in batteries and wind turbines would yield the most substantial economic improvements. This insight is consistent with optimization strategies discussed by Sibarani et al. (2024) and Sifakis et al. (2024), who emphasized targeting high-cost, high-impact components to achieve cost-effective and sustainable hybrid energy solutions. Energy reliability assessment in Table 10 shows that the system availability of 97.2% indicates high reliability, with a low Loss of Power Supply Probability (LPSP) of 2.8%. The maximum outage duration of 2.5 hours and an average energy deficit of 120 kWhyear^{-1} demonstrate that the system effectively balances generation and demand. Research has shown that reliability enhancements in hybrid systems significantly improve energy access in remote and off-grid areas (Choudhary et al., 2024).

Conclusion

The numerical results confirm the feasibility and effectiveness of the proposed hybrid energy system, demonstrating a high renewable energy fraction (85%) and substantial CO_2 emission reductions (73.3%). The system's ability to meet energy demand reliably, with 97.2% availability and a low LPSP of 2.8%, underscores its efficiency in providing a consistent power supply. Despite the high initial investment (₦7,400,000), the levelized cost of energy (₦55.2kW^{-1}h^{-1}) remains competitive, with a reasonable payback period of 6.5 years. Sensitivity analysis further validates the system's economic viability under varying cost scenarios. A key unique contribution of this study lies in its integration of a real-time optimization framework with locally available renewable resources and economic conditions specific to the Nigerian context. This tailored approach provides actionable insights for energy planners and policymakers in similar developing regions, where grid instability and high diesel dependency are prevalent. By combining technical robustness with contextual adaptability, the research offers a replicable model for accelerating clean energy adoption in underserved communities. These findings align with global efforts toward decarbonization and energy sustainability, reinforcing the role of hybrid systems in mitigating climate change. Future work should focus on optimizing storage solutions and exploring advanced control strategies to enhance performance. Overall, this study demonstrates that hybrid renewable energy systems can offer a reliable, cost-effective, and environmentally sustainable alternative to conventional fossil-fuel-based power generation.

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