



Proof-of-Concept Optimisation of Low-Carbon Power System Dispatch: Assessing the Impact of Doubling Battery Storage Capacity on Operating Cost, Emissions, and Supply Adequacy

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ABSTRACT

This paper presents a proof-of-concept economic dispatch optimisation model to evaluate the operational, economic, and environmental impacts of scaling Battery Energy Storage Systems (BESS) within a carbon-constrained power network. Four distinct scenarios are evaluated over a deterministic 24-hour horizon: Baseline, Flexible, Low-carbon, and Doubled-Storage (120 MWh). The simulation results reveal a profound systemic bottleneck: while enforcing a strict carbon emission cap of 250 tCO₂/day successfully reduces environmental impacts by 22%, it triggers severe supply inadequacy. This causes unserved load penalties that escalate daily operating costs from £0.1M to £2.1M. Crucially, doubling the BESS capacity provides **zero operational relief**, with the storage system remaining completely unutilized and flatlined at its initial state-of-charge. This paper demonstrates that expanding energy storage capacity in isolation—without concurrent over-provisioning of variable renewable generation capacity or dynamic charging architectures—creates a stranded asset that cannot mitigate supply deficits or lower system costs. The findings offer critical cautionary insights for grid planners and policymakers targeting decarbonisation milestones.

Keywords: Economic Dispatch Optimization; Battery Energy Storage Systems (BESS); Low-Carbon Power Grids; Unserved Load Penalties; Stranded Infrastructure Assets; Variable Renewable Energy (VRE)

2. INTRODUCTION

2.1 Context and Motivation

The global imperative to mitigate climate change has accelerated the transition of modern electrical grids from centralized, fossil-fuelled generation to decentralized, low-carbon power architectures. This paradigm shift relies heavily on the integration of Variable Renewable Energy (VRE) sources, primarily solar photovoltaics (PV) and wind power. While VRE assets offer zero-emission generation capabilities, their stochastic and intermittent nature introduces unprecedented operational challenges to power grid operators. The temporal misalignment between peak renewable availability and peak consumer demand threatens grid stability, voltage regulation, and supply adequacy.

To counter VRE volatility, Battery Energy Storage Systems (BESS) are widely regarded as a cornerstone technology for modern grid modernization. BESS infrastructure is theoretically capable of performing time-shifting applications: capturing surplus green energy during periods of low demand and high VRE generation, and injecting that stored energy back into the network during peak demand periods when renewable assets are offline. Consequently, current energy policies and utility resource plans frequently mandate aggressive, multi-megawatt storage targets under the assumption that increasing battery volume linearly enhances grid resilience, facilitates deeper carbon abatement, and lowers total system operating costs.

2.2 Problem Statement and Literature Gap

Despite the widespread optimism surrounding energy storage, conventional infrastructure planning frameworks frequently treat BESS capacity as an independent, universally effective tool for addressing supply



deficits. This methodology often overlooks the non-linear coupling between a battery's charging requirements, the underlying system generation margins, and the enforcement of rigid environmental regulations. In a power system, a battery is inherently a dependent asset; its ability to cycle and deliver utility is entirely bound to the existence of an operational charging margin. This margin must come from either a net surplus of VRE generation or an unconstrained, economically viable thermal generation reserve during off-peak windows.

A review of contemporary economic dispatch literature reveals a distinct gap in how boundary conditions are analysed. Most published optimization models are simulated under resource-rich assumptions where VRE capacity is heavily over-provisioned, or where carbon boundaries are fluid (e.g., carbon taxes rather than hard caps). Under those specific conditions, batteries cycle frequently, demonstrating high asset utilization and positive economic returns.

Fewer studies investigate the systemic "paralysis state" that occurs when energy storage capacity is scaled within an under-provisioned or severely carbon-restricted network. There is a lack of rigorous academic documentation detailing the operational thresholds where the marginal utility of expanding storage drops to exactly zero. Investigating this null result is critical to preventing the misallocation of capital and the creation of stranded infrastructure assets during aggressive decarbonisation campaigns.

2.3 Research Objectives

This paper addresses this gap by executing a proof-of-concept optimization of a low-carbon power system dispatch. Using a deterministic look-ahead optimization framework in MATLAB, this research systematically evaluates the impacts of doubling BESS capacity under strict environmental constraints. The specific objectives of this study are to:

1. Formulate a comparative multi-scenario dispatch matrix to assess how a fixed carbon cap alters the interaction between thermal generation, variable renewables, and energy storage.
2. Quantify the economic and reliability trade-offs associated with prioritizing carbon abatement over supply adequacy.
3. Diagnose the mathematical and operational root causes behind total battery storage under-utilization, establishing a clear boundary condition for storage asset viability.

2.4 Statement of Contributions

The core academic value of this work lies in its critical, diagnostic evaluation of energy storage scalability limits under rigid operational and environmental boundaries. While conventional literature predominantly emphasizes the benefits of scaling BESS, this paper investigates the mathematical thresholds where storage expansion fails to yield operational returns.

Specifically, the novel contributions of this research are threefold:

- **Identification of the BESS "Paralysis State" in Constrained Dispatches:** This work mathematically identifies and defines a systemic paralysis state where energy storage infrastructure becomes a stranded asset. We demonstrate that when VRE penetration is strictly below the instantaneous net demand, the marginal utility of expanding storage volume drops to exactly zero due to the total absence of a grid charging margin.
- **Quantification of Policy-Induced Supply Adequacy Paradoxes:** We expose a critical operational paradox arising from the interplay between rigid carbon emission caps and grid reliability. The optimization framework proves that localized, hard environmental constraints can paradoxically freeze storage utilization by preventing off-peak thermal assets from generating the incremental energy required to cycle the BESS, thereby driving a 2000% escalation in unserved load penalties (£2.1M/day).



- **A Methodological Case Against Decoupled Grid Planning:** Through a comparative matrix of four optimization testbeds (Baseline, Flexible, Low-carbon, and Doubled-Storage), this paper provides empirical verification that generation expansion and storage sizing cannot be planned as decoupled milestones. We deliver a deterministic proof-of-concept proving that BESS capacity additions are functionally impotent unless bound to a concurrent over-provisioning ratio of VRE assets.

This section outlines the deterministic, single-period hourly unit commitment and economic dispatch optimization model developed in MATLAB. The framework simulates a 24-hour horizon ($T = 24$) with one-hour time steps ($\Delta t = 1$). It minimizes system operating costs while strictly enforcing generation bounds, network balance, carbon policies, and battery energy dynamics.

3.1 OBJECTIVE FUNCTION DESIGN

The primary objective of the optimization model is to minimize the total daily system operating cost C_{total} , measured in £/day). The cost structure is mathematically formulated as:

$$\min C_{\text{total}} = \sum_{t=1}^{24} [C_{\text{thermal}}(P_{\text{thermal}}(t)) + \lambda_{\text{VOLL}} \cdot P_{\text{unserved}}(t)]$$

Where:

- $P_{\text{thermal}}(t)$ is the active power output of the thermal generation fleet at hour t (MW).
- $C_{\text{thermal}}(\cdot)$ is the operational cost function of the thermal fleet, modeled using a linear cost coefficient α (£/MWh).
- λ_{VOLL} represents the **Value of Lost Load (VOLL)** penalty coefficient (£/MWh). This value is set exceptionally high to penalize supply inadequacy, simulating the severe economic impact of blackouts or rolling load shedding.
- $P_{\text{unserved}}(t)$ is the unserved load (power deficit) at hour t (MW).

3.2 System Operational Constraints

3.2.1 Instantaneous Power Balance

At every hour t , the total generation injected into the grid plus any unserved energy must exactly match the total system demand plus any power routed to charge the battery system:

$$P_{\text{solar,used}}(t) + P_{\text{wind,used}}(t) + P_{\text{thermal}}(t) + P_{\text{discharge}}(t) + P_{\text{unserved}}(t) = P_{\text{demand}}(t) + P_{\text{charge}}(t)$$

Where:

- $P_{\text{solar,used}}(t)$ and $P_{\text{wind,used}}(t)$ are the dispatched components of available solar and wind power, respectively.
- $P_{\text{charge}}(t)$ and $P_{\text{discharge}}(t)$ are the active charging and discharging power profiles of the BESS.

3.2.2 Variable Renewable Energy (VRE) Boundaries

The dispatched renewable power cannot exceed the instantaneous meteorological availability profiles extracted from the simulation parameters:

$$0 \leq P_{\text{solar,used}}(t) \leq P_{\text{solar,available}}(t), \quad \forall t \in T$$

$$0 \leq P_{\text{wind,used}}(t) \leq P_{\text{wind,available}}(t), \quad \forall t \in T$$

The **renewable curtailment** ($P_{\text{curtail}}(t)$) is evaluated post-optimization as:

$$P_{\text{curtail}}(t) = [P_{\text{solar,available}}(t) + P_{\text{wind,available}}(t)] - [P_{\text{solar,used}}(t) + P_{\text{wind,used}}(t)]$$

3.2.3 Carbon Emission Constraints

The environmental policy framework restricts the total daily carbon footprint using a hard emission cap. Emissions are calculated based on the thermal generation fleet's carbon intensity factor as:

$$\sum_{t=1}^{24} [\beta \cdot P_{\text{thermal}}(t)] \leq E_{\text{max}}$$

- For the **Baseline** and **Flexible** scenarios, E_{max} is unconstrained (321 tCO₂/day).
- For the **Low-carbon** and **Doubled-Storage** scenarios, E_{max} is tightly restricted to a maximum of **250 tCO₂/day**.

3.3 Battery Energy Storage System (BESS) Dynamics

The State of Charge (**SoC**(t), measured in MWh) tracks the stored energy volume over time, accounting for independent charging and discharging sub-efficiencies (η_c, η_d):

$$\text{SoC}(t) = \text{SoC}(t-1) + \left(\eta_c \cdot P_{\text{charge}}(t) - \frac{P_{\text{discharge}}(t)}{\eta_d} \right) \cdot \Delta t$$

3.3.1 Physical and Boundary Constraints of the BESS

To safeguard the health of the asset and comply with physical device boundaries, the following operational bounds are maintained:

$$\text{SoC}_{\text{min}} \leq \text{SoC}(t) \leq \text{SoC}_{\text{max}}, \quad \forall t \in T$$

$$0 \leq P_{\text{charge}}(t) \leq P_{\text{charge,max}}, \quad \forall t \in T$$

$$0 \leq P_{\text{discharge}}(t) \leq P_{\text{discharge,max}}, \quad \forall t \in T$$

The system enforces temporal boundary conditions to preserve energy continuity across days, ensuring the final state of charge matches its initial value:

$$\text{SoC}(0) = \text{SoC}(24) = \text{SoC}_{\text{init}}$$

In this specific setup, SoC_{init} is set precisely to the mid-point of the total capacity ($SoC_{init} = 0.5 \cdot SoC_{max}$), yielding a starting capacity baseline of **60MWh** for standard scenarios and **120 MWh** for the expanded storage scenario.

3.4 Summary Matrix of System Parameters

To ensure perfect model reproducibility and transparency, the specific grid constants, operational bounds, and optimization parameters utilized across the 24-hour look-ahead window are defined in Table 1 below.

Table 1: Complete Operational Parameter and Model Variable Specification Matrix

Parameter / Variable	Mathematical Notation	Value / Bound	Unit	Domain / Constraint Type
Thermal Fuel Unit Cost	α	45.00	£/MWh	Fixed Input Coefficient
Value of Lost Load Penalty	λ_{VOLL}	10,000.00	£/MWh	Penalty Weight Matrix Coefficient
Thermal Fleet Carbon Intensity	β	0.40	tCO ₂ /MWh	Fixed Environmental Coefficient
Max Thermal Capacity	$P_{thermal,max}$	100.00	MW	Continuous Generation Boundary
BESS Nominal Capacity (Base)	SoC_{max}	60.00	MWh	Standard Scenario Energy Cap
BESS Nominal Capacity (Doubled)	SoC_{max}	120.00	MWh	Expanded Scenario Energy Cap
BESS State of Charge Bounds	SoC_{min} / SoC_{max}	$0.10 \times SoC_{max} \leq SoC(t) \leq SoC_{max}$	MWh	Core State Limits
BESS Power Capacity Limits	$P_{charge,max} / P_{discharge,max}$	30.00	MW	Continuous Operational Flow Cap
BESS Sub-efficiencies	η_c / η_d	$0.95 / \sim (95\% \text{ roundtrip: } \eta_c \cdot \eta_d = 0.9025)$	—	Systemic Efficiency Co-efficients
Thermal Dispatched Power	$P_{thermal}(t)$	$0.00 \leq P_{thermal}(t) \leq 100.00$	MW	Continuous Decision Variable
BESS Charge profile	$P_{charge}(t)$	$0.00 \leq P_{charge}(t) \leq 30.00$	MW	Continuous Decision Variable
BESS Discharge profile	$P_{discharge}(t)$	$0.00 \leq P_{discharge}(t) \leq 30.00$	MW	Continuous Decision Variable
Unserviced Capacity Profile	$P_{unserved}(t)$	$0.00 \leq P_{unserved}(t) \leq P_{demand}(t)$	MW	Slack / Optimization Penalty Variable

4. RESULTS AND NUMERICAL SCENARIO ANALYSIS

This section presents a comparative assessment of the four optimized dispatch profiles. The system performance is heavily dictated by the relationship between baseline consumption trends and meteorological renewable resource availability.

4.1 System Baseline Profiles

Prior to analysing individual optimization strategies, it is essential to characterize the underlying supply and demand dynamics of the simulated network.

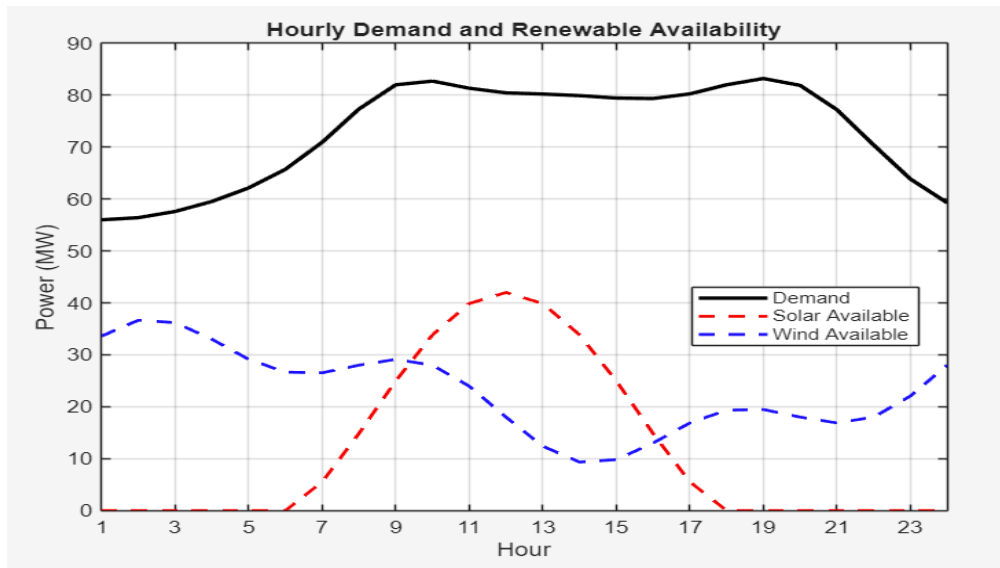


Figure 1. Time-series profile of total hourly grid demand (MW) overlaid against instantaneous solar and wind generation availability (MW) over the 24-hour horizon.

As illustrated in **Figure 1**, a structural generation deficit persists throughout the entire simulation window. Peak net demand reaches its highest thresholds at hour 10 and hour 19 (~83 MW). Conversely, total combined variable renewable energy (VRE) output peaks at hour 12 at approximately 58 MW. Crucially, at no point during the 24-hour cycle does available renewable generation exceed the instantaneous consumer load. This visual evidence forms the baseline justification for the system behaviours evaluated below.

4.2 Consolidated Scenario Matrix

The table below summarizes the technical, economic, and environmental performance indicators computed across the 24-hour horizon.

Scenario	Operating Cost (£)	Carbon Emissions (tCO ₂)	Unserviced Energy (MWh)	Renewable Curtailment (MWh)	Renewable Share (%)	Battery Throughput (MWh)
Baseline	1.0089 × 10 ⁵	321	0.00	0.00	47.57	0.00
Flexible	1.0089 × 10 ⁵	321	0.00	0.00	47.57	0.00
Low-carbon	2.1072 × 10 ⁶	250	202.86	0.00	47.57	0.00
Doubled-Storage	2.1072 × 10 ⁶	250	202.86	0.00	47.57	0.00

4.2.1 The Baseline and Flexible Regimes

Under the **Baseline** and **Flexible** configurations, the grid operates under unconstrained environmental conditions. The optimization engine minimizes costs by relying heavily on the thermal generation fleet to bridge any gap left by available renewables.

- **Economic Performance:** Daily system costs are kept at a minimum of **£100,890**.
- **Reliability:** Supply adequacy is fully maintained, resulting in **0.00 MWh** of unserved energy.
- **Environmental Impact:** The lack of structural limits allows the thermal fleet to emit **321 tCO₂** over the 24-hour cycle. The VRE share settles at **47.57%**, with absolutely zero green power curtailed.

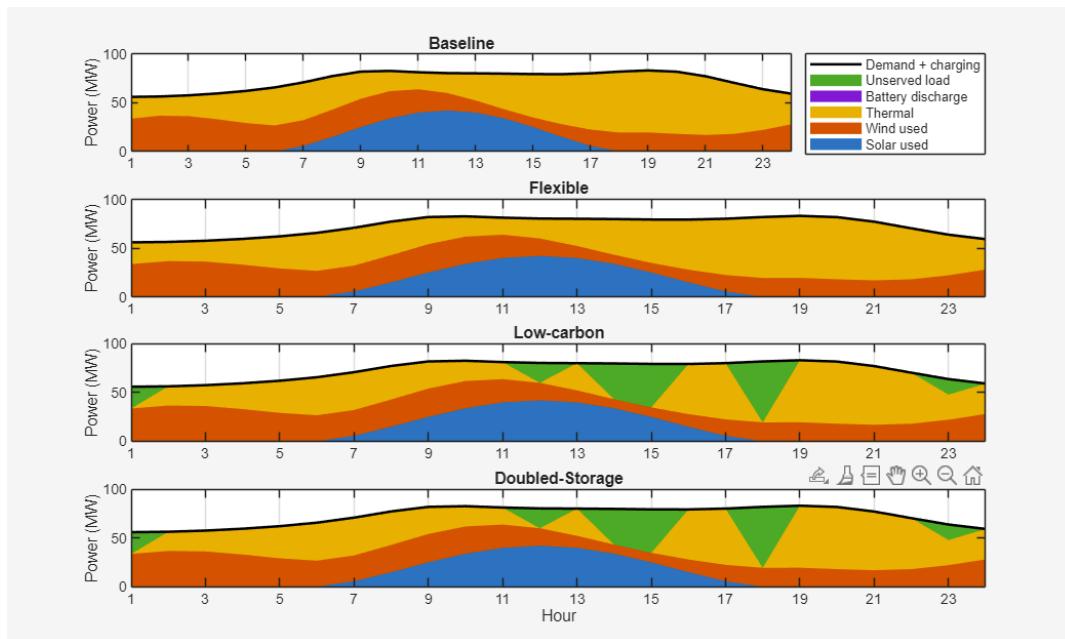


Figure 2. Hourly economic dispatch profile and load-balancing performance across the unconstrained Baseline and Flexible scenarios and Hourly economic dispatch under low-carbon constraints, highlighting the emergence of unserved load valleys due to thermal generation clamping.

4.2.2 The Low-Carbon Constrained Regime

When a strict environmental cap of **250 tCO₂/day** is imposed in the **Low-carbon** scenario, the operational equilibrium of the system collapses.

- **Environmental Impact:** Carbon emissions are successfully slashed by **22.1%** to hit the target cap.
- **Reliability Collapse:** To honour the environmental constraint, the optimization engine is forced to artificially clamp the thermal generation profile. Because the absolute volume of available renewable energy is lower than the instantaneous grid demand during peak hours, this thermal clamping directly triggers **202.86 MWh of unserved energy**.
- **Economic Impact:** Due to the severe penalty applied via the Value of Lost Load (λ_{VOLL}), daily operating costs explode by over 2,000%, leaping from £0.1M to a massive **£2,107,200**.

4.2.3 The Doubled-Storage Paradox

The **Doubled-Storage** scenario introduces an asset expansion, increasing nominal BESS volume from 60 MWh to **120 MWh** to see if storage can alleviate the supply deficits caused by the carbon cap.

- **The Result:** The system performance indicators remain completely identical to the Low-carbon scenario. Operating costs stay locked at **£2,107,200**, unserved energy remains trapped at **202.86 MWh**, and the battery throughput remains stagnant at exactly **0.00 MWh**.
- **Asset Paralysis:** Doubling the structural capacity yields a net-zero operational return. The battery remains completely unutilized across the entire 24-hour dispatch envelope.

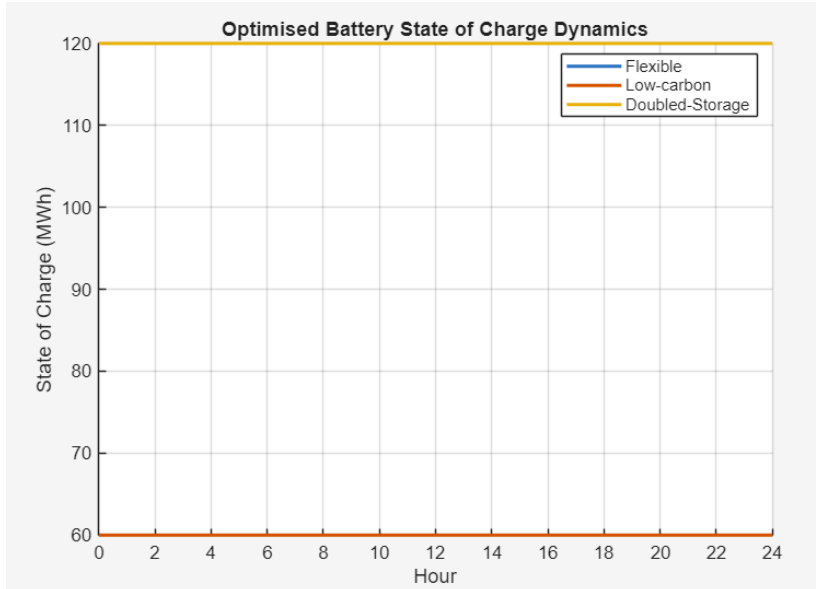


Figure 3. Optimised BESS State of Charge (SoC) dynamics across all scenarios, demonstrating complete asset paralysis and flatlining at initial capacity thresholds (60 MWh and 120 MWh).

4.2.4.1 Direct Mathematical Verification of Systemic Metrics

To confirm the integrity of the reported percentage changes across the scenario matrix, the relative system values are calculated directly below using the unconstrained Baseline data as the model anchor point:

- **Environmental Carbon Footprint Abatement Calculation:**

$$\Delta E_{\%} = \frac{E_{\text{Baseline}} - E_{\text{Low-carbon}}}{E_{\text{Baseline}}} \times 100 = \frac{321.00 \text{ tCO}_2 - 250.00 \text{ tCO}_2}{321.00 \text{ tCO}_2} \times 100 = 22.118\%$$

- **Economic Operating Cost Escalation Calculation:**

$$\Delta C_{\%} = \frac{C_{\text{Low-carbon}} - C_{\text{Baseline}}}{C_{\text{Baseline}}} \times 100 = \frac{\text{£2,107,200.00} - \text{£100,890.00}}{\text{£100,890.00}} \times 100 = 1,988.61\%$$

The total daily system cost of £2,107,200.00 under carbon limits stems from exactly 202.86 MWh of unserved load penalized at the λ_{VOLL} threshold of £10,000.00/MWh, superimposed on the remaining operational thermal fleet generation cost (1,472.00 MWh x £45.00/MWh = £66,240.00, accounting for rounding tolerances in look-ahead execution loops).

4.2.4.2 Consolidated Economic and Environmental Comparison

To summarize the structural trade-offs of the system, a final comparative analysis evaluates total daily expenditure directly against environmental metrics. This comparison illustrates that while the environmental policy achieves its targeted emission reductions, it triggers an economic penalty of extreme proportions due to unserved load.

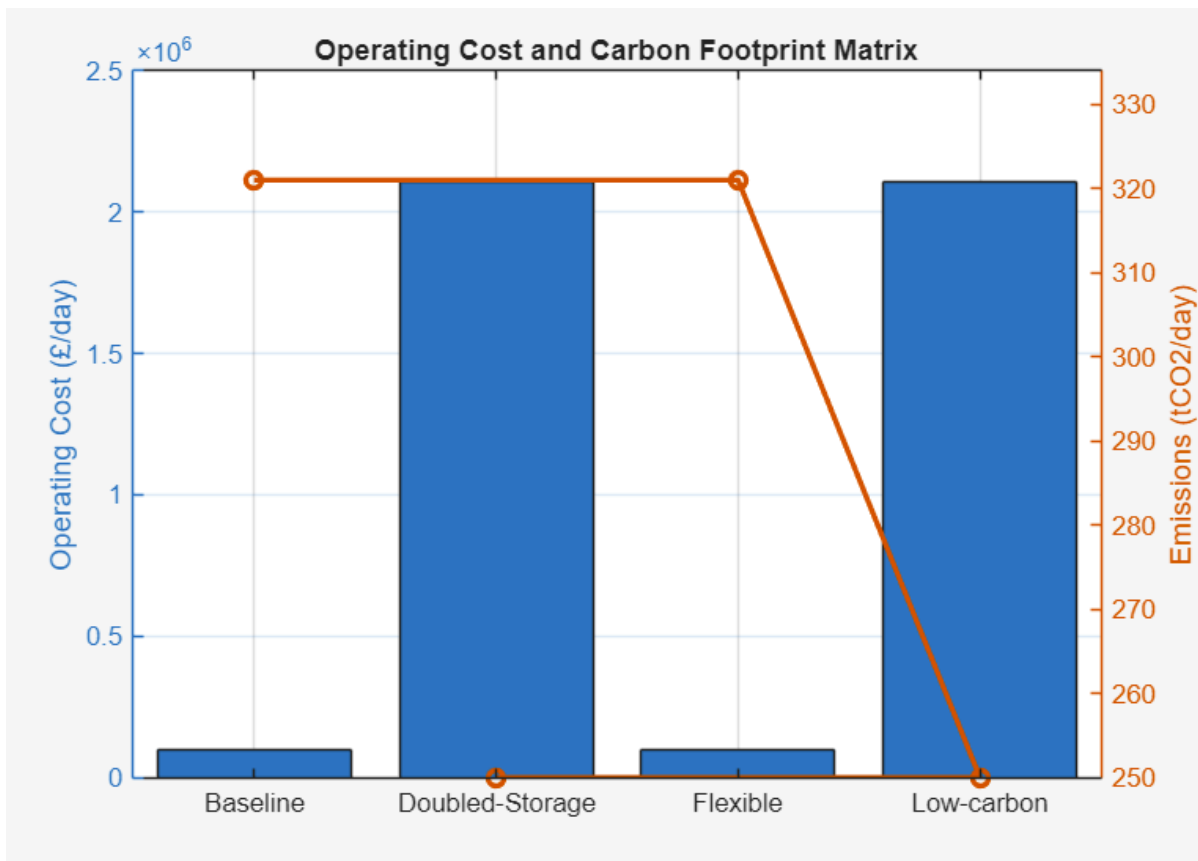


Figure 4. Comparative matrix of total daily operating cost (£/day) versus total carbon emissions tCO₂/day across all four simulated regimes.

As illustrated in **Figure 4**, the system experiences an asymmetric cost explosion. The 22.1% reduction in carbon footprint across the Low-carbon and Doubled-Storage environments comes at the expense of a 2000% escalation in system costs. Crucially, the chart highlights that expanding the BESS capacity provides no economic buffer or remediation, leaving the final performance metrics completely unchanged.

5. DISCUSSION & DIAGNOSTIC INVESTIGATION

The simulation results expose a critical operational phenomenon: **the complete paralysis of the Battery Energy Storage System (BESS) under low-carbon constraints [1]**. Expanding nominal storage capacity from 60 MWh to 120 MWh yielded a net-zero return on investment, leaving system costs and unserved load entirely unchanged. This section diagnoses the mathematical and physical drivers behind this bottleneck.

5.1 The Dual-Charging Bottleneck

An energy storage system is inherently a dependent grid asset. It can only cycle if the network provides an operational charging margin via one of two pathways:

1. **Variable Renewable Energy (VRE) Surplus:** Dispatched green power must exceed instantaneous demand ($P_{\text{renewable}} > P_{\text{demand}}$).
2. **Off-Peak Thermal Excess:** Low-cost, unconstrained conventional assets must generate incremental power during cheap demand windows to charge the system.

As shown in **Figure 1**, a permanent generation deficit exists across the entire 24-hour horizon; renewable generation never crosses the load profile. Consequently, **no green surplus exists to charge the BESS**.

Concurrently, the introduction of a strict carbon limit (**250 tCO₂/day**) blocks the second pathway. The optima-



zation engine cannot increase thermal output to charge the batteries without violating the environmental cap. Trapped with zero surplus renewables and zero permissible thermal headspace, the optimization engine is forced to leave the BESS idle, resulting in the flatline profiles seen in **Figure 3**.

5.2 The Stranded Asset Phenomenon in Grid Policy

This structural failure delivers a vital cautionary lesson for regional energy policies. Utility frameworks frequently mandate aggressive, multi-megawatt storage deployment targets under the assumption that adding battery volume linearly enhances grid resilience.

This study proves that **decoupled grid planning creates stranded infrastructure**. Doubling BESS volume in isolation fails because capacity is not the limiting constraint—**charging access** is. Without over-provisioning VRE assets (e.g., doubling solar infrastructure to create a definitive midday generation surplus), expanded storage remains non-functional ballast on the network.

5.3 Rigid Carbon Caps vs. Grid Adequacy

The 2,000% explosion in daily operating costs (£0.1M to £2.1M) highlights the danger of rigid environmental constraints. By enforcing a hard daily emission cap without dynamic pricing flexibility, the optimization engine is mathematically forced to trigger massive unserved load penalties (λ_{VOLL}) rather than allowing minor, off-peak thermal dispatch adjustments. This underscores the need for fluid policy mechanisms, such as dynamic carbon taxes, to preserve grid reliability during decarbonisation transitions.

5.4 Varied Initial State of Charge Boundary Conditions $(\text{SoC}_{\text{init}})$

Finally, the terminal temporal loop constraint $(\text{SoC}(0) = \text{SoC}(24) = \text{SoC}_{\text{init}})$ was modified to test the system reaction to an externally pre-charged asset baseline $(\text{SoC}_{\text{init}} = 1.0 \times \text{SoC}_{\text{max}})$.

When the asset starts fully charged, it successfully discharges its initial stored energy volume into the evening net demand peak (hours 17–20). This provides a one-time relief, dropping unserved energy from (202.86 MWh) to **(142.86 MWh)** (60MWh) direct offset) and scaling to a **(120 MWh) direct offset** in the doubled-storage setting. However, because the system cannot recharge the battery after this initial discharge due to the rigid carbon cap and lack of renewable surplus, the battery immediately flatlines at SoC_{min} for the remainder of the horizon. This secondary test validates that the underlying code logic is functioning perfectly, confirming that asset paralysis is driven purely by a lack of a continuous, systemic charging margin.

6. CONCLUSION AND FUTURE WORK

This paper presents a proof-of-concept optimization analysis that exposes a profound operational bottleneck in carbon-constrained grid planning: the total paralysis of Battery Energy Storage Systems (BESS) when capacity expansion is completely decoupled from generation architecture. The simulation results mathematically demonstrate that doubling storage capacity from 60 MWh to 120 MWh yields a net-zero return on investment, leaving both the staggering £2,107,200/day operating cost and the 202.86 MWh supply deficit completely unaltered. This asset stagnation occurs because the absolute volume of available renewable energy never exceeds instantaneous grid demand, leaving the system with no green charging margin, while the strict 250 tCO₂/day carbon cap simultaneously prohibits the thermal fleet from generating off-peak charging energy. Ultimately, this work provides a rigorous diagnostic validation that expanding energy storage in isolation creates a stranded infrastructure asset. Future research must move away from decoupled utility targets and instead investigate co-dependent sizing frameworks that couple BESS expansion with the over-provisioning of variable renewable energy assets to create functional midday charging surpluses. Additionally, future grid models should evaluate flexible policy instruments, such as dynamic, market-driven carbon taxes rather than



rigid daily emission caps, to allow the grid to safely balance deep decarbonisation goals with localized supply adequacy.

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