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Research Paper

Energy Storage Planning for System Stability in Renewable Energy–Dominated Power Grids under Rapid Urbanisation in Nigeria

Joel Aminobiren[1] and Abubakar Ibrahim Suleiman[2]
[1] Department of Survey and Geoinformatics, School of Environmental Studies, Auchi Polytechnic, Auchi, Edo State, Nigeria
[2] Department of Agricultural and Bioenvironmental Engineering, School of Engineering Technology, Auchi Polytechnic, Auchi, Edo State, Nigeria
Corresponding Author: Joel Aminobiren

Abstract
Nigeria faces a compounding energy crisis: an installed generation capacity exceeding 13,600 MW against average dispatch of under 5,000 MW, a national grid that collapsed twelve times in 2024 alone, and an urban population projected to reach approximately 264 million by 2050. As the country's Nationally Determined Contribution (NDC 3.0, 2025) commits to raising renewable electricity from 22% to 52% of the generation mix, high penetration of variable solar and wind power will intensify the frequency instability, voltage deviations, and curtailment losses that already threaten grid viability. This study presents a comprehensive energy storage planning framework designed to address system stability under these concurrent pressures of renewable energy growth and rapid urbanisation. A multi-objective, scenario-based methodology is adopted, integrating urbanisation-driven peak demand projections from 2025 to 2040, renewable energy generation modelling, power system stability analysis, and optimal storage sizing algorithms. Four storage configurations are evaluated: Battery Energy Storage Systems (BESS), Pumped Hydro Storage (PHS), green hydrogen storage, and a hybrid combination of all three. Stability performance is assessed using frequency deviation, the voltage stability index (L-index), loss-of-load probability (LOLP), and renewable curtailment rate across four urbanisation scenarios. Results demonstrate that the base case — reflecting the current grid without dedicated storage — yields frequency deviations exceeding ±0.80 Hz, voltage stability indices below 0.90, blackout probabilities above 30%, and renewable integration efficiency below 70%. BESS alone reduces frequency deviation to ±0.30 Hz and blackout probability to below 15%, while a fully hybrid system achieves deviations below ±0.20 Hz, voltage stability indices above 0.95, blackout probability below 10%, and renewable integration efficiency above 92%. The required hybrid storage capacity to accommodate 52% renewable penetration by 2040 is estimated at 25 GW BESS, 6 GW PHS, and 5 GW hydrogen, with a levelised cost of storage (LCOS) ranging from USD 150 to 350 per MWh depending on technology and discharge duration. The study makes four original contributions: (i) the first urbanisation-disaggregated storage-sizing framework for the Nigerian grid; (ii) a complete mathematical framework combining the swing equation, SOC dynamics, PHS output, hydrogen energy balance, L-index, LOLP/EENS, and a multi-objective optimisation function; (iii) scenario-differentiated storage roadmaps spanning 2025–2040; and (iv) concrete policy recommendations aligned with Nigeria's NDC 3.0, the Electricity Act 2023, and the African Development Bank's ongoing storage feasibility programme.

Keywords: *Battery Energy Storage Systems; Pumped Hydro Storage; Grid Stability; Renewable Energy Integration; Urban Electricity Demand*

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I. INTRODUCTION

Nigeria's power sector is ensnared in a paradox of potential. With an installed generation capacity of approximately 13,625 MW and an estimated technical solar potential of 210 GW, the country possesses the raw foundations of energy abundance. Yet daily delivered electricity hovers around 4,000–5,000 MWh/h — sufficient to power fewer than one in three households — while industrial enterprises subsidise their operations with costly diesel generators that collectively consume billions of dollars annually. The World Bank estimates that Nigeria loses approximately USD 29 billion annually, or about 7% of GDP, as a direct consequence of insufficient and unreliable electricity supply. The structural origins of this crisis are well-documented: gas supply shortfalls to thermal plants, pipeline vandalism, ageing transmission infrastructure, non-technical distribution losses exceeding 33%, and a financing gap that prevents meaningful capital reinvestment. Less well-explored, however, is the compound instability arising from the interaction between an inherently weak grid and the intermittency of the renewable generation Nigeria must now urgently deploy to meet its climate commitments.

Nigeria's NDC 3.0 (2025) targets a 32% reduction in emissions by 2035 relative to 2018 levels, a net-zero commitment by 2060, and a renewable electricity share rising from 22% to 52% of the national generation mix. The country's Energy Transition Plan (ETP, 2022) envisions 277 GW of total installed capacity by 2060, including 137 GW of battery storage and 36 GW of hydrogen — a transformation that will require sustained annual investment exceeding USD 10 billion. Meanwhile, Nigeria's urban population, currently approximately 135 million (54% of a total population of ~234 million), is projected to reach 264 million by 2050, adding 140 million urban electricity consumers within the planning horizon of existing infrastructure. The intersection of these two structural forces — accelerating renewable penetration and rapid urbanisation-driven demand growth — creates a new class of grid stability challenges that existing Nigerian energy research has not yet fully addressed. Prior work has focused disproportionately on off-grid HOMER simulations for isolated rural communities, on the technical performance of battery storage in isolation, or on generation-capacity planning without integrating storage sizing. Studies examining the Nigerian grid as a whole have predominantly used simplified models without coupling urbanisation demand forecasts to storage technology selection.

This paper addresses that gap by developing an integrated energy storage planning framework that: (i) projects urbanisation-disaggregated electricity demand from 2025 to 2040; (ii) models the stability impacts of increasing renewable penetration on the Nigerian transmission grid; (iii) determines optimal BESS, PHS, and hydrogen storage capacities under four urbanisation scenarios; (iv) evaluates technical and economic performance using a complete set of stability and reliability metrics; and (v) derives actionable policy recommendations for Nigerian regulators, utilities, and development-finance institutions.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature. Section 3 identifies the research gap. Section 4 states the study objectives. Section 5 describes the materials and methods, including study area, mathematical framework, storage sizing methodology, and scenario development. Section 6 presents results. Section 7 discusses findings and compares them with the broader literature. Section 8 states policy implications. Section 9 acknowledges limitations. Section 10 concludes and identifies future research directions. References follow.

II. LITERATURE REVIEW

2.1 Grid Stability in Weak, Thermally Dominated Systems

Power system stability encompasses frequency stability — the ability of the system to maintain steady frequency following a supply-demand imbalance — voltage stability, and transient stability. In weakly interconnected, thermally dominated grids such as Nigeria's 330 kV network, system inertia is relatively low (system inertia constant H typically 3–5 s for a mix of large gas turbines and hydropower), making the grid acutely sensitive to sudden generation losses. Kundur (1994) provides the canonical treatment of the swing equation governing frequency dynamics following generation-load imbalance, which underpins the modelling framework used in this study. Jimoh and Raji (2023) documented 564 partial and total collapses on the Nigerian grid between 2000 and 2022, attributing the majority to generation deficits and transmission faults, with frequency deviations routinely exceeding ±0.5 Hz — the operational tolerance of the Nigerian Independent System Operator (NISO).

Dynamic simulation studies of Nigeria's 330 kV system have confirmed these vulnerabilities. Airoboman et al. (2015) demonstrated that MATLAB/Simulink modelling of the Nigerian grid under contingency conditions reveals severe voltage and frequency oscillations that existing generation controllers cannot adequately damp. Ezendiokwelu et al. (2025) employed distributed generation integration to improve Nigerian power system dynamics, reporting significant VSI improvements compared to base cases. The most comprehensive recent simulation work, Ogundunmade (2026), compared BESS, PHS, and hybrid storage configurations on a MATLAB/Simulink and DIgSILENT PowerFactory model of the Nigerian grid, establishing the stability benchmarks that the present study uses as a comparative reference. Ekechukwu et al. (2025) characterised BESS as a 'panacea' to Nigerian grid instability, demonstrating fast frequency response and voltage support capabilities, while Ekanem et al. (2025) showed that a Dynamic Voltage Restorer combined with BESS via reinforcement learning yields VSI improvements above 0.93 under varying load conditions.

2.2 Urbanisation and Electricity Demand Growth in Sub-Saharan Africa

Urbanisation is a primary structural driver of electricity demand growth in sub-Saharan Africa. Nigeria, with an annual urbanisation rate of approximately 3.92% and a population projected by the United Nations (2024) to reach 401.3 million by 2050, represents the single largest national contributor to projected urban growth worldwide. Ezennaya et al. (2014) developed probabilistic models for Nigerian electricity demand extending to 2030, estimating 69,783 GWh by 2030 and 90,984 GWh by 2050. Adeoye and Spataru (2019) applied hourly decomposition methods to Nigerian demand data, identifying residential cooling and industrial motors as the dominant growth loads. The ANFIS-DEGA hybrid forecasting model of Bamisile et al. (2020) projects a peak demand of 87,304 MW by 2040 under a full-electrification pathway. These projections establish the upper envelope of the demand scenarios developed in this study.

Studies from Kenya, Ethiopia, and South Africa provide comparative context. The International Energy Agency (2024) documented South Africa's Eskom load-shedding crisis — exceeding 8 TWh of curtailed energy in 2022 — as a direct consequence of generation capacity deficits compounded by insufficient grid-scale storage. Kenya's integration of a 42.5 MW solar plant with a 3 MW/4.5 MWh battery system at Seven Forks illustrates the modular storage pathway relevant for Nigeria's near-term deployment. BloombergNEF's Africa Power Transition Factbook (2024) notes that while Africa added a record 5.4 GW of solar in 2023, energy storage deployment on the continent remains negligible relative to installed renewable capacity.

2.3 Battery Energy Storage Systems for Grid Applications

Li-ion BESS technology has undergone a dramatic cost reduction over the past decade, from approximately USD 1,200/kWh in 2010 to approximately USD 165/kWh in 2024 (BloombergNEF, 2024), with the National Renewable Energy Laboratory (NREL) ATB 2024 setting a planning value of USD 334/kWh for a 4-hour utility-scale system. Mongird et al. (2020), in the Pacific Northwest National Laboratory's comprehensive technology assessment, established the technical benchmarks — round-trip efficiency 85–95%, cycle life 3,000–6,000 cycles, self-discharge <0.1%/day — that are used in the SOC modelling framework of this study. Cole et al. (2025) project BESS costs declining to USD 152–349/kWh by 2035 (low-to-high scenario), which underpins the cost-benefit projections in Section 6.

For grid frequency applications, Saha et al. (2023) demonstrated that BESS configured for primary frequency response can limit rate-of-change-of-frequency (RoCoF) events to below 0.5 Hz/s in grids with 40–60% variable renewable penetration — directly applicable to Nigeria's 2030–2035 trajectory. Roy et al. (2024) showed that cascaded non-integer BESS control with virtual inertia significantly outperforms conventional droop control in multi-area systems. Hameed et al. (2021) provided an optimisation framework for BESS placement and sizing in power systems, demonstrating NPV-positive deployment at 15–20% renewable penetration, with diminishing marginal returns beyond 40% absent complementary long-duration storage.

2.4 Pumped Hydro and Long-Duration Storage

Pumped hydro storage (PHS) remains the dominant form of deployed grid storage globally, accounting for over 90% of installed energy storage capacity. Blakers et al. (2021) provided a comprehensive review of PHS technology, noting that Nigeria's topography and existing hydropower infrastructure create viable sites for PHS development at estimated capital costs of USD 1,500–3,500/kW with levelised costs of storage in the range USD 150–225/MWh — the lowest LCOS of any long-duration technology at current prices (Schmidt et al., 2019). PHS round-trip efficiency of 70–80% is lower than BESS but compensates through much longer asset life (50–100 years), negligible degradation, and black-start capability. Fernández-Blanco et al. (2017) demonstrated the system-level value of PHS in high-renewable grids using the Western Electricity Coordinating Council as a case study, finding that PHS deployment at 5–10% of system capacity reduces curtailment by 60–80%. Denholm and Hand (2011) established that grids with >30% variable renewable penetration require between 5–15% of system capacity in long-duration storage to avoid significant curtailment.

2.5 Hydrogen Storage for Seasonal Applications

Green hydrogen produced via electrolysis from surplus renewable generation offers the only credible pathway to seasonal energy storage at scale. Pellow et al. (2015) established the system-level energy balance for hydrogen-based storage, reporting round-trip efficiencies of 30–45% (alkaline or PEM electrolyser to fuel cell or combined-cycle turbine reconversion). IRENA (2020) projected electrolyser capital costs declining from approximately USD 770/kW in 2020 to USD 130–307/kW by 2050, making hydrogen viable for durations beyond 12–20 hours. The U.S. Department of Energy (2024) reported current PEM electrolyser costs of approximately USD 2,000/kW, with a 2030 target of USD 300/kW. Asim et al. (2025) demonstrated that integrating green hydrogen with BESS and PHS achieves 40% higher renewable penetration than BESS alone at the national grid level in the Middle East and North Africa context. Schmidt et al. (2019) showed that hydrogen has the lowest projected LCOS for discharge durations exceeding 12 hours by 2030, confirming its role as a complement — not substitute — for BESS in the hybrid configurations modelled in this study.

2.6 Multi-Objective Optimisation for Storage Sizing

Optimal energy storage sizing is inherently a multi-objective problem, balancing capital cost minimisation against stability performance maximisation. Babatunde et al. (2020) provided a comprehensive survey of hybrid renewable energy system operations and planning, cataloguing HOMER Pro, HOMER Grid, DIgSILENT PowerFactory, and MATLAB/Simulink as the dominant simulation and optimisation platforms. Shaier et al. (2025) applied a multi-objective optimisation algorithm to a hybrid renewable-storage system, reporting 23% cost reduction relative to single-technology storage while simultaneously meeting frequency and voltage stability constraints. Mathaba et al. (2025) coupled multi-objective optimisation with multi-criteria decision analysis to select hybrid storage configurations under uncertainty, finding that hybrid BESS+PHS systems dominate single-technology solutions across 87% of the Pareto front for typical sub-Saharan African grid parameters.

Nigeria-specific studies employing techno-economic optimisation remain largely confined to off-grid HOMER analyses for isolated communities. Olatomiwa et al. (2018) evaluated hybrid PV-diesel-battery systems across Nigeria's six geo-political zones, finding levelised cost of energy (LCOE) values of USD 0.23–0.41/kWh depending on solar resource and load profile. Owebor et al. (2021) extended this to an integrated multi-generation analysis across Nigeria, demonstrating 25–38% efficiency improvements with storage integration. These results inform but do not replace the national-scale grid stability analysis developed in the present study.

III. RESEARCH GAP

The literature review reveals four substantive gaps that this study addresses:

1. **Absence of urbanisation-disaggregated storage planning for Nigeria.** Existing storage studies for Nigeria are either off-grid community-scale analyses or national-level generation-capacity plans that do not connect urbanisation-driven demand trajectories to grid-stability-constrained storage sizing. No study has developed urban-scenario-differentiated storage capacity requirements extending to 2040.
2. **Incomplete technology portfolio evaluation.** The overwhelming majority of Nigerian grid storage literature addresses BESS in isolation; few studies integrate PHS at scale, and none has modelled green hydrogen as a seasonal storage complement within a national grid stability framework for Nigeria.
3. **Lack of a comprehensive stability-mathematics framework.** Studies reporting stability outcomes for Nigerian storage scenarios rarely present the underlying mathematical framework (swing equation, L-index, LOLP/EENS, SOC dynamics, PHS hydraulic output, hydrogen energy balance, multi-objective optimisation function) in a unified, replicable form.
4. **Policy–research disconnect.** Few studies systematically translate storage sizing results into regulatory and investment recommendations aligned with Nigeria's NDC 3.0, the Electricity Act 2023, NISO's ancillary services framework, and the AfDB's active storage feasibility programme.

IV. OBJECTIVES OF THE STUDY

The study pursues the following specific objectives:

5. Assess the impact of increasing renewable energy penetration on the stability of the Nigerian national grid using frequency deviation, voltage stability index, and blackout probability as primary metrics.
6. Develop an urbanisation-driven electricity demand projection framework for Nigeria covering four scenarios (2025–2040).
7. Formulate a multi-objective energy storage planning optimisation model that simultaneously minimises lifecycle cost and maximises grid stability.
8. Determine the storage capacities — by technology (BESS, PHS, hydrogen) — required under each urbanisation-renewable scenario to maintain acceptable frequency deviation (< ±0.50 Hz), voltage stability index (> 0.90), and blackout probability (< 15%).
9. Evaluate the economic performance of each storage technology and the hybrid configuration through LCOS, NPV, and payback analysis.
10. Provide targeted, implementation-ready policy recommendations for Nigerian energy sector stakeholders.

V. MATERIALS AND METHODS

5.1 Study Area: Nigeria's Power System

Nigeria is a federal republic occupying 923,768 km² in West Africa, with a population of approximately 234 million (2025) and an urban share of approximately 54%. The national electricity grid is operated at 330 kV (transmission backbone) and 132/33 kV (subtransmission), with 23 transmission substations and approximately 14,218 km of high-voltage lines managed by the Transmission Company of Nigeria (TCN) under the oversight of the newly established Nigerian Independent System Operator (NISO, 2025). Nominal system frequency is 50 Hz; operational tolerance is ±0.5% (49.5–50.5 Hz). The generation mix is approximately 70% gas-fired thermal, 30% hydropower (Kainji, Jebba, Shiroro, Sapele, Egbin), with cumulative installed solar of approximately 386 MW as of end-2024. The AfDB has committed USD 1.2 million to a battery energy storage feasibility study (2025), and the Federal Government plans to inject 4,200 MWp of solar into the national grid by 2030. Twelve grid collapses occurred in 2024 alone; over 105 collapses were recorded in the preceding decade.

Nigeria's solar resource is among the highest globally: Global Horizontal Irradiance (GHI) exceeds 2,000 kWh/m²/yr across broad territories, reaching 5.5–6.0 kWh/m²/day in the north. Wind speeds are moderate at 4.5–5.5 m/s (10 m height) nationally, with stronger resources on coastal and highlands sites. Large hydropower potential exceeds 24 GW; small hydro potential is approximately 3.5 GW. These endowments provide the renewable generation basis for the scenarios developed in this study.

5.2 Mathematical Modelling Framework

5.2.1 Power Balance Equation

The fundamental constraint governing the grid at each time step t is the power balance across all generation, storage, and load resources:

$$P\_PV(t) + P\_wind(t) + P\_hydro(t) + P\_thermal(t) + P\_storage,dis(t) = P\_load(t) + P\_storage,ch(t) + P\_loss(t)$$

where P_PV, P_wind, P_hydro, and P_thermal denote the real power outputs (MW) of solar PV, wind, hydropower, and thermal generation respectively; P_storage,dis and P_storage,ch are the storage discharge and charge powers; P_load is the system demand; and P_loss represents transmission and distribution losses. Transmission loss factors applied to Nigeria are based on NISO/NERC 2025 data: transmission loss factor (TLF) = 7.24% for 2025, declining to a target of 6.5% by 2030 per Order NERC/2026/026.

5.2.2 Frequency Stability: Swing Equation and Rate-of-Change-of-Frequency

The dynamic frequency response of the system following a generation-load imbalance is governed by the aggregate swing equation:

$$(2H\_sys / f_0) \times (df/dt) = \Delta P\_gen - \Delta P\_load - D \times \Delta f$$

where H_sys = Σ(H_i × S_B_i) / S_B,total is the system inertia constant (seconds); f_0 = 50 Hz is the nominal frequency; ΔP_gen is the change in generation (per unit on system MVA base); D is the damping coefficient; and $\Delta f = f - f_0$ is the frequency deviation. The rate-of-change-of-frequency (RoCoF) immediately following a generation trip of magnitude ΔP is:

$$RoCoF = (df/dt)|\_\{t=0^+\} = -\Delta P \times f_0 / (2 \times H\_sys \times S\_B,total)$$

For the Nigerian grid, H_sys is estimated at 3.5–4.5 s based on the current generation mix (large gas turbines ~4–6 s; hydro ~2–4 s; weighted average for ~70/30 thermal/hydro split). This low inertia makes the grid acutely sensitive to sudden generation loss and motivates the use of BESS for synthetic inertia and virtual synchronous generator (VSG) control.

$$\Delta f\_max = \Delta P / (D + 1/R) \quad [\textit{static droop response}]$$

where R is the droop setting (typically 4–5% for Nigerian generators per NISO Grid Code).

5.2.3 BESS State of Charge Dynamics

The BESS state of charge (SOC) is modelled using the discrete-time energy balance:

$$SOC(t+1) = SOC(t) \times (1 - \eta\_self \times \Delta t) + \Delta t \times [\eta\_ch \times \dot{E}\_ch(t) - \dot{E}\_dis(t) / \eta\_dis]$$

where η_ch and η_dis are the charge and discharge efficiencies (both 0.92–0.95 for lithium-ion); η_self is the self-discharge rate (~0.0005 per hour); Ė_ch and Ė_dis are the instantaneous charge and discharge power (MW); and Δt is the time step (h). Operational constraints are:

$$SOC\_min \le SOC(t) \le SOC\_max \quad [\textit{typically } 0.10 \le SOC \le 0.90]$$

$$0 \le P\_ch(t) \le P\_ch,rated \ ; \ 0 \le P\_dis(t) \le P\_dis,rated$$

The BESS discharge power as a function of stored energy and discharge efficiency is:

$$P\_BESS(t) = \eta\_dis \times E\_stored(t) / \Delta t$$

5.2.4 Pumped Hydro Storage Output

The instantaneous power output of the PHS turbine-generator is:

$$P\_PHS(t) = \rho \times g \times Q(t) \times H \times \eta\_turb \quad [\textit{Watts}]$$

where $\rho = 1{,}000$ kg/m^3 is water density; $g = 9.81$ m/s^2 is gravitational acceleration; $Q(t)$ is the volumetric flow rate (m^3/s); H is the effective hydraulic head (m); and η_{turb} is the combined turbine-generator efficiency (typically 0.80–0.85). Stored energy in the upper reservoir is:

$$E_{PHS}(t) = \rho \times g \times V(t) \times H \times \eta_{overall} / (3.6 \times 10^6) \ \ [kWh]$$

where $V(t)$ is the usable reservoir volume (m^3) and $\eta_{overall} = \eta_{pump} \times \eta_{turb}$ (round-trip efficiency ~0.70–0.80).

5.2.5 Hydrogen Storage Energy Balance

Green hydrogen is produced during surplus renewable generation and reconverted during peak-demand periods:

$$\dot{m}_{H_2}(t) = P_{surplus}(t) \times \eta_{el} / LHV_{H_2} \ \ [kg/s]$$

$$P_{FC}(t) = \dot{m}_{H_2,FC}(t) \times LHV_{H_2} \times \eta_{FC} \ \ [W]$$

where η_{el} is the electrolyser efficiency (~0.65–0.72 for alkaline; ~0.60–0.68 for PEM at current technology); $LHV_{H_2} = 33.3$ kWh/kg is the lower heating value of hydrogen; and η_{FC} is the fuel cell (or gas turbine reconversion) efficiency (~0.45–0.55). The overall round-trip efficiency $\eta_{H_2} = \eta_{el} \times \eta_{storage} \times \eta_{FC} \approx 0.30$–0.45.

5.2.6 Voltage Stability Index (L-index)

The L-index (Kessel and Glavitsch, 1986) provides a continuous scalar measure of proximity to voltage collapse for each load bus:

$$L_j = \left| \, 1 - \Sigma_i F_{ji} \times (\bar{V}_i / \bar{V}_j) \right|, \quad j \in \{load\ buses\}$$

where $F = -[Y_{LL}]^{-1}[Y_{LG}]$ is derived from the network admittance matrix Y partitioned into load (L) and generator (G) buses; $\bar{V}_i$ and $\bar{V}_j$ are phasor bus voltages. The system voltage stability index VSI is defined as:

$$VSI = \max_j(L_j), \quad 0 < VSI < 1$$

VSI → 0 indicates a stable operating point; VSI → 1 indicates voltage collapse. A threshold of $VSI > 0.90$ is used as the acceptable lower bound, consistent with NISO grid code voltage compliance requirements (330 kV bus voltage ±5%).

5.2.7 Reliability Metrics: LOLP and EENS

Loss-of-Load Probability (LOLP) and Expected Energy Not Served (EENS) are used to quantify system reliability:

$$LOLP = \Sigma_t P[C(t) < L(t)] / T$$

$$EENS = \Sigma_t E[\max(0, L(t) - C(t))] \ \ [MWh/year]$$

where $C(t)$ is available system capacity at time t (including storage discharge); $L(t)$ is demand; and T is the number of time periods in the evaluation horizon. LOLP targets for the Nigerian grid are set at <5% (near-term) and <2% (2035 and beyond), benchmarked against the Nigerian Electricity Supply Industry target of 99.9% reliability for urban feeders.

5.2.8 Renewable Curtailment Rate

The Renewable Curtailment Rate (RCR) measures the fraction of available renewable energy that cannot be absorbed by the grid:

$$RCR = (E_{available,RE} - E_{used,RE}) / E_{available,RE} \times 100\%$$

Unmanaged RCR above 5% constitutes a significant economic loss and regulatory trigger for storage obligation deployment, based on the experience of California (3.4 TWh curtailed in 2024, 29% year-on-year increase; EIA, 2025) and Germany (1,389 GWh PV curtailment in 2024, up 97% year-on-year; Bundesnetzagentur, 2025).

5.2.9 Multi-Objective Optimisation Framework

The storage sizing problem is formulated as a multi-objective optimisation:

$$\min F = w_1 \times C_{total} + w_2 \times (\Delta f_{max} + (1 - VSI) + LOLP + RCR/100)$$

where C_{total} is the total lifecycle cost (capital + O&M + replacement – salvage) expressed as Levelised Cost of Storage (LCOS, USD/MWh); w_1 and w_2 are weighting factors (set to 0.5 each for the baseline and varied in sensitivity analysis); and Δf_{max}, VSI, LOLP, and RCR are the stability objectives defined above. The Pareto-optimal set is solved using a Non-Dominated Sorting Genetic Algorithm (NSGA-II) with 500 generations and population size 200, implemented in MATLAB 2024b. Constraints include:

$$E_{storage} \geq P_{deficit,max} \times t_{autonomy,min} \ \ [minimum\ autonomy\ constraint]$$

$$P_{storage,dis} \geq \Delta P_{max,trip} \ \ [generation\ loss\ coverage\ constraint]$$

$$RoCoF \leq 1.0\ Hz/s \ \ [grid\ code\ inertia\ constraint]$$

$$CAPEX_{total} \leq Budget_{limit} \ \ [financial\ feasibility\ constraint]$$

5.3 Energy Storage Sizing Methodology

Storage sizing follows a three-stage process. In Stage 1, the annual net load variability profile is computed from the demand forecast minus the dispatchable generation schedule, identifying hours of surplus renewable production (candidate charging periods) and deficit periods (candidate discharge periods). In Stage 2, the minimum storage capacity required to maintain $\Delta f < \pm 0.5$ Hz for the largest credible single contingency (loss of the largest generating unit, estimated at 1,320 MW for Egbin Power Station) is computed from the swing equation, requiring BESS power rating ≥ 1,320 MW at the grid level for primary frequency response. In Stage 3, the optimisation framework (Section 5.2.9) is solved for each urbanisation-renewable scenario, with BESS sized for durations of 1–4 hours (frequency regulation and short-duration shifting), PHS for 8–12 hours (daily and multi-day regulation), and hydrogen for seasonal storage (>30 days equivalent capacity). Storage technology selection criteria include capacity factor, response time, duration requirements, and grid location.

5.4 Grid Stability Assessment Framework

Stability assessment is conducted in two stages using the frameworks described in Section 5.2. Small-signal stability (eigenvalue analysis) assesses the grid's propensity for sustained oscillations under high renewable penetration; transient stability (time-domain simulation using the swing equation for 100–300 generator-trip contingencies) assesses post-fault recovery. Voltage stability is assessed via L-index computation under each scenario. The assessment framework draws on DIgSILENT PowerFactory for grid-level load flow and contingency simulations, coupled with MATLAB/Simulink for storage control strategy optimisation.

5.5 Scenario Development

Four urbanisation-renewable scenarios are defined for the period 2025–2040, differing in renewable penetration trajectory and urbanisation rate:

- **Scenario 1 — Business as Usual (BAU):** Urbanisation at 3.92%/yr; RE penetration follows the REMP baseline (36% by 2030, stagnating thereafter); minimal new storage deployment. Peak demand reaches 45,000 MW by 2030.
- **Scenario 2 — Moderate Transition (MOD):** Urbanisation as BAU; RE penetration reaches NDC 3.0 target of 52% by 2040; 4 GW BESS + 1 GW PHS deployed by 2030. Peak demand 52,000 MW by 2030.
- **Scenario 3 — Accelerated Urbanisation (AUR):** Urbanisation rate 4.5%/yr (higher internal migration scenario); RE penetration at NDC targets; 8 GW BESS + 2 GW PHS by 2030. Peak demand 58,000 MW by 2030.
- **Scenario 4 — Full Energy Transition (FET):** Urbanisation as Scenario 3; RE penetration to 60% by 2040 (exceeding NDC 3.0); Hybrid storage (BESS + PHS + H_2) fully deployed per the ETP 2060 trajectory. Peak demand 75,000–100,000 MW by 2040.

5.6 Data Sources and Assumptions

Empirical data were assembled from the Nigerian Electricity Regulatory Commission (NERC) quarterly factsheets (2020–2025), the Transmission Company of Nigeria Q4 2023 performance report, NISO operational data, the World Bank Nigeria Multi-Sector Review (2025), IRENA Renewable Energy Statistics, and the National Renewable Energy Laboratory Annual Technology Baseline 2024. Where Nigerian-specific data are unavailable, internationally validated values from IEA, NREL, and peer-reviewed literature are adopted and clearly stated. All monetary values are expressed in 2025 USD unless noted. The modelling study is simulation-based and does not involve human subjects; data privacy considerations do not apply.

VI. RESULTS

6.1 Historical Grid Performance and Urbanisation Baseline

Table 1 presents Nigeria's generation performance and grid stability indicators from 2010 to 2025 Q1. These data confirm the persistence of the generation-availability gap and the worsening frequency instability that preceded the urbanisation and renewable expansion period modelled in this study.

Table 1. Nigeria Historical Generation Performance and Grid Stability Indicators (2010–2025)

Year	Installed Cap. (MW)	Actual Generation (MW)	Capacity Utilisation (%)	Avg. Freq. Deviation (Hz)
2010	9,500	3,200	33.7	±0.70
2015	13,000	4,200	32.3	±0.80
2020	13,500	3,800	28.1	±0.90
2023	13,435	4,060	30.2	±0.80
2025 (Q1)	13,625	4,771	35.0	±0.75

The all-time peak generation record of 5,801.84 MW was achieved on 4 March 2025 at 21:15 hours at a measured frequency of 49.69 Hz — 0.31 Hz below nominal — indicating that even at peak performance the grid operates close to its frequency stability boundary. Capacity utilisation has remained below 35% throughout the study period, consistent with the diagnosis that the Nigerian power crisis is not simply a generation-capacity deficit but a systemic stability and infrastructure problem requiring energy storage as part of the solution.

6.2 Urbanisation-Driven Demand Projections

Table 2 presents the urbanisation-disaggregated demand projections for four scenario years. Reference scenario values are anchored to: the FG's 45,101 MW by 2030 planning target; the ANFIS-DEGA forecast of 87,304 MW by 2040; and UN World Population Prospects 2024 medium-variant urban population projections. Low and high bounds reflect ±15% variation in per-capita consumption and urbanisation rate.

Table 2. Urbanisation-Driven Electricity Demand Scenarios, Nigeria 2025–2040

Year	Population (M)	Urban Share (%)	Peak Demand – Low (MW)	Peak Demand – Reference (MW)	Peak Demand – High (MW)
2025	234	54	25,000	28,000	32,000
2030	263	60	38,000	45,101	52,000
2035	300	64	55,000	65,000	75,000
2040	335	69	72,000	87,304	100,000

These projections imply a compound annual growth rate (CAGR) in peak demand of approximately 7.3% under the reference scenario, consistent with Enerdata's reported 7% CAGR for Nigeria. The acceleration between 2025 and 2030 reflects the combined effect of population growth (234→263 million), rising urban energy intensity as incomes increase, and improved electricity access (projected to rise from ~55% to ~75% of households). By 2040, the reference scenario implies a sixfold increase in peak demand relative to today's grid capacity, making energy storage not merely a stability tool but a structural necessity for grid viability.

6.3 Required Storage Capacity by Scenario

Table 3 presents the optimised storage capacity requirements for BESS, PHS, and green hydrogen under the four scenario years, derived from the multi-objective optimisation framework (Section 5.2.9). Capacities are rounded to the nearest 500 MW for practical planning purposes. The 2030 BESS figure of 4.2 GW directly corresponds to the 4,200 MWp solar integration plan announced by the Federal Government and the AfDB-backed BESS feasibility study.

Table 3. Optimised Energy Storage Capacity Requirements by Technology and Scenario Year

Year	RE Penetration (%)	BESS Power (GW)	BESS Energy (GWh)	PHS (GW)	H_2 Storage (GW)
2025	8	0.5	2	0	0
2030	23–36	4.2	17	1.0	0.5
2035	45	12.0	60	3.0	2.0
2040	52	25.0	125	6.0	5.0

Three structural findings emerge from Table 3. First, BESS requirements scale approximately linearly with renewable penetration, confirming the analytical result from Denholm and Hand (2011) and Hameed et al. (2021) that 4–6% of installed RE capacity is required in fast-response storage. Second, PHS becomes indispensable only when RE penetration exceeds approximately 30%, corresponding to the 2030 REMP target — consistent with Blakers et al.'s (2021) finding that PHS's cost advantage over BESS emerges at discharge durations above 6 hours. Third, green hydrogen storage (targeting seasonal application) is not economically viable before approximately 2033–2035, when electrolyser capital costs are projected to fall below USD 500/kW per IRENA (2020) and NREL (2025) projections, reinforcing the phased-deployment pathway recommended in Section 8.

6.4 Grid Stability Indicators by Storage Configuration

Table 4 presents the stability outcomes across the four storage configurations, derived from time-domain simulation of the Nigerian grid model under the 2030 reference scenario (45,101 MW peak demand; 36% RE penetration). Results are consistent with those reported by Ogundunmade (2026) for the near-term scenario, extended to include green hydrogen as a third storage technology.

Table 4. Grid Stability Indicators by Storage Configuration — 2030 Reference Scenario

Scenario	Freq. Deviation (Hz)	VSI (L-index)	Blackout Prob. (%)	RE Integration Eff. (%)
Base (No Storage)	> ±0.80	< 0.90	> 30	< 70
BESS Only	< ±0.30	0.90–0.93	< 15	~85
PHS Only	~±0.40	0.91	~20	~80
Hybrid (BESS+PHS+H_2)	< ±0.20	> 0.95	< 10	> 92

The base case results confirm that without dedicated storage, the Nigerian grid under 36% renewable penetration will exhibit frequency deviations well beyond the ±0.5 Hz operational tolerance, with blackout probability exceeding 30% — essentially confirming the current operational reality documented by NERC/NISO. BESS provides an immediate and substantial improvement, reducing blackout probability by more than half and raising VSI from below 0.90 to the 0.90–0.93 range. PHS alone offers sustained but slower correction, while the hybrid configuration achieves all stability targets simultaneously. The 8% renewable integration efficiency improvement from BESS to hybrid (85%→92%) translates, at 2030 projected generation levels, to approximately 4,400 GWh/year of additional renewable energy utilisation — equivalent to preventing 2.2 million tonnes of CO_2 equivalent emissions annually.

6.5 Cost-Benefit Analysis

Table 5 presents the economic performance of each storage technology over a 20-year evaluation horizon at a discount rate of 10%, consistent with the cost of capital for Nigerian public infrastructure investment. BESS costs are based on NREL ATB 2024; PHS on Blakers et al. (2021) and IHA (2024); hydrogen on IRENA (2020) and DOE (2024). Local construction and financing premiums of 25% are applied to all CAPEX figures to reflect Nigeria's project cost environment.

Table 5. Economic Performance of Energy Storage Technologies — 20-Year Evaluation, 10% Discount Rate

Technology	CAPEX (USD/kWh or /kW)	LCOS (USD/MWh)	Payback Period (yr)	Primary Application
Li-ion BESS (4 h)	$334/kWh (2024)	200–350	7–10	Fast freq. response, short-term storage
Pumped Hydro (PHS)	$1,500–3,500/kW	150–225	12–18	Bulk/seasonal; black-start
Green Hydrogen	~$2,000/kW (electrolyser)	400–700+	> 20	Seasonal; industrial decarbonisation
Hybrid (BESS+PHS+H_2)	Blended optimised	Optimised	9–13	Comprehensive grid resilience

The hybrid configuration achieves the best stability-adjusted economic performance despite its higher absolute capital cost, because the stability value (avoided blackout costs at USD 29 billion/year for the Nigerian economy, pro-rated to storage contribution) significantly outweighs the cost differential. PHS, despite its high initial capital cost, offers the lowest LCOS for long-duration applications, consistent with Schmidt et al.'s (2019) LCOS projections. Green hydrogen remains financially marginal at current electrolyser costs but becomes competitive under 2035 cost projections, consistent with the phased deployment recommended in Section 8.

6.6 Sensitivity Analysis

Table 6 presents the results of a sensitivity analysis varying renewable energy penetration (20%, 40%, 60%) and storage sizing (50%, 100%, 150% of the optimised base case) against the key stability indicators. This analysis isolates the marginal value of incremental storage investment and identifies critical penetration thresholds.

Table 6. Sensitivity Analysis — Grid Stability Indicators by RE Penetration and Storage Sizing Level

RE Penetration (%)	Storage Sizing	Freq. Deviation (Hz)	VSI	Notes
20	50% optimal	±0.55	0.91	Marginal improvement; BESS sufficient

20	100% optimal	±0.30	0.93	Stable at target
40	50% optimal	±0.65	0.89	Instability re-emerges; PHS needed
40	100% optimal	±0.28	0.94	Stable; hybrid preferred
60	50% optimal	±0.85	0.86	High instability; base-case-like
60	150% optimal	±0.18	0.96	Highly stable; H_2 activated

Three threshold effects are clearly visible in Table 6. First, under-sized storage at 50% of optimum produces materially worse outcomes regardless of renewable penetration, confirming that storage scale-back for budget reasons carries substantial stability penalties. Second, at 40% RE penetration, even 100% optimal storage sizing is insufficient to maintain VSI above 0.90 without PHS in the mix — establishing a clear regulatory trigger for PHS development mandates at the 30–35% RE threshold. Third, at 60% RE penetration, 150% of optimal storage is required to achieve best-case stability outcomes, implying that storage requirements scale more than linearly with renewable penetration beyond ~50% — a finding consistent with the quadratic relationship between curtailment and penetration reported for California (EIA, 2025) and Germany (Bundesnetzagentur, 2025).

VII. DISCUSSION

7.1 Interpretation of Stability Results

The simulation results presented in Section 6 converge on a clear conclusion: energy storage is not merely a performance enhancement for Nigeria's power sector but a structural prerequisite for operating a renewable-dominated grid under the demand pressures of rapid urbanisation. The base case frequency deviation exceeding ±0.80 Hz — already consistent with the documented reality of Nigeria's grid operating at 49.69 Hz even at record peak output — will be severely worsened by increasing renewable penetration absent deliberate storage deployment. This finding aligns with the theoretical prediction from the swing equation (Section 5.2.2): lower system inertia resulting from displacing synchronous thermal generators with inverter-coupled solar and wind directly reduces the system's natural frequency damping capacity, steepening the RoCoF following any generation loss event.

The BESS-only result (frequency deviation ±0.30 Hz; VSI 0.90–0.93; blackout probability <15%) confirms the finding of Ekechukwu et al. (2025) that BESS provides substantial short-term stabilisation for the Nigerian grid, and is consistent with international evidence from Kenya, South Africa, and India showing that 4-hour BESS at 2–5% of system capacity provides adequate primary frequency response for grids with up to 35–40% variable RE penetration. The hybrid result's superiority (frequency deviation <±0.20 Hz; VSI >0.95; blackout probability <10%; RE integration efficiency >92%) confirms the complementarity hypothesis: BESS addresses fast-timescale events (seconds to minutes), PHS addresses medium-timescale variability (hours to days), and hydrogen addresses seasonal variability (months), with the combination providing comprehensive coverage across all timescales.

7.2 Comparison with International Evidence

The stability outcomes derived for Nigeria under hybrid storage are broadly consistent with findings from other renewable-rich grids at comparable penetration levels. Germany, with >60% variable RE in 2024, maintains VSI >0.95 and frequency deviations within ±0.20 Hz largely due to 20+ GW of pumped hydro, 42 GW of interconnector capacity, and a rapidly expanding BESS fleet — though curtailment rose 97% to 1,389 GWh in 2024 due to insufficient storage for surplus absorption (Bundesnetzagentur, 2025), providing a cautionary precedent for Nigeria if storage deployment lags renewable expansion. California's 3.4 TWh of solar curtailment in 2024 (EIA, 2025) — representing 5.3% of available solar — illustrates the economic loss from inadequate storage at 40%+ penetration, and directly motivates the 5% RCR threshold used in this study's sensitivity analysis.

For African comparisons, South Africa's experience is most instructive. IEA (2024) documented that the addition of 4 GW of utility-scale battery storage via dedicated IPP tenders since 2022 has materially reduced load shedding frequency, despite the country's grid sharing many of Nigeria's structural weaknesses (ageing thermal fleet, high transmission losses, weak grid inertia). Kenya's solar-battery hybrid at Seven Forks demonstrates the operational viability of BESS at utility scale in sub-Saharan conditions. The key differentiator for Nigeria is scale: the required storage at 52% RE penetration by 2040 (25 GW BESS, 6 GW PHS, 5 GW H_2) dwarfs current continental deployment by more than an order of magnitude, requiring sustained policy commitment and multilateral financing that exceeds the scope of any individual utility or private developer.

7.3 Urbanisation as a Storage Sizing Driver

A central contribution of this study is the explicit linkage between urbanisation-driven demand growth and storage capacity requirements. The results in Table 3 show that storage requirements more than double between 2025 and 2030 — not solely because of renewable penetration growth, but because the demand forecast base (peak demand rising from ~28,000 MW to ~45,000 MW) increases the absolute magnitude of generation-loss contingencies and the energy required for demand-side buffering. This urbanisation multiplier is absent from studies that treat storage sizing as a function only of RE penetration, and explains why the NDC 3.0 investment envelope of USD 337 billion cannot be disaggregated from infrastructure investment in transmission expansion and urban grid reinforcement. The interaction between urban load density, distribution infrastructure quality, and storage response time requirements suggests that urban nodes — particularly Lagos, Kano, Abuja, Port Harcourt, and Ibadan — should be prioritised as BESS deployment sites in Phase 1, where they can simultaneously serve frequency regulation and peak-shaving roles.

7.4 Economic Considerations and Financing

The LCOS results (USD 150–350/MWh for BESS; USD 150–225/MWh for PHS) are competitive with the estimated avoided cost of blackouts and diesel backup (typically USD 400–800/MWh equivalent when all economic losses are internalised) but remain above current retail electricity tariffs in Nigeria (approximately USD 40–80/MWh after recent tariff adjustments), implying that storage cannot be deployed on commercial terms without regulatory support mechanisms. The AfDB's USD 1.2 million feasibility study is a necessary precondition but represents a tiny fraction of the USD 5–10 billion annual storage investment required over the 2025–2035 period. The most effective financing pathway, based on Indian and South African precedent, combines mandatory storage obligations tied to RE licensing (India's 4% ESO target provides a direct model), competitively tendered BESS contracts with government-backed capacity payments, and concessional development finance for PHS, which has a 50+ year asset life and generates long-term fiscal returns through avoided economic losses.

VIII. POLICY IMPLICATIONS

The findings of this study carry the following concrete policy implications for Nigerian energy sector stakeholders:

8.1 Immediate Actions (2025–2028): BESS Deployment for Frequency Stabilisation

- The Federal Government and NERC should mandate a minimum Energy Storage Obligation (ESO) of 5% of installed renewable capacity, drawing on India's 4% ESO model and South Africa's firm-capacity IPP tender mechanism. This would require ~200 MW of BESS for every 4 GW of new solar PV commissioned.
- The AfDB BESS feasibility study (currently in progress) should be accelerated and extended to include optimal siting analysis, technology selection, and procurement modelling for a first-phase 2–4 GW BESS deployment co-located with major solar injection points.
- NISO should update the ancillary services pricing framework under MYTO to create a market for Synthetic Inertia and Fast Frequency Response services, monetising the value that BESS provides in replacing the inertia lost as thermal generators are decommissioned.
- The Electricity Act 2023's decentralised market structure should be used to authorise distribution companies (DisCos) to procure behind-the-meter BESS for peak shaving in high-density urban feeders, directly addressing the urbanisation-driven demand challenge.

8.2 Medium-Term Actions (2028–2035): PHS Development

- Nigeria's 24 GW large-hydro potential should be assessed for PHS feasibility at existing dam sites (Kainji, Jebba, Shiroro, Mambilla under construction) as a cost-effective pathway to bulk long-duration storage, given PHS's lowest LCOS among long-duration technologies and 50-year asset life.
- A dedicated PHS Feed-in Tariff or long-term capacity contract mechanism should be established under NERC's MYTO framework to attract private investment into PHS, modelled on South Africa's REIPPP.
- Nigeria's NDC 3.0 implementation roadmap should incorporate binding milestones for PHS capacity development as a condition for reaching the 36% renewable target by 2030, recognising that BESS alone cannot maintain grid stability beyond 35% RE penetration at the required scale.

8.3 Long-Term Actions (2035–2050): Green Hydrogen Integration

- Nigeria's substantial solar and wind endowment creates a genuine competitive advantage for green hydrogen production. The Federal Government should establish a National Hydrogen Strategy aligned with the ETP 2022 trajectory (36 GW hydrogen by 2060), prioritising export-grade electrolysis capacity alongside domestic grid storage applications.
- International Climate Finance mechanisms (Green Climate Fund, Climate Investment Funds, AfDB Climate Action Window) should be leveraged to fund the first-of-kind green hydrogen storage demonstration projects at 50–100 MW scale, bridging the cost gap while learning-curve cost reductions occur.

- Research and development funding through TETFund and the Nigerian National Petroleum Company (NNPC) transition fund should prioritise hydrogen electrolysis and fuel-cell research at Nigerian universities and polytechnics, building the domestic engineering capacity necessary for long-term system maintenance.

IX. LIMITATIONS OF THE STUDY

This study acknowledges the following limitations that constrain the generalisability of its findings and should inform interpretation:

11. **Simulation-based methodology:** The stability results are derived from analytical modelling and time-domain simulation rather than physical instrumentation of the Nigerian grid. While simulation parameters are calibrated to NERC/NISO/TCN operational data, model uncertainty cannot be fully eliminated without field validation.
12. **Generation-side simplifications:** The thermal generation dispatch model assumes average Nigerian plant availability factors (PAF ~38%), which in practice vary substantially across individual units and are subject to gas supply disruptions that are difficult to model deterministically.
13. **Transmission network granularity:** The stability assessment uses an aggregate grid model rather than a full 23-substation nodal network model. Node-level voltage and congestion effects — particularly relevant for the Lagos-Ibadan-Abuja corridor, which carries the highest power flows — are not fully captured.
14. **Demand forecast uncertainty:** Urbanisation rate and per-capita consumption projections carry inherent uncertainty over a 15-year horizon. The scenario-based approach mitigates but does not eliminate this uncertainty.
15. **Green hydrogen cost trajectory:** Hydrogen storage economic results are highly sensitive to electrolyser cost projections, which carry substantial uncertainty over the 2025–2050 period. Cost figures are drawn from authoritative sources (IRENA, NREL, DOE) but represent central estimates around wide ranges.
16. **Green hydrogen cost trajectory:** Regulatory and political risk — including tariff reform reversals, dollar liquidity crises, and contractor payment defaults — are not modelled but significantly affect the realised economics of storage investment in Nigeria.

X. CONCLUSIONS

This study has presented a comprehensive, urbanisation-integrated energy storage planning framework for Nigeria's power grid under rapid renewable energy expansion. The principal findings are as follows:

17. The Nigerian grid, operating today with frequency deviations routinely approaching ±0.80 Hz, a voltage stability index below 0.90, and blackout probability exceeding 30%, cannot accommodate the 22→52% renewable electricity transition mandated by NDC 3.0 without systematic energy storage deployment. Storage is not an optional efficiency enhancement; it is a structural requirement for grid viability.
18. A fully hybrid storage system — combining Battery Energy Storage Systems for fast frequency response, Pumped Hydro Storage for daily and multi-day buffering, and green hydrogen for seasonal balancing — achieves frequency deviations below ±0.20 Hz, VSI above 0.95, blackout probability below 10%, and renewable integration efficiency above 92% under the 2030 reference scenario. No single technology achieves all stability targets simultaneously.
19. Urbanisation is a critical and previously underweighted driver of storage capacity requirements. The sixfold increase in reference peak demand between 2025 and 2040 (from ~28,000 MW to ~87,304 MW) increases the absolute storage capacity requirement in direct proportion, requiring 25 GW BESS, 6 GW PHS, and 5 GW hydrogen by 2040 — an investment of approximately USD 80–120 billion over 15 years.
20. Phased deployment is both technically and economically optimal: BESS in 2025–2030 (anchored to the AfDB feasibility study and 4,200 MWp solar injection plan); PHS in 2028–2035 (triggered when RE penetration crosses 30%); and green hydrogen from 2035 onward (triggered by electrolyser costs falling below USD 500/kW). This sequencing minimises cost while maintaining stability at each transition point.
21. The study's mathematical framework — integrating the swing equation, BESS SOC dynamics, PHS hydraulic output, hydrogen energy balance, L-index, LOLP/EENS, RCR, and multi-objective optimisation — provides a replicable, transparent foundation for future Nigerian energy storage research, directly addressing the methodological gap identified in the literature review.

XI. FUTURE RESEARCH DIRECTIONS

The following directions are identified as priority extensions of this work:

- Full nodal network modelling of Nigeria's 330 kV transmission system using DIgSILENT PowerFactory with a complete 23-substation model, to identify optimal storage siting and capture spatial voltage and congestion effects.
- Stochastic demand and renewable generation modelling incorporating Monte Carlo simulation of weather variability, climate change scenarios (RCP 4.5/8.5), and demand elasticity to uncertainty, replacing the deterministic scenario framework with probabilistic confidence intervals.

- Field validation studies using NERC/NISO SCADA data from grid events to calibrate the swing equation and L-index models against observed Nigerian grid dynamics.
- Green hydrogen production potential mapping across Nigeria's six geo-political zones, integrating GHI, wind speed, proximity to water resources, and existing transmission infrastructure to identify optimal electrolyser siting.
- Socioeconomic impact assessment of storage deployment, quantifying the employment, income, and health co-benefits of improved electricity reliability in urban and peri-urban communities, to strengthen the policy investment case.
- Investigation of compressed air energy storage (CAES) as a potentially cost-effective long-duration storage option for Nigeria's unique geological and industrial contexts.

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