

STORAGE AND INTERCONNECTION IN WEST AFRICAN POWER SYSTEMS WITH HIGH SOLAR PENETRATION: A CO-OPTIMIZATION FRAMEWORK FOR SENEGAL

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ABSTRACT

The accelerating deployment of solar generation across West Africa renders storage planning inseparable from regional transmission decisions. Utility-scale batteries sited in Senegal shift photovoltaic output across time and provide local system support, whereas cross-border interconnections confer access to external resources only to the extent that the corridor is available and upstream conditions permit. We develop a regional planning framework that co-optimizes PV capacity, BESS power and energy ratings, interconnection reinforcements, and cross-border exchanges. Senegal is represented at the highest granularity allowed by available network data, while neighboring systems are initially modeled as aggregated zones. The objective accounts for annualized costs, solar curtailment, and unserved energy, subject to constraints on power balance, transfer limits, reserves, N-1 security, and state-of-charge evolution. To quantify substitution effects, we define SISP and SISE, which measure how marginal increases in transfer capability alter the optimal battery power and energy capacities. Eight scenarios (R0–R7) span storage and transmission investment choices, corridor outages, spatiotemporally correlated solar extremes, and varying levels of regional market integration. Scenario design is anchored in 2025 operating records, the Walo Storage facility (10 MW/20 MWh), and a historical PATRP case with 358 MW of imports in 2022; none is intended to represent a current optimum. The analysis will delineate where storage and interconnection are substitutes, where they are complementary, and where domestic flexibility remains indispensable.

KEYWORDS: West African Power Pool; battery energy storage systems; cross-border interconnection; transmission expansion planning; solar photovoltaics; operational flexibility; co-optimization; regional electricity markets; Senegal.

Nomenclature and abbreviations

Symbol / abbreviation	Definition
BESS	Battery energy storage system
WAPP / WAPPITS	West African Power Pool / WAPP Interconnected Transmission System
OMVS / OMVG	Senegal River / Gambia River basin development organizations
PV	Photovoltaic
SOC	State of charge
EENS	Expected energy not supplied
TAC	Total annualized cost
PRM	Planning reserve margin
KPV,n	New PV capacity in zone n (MW)
PB,n / EB,n	BESS power (MW) / energy capacity (MWh) in zone n
ΔF_ℓ	Reinforcement of corridor ℓ (MW)
$F_{\ell,t,s}$	Cross-border flow on corridor ℓ at time t in scenario s (MW)

SIS_P / SIS_E	Interconnection–BESS substitution elasticities for power / energy
IMS / SMS	Marginal system value of interconnection / storage
SPS-2025	Senegalese power system research model updated for 2025
PATRP	Power Africa Transmission Roadmap to 2035

1. INTRODUCTION

As West African grids become increasingly interlinked, flexibility must be evaluated both within borders and across them. A battery sited in Senegal can absorb excess photovoltaic output, supply operating reserves, and curb curtailment. A cross-border line can relocate that surplus, import dispatchable resources and hydropower, and pool reserves. Although these functions intersect, their marginal value is highly contingent on geography and the prevailing network state.^[12–15]

Analyses of the WAPP have documented the contribution of batteries to primary frequency control and explored portfolios that pair BESS with conventional reserve products.^[1,2] Other studies indicate that storage needs vary markedly among West African subregions, and that adverse solar conditions can span several countries at once.^[3,4] Interconnections therefore provide useful flexibility only when transfer capacity is available and a neighboring system can actually export at the moment of scarcity.

The preceding four papers focused on Senegal's internal flexibility, addressing PV hosting capacity, BESS siting and sizing, predictive dispatch, and fast dynamic support. The present article shifts to the regional dimension: how do Senegal's optimal storage requirements evolve when exchanges via OMVS, OMVG, and the broader WAPP are treated as decision variables in planning?

1.1. Research question and contributions

The core question is under which circumstances local BESS, reinforced cross-border capacity, or a joint deployment of both achieves the least-cost integration of solar while preserving adequacy and system security.

Joint optimization of PV capacity, BESS power and energy ratings, and cross-border transfer capability at the regional level.

Quantification of substitution and complementarity between storage and interconnection services. Explicit separation of the power value and the energy value provided by BESS.

Modeling of spatial correlation in solar generation and correlated availability of interconnections.

A Senegal-focused application that ties national storage needs to exchanges through OMVS, OMVG, and the wider WAPP.

Transparent differentiation among empirical observations, historical baselines, sensitivity assumptions, and optimization outputs.

2. Regional context and literature

The WAPP aims to consolidate generation and reserve resources and to streamline cross-border trade among national systems. Through the OMVS and OMVG corridors, Senegal can access a portion of this regional flexibility. In the historical PATRP peak scenario for 2022, modeled imports total 358 MW, comprising 116 MW via OMVS, 30 MW from SOMELEC, and 212 MW through OMVG.^[6] This serves as a useful anchor for scenario design, while not reflecting realized exchanges in 2025.

Regional investment programs increasingly incorporate storage. ECOWAS communications from 2025–2026 indicate that the ECOWAS–World Bank BEST initiative includes 205 MWh of batteries across five countries to enhance WAPP stability and renewable integration.^[9,10] The WAPP 2019–2033 master plan similarly positions storage alongside generation and transmission expansions.^[11] Abayateye and co-authors study battery contributions to primary frequency control^[1], and Abayateye and Zimmerle evaluate portfolios combining batteries with conventional reserves.^[2] Collectively, these works highlight the need to compare the specific, non-fungible services delivered by each class of investment.

The benefits of geographic diversity are not limitless. Lin and colleagues^[3] find pronounced differences in cost-effective solar and storage configurations across WAPP zones. Adigun and co-authors^[4] show that extreme PV conditions can coincide across multiple African regions. Treating national solar outputs as independent may thus overstate the export capability of neighbors during Senegalese deficits.

2.1. Research gap

Storage, transmission, security, and climate risk are often analyzed in isolation. Here they are embedded in a single planning framework, enabling estimation of how marginal changes in transfer capacity shape the optimal power and energy ratings of batteries under a consistent set of assumptions. The practical issue is to delineate which services transmission and storage can substitute for, or complement, each other in delivering, and under which network configurations and meteorological regimes.^[12–16,19,20]

3. Data, scope, and modeling architecture

Each system is modeled to the granularity supported by available evidence. SPS-2025 underpins a comparatively detailed representation of Senegal. Neighboring countries initially appear as zonal aggregates with total generation, demand, renewable profiles, hydropower, and exchange limits. Network detail will be refined where verifiable data allow.^[17,18]

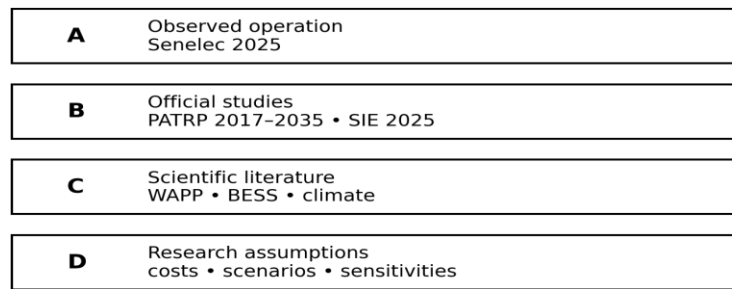


Figure 1: Data provenance hierarchy used in the study (author's illustration).

The official sources describe different years and must be read accordingly. SIE 2025 gives the 2024 energy balance, including 1,903.81 MW of installed capacity, 267.01 MW of grid-connected solar, 159 MW of wind, and 127 MW of hydropower.^[7] Senelec's 2025 operating

report records a 1,261 MW peak and describes Walo Storage (10 MW/20 MWh). We use these figures for their respective purposes without combining them into a single assumed network state.

3.1. Representation levels

Table 1: Progressive architecture of the regional model.

Level	Representation	Purpose	Indicative tool
L1	Detailed Senegal + equivalent neighbors	Consistency with detailed national model	PowerFactory / pandapower
L2	Multizone WAPP model	Regional dispatch and flexibility	PyPSA / linear OPF ^[17,18]
L3	Selected corridors	Congestion and reinforcement	PyPSA / DC-OPF ^[17,18]
L4	Selected dynamic cases	Frequency/security check	PowerFactory / PSS/E or equivalent

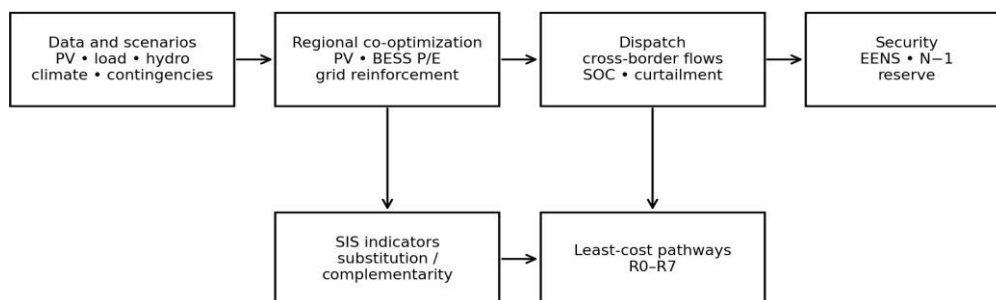


Figure 2: Storage and interconnection co-optimization workflow (author's illustration).

4. Mathematical Formulation

4.1. Decision variables

KPV, $n \geq 0$: incremental photovoltaic capacity installed in zone n (MW). PB, $n \geq 0$: BESS power rating in zone n (MW).

EB, $n \geq 0$: usable BESS energy capacity in zone n (MWh).

$\Delta F_l \geq 0$: additional transfer capacity on corridor or interconnector l (MW). $P_{g,t,s}$: dispatch level of generator g at time t in scenario s (MW).

$P_{ch,n,t,s}$ and $P_{dis,n,t,s}$: BESS charging and discharging power in zone n at time t in scenario s (MW). $F_{l,t,s}$: power flow on corridor l at time t in scenario s (MW).

$CurtPV,n,t,s$: curtailed PV output in zone n at time t in scenario s (MW). $ENS_{n,t,s}$: unserved power in zone n at time t in scenario s (MW).

4.2. Objective Function

$\min TAC = C_{gen} + CPV + CBESS,P + CBESS,E + C_{trans} + CO\&M + C_{fuel} + C_{curt} + CENS.$ ^[1]

Capital expenditures are annualized using technology-specific asset lifetimes and discount rates. Power and energy components of BESS costs are modeled separately, since enhanced interconnection can alter optimal MW and MWh needs in different proportions. Where robust estimates of corridor costs exist, they will be applied; otherwise, they will be explored across a documented range.^[12–16,19,20]

4.3. Zonal power balance

For each zone n , time t , and scenario s , the nodal balance is $\sum_{g \in n} P_{g,t,s} + PPV_{n,t,s} + P_{dis,n,t,s} - P_{ch,n,t,s} + \sum_{l \in n} F_{l,t,s} - \sum_{l \in out} F_{l,t,s} + ENS_{n,t,s} = P_{Load,n,t,s}.$ ^[2]

4.4. BESS constraints

The BESS state-of-charge (SOC) evolves as $SOC_{n,t+1,s} = SOC_{n,t,s} + \eta_{ch} P_{ch,n,t,s} \Delta t / EB_{n,t,s} - P_{dis,n,t,s} \Delta t / (\eta_{dis} EB_{n,t,s}).$ ^[3] State-of-charge bounds are enforced.

$SOC_{min} \leq SOC_{n,t,s} \leq SOC_{max}.$ ^[4]

Charging and discharging power are limited by the installed rating.

$$0 \leq P_{ch,n,t,s} \leq P_{B,n}; 0 \leq P_{dis,n,t,s} \leq P_{B,n}^{[5]}$$

Simultaneous charging and discharging is precluded using binary variables, a complementarity condition, or an equivalent solver-supported approach. A terminal SOC constraint is also imposed to prevent representative periods from appearing spuriously inexpensive by finishing with a depleted battery.^[13–16]

4.5. Interconnection and security constraints

Line flows respect thermal limits inclusive of reinforcements.

$$-(F_{l,exist} + \Delta F_l) \leq F_{l,t,s} \leq F_{l,exist} + \Delta F_l^{[6]}$$

Reinforcements are bounded.

$$0 \leq \Delta F_l \leq \Delta F_{l,max}^{[7]}$$

System adequacy and curtailment constraints are enforced.

$$EENS \leq EENS_{max}; PRM \geq PRM_{min}; CurtPV \geq 0^{[8]}$$

Where tractable, critical N–1 contingencies are enforced within the optimization; otherwise, candidate portfolios are validated against them ex post. PATRP limits inform historical stress tests but are not treated as fixed 2025 constraints.^[16,19]

5. Uncertainty and climate correlation

PV production in zone n is scenario dependent and given by $PPV_{n,t,s} = KP_{V,n} \cdot CF_{solar,n,t,s}^{[9]}$

Cross-country solar deviations preserve spatial correlation: $\text{Corr}(\varepsilon_{solar,n}, \varepsilon_{solar,m}) = \rho_{nm}^{[10]}$

Expected total annual cost is evaluated over scenarios.

$$E[TAC] = \sum_s p_s \cdot TAC_s^{[11]}$$

Solar scenarios retain inter-country dependence, including hours with jointly anomalous low or high output. When data permit, uncertainty in demand, hydrology, line outages, and fuel prices is also represented. Representative days or weeks maintain computational tractability. The optimized portfolios are then replayed on longer chronological series to assess SOC dynamics, curtailment levels, seasonal exchanges, and tail events.^[3,4,17,18]

6. Storage–interconnection substitution indicators

$$SISP = -(\Delta P_{BESS,opt} / P_{BESS,opt}) / (\Delta F_{inter} / F_{inter})^{[12]} \quad SISE = -(\Delta E_{BESS,opt} / E_{BESS,opt}) / (\Delta F_{inter} / F_{inter})^{[13]} \quad IMS = \Delta \text{SystemCost} / \Delta F_{inter}^{[14]} \quad SMS = \Delta \text{SystemCost} / \Delta E_{BESS}^{[15]}$$

A positive SISP or SISE indicates that expanding transfer capacity reduces the corresponding optimal BESS requirement. Values near zero imply limited interaction. Negative values signal complementarity, for example when a new export path makes additional storage profitable to time-shift solar generation before sale. These abbreviations are used for reporting and do not assert any new terminology.

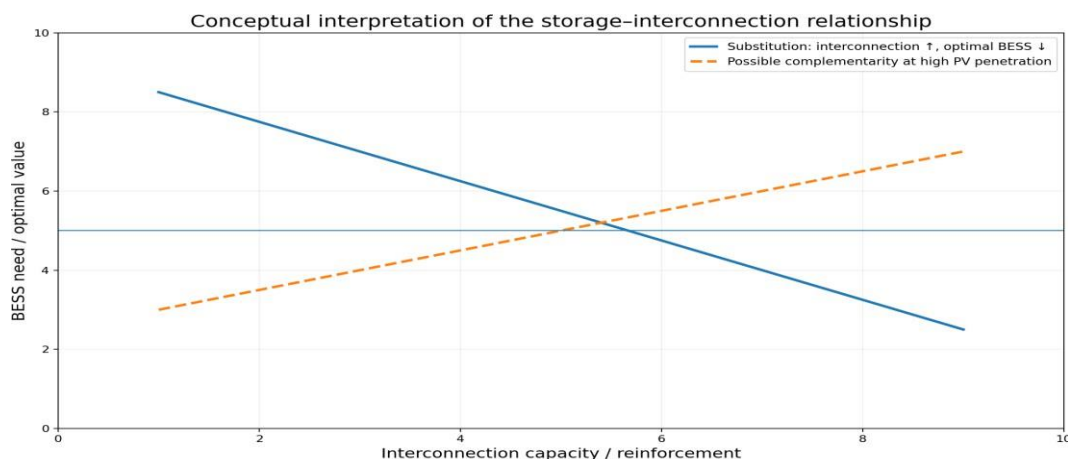


Figure 3: Conceptual interpretation of substitution and complementarity regions (author's illustration).

7. Planning and security scenarios

Table 2: R0–R7 matrix comparing flexibility pathways.

Case	Storage	Interconnection	Solar	Purpose
R0	Existing	Existing	Reference	Base case
R1	Optimized	Fixed existing	High	Storage only pathway
R2	Fixed existing	Optimized reinforcement	High	Transmission only pathway
R3	Optimized	Optimized	High	Co-optimization
R4	Optimized	Optimized	Very high	Deep solar transition
R5	Optimized	Weak / unavailable	High	Interconnection security stress
Case	Storage	Interconnection	Solar	Purpose
R6	Optimized	Optimized	High + correlated extremes	Climate stress
R7	Optimized	Optimized	High + regional market	Market integration

8. Empirical basis in Senegal

Three sources establish the scale of the Senegalese case. Senelec's 2025 report records a system peak of 1,261 MW and Walo Storage (10 MW/20 MWh), an operating installation rather than an estimate of national optimal

storage. PATRP describes an earlier network configuration, including a 2022 peak scenario with 358 MW of imports through OMVS, SOMELEC, and OMVG.^[6] SIE 2025 compiles statistics for 2024.^[7] Each scenario identifies the year to which its source applies.

Table 3: Documented benchmarks used for the Senegalese case; reporting years are kept separate.

Benchmark	Value	Year	Use
Walo Storage	10 MW / 20 MWh	2025	Empirical BESS reference
National peak	1,261 MW	2025	System scale
PATRP imports	358 MW = 116 OMVS + 30 SOMELEC + 212 OMVG	Historical 2022	Regional sensitivity case
SIE installed capacity	1,903.81 MW	2024	Energy context
SIE grid connected solar	267.01 MW	2024	Renewable context
SIE wind	159 MW	2024	Renewable diversity
SIE hydropower	127 MW	2024	Regional / national resource

9. Research hypotheses

H1: With moderate solar penetration, regional interconnection can lower certain national BESS requirements by enabling reserve sharing, exploiting geographic diversity, and accessing dispatchable generation across borders.

H2: Where rapid local response remains indispensable, transmission acts as a stronger substitute for BESS energy capacity than for BESS power capacity.

H3: At high solar shares, storage and transmission may become complementary; interconnection reallocates energy spatially while storage shifts energy temporally and relieves selected local constraints.

H4: Spatially correlated regional solar extremes diminish the diversification benefits of interconnection compared with models that assume independent national photovoltaic profiles.

H5: Transmission congestion, derating, or outages increase the marginal value of domestic flexibility and may warrant a minimum national requirement for BESS or reserves.

10. Analysis protocol, validation, and hypothesis tests

We keep demand, solar resource, cost, and availability assumptions identical across R0 to R7 so that any observed variation is attributable to the flexibility options under test. For each configuration, we will report the optimal investment portfolio, total annualized cost with its disaggregation, curtailment, unserved energy, cross-border exchanges, reserve provision, congestion indicators, and state-of-charge trajectories. Finite differences across comparable optima will be used to estimate SISP and SISE. To ensure reproducibility, the numerical setup will specify discount rates, asset lifetimes, unit costs, conversion efficiencies, SOC bounds, corridor transfer capacities, hydropower availability, climate years, and solver convergence tolerances. Historical benchmarks used to parameterize the cases will be documented separately from model outputs.^[12, 16,19,20]

Table 4: Output and reproducibility matrix for the co-optimization framework.

Output	Metric	Interpretation
Optimal portfolio	PV, PBESS, EBESS, ΔF	Investment structure
System cost	TAC and components	Economic effect
Adequacy	EENS, PRM	Reliability
PV integration	Curtailment, renewable share	Solar utilization
Exchanges	Imported/exported MWh, peak flows	Regional value
Substitution	SIS_P, SIS_E	Effect on BESS MW and MWh
Robustness	R5–R6	Interconnection/climate
Dynamic security	RoCoF, nadir, voltage, and recovery time in selected cases	Validation of planning solutions

10.1. Hypothesis tests

H1 is corroborated when an expansion of transfer capacity permits a reduction in the optimal BESS power or energy without any degradation in the prescribed service level. H2 is assessed by directly contrasting the magnitudes of SISE and SISP. H3 requires high-PV configurations in which both transfer capability and

battery capacity increase while total cost or curtailment decreases. H4 compares simulations that treat solar time series as independent with simulations that retain cross-country correlation. H5 employs R5 to quantify the additional domestic flexibility needed following an interconnection outage or derating event.

11. Empirical basis and documented findings

11.1. Established empirical benchmarks

The available evidence constrains scale but does not reveal an optimal allocation among technologies. In the PATRP 2022 peak case, imports attained 358 MW, a sizeable contribution relative to the Senegalese system.^[6] Operating records for 2025 document a 10 MW/20 MWh BESS and a continuing rise in solar output.^[8] The BEST initiative cites 205 MWh of storage developed within a regional framework to enhance WAPP stability and support renewable integration.^[9,10] Peer-reviewed technical literature confirms that batteries deliver rapid frequency response and analyzes the costs and performance implications of pairing them with conventional reserves.^[1,2] Climate research further justifies an explicit treatment of correlated solar conditions across countries.^[3,4]

11.2. Analytical scope and interpretation

These benchmarks do not reveal how many MW or MWh of storage a specific corridor reinforcement would substitute. Nor do they delineate the circumstances under which a stronger interconnection enhances the marginal value of storage. Such quantities are outputs of the proposed co-optimization, evaluated under the assumptions in Table 4, rather than empirical attributes of the present Senegalese system.

12. DISCUSSION

The preferred portfolio is contingent on spatial configuration of resources, the duration and type of flexibility required, the degree of solar correlation across jurisdictions, and the applicable security criteria. Access to external generation can displace several hours of battery energy, yet a residual need for local power may remain to address fast contingencies, alleviate internal constraints, or provide voltage support. Batteries can postpone localized reinforcements but cannot deliver geographical diversification or unlock hydropower in neighboring systems.^[12, 16]

The PATRP peak scenario with 358 MW of imports illustrates the prospective magnitude of regional assistance.^[6] It nonetheless represents a specific 2022 context and is used here as a sensitivity benchmark, not a target for 2025. The Walo Storage facility demonstrates that a BESS operates in Senegal; its 10 MW/20 MWh rating does not, by itself, indicate an optimal national capacity.

Geographic diversification is beneficial only when neighboring systems possess surplus generation coincident with Senegal's needs. If low irradiance spans the region simultaneously, the apparent advantage can disappear.^[4] Hydropower should likewise be evaluated across hydrological regimes rather than assumed to be continuously available.

Economic feasibility alone is inadequate if the portfolio fails security assessments. Concentrating reliance on a

single corridor creates exposure to its outage or derating. We will analyze these contingencies and subject the most demanding cases to a dedicated dynamic study for validation.^[16,19,20]

13. Implications for planning and markets

Coordinate national BESS planning with the schedule and topology of WAPP corridor expansions.

Disaggregate and remunerate BESS services individually, including energy shifting, reserves, congestion management, voltage support, and fast frequency response.

Represent interconnection outages and correlated climatic extremes explicitly in regional analyses.

Maintain a floor of domestic flexibility where cross-border exchanges cannot assure system security.

Enhance data sharing among system operators so that demand, renewable output, outages, transfer limits, and reserves are consistently aligned.

Appraise investments as portfolios instead of evaluating technologies in isolation.

14. Limitations and reproducibility

The model's spatial resolution mirrors the granularity of the underlying data. We will not impute unverified network parameters to neighboring grids. Prospective costs of batteries, transmission, and fuels require systematic sensitivity analyses, as do climate years, hydrological states, market rules, and transfer constraints. Upon publication of numerical results, we will disclose scenario definitions, input time series or their construction methods, economic assumptions, solver version, and convergence criteria to enable reproducibility.^[17-19]

15. CONCLUSION

Both batteries and interconnections facilitate solar integration, but their relative value depends on service type, siting, and temporal scales. This study develops a regional model that endogenously chooses battery power and energy separately from corridor capacity, with SISP and SISE characterizing their interactions. Senegalese operating evidence from 2025 and historical PATRP scenarios function as benchmarks, with their reporting years kept distinct. Cases R0-R7 span separate and joint investments, corridor losses, correlated solar events, and regional market coupling. Existing evidence does not yet identify Senegal's optimal BESS or interconnection capacity. Determination requires running the model with harmonized time series and verifying the security performance of resulting portfolios. Only then can the value of a corridor be compared rigorously with the specific battery services, capacities, and locations it could supplant.

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