Evaluating Deployment Strategies for Battery Storage in the Mainland Spain Electricity System

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***Abstract*—This paper investigates strategies for deploying battery energy storage systems (BESS) in the Spanish electricity grid using a multi-period DC Optimal Power Flow (DC-OPF) model. The framework minimizes system operating costs over representative days for the four seasons, incorporating renewable generation, thermal plants, and storage dynamics. Two allocation strategies are evaluated: equal distribution of storage across nodes and distribution proportional to renewable curtailment levels. The results show that while both strategies reduce operating costs and curtailment compared to a low-storage baseline, the curtailment-based approach delivers superior performance at higher integration levels. In particular, it achieves greater cost savings and significantly reduces curtailment in all seasons. These outcomes highlight the importance of aligning BESS deployment with curtailment patterns to maximize renewable utilization and economic efficiency.**

***Index Terms*—Optimal power flow, battery storage, renewable energy, decarbonization scenarios.**

NOMENCLATURE

Indices and Sets

$i, j, \mathcal{N}$	Indices and set of nodes.
$g, \mathcal{G}$	Index and set of generators.
$d, \mathcal{D}$	Index and set of loads.
$r, \mathcal{R}$	Index and set of RES.
$s, \mathcal{S}$	Index and set of storage.
$t, \mathcal{T}$	Index and set of time periods.

Constants and Parameters

C_g	Cost function of generator g (€/MWh).
P_r	Power available from RES r (MW).
P_d	Power demanded by load d (MW).
$\mathrm{P}_g^{\min}$, $\mathrm{P}_g^{\max}$	Min/Max generation of generator g (MW).
$\mathrm{P}_{ij}^{L,\max}$	Maximum power limit of line ij (MW).
$\mathrm{E}_s^{\min}$, $\mathrm{E}_s^{\max}$	Min/Max energy stored by storage s (MWh).
$\eta_s^{\mathrm{cha}}, \eta_s^{\mathrm{dis}}$	Charge/Discharge efficiency of storage s.
b_{ij}	Line susceptance between nodes i and j.
$\mathrm{P}_g^{\mathrm{rd}}, \mathrm{P}_g^{\mathrm{ru}}$	Ramp-down and ramp-up limits of generator g (MW).

Decision Variables

P_g	Power produced by generator g (MW).
P_{ij}^L	Power flow between nodes i and j (MW).
θ_i	Phase angle of the voltage at node i (rad).
E_s	Charge level of storage s (MWh).
$P_s^{\mathrm{cha}}, P_s^{\mathrm{dis}}$	Charge/Discharge power of storage s (MW).
y_s	Binary variable. Charging and discharging state of storage s.
y_g	Binary variable. Decision variable for on/off of thermal generators s.
P_r^{curt}	Power curtailed from RES r (MW).

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I. INTRODUCTION

The integration of energy storage systems into electrical grids is increasingly recognized as a key strategy to address the imbalances between electricity generation and consumption that arise during system operation. These imbalances are expected to intensify with the growing penetration of variable renewable energy sources (RES), such as wind and solar photovoltaic (PV). Energy storage technologies can mitigate these challenges by providing flexibility, reducing curtailment, and enhancing the reliability and efficiency of power system operation [1], [2].

In response to this need, many countries have begun to incorporate energy storage into their national energy strategies [3], [4]. In particular, Spain's National Integrated Energy and Climate Plan ('*Plan Nacional Integrado de Energía y Clima*', PNIEC) [5] outlines a significant expansion of storage capacity, aiming to increase current levels nearly sevenfold to reach 22.5 GW by 2030. Of this total, 12.5 GW is intended for daily and weekly flexibility needs, and an additional 10 GW is for seasonal storage. Although the PNIEC does not explicitly assign technologies to these targets, battery energy storage systems (BESS) are widely recognized as the most viable and scalable solution for short- to medium-term applications and are therefore expected to play a central role. Despite this ambitious goal, the plan lacks a coordinated framework for optimal spatial allocation and integration of this storage capacity into the transmission network.

This lack of strategic planning can lead to suboptimal deployment, resulting in higher operating costs, increased network congestion, and underutilized storage assets. To address this issue, this paper explores different strategies for the deployment of short-duration BESS into the mainland Spanish electricity system. The objective is to determine how alternative allocation methods for 2 hour-duration BESS can reduce system operating costs and RES curtailment. While the PNIEC sets a target of 12.5 GW of daily and weekly storage

979-8-3315-8138-1

by 2030, this goal is widely regarded as highly ambitious given current industry capabilities and deployment rates. Therefore, this study first considers a more conservative and realistic scenario with 1 GW of BESS capacity installed in the Spanish grid, representing a plausible milestone for 2030.

The study is based on a multi-period DC-OPF formulation implemented in the Julia programming language. The model aims to minimize total generation costs while considering different spatial distributions of BESS capacity across the network. Different scenarios are analyzed to assess the economic and operational impacts of these storage configurations.

Specifically, the main contributions of this paper are:

1) A comparative analysis of different strategies for allocating 2-hour duration BESS in the Spanish power system, based on a conservative and realistic capacity scenario of 1 GW. The results are then extrapolated and discussed to assess the potential system-wide impacts of reaching the full 22.5 GW PNIEC target.
2) The development and implementation of a multiperiod DC-OPF framework using a network model derived from PyPSA-EUR to represent the Spanish system. This enables the evaluation of BESS deployment strategies under realistic operational constraints and temporal variations in demand and renewable generation.

The remainder of the paper is organized as follows. Section II describes the methodology and modeling framework, including the DC-OPF formulation and the data sources used. Section III presents case studies and analyzes the results of the different BESS deployment strategies. Finally, Section IV summarizes the conclusions and suggests directions for future research.

II. Methodology

A. Multi-Period OPF

A multi-period DC-OPF is used to assess BESS deployment in the mainland Spanish electricity system. The model minimizes the total generation cost over a time horizon under system constraints, capturing time-coupled effects on costs and efficiency. The operation of BESS is modeled from the perspective of the system operator, that is, charging during excess RES and discharging during scarcity to enhance flexibility, without considering market-based arbitrage or owner profits.

The optimization problem is formulated as **Model 1**. Eq. (1a) defines the objective function, which aims to minimize the total generation cost over the time horizon considered in the study. Only the costs associated with non-renewable generation sources are included, while RES (i.e., wind and PV) are assumed to have zero marginal cost. Eq. (1b) ensures the nodal power balance at each time step, which already incorporates the power contributions from RES as well as the energy charged to or discharged from the BESS. Eq. (1c) represents the linearized power flow relationship between the network nodes. Constraints (1d) and (1e) impose operational limits on generation output and transmission line flows, respectively.

Model 1: Multi-period DC-OPF Formulation

$$\min \quad \sum_{t \in \mathcal{T}} \sum_{g \in \mathcal{G}} \mathrm{C}_g \cdot P_{g,t} \tag{1a}$$

s.t.

$$\sum_{g \in \mathcal{G}_i} P_{g,t} - \sum_{d \in \mathcal{D}_i} \mathrm{P}_{d,t} + \sum_{r \in \mathcal{R}_i} P_{r,t} - \sum_{r \in \mathcal{R}_i} P^{\mathrm{curt}}_{r,t} + \sum_{s \in \mathcal{S}_i} P^{\mathrm{dis}}_{s,t} - \sum_{s \in \mathcal{S}_i} P^{\mathrm{cha}}_{s,t} = \sum_{j \in \mathcal{N}_i} P^{L}_{ij,t} \quad \forall i, \forall t \tag{1b}$$

$$P^{L}_{ij,t} = -\mathrm{b}_{ij} \cdot (\theta_{i,t} - \theta_{j,t}) \quad \forall ij, \forall t \tag{1c}$$

$$\mathrm{P}^{\min}_g \le P^{G}_{g,t} \le \mathrm{P}^{\max}_g \quad \forall g, \forall t \tag{1d}$$

$$-\mathrm{P}^{L,\max}_{ij} \le P^{L}_{ij,t} \le \mathrm{P}^{L,\max}_{ij} \quad \forall ij, \forall t \tag{1e}$$

$$\mathrm{E}^{\min}_s \le E_{s,t} \le \mathrm{E}^{\max}_s \quad \forall s, \forall t \tag{1f}$$

$$E_{s,t} = E_{s,t-1} + \left(\eta^{\mathrm{cha}}_s \cdot P^{\mathrm{cha}}_{s,t} - \frac{P^{\mathrm{dis}}_{s,t}}{\eta^{\mathrm{dis}}_s} \right) \quad \forall s, \forall t \tag{1g}$$

$$0 \le P^{\mathrm{cha}}_{s,t} \le (1 - y_{s,t}) \cdot P^{\mathrm{cha,max}}_{s,t} \quad \forall s, \forall t \tag{1h}$$

$$0 \le P^{\mathrm{dis}}_{s,t} \le y_{s,t} \cdot P^{\mathrm{dis,max}}_{s,t} \quad \forall s, \forall t \tag{1i}$$

$$0 \le P^{\mathrm{curt}}_{r,t} \le \mathrm{P}_{r,t} \quad \forall r, \forall t \tag{1j}$$

$$-\mathrm{P}^{\mathrm{rd}}_g \le P_{g,t} - P_{g,t-1} \le \mathrm{P}^{\mathrm{ru}}_g \quad \forall g, \forall t \tag{1k}$$

Constraints (1f)–(1i) describe the operational behavior of the BESS. In particular, the constraint (1g) governs the intertemporal energy balance of the storage units by linking the state of charge at each time step with the previous state, accounting for both charging and discharge actions. To ensure mutual exclusivity between the charging and discharging operations, a binary variable y_s is introduced, where $y_s = 1$ indicates the discharging and $y_s = 0$ indicates the charging. It should be noted that in this study, the initial condition of BESS is assumed to be fully uncharged.

The constraint (1j) introduces a curtailment variable that enables the model to discard excess renewable generation when it exceeds local demand or available network capacity. This constraint plays a critical role in the design of case studies, as the spatial and temporal distribution of the curtailment directly influences the optimal location and size of BESS.

Finally, constraint (1k) imposes ramping constraints on non-renewable thermal generators, limiting the rate at which their output can increase or decrease between consecutive time steps. This reflects the physical limitations of thermal generation technologies and enhances the realism of the system's operational flexibility.

B. Peninsular Electricity Grid and Data

The Spanish peninsular electricity grid considered in this study is derived from the PyPSA-Eur data set, an open-source model of the European transmission system built on the PyPSA framework [6], [7]. PyPSA-Eur includes a node clustering workflow that allows large-scale networks to be reduced while preserving their main electrical characteristics. Using this approach, the Spanish system was simplified to a 19-node network, as shown in Fig. 1.

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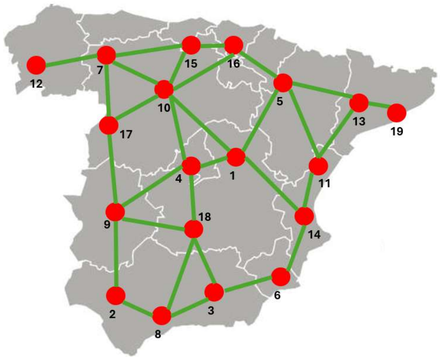

Fig. 1. Spanish electricity grid simplified to 19 nodes.

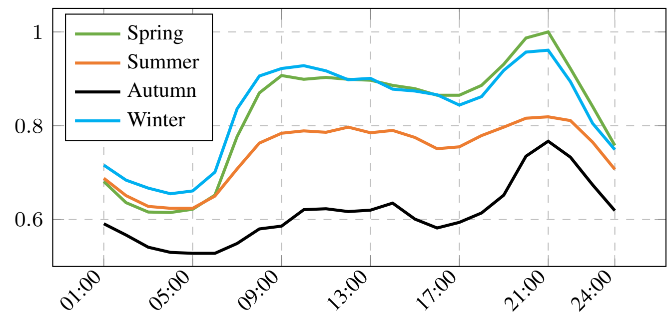

Fig. 2. Hourly electricity demand profiles by season.

The outputs obtained from PyPSA-Eur include distribution data on thermal and nuclear generation plants, as well as transmission network parameters, and power flow limits for the reduced model. However, to ensure up-to-date information for renewable generation and electricity demand, this study incorporates data from 2024 to 2025, sourced from the Spanish System Operator's Information System [8].

To account for seasonal variability in demand and renewable generation, the analysis considers a representative day from each of the four seasons. Specifically, the following days were selected: summer - 21/06/2024, autumn - 20/10/2024, winter - 21/02/2025, and spring - 07/04/2025. These days were deliberately chosen to support the exploratory and comparative nature of the study. They correspond to typical operating conditions for each season in terms of demand levels and wind and solar availability, and are intended to be broadly representative of average seasonal behavior rather than extreme or atypical conditions.

The demand profile for each day is presented in Fig. 2 as a capacity factor based on a total of 34.7 GW. The selected daily profiles of wind and PV generation are shown in Fig. 3 as capacity factors based on installed capacity of 14.14 GW and 18.72 GW, respectively. Wind generation is generally higher in winter and autumn, offering a more consistent supply, while PV generation peaks in summer and spring. These seasonal variations are essential for assessing the effectiveness and performance of energy storage systems.

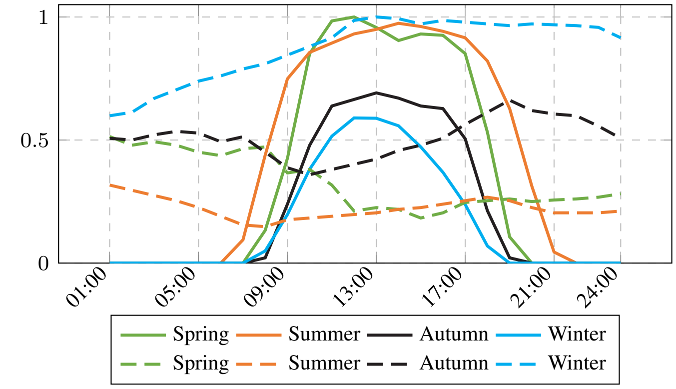

Fig. 3. Hourly capacity factor from PV (solid lines) and wind (dashed lines) sources across the four seasons.

III. Case Studies

This section compares alternative deployment strategies for BESS in the Spanish transmission grid, assessing their impact on total system operating costs throughout the four seasons of the year. To ensure a fair comparison, the base case, where only the actual 25 MW of battery storage is installed, is used as a reference point. Two deployment strategies are evaluated:

1) In Scenario 1, the 1 GW of storage capacity is evenly distributed across the 19 nodes of the reduced Spanish network.
2) Scenario 2 allocates the BESS capacity proportionally to the levels of RES curtailment at each node, as verified in the base case (i.e., 25 MW of BESS). For example, if a node accounts for 10% of the total curtailment verified in the system, 100 MW of the 1 GW available of BESS capacity is assigned to it. This scenario enables the evaluation of a more needs-based, targeted deployment strategy.

In Scenarios 1 and 2, the BESS units are assumed to have a 2-hour energy capacity. In all cases, a round-trip charge/discharge efficiency of 95% is assumed. The optimization model is implemented in `Julia-JuMP` [9] and solved using `Gurobi 12.0.2`. All code and data are publicly available at the repository [10].

A. Scenario 1: Even Distribution

In this scenario, the total BESS capacity of 1 GW is evenly distributed across the 19 nodes of the reduced Spanish transmission network. Table I presents the operating costs of the system and the corresponding cost savings for each season of the year, compared to the base case.

From Table I, it is possible to verify that the system operating costs are highest in summer and spring. This is mainly due to the lower contribution of wind generation during these seasons, which is not offset by the greater availability of photovoltaic generation. Consequently, a greater share of non-renewable generation is required to meet demand. Under these conditions, the integration of battery storage has a more pronounced economic impact, as it enables the displacement of

979-8-3315-8138-1

TABLE I
SYSTEM OPERATING COSTS AND SAVINGS WITH 1 GW OF EQUALLY DISTRIBUTED BESS CAPACITY

Season	Cost [M€]	Savings [%]
Spring	12.470	0.44
Summer	12.803	0.27
Autumn	8.992	0.26
Winter	10.495	0.32

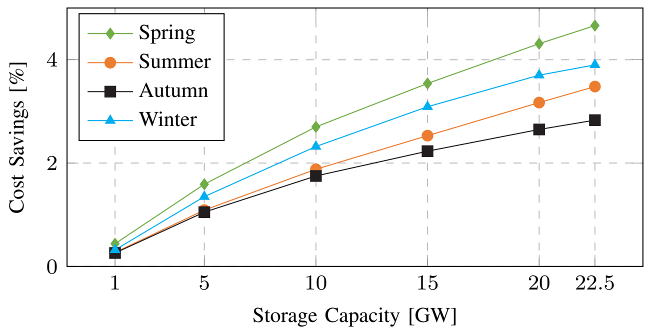

Fig. 4. Scenario 1 - Evolution of cost savings as a function of storage capacity.

costlier non-renewable generation by storing excess renewable energy and releasing it during periods of higher demand. In contrast, during autumn, the high penetration of RES causes the system to quickly reach the minimum allowable levels of thermal generation.

In addition to analyzing the initial 1 GW of storage, this study also investigates how cost savings evolve as storage capacity increases to the 22.5 GW target proposed by the PNIEC, also considering the even distribution of BESS. The resulting cost savings are illustrated in Fig. 4, which shows that increasing storage capacity leads to greater cost savings throughout all seasons. The maximum savings reach approximately 4.5% in spring and 4% in winter when the full 22.5 GW of storage is implemented using BESS. It is important to note that these savings could be even higher in the future, given the expected growth in electricity demand, the expansion of renewable energy capacity, and the reinforcement of the network to transport the energy, and the usage of different multiple time-scales storage systems, such as longer duration BESS or pumped storage, which can enhance the mid- to long-term seasonal variabilities and cost savings.

B. Scenario 2: Distribution based on Power Curtailment

In the second scenario, the 1 GW of battery storage is allocated across the 19 nodes according to the spatial distribution of renewable energy curtailment observed in the base case, i.e., 25 MW of BESS. Specifically, the share of curtailed renewable generation was calculated at each node and the total storage capacity was allocated proportionally. As a result, nodes with higher curtailment were assigned more storage.

The simulations are based on typical days for each season, and since curtailment levels vary slightly across them, one might expect different BESS allocations per season. However, varying storage allocation seasonally is neither practical nor cost-effective. Therefore, a single curtailment distribution must be chosen. Among the simulated cases, the winter-based distribution achieved the highest overall operating cost savings. The highest curtailment occurs at nodes with abundant renewable generation but relatively low local demand, such as node 9, which is the one with the highest PV capacity installed. Because local consumption cannot absorb all the renewable output and transmission capacity can be limited, part of the energy is curtailed. This underscores the spatial mismatch between renewable generation sites and demand centers and highlights the need for a more targeted strategy for the deployment of BESS.

TABLE II
SYSTEM OPERATING COSTS AND SAVINGS WITH 1 GW OF BESS CAPACITY ALLOCATED BY CURTAILMENT LEVEL

Season	Cost [M€]	Savings [%]
Spring	12.475	0.40
Summer	12.794	0.34
Autumn	8.983	0.36
Winter	10.493	0.34

Introducing 1 GW of storage with the curtailment-based allocation strategy produces the results shown in Table II. Compared with the base case of 25 MW, cost savings are observed across all seasons. However, when these results are compared with the evenly distributed allocation in Table I, the results are mixed. Spring shows smaller cost reductions under the curtailment-based strategy, while summer, autumn, and winter deliver greater savings. This suggests that relying solely on the 1 GW case to identify which allocation strategy is preferred may be misleading. A more robust comparison requires analyzing scenarios with higher levels of BESS integration to better capture the benefits of each approach.

Fig. 5 shows the evolution of operating cost savings as BESS capacity increases under the curtailment-based deployment strategy. Relative to the evenly distributed case, this strategy consistently achieves higher savings across all seasons, with the differences becoming more pronounced as storage penetration approaches the PNIEC target. In spring, for instance, evenly distributed storage results in savings of approximately 4.5%, whereas the curtailment-based strategy increases savings to nearly 7%. A similar improvement is observed in summer, where cost reductions reach around 6% under curtailment-based deployment. Winter exhibits comparable savings to the uniform case, while autumn shows a clear enhancement, with savings rising to about 5% at the full PNIEC target.

Fig. 6 compares the curtailed power under even distribution and curtailment-based strategies. In both cases, the curtailment decreases as storage capacity increases. At low capacities, the curtailment is highest in spring and summer due to abundant renewable generation, but as the capacity expands, the spilled power drops substantially, approaching zero in autumn and winter and reaching much lower levels in spring and summer. Although the two strategies show little difference in autumn

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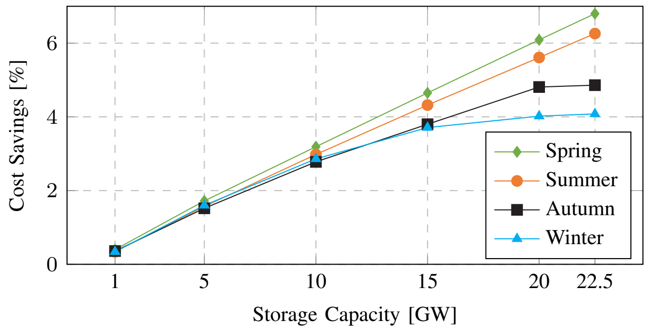

Fig. 5. Scenario 2 - Evolution of cost savings as a function of storage capacity.

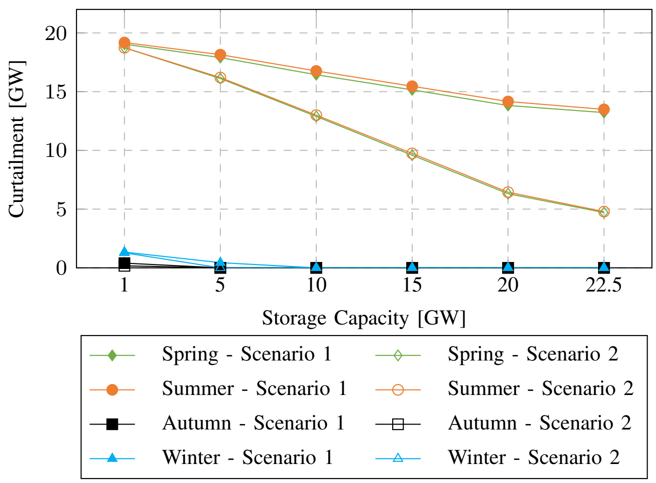

Fig. 6. Comparison of curtailment evolution for Scenario 1 and Scenario 2 (Winter Curtailment) as a function of storage capacity.

and winter, the contrast becomes evident in spring and summer. With the full installed capacity planned in the PNIEC, curtailment in Scenario 2 during spring and summer is less than half of that observed in Scenario 1. This improvement maximizes renewable use and helps to reduce CO2 emissions.

IV. Conclusion

This paper presented a comparative, system-level analysis of spatial deployment strategies for short-duration BESS in the Spanish peninsular electricity grid. A multi-period DC-OPF model was implemented in Julia and applied to a reduced 19-node network derived from PyPSA-Eur. The analysis was conducted using one representative day for each of the four seasons, selected to reflect typical operating conditions in terms of demand and renewable availability. Two intuitive allocation strategies were evaluated: an even distribution across nodes and a distribution proportional to baseline renewable curtailment.

The results consistently show that the integration of short-duration BESS reduces both operating costs and renewable curtailment across all seasons. As storage capacity increases toward the PNIEC target, the curtailment-based allocation systematically outperforms uniform deployment, yielding higher cost savings, particularly in spring and summer, and leading to more pronounced reductions in curtailed renewable energy, highlighting the benefit of aligning storage placement with spatial curtailment patterns.

These findings should be interpreted within the scope and assumptions of the study. The use of a limited set of representative days provides a controlled and transparent framework for comparing allocation heuristics, but it does not capture intra-seasonal variability, differences between weekdays and weekends, extreme weather events, or rare demand and renewable generation combinations. Consequently, the results are indicative of relative performance trends under typical seasonal operation, rather than definitive long-term planning outcomes. Moreover, the analysis focuses exclusively on short-duration technology and it does not encompass the multiple time-scale storage needs, particularly the seasonal storage component. As such, the extrapolation of results to the full 22.5 GW target should not be interpreted as a proxy for the complete PNIEC storage portfolio, but rather as an exploration of the potential impacts of large-scale deployment of short-duration BESS under different spatial allocation strategies.

Future work will extend this analysis toward longer time horizons to better capture intra-seasonal variability and extreme operating conditions. Further developments may include randomized initial state of charge, heterogeneous storage durations, detailed unit commitment formulations, alternative allocation baselines, and co-optimization frameworks in which storage siting and sizing are treated as decision variables. These enhancements progressively bridge the gap between heuristic deployment analysis and comprehensive planning-oriented models.

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