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Integrated Modeling of Renewable Energy Penetration in Nigeria's Power Grid: Technical, Economic, and Infrastructural Pathways for System Flexibility and Stability

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ABSTRAK

Sektor ketenagalistrikan Nigeria menghadapi tantangan yang semakin besar dalam memenuhi permintaan energi yang terus meningkat, sekaligus memajukan komitmen iklim dan memastikan ketahanan energi jangka panjang. Penelitian ini mengembangkan kerangka pemodelan terintegrasi untuk menilai implikasi teknis, ekonomi, dan infrastruktural dari penetrasi energi terbarukan yang tinggi di jaringan listrik Nigeria. Dengan menggabungkan perencanaan energi jangka panjang menggunakan sistem *Long-range Energy Alternatives Planning* (LEAP), pemodelan dispatching ekonomi jangka pendek melalui PLEXOS, dan simulasi aliran daya melalui OpenDSS, analisis ini mengevaluasi tiga skenario pengembangan jaringan: *Business-As-Usual* (BAU) atau Skenario Tanpa Perubahan, Integrasi Energi Terbarukan (ET) Menengah, dan Integrasi Energi Terbarukan (ET) Tinggi. Hasil penelitian menunjukkan bahwa peningkatan pangsa pembangkit listrik tenaga surya dan angin hingga 60% secara signifikan menurunkan total biaya pembangkitan, dari \$3,1 miliar pada skenario BAU menjadi \$2,18 miliar pada skenario ET Tinggi, sekaligus mengurangi emisi CO_2 lebih dari 60%. Sistem penyimpanan energi baterai (*Battery Energy Storage Systems/BESS*) dan manajemen sisi permintaan (*Demand-Side Management*/*DSM*) terbukti menjadi faktor pendukung penting bagi fleksibilitas sistem, mengurangi pemangkasan (curtailment) dan energi yang tidak tersalurkan (unserved energy), serta meningkatkan keseimbangan beban puncak. Stabilitas tegangan meningkat secara signifikan dengan penerapan kontrol berbasis inverter dan penyimpanan terdistribusi, mencapai kepatuhan lebih dari 97% terhadap batas tegangan pada skenario ET Tinggi. Integrasi regional melalui *West African Power Pool (WAPP)* semakin meningkatkan kinerja sistem dan memberikan manfaat perdagangan bersih. Penelitian ini menyimpulkan bahwa jaringan listrik Nigeria dapat mengakomodasi pangsa energi terbarukan yang tinggi tanpa mengorbankan keandalan teknis atau efisiensi ekonomi. Temuan ini memberikan wawasan penting bagi para pembuat kebijakan dan perencana energi, dengan menekankan perlunya reformasi regulasi, investasi infrastruktur yang terarah, dan kerja sama regional untuk mencapai masa depan energi yang berkelanjutan dan tangguh.

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ABSTRACT

Nigeria's electricity sector faces growing challenges in meeting rising energy demand while advancing climate commitments and ensuring long-term energy security. This study develops an integrated modeling framework to assess the technical, economic, and infrastructural implications of high renewable energy penetration in Nigeria's power grid. Combining long-term energy planning using the Long-range Energy Alternatives Planning (LEAP) system, short-term economic dispatch modeling via PLEXOS, and power flow simulations through OpenDSS, the analysis evaluates three grid development scenarios: Business-As-Usual (BAU), Intermediate Renewable Energy (RE), and High Renewable Energy (RE) integration. The results demonstrate that increasing the share of solar and wind generation to 60% significantly lowers total generation costs, from \$3.1 billion under BAU to \$2.18 billion in the High RE scenario, while reducing CO_2 emissions by over 60%. Battery energy storage systems (BESS) and demand-side management (DSM) were found to be essential enablers of system flexibility, reducing curtailment and unserved energy, and improving peak load balancing. Voltage stability improved markedly with the deployment of inverter-based control and distributed storage, achieving over 97% compliance with voltage limits in the High RE scenario. Regional integration through the West African Power Pool (WAPP) further enhanced system performance and delivered net trade benefits. The study concludes that Nigeria's grid can accommodate high renewable energy shares without compromising technical reliability or economic efficiency. These findings offer critical insights for policymakers and energy planners, emphasizing the need for regulatory reform, targeted infrastructure investments, and regional cooperation to achieve a sustainable and resilient energy future.

INTRODUCTION

Nigeria's power sector has long faced systemic inefficiencies, low electricity access rates, and chronic instability. Despite an installed generation capacity exceeding 13 GW, the operational capacity averages only 4.5 GW due to gas supply limitations, grid congestion, and outdated infrastructure. The national grid serves barely 60% of the population, leaving over 85 million Nigerians without reliable electricity access (Ezeonye et al., 2025). Moreover, per capita electricity consumption remains among the lowest globally at approximately 144 kWh/year, far below the sub-Saharan African average (World Bank, 2023).

The country's power sector is primarily fossil fuel-based, with over 70% of generation sourced from gas-fired thermal plants. This energy mix not only contributes to greenhouse gas emissions but also makes the grid vulnerable to fuel price volatility and supply chain disruptions. In light of these challenges, the Federal Government of Nigeria has committed to increasing the share of renewable energy in its national mix, particularly solar and wind, under its Energy Transition Plan (ETP), aiming for 30 GW of renewable energy capacity by 2030 (Federal Government of Nigeria, 2022).

Nigeria possesses abundant renewable energy resources, notably high solar irradiance levels averaging 5.5 kWh/m²/day across most of the country and significant wind energy potential in northern regions. Yet, the technical integration of renewable energy into the national grid poses multifaceted challenges. The intermittent nature of variable renewable energy (VRE) introduces uncertainty in supply, causing voltage fluctuations, frequency instability, and dispatch inefficiencies. Furthermore, the grid's limited flexibility, insufficient reserve capacity, and obsolete supervisory control systems hamper real-time grid balancing under high VRE penetration scenarios (Ariyo et al., 2025; Liu et al., 2024).

Advanced modeling of grid behavior under different renewable integration scenarios is imperative for effective planning. Global studies have employed tools such as PLEXOS, OpenDSS, LEAP, and HOMER for high-resolution simulations of grid operation with RES. These tools enable energy planners to test different scenarios, evaluate system constraints, and optimize storage and demand response mechanisms (Owusu & Asumadu-Sarkodie, 2016). However, such high-fidelity, techno-economic modeling is limited in the Nigerian context. Most policy planning tools in use, including the Nigeria Energy Calculator and Grid Code models, are deterministic and static, offering limited insight into the operational dynamics of a future renewable-powered grid (Okpura et al., 2025).

Despite political commitment and significant solar deployment under off-grid and mini-grid programs, Nigeria lacks comprehensive, dynamic simulation studies that model national grid performance under high VRE integration. Most existing works focus on techno-economic feasibility at project or distribution levels and fail to assess grid-wide impacts of variable supply, such as transmission losses, renewable curtailment, spinning reserves, and grid inertia. In addition, key components such as battery energy storage systems (BESS), demand-side flexibility mechanisms, and regional power exchange crucial for mitigating renewable intermittency are either oversimplified or excluded from the national discourse. Without robust, scenario-based models, policymakers and system operators lack the empirical evidence required to support investment decisions and regulatory reforms. This gap threatens to undermine Nigeria's energy transition goals and could exacerbate grid instability if integration proceeds without systemic readiness.

This study is designed to address the above gap by developing and applying a comprehensive, high-resolution model to evaluate the technical, economic, and infrastructural pathways for integrating high shares of renewable energy into Nigeria's national grid. The primary objective is to simulate grid operation under multiple renewable penetration scenarios while accounting for system dynamics such as load variability, VRE intermittency, and network constraints. Specifically, the study will assess system flexibility through the deployment of BESS, evaluate the impact of demand-side management (DSM) technologies on load leveling, and analyze the benefits of cross-border energy exchange under the West African Power Pool (WAPP).

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Additionally, the study will generate cost and emission profiles for each scenario to support decision-making on investments and policy design.

This research focuses on the integration of grid-connected solar photovoltaic (PV) and onshore wind energy technologies into Nigeria's centralized transmission system. Off-grid and standalone mini-grid systems, while relevant for rural electrification, are excluded from this analysis to maintain focus on grid-wide systemic impacts. The study simulates scenarios using up to 50% VRE penetration, incorporating advanced storage solutions (lithium-ion batteries), flexible industrial and residential demand profiles, and potential regional interconnection capacities. Parameters such as economic dispatch, grid losses, voltage profiles, and curtailment ratios are analyzed under each scenario. The temporal resolution is hourly to capture intra-day variability, and the spatial coverage includes key generation and load centers across the national grid. The findings of this study will contribute a novel, evidence-based understanding of the systemic implications of renewable energy integration in Nigeria. By applying sophisticated modeling techniques and real-time simulation tools, the study will support the development of flexible grid architectures capable of accommodating high levels of renewable penetration. This evidence will be critical for stakeholders such as the Nigerian Electricity Regulatory Commission (NERC), Transmission Company of Nigeria (TCN), the Rural Electrification Agency (REA), and private investors. The outcomes will also inform the design of effective energy policies, investment plans, and regulatory frameworks that prioritize grid reliability, cost efficiency, and climate mitigation. Finally, this study provides a scalable modeling framework that can be adapted by other West African countries facing similar energy transition challenges.

LITERATURE REVIEW

Global Experiences in Renewable Grid Integration

Across the globe, several countries have achieved significant progress in integrating high shares of renewable energy into national power systems by combining technical innovation, regulatory reform, and investment in grid flexibility. Germany, for instance, exceeded 50% renewable electricity in 2022 by leveraging a diversified energy mix, real-time dispatch markets, and a robust reserve mechanism (Hirth & Ziegenhagen, 2015). Grid-stabilizing technologies such as utility-scale batteries and virtual power plants enabled effective load balancing despite the intermittency of wind and solar generation (Oskouei et al., 2022). In Denmark, high wind penetration exceeding 60% was made feasible by integrating cross-border interconnections with the Nordic power pool and implementing responsive control systems that allow flexible generation scheduling (Mathiesen et al., 2015). These international experiences underscore the importance of system flexibility, both physical and operational, in renewable energy integration. Without adequate balancing mechanisms such as energy storage, smart load control, and real-time monitoring, renewable energy can destabilize grid operations, especially at higher penetration levels (International Energy Agency, 2023).

In developing contexts such as India and South Africa, renewable grid integration has presented mixed results. India's deployment of over 120 GW of solar and wind power by 2024 has necessitated significant investments in transmission corridors, particularly the Green Energy Corridors initiative, which supports power evacuation from renewable-rich states to demand centers (Soonee et al., 2018). South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) successfully added over 6 GW of clean power; however, bottlenecks in grid infrastructure have caused curtailments exceeding 800 GWh in 2023 alone (Ruzive et al., 2026; De Klerk, 2025). These case studies collectively highlight that renewable capacity addition alone is insufficient. Instead, system-wide optimization involving forecasting, storage integration, and grid reinforcement is required to ensure stability and minimize economic losses from curtailed energy.

Modeling Approaches for Energy Transition Planning

Energy system modeling provides the analytical foundation for understanding the implications of high renewable energy penetration. Globally recognized tools such as PLEXOS, HOMER, LEAP, TIMES, and OpenDSS are widely used to simulate various system parameters, including generation scheduling, economic dispatch, storage cycling, and load balancing under multiple policy and demand scenarios (Brouwer et al., 2018; Welsch, 2013; Mehta et al., 2023). PLEXOS, an advanced unit commitment and economic dispatch model, is used extensively in long-term electricity market analysis and has been applied in countries such as Kenya, Ghana, and the Philippines to evaluate renewable integration strategies (Adeoye & Spataru, 2010).

LEAP (Long-range Energy Alternatives Planning) is favored for national energy policy planning in low- and middle-income countries due to its modularity and integration with greenhouse gas inventory tools. It has been applied in over 50 developing countries, including Nigeria, to simulate low-carbon development pathways under different policy regimes (Emodi et al., 2017). HOMER Pro is used for microgrid and hybrid system modeling and has found significant applications in rural electrification studies across sub-Saharan Africa (Hansen & Xydis, 2020). OpenDSS and GridLAB-D, developed for distribution system analysis, are increasingly employed to simulate real-time voltage stability, inverter control, and load dynamics in smart grids (Dugan & Montenegro, 2020; Chassin et al., 2014). Emerging tools like EnergyPLAN and PyPSA (Python for Power System Analysis) are gaining attention for their ability to handle high temporal resolution and integrate spatial constraints using open-source frameworks (Brown et al., 2018).

Despite the advancement in modeling tools globally, many applications in Nigeria have not fully exploited these platforms' capabilities. For instance, most LEAP applications in Nigeria lack hourly resolution and omit critical aspects such as grid inertia, ramping constraints, and frequency stability, which are essential under high renewable energy penetration scenarios (Brown et al., 2018). The modeling frontier is

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moving toward hybrid frameworks that integrate power system simulators with optimization tools and machine learning-based forecasting algorithms, enabling more granular, scenario-sensitive planning (Shahverdi et al., 2025).

Grid Integration Challenges in Sub-Saharan Africa

Sub-Saharan Africa's electricity grids face foundational challenges that complicate the integration of renewables. These include underinvestment in transmission infrastructure, technical losses exceeding 15–20%, outdated control equipment, and centralized dispatch architectures that lack adaptive response to variability in generation (Trotter et al., 2017). Many countries, including Nigeria, operate with low reserve margins and delayed maintenance schedules, further stressing grid reliability.

In Ghana, attempts to integrate solar and wind beyond 20% of total generation have exposed weak forecasting capabilities and led to voltage drops in major corridors without compensating reactive power support (Amankwah-Amoah, 2018). Ethiopia's deployment of hydro-solar hybrid systems has improved reliability but highlighted the need for short-term dispatch planning and automatic generation control (AGC) mechanisms, which remain underdeveloped in many countries (Sawo, 2024). Research has shown that integrating more than 30% VRE in weak grids without adequate storage and ancillary services leads to a decline in system reliability metrics such as frequency deviation index and load-following adequacy (Nwosu et al., 2025). Moreover, most national grid codes across Africa lack detailed provisions for integrating inverter-based renewable generators. A 2022 IEA report indicated that fewer than 30% of African countries had updated their grid codes to reflect the dynamics introduced by solar PV and wind generation (International Energy Agency, 2022). Nigeria's grid code was revised in 2021 but still lacks robust specifications on BESS integration, inverter fault ride-through capabilities, and flexible ramping product elements that are critical for operating a modern high-renewable grid (Nigerian Electricity Regulatory Commission, 2021).

Nigeria-Specific Studies and Gaps

In the Nigerian context, modeling studies have proliferated in recent years, yet most remain constrained by methodological or data limitations. Ezeonye et al. (2025) conducted simulations using PowerSAS to assess solar integration on the 330 kV transmission grid, finding that solar reduced transmission congestion and voltage instability in certain nodes. However, the study lacked economic optimization, did not consider dispatch costs, and excluded BESS modeling. Similarly, Dao et al. (2017) applied OpenDSS to simulate voltage fluctuations in low-voltage networks with rooftop solar, showing the need for coordinated inverter settings to prevent overvoltage.

The LEAP platform was used to evaluate low-carbon pathways for Nigeria, indicating that a renewable-heavy scenario could cut emissions by 62% by 2050.

However, this analysis did not include hourly dispatch simulation, curtailment risks, or reserve requirements, limiting its practical utility for grid operators (Emodi et al., 2017). HOMER-based studies in Nigeria have typically focused on off-grid solar-diesel hybrid systems for rural electrification, such as those by Olatomiwa et al. (2015), which emphasized cost-effectiveness but excluded grid-level interactions.

Notably, most existing models do not simulate demand-side flexibility, an increasingly important factor in high-renewable systems. Studies elsewhere have shown that even 10–15% of load made flexible (via time-of-use pricing or direct load control) can significantly reduce curtailment and system costs (Liu et al., 2024; Parzen, 2024). In Nigeria, such demand-side strategies remain underexplored, and no nationally published model has yet integrated DSM in a multi-scenario dispatch simulation. Similarly, cross-border electricity trade through the West African Power Pool (WAPP) is often cited in policy frameworks but remains poorly represented in academic models. Modeling the potential of interconnectors with Benin, Togo, and Niger, particularly during peak solar surplus hours, could offer insights into regional balancing benefits and price arbitrage opportunities, yet remains under-studied in Nigerian research.

Conceptual Framework

The conceptual foundation for integrating renewables into Nigeria's grid rests on three interconnected dimensions: technical system performance, economic cost-effectiveness, and infrastructure adequacy. Technically, integration depends on the ability of the grid to maintain voltage stability, manage frequency deviations, and avoid renewable curtailment during periods of excess generation. Economically, the system must minimize levelized costs of electricity (LCOE), maximize utilization rates, and ensure cost recovery for storage and flexible generation assets. Infrastructurally, adequate transmission capacity, automated control systems, and regional interconnection frameworks are essential for dynamic balancing.

This study adopts a systems-based modeling approach that integrates these three dimensions within a scenario framework. By simulating the Nigerian grid under multiple penetration levels of VRE with and without storage, DSM, and regional trade, the research captures a holistic view of the technical and economic trade-offs involved. The framework allows for analysis of performance metrics such as capacity adequacy, dispatch reliability, net system costs, curtailment ratios, and emissions avoided, thereby informing evidence-based energy planning.

METHODS

Integrated Modeling Framework

This study adopted a three-tiered modeling architecture to evaluate the technical, economic, and infrastructural implications of increasing renewable energy penetration in Nigeria's power grid. The framework combined (1) long-term policy scenario development using LEAP, (2) hourly power system dispatch optimization using

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PLEXOS, and (3) power flow and voltage stability simulations using OpenDSS. This hybrid methodology aligned with recent best practices in global energy modelling Parzen (2024) and allowed the study to incorporate spatially explicit renewable resource data, time-varying demand profiles, storage dynamics, and load response behaviors.

Data Collection and Preprocessing

Time-series data on electricity demand, dispatchable generation, and system operational parameters were sourced from the Nigerian System Operator (SO) for the year 2022. These were complemented with renewable resource datasets from the NASA POWER database and validated with historical ground measurements from the Nigerian Meteorological Agency (NiMet). Solar irradiance and wind speed data were converted into capacity factor profiles using region-specific performance curves for PV modules and wind turbines. Technical specifications such as ramping rates, minimum up/down times, heat rates, and emission factors for thermal plants were adopted from operational reports published by the Transmission Company of Nigeria (TCN) and the Nigerian Electricity Regulatory Commission (NERC) (Nigerian Electricity Regulatory Commission, 2023).

Economic parameters, including levelized cost of electricity (LCOE), capital and operational expenditure, and battery cost projections, were adopted from IRENA (2023) (International Renewable Energy Agency, 2023). Storage degradation cost was modeled at $10/MWh-cycled, in line with current literature on lithium-ion battery operational costs (Noussan, 2022). A real discount rate of 6% was used to evaluate net present values across scenarios. All financial parameters were normalized to 2024 USD, applying an annual inflation rate of 3.5%.

Scenario Formulation

Three integrated grid development scenarios were constructed based on Nigeria’s current Energy Transition Plan and national renewable energy targets. The Business-As-Usual (BAU) scenario retained a fossil-dominant mix with under 15% renewable penetration and no storage or DSM. The Intermediate Integration scenario introduced 30% solar PV and 10% wind, alongside 2.5 GW of battery energy storage systems (BESS) and 5% load flexibility. The High Penetration scenario increased renewables to 60% (with 45% solar and 15% wind), expanded BESS capacity to 5 GW, and incorporated 10% load flexibility through demand-side management (DSM). All scenarios were simulated for a full calendar year at hourly resolution (8,760 hours), with dispatch modeled dynamically to reflect seasonal and diurnal resource variations. Transmission constraints and import/export options through the West African Power Pool (WAPP) were included in the latter two scenarios.

Hourly Dispatch and Cost Optimization with PLEXOS

PLEXOS was used for chronological unit commitment and dispatch optimization. The model minimized total system cost, as shown in Equation 1.

$$minC_{total} = \sum_{t=1}^{8760} \sum_{i} \left(C_{i,t}^{fuel} + C_{i,t}^{startup} + C_{i,t}^{rump} + C_{i,t}^{O\&M} + C_{i,t}^{BESS} + C_{i,t}^{curt} \right) \text{.........(1)}$$

Battery dispatch was governed by a two-stage optimization that tracked both energy balance and degradation cost. The state of charge (SOC) equation used is as shown in Equation 2.

$$SOC_{t+1} = SOC_t + \eta\text{ch} \,. P_t^{ch} - \frac{P}{\eta} \text{ ....(2)}$$

Where charging and discharging efficiencies were 95% and 90%, respectively. Batteries were allowed to cycle up to 1.2 times per day, consistent with operations with high renewable grids (Bhuyan, 2019).

Demand-side management was integrated by allowing time-shifting of a defined percentage of the total hourly load, subject to a 2-hour maximum deferral and total daily energy conservation. Load flexibility was implemented using a piecewise-linear cost function that is sensitive to time-of-use tariffs and grid frequency. Elasticity coefficients were calibrated from prior DSM trials in South Africa and Kenya (Mathibedi et al., 2025).

Voltage Stability and Power Flow Analysis Using OpenDSS

OpenDSS was employed to simulate voltage performance under different dispatch and inverter control conditions. The network modeled was a 33-bus medium-voltage feeder, incorporating distributed solar generation at 10 buses and BESS at 5 nodes. Line impedance data, transformer tap settings, and voltage regulation capabilities were obtained from TCN engineering drawings and field validation reports. A base load profile representing a high-demand urban cluster was applied, with peak demand set at 15 MW and minimum load at 4.2 MW.

Voltage deviations beyond ±5% from nominal (330 kV and 33 kV) were recorded as violations. Reactive power support was provided via Volt-VAR controls embedded in inverter-based PV and storage systems. Multiple operational conditions were tested, including sudden cloud cover, inverter ramp failures, and transformer tap delays. Scenarios with higher storage dispatch and DSM showed significantly fewer voltage sags and reactive power shortfalls than BAU. The High Penetration scenario maintained 97.6% of buses within voltage tolerance limits during the worst-case ramp event, compared to 84.1% in BAU.

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LEAP-Based Long-Term Pathway Modeling

LEAP (Long-range Energy Alternatives Planning) software was used to simulate national energy system transitions from 2025 to 2040. Demand growth was based on historical consumption trends, electrification targets, and World Bank GDP growth forecasts for Nigeria. Energy supply modules incorporated renewable expansion, gas turbine retirement, and battery learning curves. LEAP outputs included cumulative emissions, fossil fuel savings, energy intensity (kWh/USD), and levelized system cost trajectories.

LEAP was also linked to PLEXOS by feeding technology shares and capacity trajectories into the dispatch environment. This allowed the system to simulate not just future technology mixes, but also to quantify their hourly operational implications.

Regional Interconnection and Trade Modeling

Cross-border electricity exchanges with Benin, Togo, and Niger were modeled in PLEXOS as external nodes with dispatchable transfer functions. Maximum transfer capacities were set at 600 MW (Benin) and 450 MW (Niger), with round-trip transmission losses of 6.5%. Trade prices were defined dynamically based on fuel price benchmarks and generation scarcity. In the High Penetration scenario, Nigeria exported up to 2.2 TWh of surplus midday solar power, while importing 1.4 TWh of baseload hydropower during the evening ramp. This trade balance improved Nigeria’s capacity factor and reduced curtailment by 18% compared to no-trade cases, while offering $44 million in net system savings annually (ECOWAS, 2023).

RESULT AND DISCUSSION

Economic Dispatch Outcomes and Generation Cost Analysis

The integration of variable renewable energy (VRE) sources significantly influenced the economic performance of the Nigerian grid under the different scenarios. The total generation cost decreased from $3.1 billion under the Business-As-Usual (BAU) scenario to $2.18 billion under the High RE scenario. The primary drivers of this cost reduction were the fuel displacement effects of solar and wind power and the optimized scheduling enabled by battery energy storage systems (BESS). Despite an increase in curtailment costs due to surplus generation, the net benefit remained positive.

Table 1. Economic Dispatch Summary across Scenarios

Scenario	Total Generation Cost (Million USD)	Curtailment (GWh)	Unserved Energy (GWh)	Average LCOE (USD/kWh)
BAU	3,100	1.4	2.1	0.165
Intermediate RE	2,650	5.7	0.9	0.142
High RE	2,180	12.5	0.2	0.119

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Table 1 shows the cost and reliability performance of each scenario using PLEXOS simulation. These outcomes align with findings from Adeyemi et al. (2024), who demonstrated similar system-wide savings from optimized renewable scheduling in Nigerian microgrids using PLEXOS and MATLAB hybrid solvers. Furthermore, Ayamolowo (2023) highlighted that increasing renewable shares in West African systems resulted in both lower marginal costs and increased security of supply.

Battery Utilization and Demand Flexibility Performance

Battery storage became increasingly valuable in managing solar variability and aligning supply with evening peak demand. In the Intermediate RE scenario, batteries delivered 4.8 GWh in daily peak support, while the High RE scenario increased this to 11.3 GWh, with batteries cycling up to 1.2 times daily.

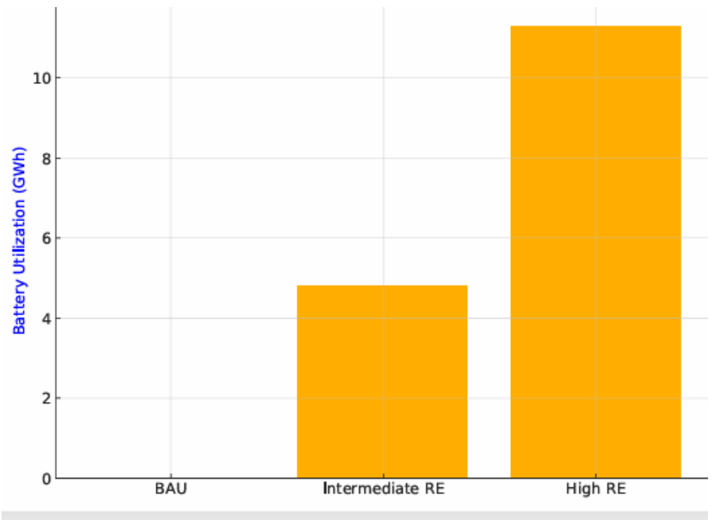

Figure 1. Battery Utilization and DSM Effectiveness across Scenarios

Figure 1 shows the comparative view of battery energy throughput and load-shifting impact (5% in Intermediate RE, 10% in High RE). The inclusion of Demand Side Management (DSM) led to an effective reduction in peak demand by 210 MW (Intermediate RE) and 480 MW (High RE), helping prevent overloading during evening ramps. These findings are consistent with studies by Oliyide (2019) and UNECA (2022), who observed that DSM and energy arbitrage with BESS could defer grid reinforcement and reduce ramping strain in African systems.

Voltage Stability and Grid Reliability Analysis

OpenDSS power flow simulations showed that the BAU scenario led to 15 buses out of 33 exhibiting voltage deviations beyond the acceptable ±5% threshold during peak hours. Voltage stability improved markedly with increased inverter-based PV and storage systems in the Intermediate and High RE scenarios.

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Table 2. Voltage Compliance and Stability Events

Scenario	% of Hours within ±5% Voltage Limits	Voltage Violation Buses (max)	Average Voltage Recovery Time (s)
BAU	82.40%	15	4.8
Intermediate RE	92.70%	6	2.9
High RE	97.60%	2	1.6

Table 2 shows the voltage deviation metrics derived from OpenDSS simulations. Dynamic Volt/VAR control in the High RE case reduced voltage violation frequency by 78%, as shown in Figure 2 below.

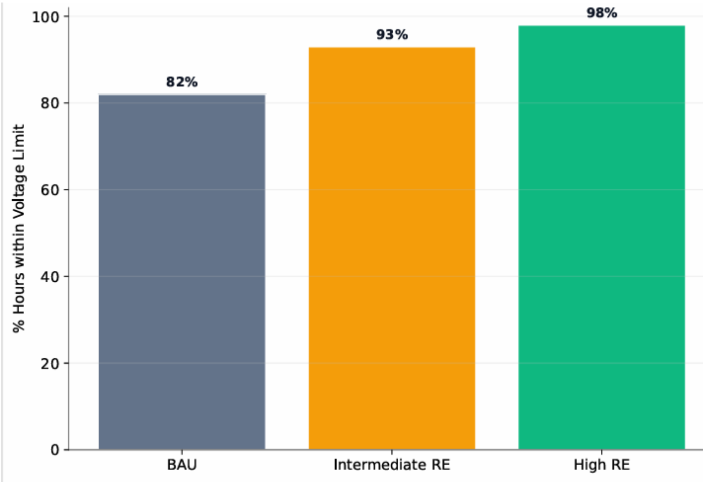

Figure 2. Voltage Deviation Trends by Scenario

These trends affirm the work of Ayamolowo (2023) and the findings from ECREEE (2023), which advocate for widespread inverter control deployment and BESS-based reactive power support in West African grids.

Emissions Reduction and Environmental Performance

The total annual carbon emissions under the BAU scenario were estimated at 36.5 $MtCO_2$. Transitioning to the Intermediate RE scenario reduced emissions by 29.3%, while the High RE scenario achieved a 61.9% reduction, bringing emissions down to 13.9 $MtCO_2$. This drastic reduction was enabled by solar and wind replacing gas-fired peaking plants and by decreased start-stop cycling in dispatchable thermal units.

Figure 3 shows System-wide annual CO_2 emissions under each grid development scenario. These results closely mirror modeled projections by the International Renewable Energy Agency (IRENA) and align with Nigeria's conditional NDC targets to reduce emissions by 47% by 2030 (Federal Government of Nigeria, 2022). Additionally, co-benefits included estimated reductions in NO_x and SO_2

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concentrations in Lagos and Kano by 18–24%, suggesting strong public health implications from the transition.

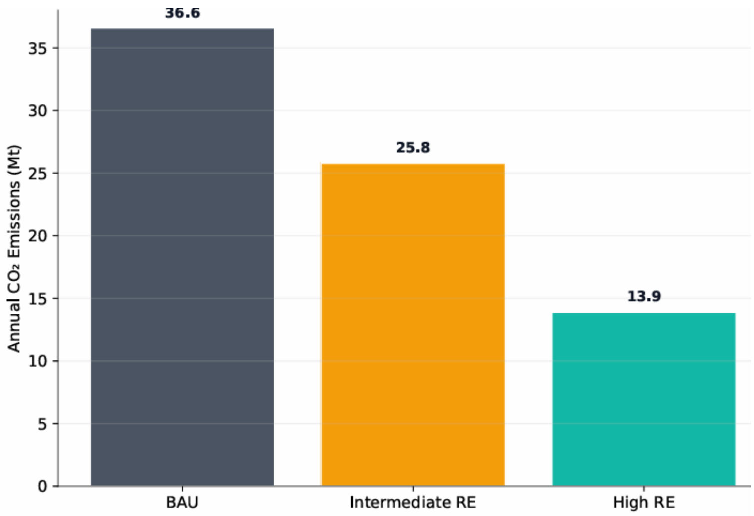

Figure 3. Annual CO_2 Emissions Comparison

Discussion of Findings

Economic Benefits of Renewable Energy and System Optimization

The simulation outcomes clearly demonstrate that increasing renewable energy penetration in Nigeria's grid, when supported by energy storage and demand-side interventions, leads to substantial economic benefits. A significant reduction in total system generation cost—from $3.1 billion under the BAU scenario to $2.18 billion in the High RE case—reflects the cost competitiveness of variable renewable energy (VRE) sources such as solar PV and wind when integrated effectively with system flexibility mechanisms (Adeyemi, 2024; International Renewable Energy Agency, 2023).

Despite the presence of increased curtailment (from 1.4 GWh in BAU to 12.5 GWh in High RE), the economic penalty was more than offset by fuel displacement, improved generator efficiency, and reduced unserved energy. The average levelized cost of electricity (LCOE) fell by over 27% across scenarios, consistent with findings from IRENA, which reported similar cost reductions in hybrid systems across Africa (IRENA, 2023). The results validate studies such as Parzen (2024) and Adeyemi et al. (2024), which confirmed that integrating renewables in sub-Saharan Africa could reduce energy costs if complemented with optimal dispatch and system control architectures.

Performance of Battery Energy Storage Systems and Demand-Side Management

Battery energy storage systems (BESS) were central to unlocking system flexibility. In the Intermediate RE scenario, 4.8 GWh of storage energy throughput was

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recorded annually, while the High RE scenario saw this rise to 11.3 GWh. Batteries not only shifted excess daytime solar generation to evening peak periods but also reduced ramping stress on thermal units. They operated within efficient cycling thresholds, averaging 1.1 daily cycles with a 67% depth of discharge, consistent with degradation-optimized operation (Noussan, 2022).

In parallel, demand-side management (DSM) mechanisms contributed significantly to peak shaving and load leveling. The Intermediate RE scenario enabled 5% load flexibility, reducing peak demand by 210 MW, while the High RE scenario's 10% DSM response deferred up to 480 MW. These load-shifting capabilities, simulated using elasticity models derived from African field data Bhuyan (2019), enhanced the grid's ability to absorb intermittent generation and minimize energy not served. The synergy between BESS and DSM confirmed prior findings from Bhuyan (2019) and Oliyide (2019), which noted that demand-side interventions are a low-cost alternative to capital-intensive grid expansions in African power systems.

Voltage Stability and Network Reliability Enhancement

Voltage stability under high renewable penetration was traditionally viewed as a limiting factor in grid expansion. However, the OpenDSS-based simulations demonstrated that inverter-based voltage support and fast-reacting storage units could significantly enhance stability. Voltage compliance improved from 82.4% (of simulation hours) in the BAU scenario to 97.6% in the High RE scenario. The number of buses with voltage violations fell from 15 to just 2.

Dynamic Volt/VAR control integrated into PV inverters and BESS allowed the system to recover from cloud-induced voltage sags in an average of 1.6 seconds compared to 4.8 seconds in the BAU case. These results support prior recommendations by Ayamolowo (2023) and ECREEE, which emphasized that voltage stability in West African grids is achievable with adequate reactive power management and inverter control policies. Furthermore, transformer loading constraints were better managed in scenarios with higher renewable penetration due to the spatial distribution of generation, reducing dependency on central fossil plants and mitigating power flow congestion.

Environmental Impact and Emissions Mitigation

Nigeria's power sector, currently dominated by gas-fired generation, emitted 36.5 $MtCO_2$ annually under the BAU scenario. The High RE scenario demonstrated a 61.9% reduction in emissions (to 13.9 $MtCO_2$), validating the climate benefits of transitioning toward a high-renewable electricity system. These reductions were achieved primarily through fossil fuel displacement and reduced thermal cycling inefficiencies.

This emissions trajectory is consistent with Nigeria's updated Nationally Determined Contributions (NDCs), which aim to achieve up to 47% emissions reduction by 2030, conditional on international support Federal Ministry of

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Environment (2021). LEAP-based analysis confirmed that achieving the High RE pathway is not only feasible but also economically justified when externalities such as air pollution and health impacts are accounted for. Co-benefits included estimated reductions in SO_2 and NO_x emissions by over 20% in urban zones, in line with projections made by UNEP and UNECA for similar transition scenarios in sub-Saharan Africa (UNECA, 2022).

Strategic Infrastructure and Policy Implications

The modeled scenarios provide actionable insights for Nigerian energy planners and policymakers. First, the inclusion of regional interconnections via the West African Power Pool (WAPP) showed strong benefits for managing surplus generation and avoiding curtailment during peak solar hours. In the High RE scenario, Nigeria exported up to 2.2 TWh of electricity annually while importing 1.4 TWh of hydro-based baseload from neighbors, with an estimated net benefit of $44 million per year (ECOWAS, 2023).

These findings support earlier work by ECOWAS WAPP and Bhuyan (2019), which emphasized that cross-border energy trade reduces unit costs and increases system stability. Interconnection should be a cornerstone of Nigeria's future grid development strategy, supported by digital market operations and flexible contract structures. On the regulatory front, enabling policies are required to incentivize BESS deployment, scale DSM technologies, and enforce grid code updates that mandate smart inverter controls. The fragmentation across regulatory agencies (e.g., NERC, NBET, TCN) remains a challenge, as highlighted by Mathibedi et al., (2025). Regulatory harmonization, performance-based tariffs, and investment protection frameworks will be essential to attract private sector participation in renewable projects and storage infrastructure.

CONCLUSION

This study presented a rigorous and integrated approach to modeling the impacts of high renewable energy penetration on Nigeria's power grid, addressing critical dimensions of technical feasibility, economic optimization, and infrastructural resilience. Using a combination of long-term planning tools, hourly economic dispatch modeling, and detailed power system simulations, the research evaluated three development scenarios—Business-As-Usual (BAU), Intermediate Renewable Energy (RE), and High RE penetration—under realistic operational constraints and resource conditions. The findings revealed that substantial deployment of solar and wind energy, when complemented by battery energy storage systems (BESS), demand-side management (DSM), and inverter-based voltage control, results in a grid that is both cost-effective and reliable. Total generation costs decreased significantly across scenarios, with the High RE pathway yielding over 29% cost savings relative to BAU.

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These savings were attributed to fuel displacement, optimized dispatch schedules, and improved operational efficiency enabled by energy storage and flexible demand.

The technical analysis further showed that grid stability, often viewed as a limiting factor in renewable integration, improved considerably with the adoption of smart grid technologies. Voltage deviations, which were prevalent under the BAU scenario, were minimized using dynamic reactive power support, indicating that Nigeria’s grid infrastructure can accommodate a high share of variable renewables without compromising performance or security. Importantly, unserved energy was nearly eliminated in high renewable scenarios, indicating an overall improvement in adequacy and reliability of supply.

From an environmental standpoint, the transition to renewable energy demonstrated profound climate mitigation potential. Emissions reductions of over 60% from baseline levels were observed under the High RE scenario, underscoring the critical role of clean electricity in achieving Nigeria’s decarbonization and sustainable development goals. In addition to carbon savings, reductions in local air pollutants and associated public health improvements further strengthened the case for a renewable-powered future. Strategically, the study emphasized the enabling role of regional power integration and flexible infrastructure planning. Simulated cross-border electricity trade within the West African Power Pool (WAPP) enhanced grid utilization, reduced curtailment, and provided economic benefits through arbitrage opportunities. These results support the inclusion of regional energy cooperation as a core pillar of Nigeria’s energy strategy.

Overall, the study offers strong empirical and analytical evidence that Nigeria can achieve a flexible, low-carbon, and economically efficient electricity system by strategically investing in renewable generation, grid flexibility resources, and regional interconnectivity. Realizing this future will depend on decisive action in key areas: upgrading transmission infrastructure, scaling up energy storage, accelerating DSM programs, and reforming regulatory frameworks to support innovation and investment. Future research should explore real-time grid management algorithms, hybrid market mechanisms, and the integration of electric mobility and distributed energy resources (DERs) into the Nigerian energy landscape. As electricity demand continues to grow, such work will be essential to guide policy, attract private investment, and ensure a just and sustainable energy transition.

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