

MULTI-OBJECTIVE FRAMEWORK FOR SIZING AND SITING BATTERY ENERGY STORAGE SYSTEMS UNDER SOLAR AND LOAD UNCERTAINTY: APPLICATION TO THE SENEGALESE POWER SYSTEM

Issa Rohou Laye Sonko*

Ministry of Energy and Petroleum (Senegal).



*Corresponding Author: Issa Rohou Laye Sonko

Ministry of Energy and Petroleum (Senegal).

DOI: <https://doi.org/10.5281/zenodo.23118482>



How to cite this Article: Issa Rohou Laye Sonko* (2026). Multi-Objective Framework For Sizing And Siting Battery Energy Storage Systems Under Solar And Load Uncertainty: Application To The Senegalese Power System. World Journal of Pharmaceutical and Life Sciences, 12(10), 194-202.

This work is licensed under Creative Commons Attribution 4.0 International license.

Article Received on 05/09/2026

Article Revised on 25/09/2026

Article Published on 01/10/2026

ABSTRACT

Power systems subjected to pronounced solar variability are placing increasing emphasis on battery energy storage systems. Yet the contribution of storage to system performance cannot be inferred from nameplate capacity alone. It depends on the electrical location of the interconnection, the balance between power and energy ratings, operational policy, and the particular network constraint that is active at each moment. This study develops a multi-objective planning framework for the Senegalese transmission grid that ties storage siting and sizing decisions directly to secure photovoltaic hosting capacity (HCsecure). The decision space encompasses the point of connection, converter power, usable energy capacity, and storage duration. The optimization trades off annualized investment cost against photovoltaic curtailment, transmission losses, expected energy not supplied, and the increment in HCsecure. The formulation includes alternating-current power-flow physics, N-1 security, state-of-charge trajectories, reserve provision, terminal constraints, and explicit representations of solar and load uncertainty. The case study fuses official 2025 data with a reconstructed 2022 PATRP snapshot that is retained solely as a historical reference. That reconstruction reflects 358 MW of peak imports, 52 MW of spinning reserve in the documented unit commitment, eight benchmark loading conditions, and seven shunt reactors. The 10 MW/20 MWh Walo Storage facility commissioned in 2025 serves as an observed operating benchmark rather than evidence of an optimal national storage size. A B0-B9 protocol preserves a clear separation between measured observations, historical baselines, sensitivity assumptions, and solver outputs. Once the SPS-2025 AC model is parameterized with the required operator inputs, the framework can deliver auditable Pareto-optimal solutions without attributing unverified numerical outcomes to the Senegalese grid.

KEYWORDS: battery energy storage systems; optimal sizing; optimal siting; multi-objective optimization; photovoltaic integration; uncertainty; hosting capacity; Senegal; West Africa.

Abbreviations used in this paper are as follows

BESS denotes Battery Energy Storage System; PV denotes photovoltaic; HCsecure denotes secure PV hosting capacity; Δ HCsecure denotes the increase in hosting capacity attributable to storage. PB is the BESS converter rated power in megawatts; EB is the usable energy capacity in megawatt-hours; E/P is the nominal storage duration in hours; SOC is the state of charge. AC-OPF refers to alternating-current optimal power

flow; N-1 denotes the loss of a single element without violating security criteria; EENS is Expected Energy Not Supplied. OMVS is the Senegal River Basin Development Organization; OMVG is the Gambia River Basin Development Organization; PATRP is the Power Africa Transmission Roadmap to 2035; SPS is the Senegalese power system.

1. INTRODUCTION

As Senegal expands its solar portfolio, the central planning challenge has shifted from choosing a generic storage size to determining where and how storage should be deployed. Placement on a bus that is electrically remote from the elements constraining PV integration will do little to alleviate congestion, support voltages, or limit curtailment. Conversely, overspecifying power or energy inflates capital outlays without commensurate system-wide gains. A credible planning method must therefore identify the interconnection node, inverter rating, usable energy content, and the stack of grid services as a coherent package rather than as isolated choices.

Recent studies increasingly handle BESS siting and sizing as a joint decision under uncertainty rather than as sequential deterministic steps. Carpinelli et al.^[1] addressed both aspects in unbalanced active distribution networks with explicit treatment of uncertainty and planning risk. Other contributions^[2,3] combined probabilistic renewable-resource characterizations with objectives that target voltage regulation, loss reduction, and stability margins. A consistent conclusion emerges: once uncertainty is modeled explicitly, the preferred storage configuration can deviate materially from the solution obtained under deterministic assumptions.

These insights are methodologically valuable but not directly transferrable to Senegal. Much of the literature focuses on distribution feeders, IEEE prototypes, or microgrids whose operating regimes differ markedly from those of an interconnected transmission system. A recent study that applies NSGA-II with network-constrained optimal power flow to Mali's 130-bus network^[4] offers a closer regional analogue, but it also raises the bar for novelty. Replicating a familiar algorithm in another West African setting is not, by itself, a sufficient advance; the Senegalese case requires a question that is tightly coupled to its system topology and planning processes.

This paper therefore anchors storage planning in the secure PV hosting-capacity construct developed in Article 1. Storage is not introduced primarily to shave losses or correct localized voltage issues. It is treated as a

system flexibility resource whose placement, power rating, and energy capacity are justified by the additional PV that can be integrated without compromising security. This framing makes the core trade-off explicit: expand HCsecure while containing capital expenditure, curtailment, network losses, and reliability risk.

Senegal provides a compelling test environment because several structural changes are occurring concurrently: demand is rising, solar and wind projects are scaling up, the 225 kV backbone is being reinforced, cross-border exchanges are gaining prominence, and grid-scale storage has entered service. Under these conditions, the value of storage is inseparable from the prevailing network state. A location that is advantageous under one dispatch or interchange profile can become marginal under another. Recent datasets from Senelec and SIE provide the operational context for the analysis.^[5,6]

1.1. Research questions and Contributions

The guiding research question is the following: which combination of storage location, converter rating, and energy capacity maximizes secure PV integration in the Senegalese transmission system at minimum techno-economic cost under uncertainty in solar generation and demand?

- The paper contributes by jointly optimizing, at the transmission level, the BESS interconnection site, rated power, energy capacity, and duration;
- by coupling storage planning directly to the HCsecure indicator established in Article 1;
- by formulating a multi-objective problem that internalizes investment expenditure, PV curtailment, transmission losses, reliability quantified via expected energy not supplied, and the increment in secure hosting capacity;
- by contrasting deterministic planning outcomes with solutions obtained under explicit uncertainty;
- by comparing concentrated storage at a few locations with geographically dispersed portfolios; and by assessing how optimal storage requirements shift with varying levels of support from regional interconnections.

BESS planning workflow and linkage with secure PV hosting capacity

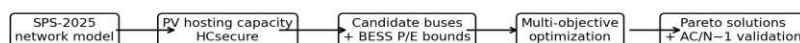


Figure 1: BESS planning methodology and linkage with secure PV hosting capacity.

2. Review of the literature and identification of the research gap

Despite extensive work on BESS placement and sizing, jointly addressing both decisions on realistic grids remains nontrivial. Siting is inherently discrete, whereas converter rating and deliverable energy are continuous design variables. These choices are coupled to state-of-

charge dynamics, the nonlinear AC power-flow equations, and uncertainty in variable generation and load. Multi-objective formulations are therefore compelling because they maintain the visibility of competing technical and economic trade-offs rather than compressing them into a single scalar objective.^[11,12,15]

Carpinelli et al.^[1] cast the task as a mixed-integer, nonlinear, multi-objective program under uncertainty and applied compromise and risk analysis to select robust plans. From a different angle, Karve et al.^[2] showed that explicitly modeling solar-resource uncertainty can increase the storage margin needed relative to deterministic designs. A complementary strand of recent work separates long-term siting and sizing from short-term operational simulation to mitigate computational burden, while still preserving nonlinear network behavior and stochasticity. Collectively, these contributions underscore that model architecture is almost as consequential as the specific optimization algorithm.

At the regional scale, recent work on Mali has demonstrated the practical feasibility of NSGA-II for allocating BESS within a real West African transmission system. The present study diverges in two respects: it ties storage allocation to a previously quantified secure PV hosting-capacity threshold and tests explicitly whether access to regional interconnection support alters the optimal BESS requirement.

The resulting research gap is more specific than the mere lack of a Senegal-focused analysis. What is needed is a transmission-level planning framework tailored to an emerging interconnected African context in which BESS siting and P/E sizing are evaluated alongside secure PV hosting capacity, uncertainty, network-security constraints, and the availability of regional support. Three insights from the literature shape the proposed methodology. First, uncertainty can reconfigure both the preferred locations and sizes of storage, which makes comparisons between deterministic and stochastic formulations indispensable.^[1,2] Second, when constraints are spatially localized, several distributed units can outperform a single device in mitigating voltage issues and losses.^[2,3] Third, recent Malian experience confirms that NSGA-II under explicit network constraints is deployable on an operational West African grid.^[4] The present work advances this line by jointly incorporating HCsecure, AC/N-1 security, uncertainty, and sensitivity to interconnection support. Additional studies^[13–16] reinforce the relevance of BESS for frequency support, relief of post-contingency overloads, and strengthening of weak grids.

3. Senegalese power system and planning context

The case study is grounded in the Senegalese power system as reported for 2025. According to Senelec's Annual Energy Movements Report, total energy reached 7,964 GWh, with national demand of 7,254 GWh. The annual peak was 1,261 MW on 4 November 2025 at 23:30, against an installed capacity of 2,310.5 MW. The same report notes the commissioning on 14 July 2025 of Walo Storage, a 10 MW/20 MWh BESS paired with 16 MWp of PV. Walo is pertinent here because it shows that utility-scale storage is already operating in Senegal, although it is not taken as evidence that 10 MW/20 MWh is system-optimal. OMVS and OMVG exchanges are also modeled, as they modify operating conditions and thereby influence the marginal value of local storage.

The planning model relies on the SPS-2025 database developed in the thesis. Buses, transmission lines, transformers, synchronous generators, PV and wind plants, loads, interconnections, and existing storage assets are represented with explicit source attribution. Unknown operator parameters are not replaced by undocumented proxies; where assumptions are unavoidable, they are treated as sensitivity variables.

Candidate buses for BESS deployment are drawn from technically salient nodes identified in Article 1, including locations associated with PV injections, congestion, voltage sensitivity, severe contingencies, and regional interties. A sensitivity variant broadens eligibility to all transmission buses to avoid an a priori bias toward currently documented sites.

3.1. Data sources and validation benchmarks

Inputs to the optimization are not accorded equal evidentiary weight. Four classes are distinguished. Class A comprises official operational measurements and reports. Class B contains official or historical technical studies. Class C covers peer-reviewed literature and verifiable manufacturer data. Class D consists of research assumptions that must be scrutinized through sensitivity analysis. This stratification is particularly salient for PATRP: its historical parameters are valuable for reconstruction and validation, but they should not be interpreted as direct measurements of the 2025 network.

Table 1: Anchor data for the Senegalese case and their role in BESS planning.

Indicator	Value	Year / status	Use in Article 2
Installed capacity	2,310.5 MW	2025 – Class A	System scale
National demand	7,254 GWh	2025 – Class A	Chronology / energy
National peak	1,261 MW	04/11/2025, 23:30 – Class A	High-load case
Walo Storage	10 MW / 20 MWh	2025 – Class A	Existing BESS reference
PV associated with Walo	16 MWp	2025 – Class A	PV–BESS coupling reference
Observed solar peak	188 MW	13/08/2025, 13:00 – Class A	High-PV case / validation
PATRP solar fluctuation	41 MW	Historical – Class B	Reserve / ramp test
PATRP potential thermal	63 MW	Historical – Class B	Reserve sensitivity

reserve			
Loss of Sendou	115 MW	Historical – Class B	Generation contingency

PATRP further flags several zones with recurrent historical overload exposure, notably Aéroport, Mbour/Malicounda, Cap des Biches to Kounoune, Hann to Patte d'Oie, Cap des Biches to Mbao, Kounoune, and Matam. These empirical indications underpin an initial shortlist of candidate nodes and corridors, which is subsequently screened with the SPS-2025 model to prevent a mechanical carryover of legacy constraints into the present system representation.

3.2. Reconstruction and validation criteria for PATRP 2022

Prior to optimizing new storage, the PATRP tables for the 2022 horizon were reconstituted as a traceable reference baseline. We intentionally avoided rebranding this historical snapshot as a 2025 network case. The published peak balance reports 900 MW and 283 MVar of Senelec demand, whereas summing the nodal entries in the detailed dataset yields 1,004 MW and 314 MVar. The resulting 104 MW mismatch is therefore retained and explicitly acknowledged as a scope discrepancy. Plausible causes include the accounting treatment of high-voltage or mining customers and divergences in scenario definition, but in the absence of corroborating evidence, no numerical reconciliation is imposed.

Excluding mining units, the peak generation program indicates approximately 561.4 MW of thermal or other synchronous output, about 620.9 MW of committed maximum capability, and 52 MW of spinning reserve. Cross-border imports in the 2022 base case total 358 MW, comprising 116 MW from OMVS, 30 MW from SOMELEC, and 212 MW from OMVG. PATRP also delineates the OMVS–Senelec, SOMELEC–Senelec, and OMVG–Senelec interconnection boundaries, although the public tables consulted do not disclose the slack bus designation in the PSS/E model.

Validation relies on eight loading benchmarks: Tobène 90/225 kV at 100%, Aéroport 90/33 kV at 119%, Malicounda–Mbour 225/33 kV at 104%, Cap des Biches to Kounoune 90 kV at 104%, Hann to Patte d'Oie 90 kV at 109%, Cap des Biches to Mbao 90 kV at 132%, Kounoune 90/225 kV at 106%, and Matam 225/33 kV at 110%. Seven shunt reactors are likewise recorded at Boké, Mansoa, Sambangalou, Tambacounda, Tanaf, Ziguinchor, and Mali. These figures are used strictly as historical replication targets and are not adopted as SPS-2025 constraints.

Data-traceability hierarchy

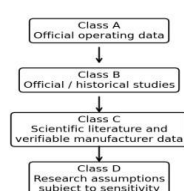


Figure 2: Data-traceability hierarchy used to distinguish

observations, historical benchmarks, assumptions, and optimization results.

3.3. System services pertinent to storage in Senegal

The MCC/Dalberg study of Senegal's storage market^[8] emphasizes a fundamental property of battery assets: a single installation can provide energy shifting, smoothing of variable renewable output, voltage regulation, frequency control, congestion mitigation, operating and replacement reserves, and, in certain configurations, black start capability. This multi-service profile underpins the formulation adopted here. The value of a BESS is not solely a function of energy throughput; it is also contingent on the point of interconnection and on prevailing system conditions at the moment the service is required.

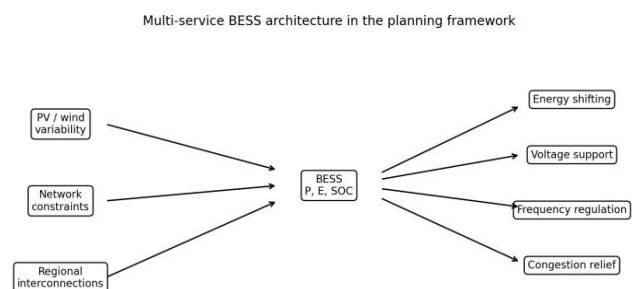


Figure 3: Multi-service functional architecture of BESS in the proposed planning framework.

4. Mathematical formulation

4.1. Decision variables

For each candidate bus i , the optimization includes the following planning variables: $z_i \in \{0,1\}$: decision to install a BESS at bus i .

$P_{B,i} \geq 0$: converter rated power (MW)

$E_{B,i} \geq 0$: usable nominal energy capacity (MWh) $\tau_i = E_{B,i} / P_{B,i}$: nominal storage duration (h) $P_{ch,i,t,s}$, $P_{dis,i,t,s}$: charge and discharge power $SOC_{i,t,s}$: state of charge.

4.2. Objective functions

The multi-objective problem is posed as: $\min F1 = \text{Cannual, BESS}$

$\min F2 = E_{\text{curtail}}$ $\min F3 = E_{\text{loss}}$ $\min F4 = E_{\text{ENS}}$

$\max F5 = \Delta HC_{\text{secure}}$

Here, $F1$ denotes the annualized investment and replacement cost; $F2$, the curtailed renewable energy; $F3$, the active-energy losses; $F4$, the expected energy not supplied; and $F5$, the increase in secure PV hosting capacity relative to the no-new-storage baseline. If a five-objective formulation yields an unduly sparse or diffuse Pareto front, a three-objective reduction may be used for the primary analysis, with the remaining indicators enforced as constraints or retained as ex post decision criteria.

4.3. BESS technico-economic model

4.3.1. Investment cost and annualization

The annualized cost of BESS assets is modeled as.

$$\text{Cannual, BESS} = \text{CRF} \cdot \sum_i (\text{cP PB}_{i,t} + \text{cE EB}_{i,t} + \text{cfix } z_i) + \text{Crepl} + \text{CO\&M}$$

The unit cost parameters cP , cE , and cfix are time-stamped techno-economic inputs and are varied in sensitivity studies. No hidden or undocumented cost adders are introduced for the Senegal application. The capital recovery factor is $\text{CRF} = r(1+r)^n / [(1+r)^n - 1]$, with r the discount rate and n the economic lifetime. Results must be reported for at least a central-cost case and for low/high cases to avoid the optimum being driven by a single cost set.^[17]

4.3.2. Efficiency, degradation, and replacement

The economic representation distinguishes installed from usable energy capacity. Charge and discharge efficiencies are explicitly applied in the SOC balance. Depending on data availability, degradation is captured either via an annualized replacement cost or through a capacity fade model as a function of time and cycling. For reproducibility, each simulation shall report η_{ch} , η_{dis} , SOCmin, SOCmax, lifetime, replacement policy, and residual value. When not derived from transparent contractual or manufacturer sources, these parameters are subjected to sensitivity analysis.^[16,18]

4.4. State-of-charge model

$$\text{SOC}_{i,t+1,s} = \text{SOC}_{i,t,s} + \eta_{\text{ch}} \text{Pch}_{i,t,s} \Delta t / \text{EB}_{i,t} - \text{Pdis}_{i,t,s} \Delta t / (\eta_{\text{dis}} \text{EB}_{i,t}) \quad \text{SOCmin} \leq \text{SOC}_{i,t,s} \leq \text{SOCmax}$$

$0 \leq \text{Pch}_{i,t,s} \leq z_i \text{ PB}_{i,t} \quad 0 \leq \text{Pdis}_{i,t,s} \leq z_i \text{ PB}_{i,t}$
Simultaneous charging and discharging is disallowed, enforced either by binary operational variables or through a complementarity or penalty formulation consistent with the solver.

4.5. AC network and security constraints

For every scenario s and time step t , the solution must satisfy AC power balance and: $V_{\text{min}} \leq V_{i,t,s} \leq V_{\text{max}}$
 $|\text{S}_{\ell,t,s}| \leq \text{S}_{\ell,\text{max}}$

$$\text{Qg}_{\text{min}} \leq \text{Qg}_{i,t,s} \leq \text{Qg}_{\text{max}}$$

The selected $N-1$ contingencies must respect emergency voltage limits and loading criteria. Definitions follow Article 1 to preserve direct comparability of hosting-capacity improvements.

4.6. Coupling with secure PV hosting capacity

$$\Delta \text{HC}_{\text{secure}} = \text{HC}_{\text{secure,BESS}} - \text{HC}_{\text{secure},0}$$

This coupling is the core of the study. Storage additions are only meaningful insofar as they expand the secure hosting-capacity envelope or materially lower the cost or operational risk at the PV penetration level under consideration.

4.7. Uncertainty model

For each scenario s

$$\text{PPV}_{t,s} = \hat{\text{P}}\text{PV}_{t,s} + \varepsilon \text{PV}_{t,s}$$

$$\text{PL}_{t,s} = \hat{\text{P}}\text{L}_{t,s} + \varepsilon \text{L}_{t,s} \quad \text{ps} \geq 0; \sum_s \text{ps} = 1$$

Scenarios are generated from Monte Carlo sampling or historical data, then reduced to a representative subset compatible with computational limits. The deterministic

benchmark uses expected profiles. Weather-driven PV forecast errors that are spatially correlated should be preserved across nearby plants rather than sampled independently.^[14,20]

4.8. Reserve, fast power, and frequency security

BESS upward reserve is limited by both converter headroom and state of charge, for example $R_{\uparrow B,i,t,s} \leq \min(\text{PB}_{i,t} - \text{Pdis}_{i,t,s} + \text{Pch}_{i,t,s}, \text{energy available above SOCmin})$. The downward reserve $R_{\downarrow B,i,t,s}$ is analogously constrained by charging headroom and SOCmax. In cases where frequency security is binding, power earmarked for frequency services is not simultaneously allocated to energy arbitrage. The system-level reserve constraint requires that the sum of effectively deployable reserves meets the scenario's requirement. PATRP values of 41 MW solar fluctuation, 54 MW wind fluctuation, 63 MW potential thermal reserve, and the 115 MW Sendou loss serve only as historical checks or sensitivity references.

4.9. Terminal conditions and energy neutrality

To avoid end-of-horizon artifacts that would overvalue terminal discharge, the terminal SOC is constrained to return to a band around its initial level, or a terminal energy target is imposed. The same terminal policy is applied across all configurations used in the main results.

5. Optimization strategy

NSGA-II is adopted to generate the Pareto set over mixed siting and sizing variables.^[11] Each chromosome encodes the active sites z_i along with $\text{PB}_{i,t}$ and $\text{EB}_{i,t}$; its fitness evaluation runs a chronological AC-OPF and, for feasible candidates, the chosen subset of $N-1$ contingencies and uncertainty scenarios. Violations of hard constraints are either rejected or penalized using a transparent, documented scheme. The compromise design is not fixed a priori: it is selected from the non-dominated front via TOPSIS^[19] or knee-point identification, then validated independently with AC and $N-1$ checks. Figure 4: outlines the computational workflow used for evaluation and selection.

NSGA-II / AC-OPF / $N-1$ computational chain

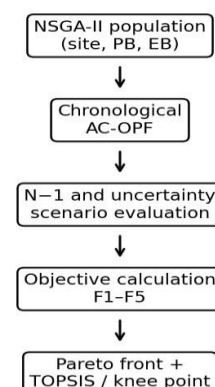


Figure 4: NSGA-II / AC-OPF / $N-1$ computational chain and Pareto-compromise selection.

Table 2: Multi-level computational framework for BESS planning, operation, security, uncertainty, and decision-making.

Level	Variables	Method	Result
Planning	zi, PB,i, EB,i	NSGA-II	Pareto-optimal portfolios
Operation	Pch, Pdis, SOC, dispatch	Chronological AC-OPF	Feasibility and cost
Security	N-1 contingencies, reserve	AC/N-1 + frequency tests	Security margin
Uncertainty	PV/load scenarios	Monte Carlo + reduction	Expectation / risk
Decision	Pareto front	TOPSIS / knee point	Selected compromise

Reproducibility and convergence requirements

For full traceability and to enable independent verification, the study protocol must explicitly detail the computational environment and all algorithmic settings, including the software stack with exact versioning; the AC-OPF solver employed; the NSGA-II configuration, namely population size, number of generations, crossover and mutation rates, and the pseudorandom seed; the bounds imposed on PB and EB; the upper limit on the number of candidate sites; the temporal

discretization Δt ; the number of scenarios before and after reduction; numerical tolerances for power-flow calculations; the Pareto-front convergence criterion, such as hypervolume improvement or inter-generation stability; total computation time; and the hardware specification. As a minimal robustness check, results should be reproduced over several independent random seeds to confirm that siting and sizing inferences are not artifacts of a single stochastic realization.

6. Simulation plan**Table 3: Consolidated matrix of BESS simulation scenarios.**

Case	System / PV condition	BESS configuration	Interconnection / uncertainty	Main test
B0	Reference SPS-2025 / Article 1 HCsecure	Existing Walo only	Observed state / deterministic	Reference without new investment
B1	PV target > HCsecure	One concentrated BESS; optimized site	Nominal / deterministic	Minimum-cost concentrated solution
B2	PV target > HCsecure	Several distributed BESS	Nominal / deterministic	Spatial value of storage
B3	PV target > HCsecure	Optimized BESS	PV-load scenarios	Effect of uncertainty
B4	PV target > HCsecure	Optimized BESS	Weak interconnection	Storage-regional support substitution
B5	PV target > HCsecure	Optimized BESS	Strong interconnection	Storage-interconnection complementarity
B6	High load / critical N-1	Optimized BESS	Selected contingencies	Thermal/voltage security
B7	Low load / high PV	Optimized BESS	High PV uncertainty	Curtailement, absorption, voltage
B8	Cloud ramp / generation loss	BESS with fast reserve	Variable regional reserve	Fast power, SOC, frequency
B9	Annual/reduced chronology	Selected Pareto BESS	Probabilistic scenarios	Energy robustness / EENS

7. Hypotheses

- H1 — For the same secure PV target, joint optimization of site, PB, and EB reduces annualized cost or total required capacity relative to a uniform/arbitrary allocation.
- H2 — Accounting for PV/load uncertainty changes the optimal portfolio and, for a fixed risk level, increases the required power/energy margin relative to the deterministic case.
- H3 — A distributed portfolio dominates a single BESS when limiting constraints are spatially dispersed; the advantage disappears or decreases when the constraint is primarily system-wide.
- H4 — The optimal E/P duration increases when the dominant objective shifts from power/reserve support toward curtailment reduction and energy shifting.
- H5 — Regional support reduces the need for fast local reserve but does not eliminate BESS required for localized thermal or voltage constraints.

7.1. Statistical tests and acceptance rules

Table 4: Evaluation framework and acceptance criteria for hypotheses H1–H5.

Hypothesis	Comparison	Indicators	Interpretation rule
H1	Optimized vs uniform/arbitrary	ΣPB , ΣEB , annualized cost, ΔHC_{secure}	Support H1 if the same ΔHC_{secure} is achieved with lower cost/capacity without degrading security
H2	Stochastic vs deterministic	PB, EB, CVaR/risk, violations	Support H2 if portfolio or margins change robustly across seeds/scenarios
H3	Distributed vs concentrated	Pareto, losses, voltages, loadings	Support H3 if the distributed solution dominates spatial constraints at comparable cost
H4	Power vs energy services	E/P, curtailment, reserve, cycles	Support H4 if optimal duration increases with the share of energy service
H5	Weak vs strong interconnection	PB, EB, local reserve, local constraints	Support H5 if BESS reserve decreases without systematically eliminating local needs

Hypotheses are categorized as supported, not supported, or indeterminate; the procedure does not, by design, force a predetermined conclusion. When stochastic algorithms are employed, multi-run evaluations summarize performance using the median and a measure of dispersion of the objective values.

8. Documentary validation outcomes and preparation of the optimization case

The documentary record is adequate for three purposes: verifying the internal coherence of the planning

framework, reconstructing a historically grounded reference state, and specifying the B0–B9 experimental configurations. It is not yet adequate to substantiate claims of Pareto-optimal siting or sizing for SPS-2025. In particular, a complete specification of transformer impedances and an unambiguous definition of the reference bus are still required to close the AC model. Consequently, the results presented below are restricted to quantities that can be traced directly to the available sources.

B0–B9 experimental protocol

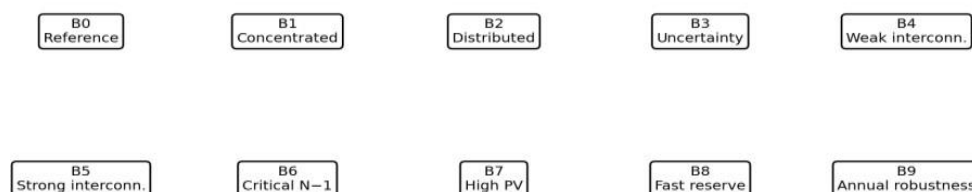


Figure 5: B0–B9 experimental protocol for isolating the effects of siting, uncertainty, interconnections, and stress states.

8.1. Empirical substantiation of the storage context

As of 2025, Walo Storage operates a 10 MW/20 MWh system, implying a nominal energy-to-power duration of 2 hours, paired with 16 MWp of photovoltaic capacity. The annual report indicates a material contribution of the BESS to evening peak management; during the 12–14 August 2025 period, it delivered 10 MW from 23:00, while the national solar output reached a maximum of 188 MW at 13:00 on 13 August and then declined on 14 August due to cloud cover. These empirical findings motivate the definition of cases B7–B8, without presupposing future optimal sizing.^[5]

8.2. Historical grid benchmarks informing siting

For the 2022 reference horizon, PATRP records contingency or peak overloading on multiple assets: Aéroport 90/33 kV (119%); Mbour/Malicounda 225/33 kV (104%); Cap des Biches–Kounoune 90 kV (104%); Hann–Patte d’Oie 90 kV (109%); Cap des Biches–Mbao 90 kV (132%); Kounoune 225/90 kV (106%); and

Matam 225/33 kV (110%). These figures are employed to stress-test the spatial preselection logic, while definitive siting will be recomputed on SPS-2025.^[7] Figure 6 depicts the historical loading targets retained for documentary validation.

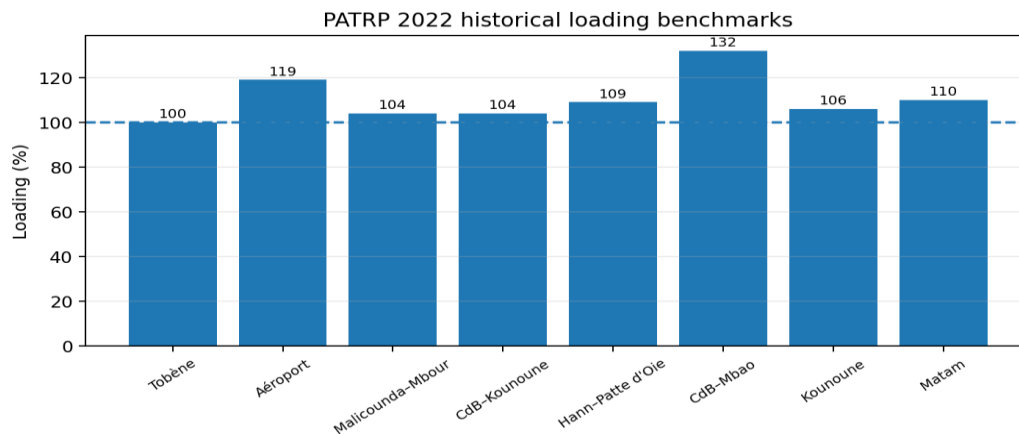


Figure 6: PATRP 2022 loading benchmarks used as historical validation targets; they do not represent SPS-2025 constraints.

8.3. Closing case B0 and reproducibility criteria

The B0 backcasting exercise satisfies the aggregate peak balance, the recorded unit dispatch, regional exchanges, N-1 targets, and shunt compensation. It simultaneously exposes two explicit gaps in the source documentation: the extracted PATRP tables omit transformer R/X impedances, and the PSS/E model does not uniquely identify the slack bus. Imputing these elements ad hoc in an AC load flow would deliver numerically exact figures that are not scientifically auditable.

Consequently, B0 is deemed closed in a documentary sense, but it does not constitute a reproduced AC power flow. The dissemination rule is as follows: historical quantities, including dispatch, imports, reserves, overloads, and shunts, are presented as validation evidence; parameters not in the public record remain operator data to be obtained or are stated explicitly as sensitivity assumptions; and no claim regarding an optimal BESS site is made until the AC model is fully closed. This approach preserves reproducibility and prevents the conflation of historical reconstruction with optimization outputs.

9. DISCUSSION

Energy capacity alone is an inadequate proxy for the system value of storage. Two portfolios with identical MWh may deliver markedly different increments in ΔHC_{secure} , since the converter rating, E/P duration, point of interconnection, and the headroom reserved for system services all condition how a battery engages with the network.

This distinction is critical when disentangling local and system-wide value. A BESS sited near a constrained PV corridor may create value primarily by relieving a thermal limit or supporting voltage, whereas the same energy capacity at a different bus may derive its value from energy shifting or curtailment reduction. Mapping these outcomes on a Pareto frontier preserves the intrinsic trade-offs rather than compressing them prematurely into a single metric.

Regional interconnections add a further dimension in the Senegalese context. In Article 1 they are part of the HCsecure envelope; here the question is whether stronger external support alters the storage requirement itself, and whether the change concerns converter power, energy capacity, or both. This matters because regional assistance may enhance frequency security while leaving a local thermal or voltage constraint largely unaffected.

The comparison with the Malian transmission study clarifies the specific contribution of this work. The issue is not the possibility of optimizing BESS siting on a West African grid, which is established, but whether storage can be planned endogenously as a response to a shortfall in secure PV hosting capacity when AC and N-1 constraints, uncertainty, and regional support are modeled jointly. Any resulting optimum remains conditional on the chronology, cost assumptions, security criteria, and interconnection representation used. These dependencies are part of the findings and should not be relegated to implementation detail.

9.1. Limitations and validity domain

Several constraints delimit the scope of valid inference. PATRP captures a historical system state and cannot be treated as a direct stand-in for the 2025 network. The reconstruction further reveals a 104-MW mismatch between the sum of extracted nodal loads and the documented Senelec peak balance; this discrepancy must be resolved prior to calibration rather than absorbed through arbitrary adjustments. Transformer impedances and the identity of the slack bus still require confirmation. Likewise, BESS cost parameters, degradation behavior, forecast-error distributions, and some emergency limits must be handled as sensitivity variables whenever transparent data are unavailable. Walo Storage offers a valuable operational reference, but it should not be construed as a planning optimum.

10. CONCLUSION

This study provides a traceable procedure for determining BESS connection points on the Senegalese transmission system and for selecting their power and energy ratings. Decisions are evaluated against

HCsecure, AC and N-1 constraints, SOC dynamics, reserve requirements, PV and load uncertainty, and regional support. The 2025 operating dataset indicates that storage planning has moved beyond a purely prospective exercise in Senegal, while the PATRP reconstruction remains useful as a historical validation baseline. The analysis also specifies what is still required before a defensible SPS-2025 optimum can be stated: reconciliation of the load perimeter, a complete set of transformer impedances, and an unambiguous slack-bus definition. The purpose of the B0-B9 sequence is precisely to keep observed evidence, historical benchmarks, modeling assumptions, and genuine optimization results analytically distinct.

REFERENCES

1. Carpinelli, G., Noce, C., Russo, A., Varilone, P., & Verde, P. (2024). Optimal siting and sizing of battery energy storage systems in unbalanced distribution systems: A multi objective problem under uncertainty. *International Journal of Electrical Power & Energy Systems*, 162: 110316. <https://doi.org/10.1016/j.ijepes.2024.110316>.
2. Karve, G. M., Thakare, M. S., & Vaidya, G. A. (2025). Optimal Siting and Sizing of Battery Energy Storage System in Distribution System in View of Resource Uncertainty. *Energies*, 18(9): 2340. <https://doi.org/10.3390/en18092340>
3. Su, R., He, G., Su, S., Duan, Y., Cheng, J., Chen, H., Wang, K., & Zhang, C. (2023). Optimal placement and capacity sizing of energy storage systems via NSGA-II in active distribution network. *Frontiers in Energy Research*, 10: 1073194. <https://doi.org/10.3389/fenrg.2022.1073194>
4. Alarcón Becerra, A., Fernández, G., Rubio Egaña, A., Roncallo, F., Mihetec, M., Tsamba, A. J., Matak, N., & Mahumane, G. (2026). Multi-Objective BESS Siting and Sizing via NSGA-II and PTDF-Constrained DC Optimal Power Flow: Application to the Mali Transmission Network. *Electricity*, 7(2): 57. <https://doi.org/10.3390/electricity7020057>
5. Senelec. (2025). Rapport Annuel Mouvements d'Énergie – Année 2025. Dakar, Sénégal.
6. Ministère de l'Énergie / Système d'Information Énergétique du Sénégal. (2025). Rapport du Système d'Information Énergétique du Sénégal 2025.
7. PATRP / Power Africa. (2017). Rapport de Fonctionnement et de Stabilité du Réseau 2017–2035.
8. Millennium Challenge Corporation / Dalberg. (2019). MCC Senegal - Storage & Ancillary Services Market Assessment: Approach & Methodology Overview.
9. Tractebel Engineering / Senelec. (2015). Étude stratégique pour l'intégration des énergies renouvelables dans le mix énergétique et définition d'un planning et d'une stratégie d'implantation - Rapport final provisoire, REN-SEN/4NT/0389398/000/00.
10. Senelec. (s.d.). Centrales PV de Senelec - fichier technique de paramètres des centrales photovoltaïques (modules, onduleurs et données électriques).
11. Deb, K., Pratap, A., Agarwal, S., & Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, 6(2): 182–197. <https://doi.org/10.1109/4235.996017>
12. Li, X., Wang, W., Wang, H., Wu, J., Fan, X., & Xu, Q. (2022). Placement and capacity selection of battery energy storage system in the distributed generation integrated distribution network based on improved NSGA-II optimization. *Journal of Energy Storage*, 52: 104716. <https://doi.org/10.1016/j.est.2022.104716>
13. Alsharif, H., Jalili, M., & Hasan, K. N. (2022). Power system frequency stability using optimal sizing and placement of Battery Energy Storage System under uncertainty. *Journal of Energy Storage*, 50: 104610. <https://doi.org/10.1016/j.est.2022.104610>
14. Cao, Y., Wu, Q., Zhang, H., & Li, C. (2023). Multi-objective optimal siting and sizing of BESS considering transient frequency deviation and post-disturbance line overload. *International Journal of Electrical Power & Energy Systems*, 144: 108575. <https://doi.org/10.1016/j.ijepes.2022.108575>
15. Ramos, A. F., Ahmad, I., Habibi, D., & Mahmoud, T. S. (2023). Placement and sizing of utility-size battery energy storage systems to improve the stability of weak grids. *International Journal of Electrical Power & Energy Systems*, 144: 108427. <https://doi.org/10.1016/j.ijepes.2022.108427>
16. Hesse, H. C., Schimpe, M., Kucevic, D., & Jossen, A. (2023). Grid-connected battery energy storage system: a review on application and integration. *Renewable and Sustainable Energy Reviews*, 182: 113400. <https://doi.org/10.1016/j.rser.2023.113400>
17. Cole, W., & Karmakar, A. (2023). Cost Projections for Utility-Scale Battery Storage: 2023 Update. National Renewable Energy Laboratory, NREL/TP-6A40-85332. <https://doi.org/10.2172/1984976>
18. Apribowo, C. H. B., Sarjiya, Hadi, S. P., & Wijaya, F. D. (2022). Optimal Planning of Battery Energy Storage Systems by Considering Battery Degradation due to Ambient Temperature: A Review, Challenges, and New Perspective. *Batteries*, 8(12): 290. <https://doi.org/10.3390/batteries8120290>
19. Hwang, C.-L., & Yoon, K. (1981). Multiple Attribute Decision Making: Methods and Applications—A State-of-the-Art Survey. *Lecture Notes in Economics and Mathematical Systems*, 186. Springer. <https://doi.org/10.1007/978-3-642-48318-9>
20. Ntube, N., & Li, H. (2023). Stochastic multi-objective optimal sizing of battery energy storage system for a residential home. *Journal of Energy Storage*, 59: 106403. <https://doi.org/10.1016/j.est.2022.106403>