Energy Proceedings
Vol 67, 2026
ISSN 2004-2965

Second-Life Batteries in Distribution Networks: A Sustainability and Economic Screening Framework

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ABSTRACT

The rise of electric vehicles raises the challenge of managing retired lithium-ion batteries. Repurposing them as second-life batteries (SLBs) offers cost and environmental benefits while supporting circular economy goals. This paper proposes a screening framework to compare SLBs and lithium-ion new battery systems (NBS) in distribution networks using three metrics: lifetime energy delivered, levelized cost of storage (LCOS), and carbon footprint (CF). A stylized case study evaluates five scenarios from fully NBS to fully SLBs and mixed portfolios. Results show that NBS minimize LCOS due to higher throughput, while SLBs lower embodied emissions and achieve the lowest CF. Overall, outcomes form a trade-off frontier, offering flexible options for planners and policymakers.

Keywords: Carbon Footprint, Distribution Networks, Energy Storage, Levelized Cost of Storage, Second-Life Batteries

1. INTRODUCTION

The rapid growth of electric vehicle (EV) adoption is creating a parallel challenge of managing the retirement of automotive lithium-ion batteries. These batteries typically retain 70 % to 80 % of their original capacity at the end of first life, making them suitable for repurposing as stationary energy storage, often referred to as second-life batteries (SLBs) [1]. Their integration into distribution networks offers potential cost reductions and sustainability benefits compared to new battery systems (NBS), while simultaneously contributing to circular economy objectives [2].

Several studies have highlighted the promise of SLBs in energy systems and grid support. A techno-economic assessment by Zhuang et al. [3] demonstrated that repurposed EV batteries could lower cost of electricity compared to NBS, especially when battery cost is below a certain threshold. Dong et al. [4] found that second-life use of EV batteries significantly reduces greenhouse gas emissions compared to manufacturing NBS, highlighting substantial life-cycle environmental benefits. Complementing these, a broader review of SLB technologies emphasized the importance of degradation modeling and uncertainty, noting that accurate testing and screening are essential to unlocking their value [5]. Further research, such as by Das [6], has shown that SLBs become attractive when their upfront cost is substantially lower than NBS. Moreover, simplified levelized cost of storage (LCOS) models indicate that stationary Li-ion systems continue to become more cost-effective over time, supporting the economic case for SLB deployment [7]. In parallel, several works also consider storage in a distribution network planning aspect [8], [9], as part of an extensive planning model, but not as SLBs, which could potentially alter outcomes and the economic appeal [10].

Despite these promising insights, a gap remains: there is still a lack of simple decision-support frameworks that compare SLBs with NBS in terms of both cost and sustainability for distribution network planning. Most existing work focuses on either technical feasibility or detailed life-cycle analysis, whereas distribution system operators (DSOs) require transparent, tractable screening tools. This paper addresses that gap by presenting a compact sustainability and economic screening tool that compares SLBs and NBS.

The main contributions of this paper are:

- A comparative framework that evaluates SLBs and lithium-ion NBS in terms of levelized cost of storage and CO_2 footprint for distribution planning.
- A stylized case study demonstrating the trade-offs of SLBs versus NBS.
- Policy-relevant insights to inform DSOs and regulators about the value of promoting battery reuse.

[1]This is a paper for the 17th International Conference on Applied Energy (ICAE2025), Dec. 8-12, 2025, Bangkok, Thailand.

The remainder of this paper is organized as follows. Section 2 presents the methodology, including assumptions for cost, lifetime, emissions, and screening metrics. Section 3 describes the case study and scenarios. Section 4 reports results and discusses economic and sustainability outcomes. Finally, Section 5 concludes with key findings and future work directions.

2. METHODOLOGY

The methodology is structured to provide a transparent comparison between SLBs, lithium-ion NBS in terms of both economic and sustainability performance. Three core equations are used to derive the screening metrics: total lifetime energy delivered, LCOS, and carbon footprint (CF). Together, these equations provide consistent measures that allow direct comparison across the different options.

The first step is to determine the technical service potential of each storage option. This is expressed as the total lifetime energy delivered, which depends on the rated capacity, round-trip efficiency, and the expected cycle life, and can be seen in equation (1).

$$E^{\text{deliver}} = E \cdot \eta \cdot N^{\text{cycles}} \quad (1)$$

where E is the usable storage capacity (kWh), η is the round-trip efficiency, and N^{cycles} is the number of charge–discharge cycles over the lifetime. This value does not include discounting and is not directly applied in the LCOS calculation. Rather, it provides a physical baseline to verify the consistency of lifetime assumptions, to highlight the shorter service horizon of SLBs relative to NBS, and to normalize environmental impacts in the sustainability assessment.

The economic evaluation is based on the LCOS, which expresses the discounted cost per unit of energy delivered, as seen in equation (2).

$$LCOS = \frac{C_0 + \sum_{t=1}^{T} \frac{C_t^{\text{op}}}{(1+\delta)^t}}{\sum_{t=1}^{T} \frac{E \cdot \eta}{(1+\delta)^t}} \quad (2)$$

where C_0 is the upfront investment cost, C_t^{op} represents annual operating costs, δ is the discount rate (4% - [11]), and T is the project lifetime in years. The denominator reflects the time-discounted stream of usable energy delivered. This formulation captures the trade-off between lower upfront cost but shorter service life (SLBs) and higher upfront cost but longer durability (NBS).

The sustainability assessment is carried out using a CF indicator, which expresses life-cycle greenhouse gas emissions per unit of energy delivered, in equation (3).

$$CF = \frac{M^{\text{CO}_2,\text{emb}} + M^{\text{CO}_2,\text{op}}}{E^{\text{deliver}}} \quad (3)$$

where $M^{\text{CO}_2,\text{emb}}$ is the embodied carbon from battery production and repurposing, $M^{\text{CO}_2,\text{op}}$ represents operational carbon emissions, calculated as the grid's carbon intensity multiplied by the total energy charged into the battery over its lifetime, and E^{deliver} is the total non-discounted lifetime energy delivered, as defined earlier. SLBs typically have a much lower $M^{\text{CO}_2,\text{emb}}$ because they avoid new cell manufacturing, whereas NBS carry the full production footprint [1], [5].

Together, LCOS (m.u./kWh) and CF ($kgCO_2e$/kWh) form the screening metrics used in the comparative analysis of Section 4.

3. CASE STUDY AND SCENARIOS

A stylized case study is developed for stationary storage deployment in distribution networks. The focus is on comparing SLBs with lithium-ion NBS under different portfolio configurations. The analysis highlights both economic and sustainability outcomes across a spectrum of scenarios, from full reliance on NBS to full reliance on SLBs.

Assumptions for parameters are based on recent literature, taken as midpoints of reported ranges. Lithium-ion NBS are assumed to cost 100–125 m.u./kWh [12], with a lifetime of 10–15 years at 4000–6000 cycles and round-trip efficiency of 90–92% [7]. SLBs, by contrast, are assumed to cost 40–80 m.u./kWh, typically 30–40% of NBS [3], but with a shorter usable life of 5–8 years and 1500–2500 remaining cycles [4]. Embedded emissions for NBS are taken as 60–100 $kgCO_2e$/kWh [13], while repurposing SLBs adds only 5–25 $kgCO_2e$/kWh [14], reflecting avoided cell production. The annual operating costs are assumed as 1.5% of the capital expenditure (CAPEX) per year for NBS and 2.0% per year for SLB [15]. Operating emissions are modeled from average European grid intensity of 210-250 gCO_2e/kWh [16]. For consistency, all results are expressed relative to a reference system with 1 MWh of usable capacity. This normalization provides absolute values while keeping LCOS and carbon footprint results independent of system size.

Based on these assumptions, five scenarios are defined, as shown in Table 1.

For all scenarios, performance is assessed using the same methodological framework:

- Technical potential is expressed as lifetime energy delivered (Eq. 1).
- Economic performance is measured via LCOS (Eq. 2).

- Sustainability performance is captured by the carbon footprint (Eq. 3).

For scenarios that include both technologies, results are obtained as a weighted average of the respective calculations for each technology, based on their share in the portfolio.

Table I. Definition of case study scenarios

Scenario	NBS share (%)	SLB Share (%)	Description
A	100	0	Conventional approach with only NBS
B	0	100	Full SLB
C	50	50	Equal share of NBS and SLBs
D	25	75	SLB-dominant portfolio
E	75	25	NBS-dominant portfolio

4. RESULTS AND DISCUSSION

Applying the screening metrics to the five scenarios in Table I yields the base-case outcomes in Table II. Calculations use midpoint assumptions in Section 3, including annual operating costs of 1.5% of CAPEX for NBS and 2.0% for SLBs, and a 4% discount rate.

All results are reported on a per-kWh basis, ensuring comparability across possible technologies and portfolio mixes.

Table II. Base-case outcomes (per kWh basis)

Scenario	$LCOS$ (m.u./ kWh)	CF ($kgCO_2e$/ kWh)	Lifetime energy (kWh delivered per kWh capacity)	$M^{CO_2,emb}$ (kg/kWh)	$M^{CO_2,op}$ (kg/kWh)
A	**0.037**	0.271	4550	0.018	0.253
B	0.043	**0.264**	1800	0.008	0.256
C	0.038	0.269	3175	0.015	0.254
D	0.040	0.267	2488	0.013	0.254
E	**0.037**	0.270	3862	0.017	0.253

Two patterns are immediately visible:

First, NBS (scenario A) minimize LCOS because their longer technical life and higher cycle budget spread costs over far more delivered energy (≈4550 kWh delivered per kWh capacity) than SLBs (≈1800 kWh).

Second, SLBs (Scenario B) minimize carbon footprint (CF) by avoiding new cell production. Yet the absolute CF difference is modest, 0.270 vs. 0.264 kg/kWh, because operational emissions dominate at current grid intensities.

Figure 1 shows lifetime energy delivered by scenario.

NBS-heavy portfolios deliver substantially more energy over their lifetime than SLB-heavy ones, which explains much of the LCOS ranking. Scenario A provides the highest throughput, while Scenario B is less than half of that. The mixed cases scale in proportion to their shares. This confirms that throughput is the critical driver of economic outcomes, as costs are spread across the total lifetime output.

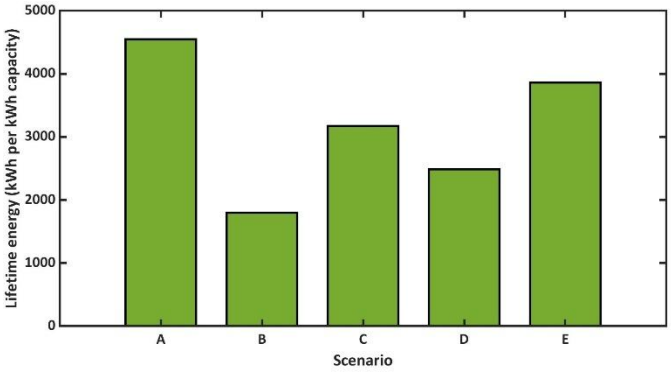

Fig. 1 Lifetime energy by scenario

Figure 2 presents LCOS and CF side-by-side for each scenario.

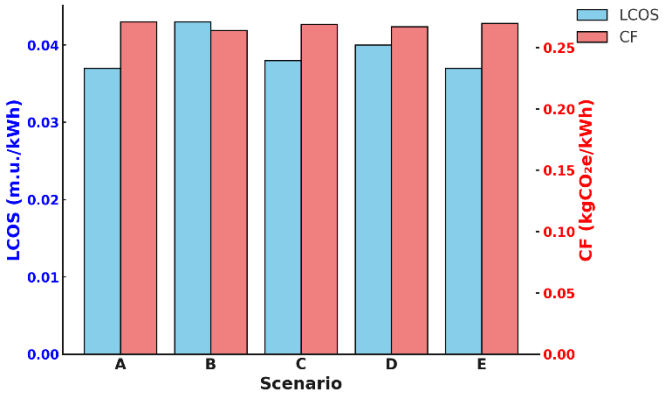

Fig. 2 LCOS and CF by scenario

The spread in LCOS is narrow, from 0.037 to 0.043 m.u./kWh, yet systematic: NBS-heavy portfolios (A, E) achieve the lowest LCOS, while SLB-heavy portfolios (B, D) are more costly per delivered kWh. CF values vary even less across scenarios, reflecting the dominance of operational emissions, but the embodied component decreases clearly as SLB share rises. This reinforces a counterintuitive result: although SLBs are cheaper upfront, their shorter life raises cost per unit delivered, while NBS, despite higher CAPEX, achieve lower LCOS thanks to higher throughput.

Figure 3 plots LCOS against CF to show the trade-off frontier.

Scenarios A and E anchor the low-cost side, B anchors the low-carbon side, and C lies in between. The alignment is nearly linear, forming a frontier of feasible outcomes where improvements in LCOS come at the expense of higher embodied carbon and vice versa. This highlights that no single option dominates; instead, the choice depends on how cost and carbon are weighted by DSOs or policymakers.

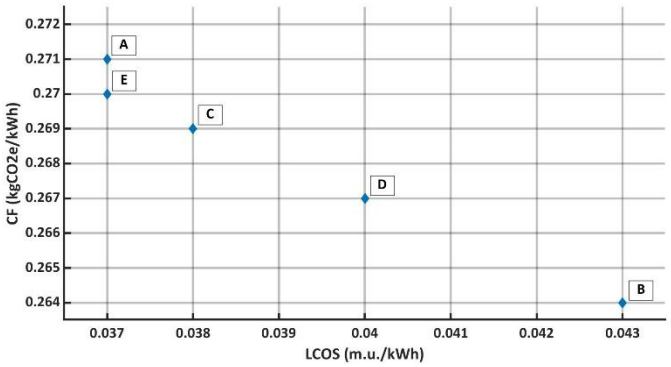

Fig. 3 LCOS vs CF trade-off scenarios

Taken together, the results point to three insights. First, the choice is not simply "NBS versus SLB"; it is about navigating a continuum of trade-offs along the LCOS–CF frontier. Second, the economics are more subtle than cost per kWh of capacity: longer-lived assets can achieve lower LCOS despite higher CAPEX, while SLBs may appear costlier per unit delivered energy unless their remaining lifetime is sufficiently high. Third, mixed portfolios offer more than a linear compromise, creating a flexible space for DSOs and regulators to hedge uncertainty in SLB performance while still capturing embodied-carbon reductions.

5. CONCLUSIONS

This paper developed a screening framework to compare SLBs and lithium-ion NBS in distribution networks using consistent technical, economic, and environmental metrics. The results show that NBS achieve the lowest LCOS, not because of lower upfront cost, but due to their longer lifetime throughput. SLBs, in contrast, reduce embodied emissions and therefore achieve the lowest CF, although the advantage is modest under current grid conditions where operational emissions dominate.

The analysis highlights that technology choice is not binary but lies along a frontier of trade-offs between cost and carbon. Mixed portfolios provide flexibility by balancing economic performance and embodied-carbon reduction, while also hedging uncertainty in SLB lifetime and reliability. Importantly, the findings show that cheaper assets can appear more costly per unit delivered energy if their technical life is short, while more capital-intensive assets can achieve better long-term economics.

Future work should extend the framework to longer planning horizons with replacement cycles, incorporate probabilistic models of SLB performance, and examine impacts under decarbonizing grid scenarios.

ACKNOWLEDGEMENT

This research has received funding from FEDER funds through the Operational Programme for Competitiveness and Internationalization (COMPETE 2020), National Funds through the FCT Portuguese Foundation for Science and Technology under project UIDB/000760/2020-10.54499/UIDB/00760/2020 (https://doi.org/10.54499/UIDB/00760/2020), CEECIND/00420/2022. Fábio Castro is supported by the FCT with Ph.D. Grant 2024.01436.BD.

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