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Exploring future circularity scenarios of lithium-ion batteries in the European Union: A system dynamics approach

Alessandro Neri [a,*], Alessio Trivella [b], Maria Angela Butturi [a], Devrim Murat Yazan [b]

[a] Department of Science and Methods for Engineering, University of Modena and Reggio Emilia, Via Amendola, 2, Reggio Emilia, 42122, Italy
[b] Department of Industrial Engineering and Management Science, University of Twente, Hallenweg, 17, Enschede, 7522, the Netherlands

HIGHLIGHTS

- System dynamics model simulates EU-27 lithium-ion battery flows until 2050.
- Scenarios link circular pathways with demand, recycling, and import dependency.
- Recycling capacity must expand to meet EU recovery targets by 2050.
- Excessive second-life use delays material recovery and weakens self-sufficiency.
- Coordinated, chemistry-specific EU policies can balance circularity and security.

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ABSTRACT

The European Union's transition toward climate neutrality is accelerating demand for lithium-ion batteries to electrify the automotive and household sectors. This makes the European region susceptible to vulnerabilities in material supply, end-of-life management, and recycling capacity. Despite growing research on battery circularity, existing models typically address single countries or isolated end-of-life pathways, lacking a comprehensive EU-wide, multi-pathway perspective. This study develops a system dynamics model to assess the long-term evolution of the vehicle and stationary battery market, end-of-life flows, and material recovery across all EU-27 countries up to 2050, integrating country-level heterogeneity and cathode chemistry transitions. The analysis quantifies how the interplay of extended use, remanufacturing, repurposing, and recycling shapes future battery demand, material dependency, and self-sufficiency. Results show that electric vehicles will dominate battery demand by 2050. Phase-out policies and high repurposing rates lower stationary demand, but increase reliance on imports for electric vehicle batteries. Collection and recycling capacity must expand substantially to meet regulatory targets, although recycling infrastructure remains concentrated in a few countries. Under coordinated expansion efforts, recovery of critical raw materials such as lithium, nickel, and cobalt could partially meet European self-sufficiency targets. The findings of this study highlight that excessive second-life deployment delays material recovery, whereas balanced integration of remanufacturing and recycling improves circularity and resource resilience. To meet European sustainability objectives, it is essential to implement flexible, chemistry-specific, and regionally integrated strategies. These strategies should connect battery design, collection, and recycling infrastructure to balance circular economy goals with resource security.

1. Introduction

Global climate change mitigation efforts are accelerating the decarbonization of energy and mobility systems. Within the context of the energy transition, the transport sector is particularly significant, accounting for approximately 25 percent of global greenhouse gas emissions [1]. Without effective mitigation policies, the proportion of emissions attributable to transport is projected to rise. The widespread adoption of electric vehicles (EVs) is significantly increasing demand for lithium-ion batteries (LIBs). In 2024, EV sales surpassed 17 million worldwide, a fifth of the global market [2]. The European Union (EU) is actively involved in this ecological transition by implementing the European Green Deal [3]. Following the Green Deal, the *Fit-for-55*

* Corresponding author.
Email address: alessandro.neri@unimore.it (A. Neri).

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package is a set of rules aimed at driving each EU country toward climate neutrality. Among the diverse strategies and policies outlined in the document, a pivotal strategy endorsed by this package is the ban on fossil-fueled vehicles by 2035 [4].

LIBs are widely regarded as the most mature technology for both automotive and power sector electrification [5–7]. EV sales are expected to reach 20 million by 2030, raising concerns about the critical raw materials (CRMs) required [8]. The EU faces persistent challenges in the LIB supply chain, largely due to its reliance on external materials and manufacturing capacity, which increases its vulnerability to disruptions [9–11]. Therefore, the EU Battery Regulation sets ambitious targets for EU-27 countries regarding sustainability and end-of-life (EOL) management of spent batteries [12]. This framework aims to support the efficient use of all valuable resources retained within batteries to address the aforementioned supply chain issues by enhancing circular activities; promoting reuse, repurposing, and remanufacturing; and enforcing ambitious targets for collection, recycling efficiency, and the recovery of materials (i.e., lithium, cobalt, manganese, and lead).

Multiple studies quantify the rising demand for critical raw materials in the coming decades, suggesting that recycling alone cannot fully close the gap in the near term [13–16]. At the same time, second-life pathways hold great potential for meeting stationary demand, but they delay the return of recyclable materials [17–22]. This creates a fundamental tension: the dynamic allocation of EOL batteries among extended use, remanufacturing, repurposing, and recycling simultaneously affects both circularity performance and resource security, and the net effect depends on the timing, scale, and regional distribution of each pathway. Current EU recycling capacity appears insufficient [23]. Most works focus on national-scale assessments, and the EU is analyzed in aggregate. Rarely is the heterogeneity across the EU-27 in EV uptake, chemistry mix, and policy implementation considered. Capacity shortfalls are frequently highlighted, but no study accounts for the dynamic co-evolution of capacity acquisition consistent with a multi-regional deployment strategy, including permitting lead times and intra-EU trade to avoid cross-border leakage of batteries.

To address these gaps, this study develops a system dynamics (SD) model to assess long-term impacts of EOL LIBs across the EU-27 from 2020 to 2050, under varying policies, technologies, and circular strategies. By capturing country-level heterogeneity, chemistry transitions, and infrastructure ramp-up dynamics, this study quantifies the implications of remanufacturing, repurposing, recycling, and collection pathways for material recovery and EU regulatory targets through 2050. Finally, this study addresses the following key research questions:

1. RQ1: How does the dynamic allocation of end-of-life batteries among extended use, remanufacturing, repurposing, and recycling shape the evolution of battery demand, infrastructure requirements, and EOL flows across EU-27 countries through 2050, under alternative policy, technology, and market scenarios?
2. RQ2: Under what conditions can secondary material recovery from recycling meet the EU's 2036 targets for lithium, nickel, and cobalt, and to what extent can it reduce dependence on primary imports, given regional capacity constraints, chemistry transitions, and intra-EU trade dynamics?

This study is structured as follows. Section 2 provides an overview of the LIB lifecycle and details global and EU capacities. It also reviews the recent literature and introduces the main modeling efforts used to analyze LIB circularity. Section 3 clarifies the research gaps identified in the existing literature and positions the specific contribution of this study. Section 4 presents the EU-27 system boundary and SD background framework, including causal relationships, stocks, flows, and feedback loops. Section 5 describes the analysis outline, detailing the input data, scenario structure, and the core indicators used for model-based inference. Section 6 presents simulation results, organized into four clusters: demand and supply, infrastructure capacity/use, second-life deployment, and material flows and targets. Section 7 interprets the findings and compares them with the previous literature, providing implications for policymakers and firms. Finally, Section 8 outlines key insights and highlights future implications. The Supplementary Material describes the data collected for the experiments and presents additional results, including detailed input assumptions, model formulations, and extended scenario analyses supporting the main findings.

2. Literature review

2.1. Life and death of a battery

The LIB lifecycle can be summarized in several steps, including production, sale, use, and final EOL management. As illustrated in Fig. 1, the framework for the circular LIB ecosystem comprises interconnected modules. This includes raw material supply, battery production for both EVs and stationary energy storage (SES), utilization phases, and post-use pathways. The latter comprises extended use, repurposing, remanufacturing, and recycling. The following sections provide a detailed description of each module.

2.1.1. The raw material issue

Depending on their chemistry, LIBs require multiple raw materials for their manufacture, such as lithium, cobalt, nickel, manganese, and graphite. Raw material extraction and processing capacities are localized in a limited number of countries, whose policies could frequently threaten global battery production [24]. Nowadays, over half of cobalt extraction is concentrated in the Democratic Republic of the Congo, while lithium is primarily sourced from South America and Australia [25]. Specifically, these two materials present considerable challenges concerning environmental and social sustainability [26]. The extraction of the former necessitates substantial water consumption and leads to soil degradation, while the latter is associated with harmful working conditions [9]. Moreover, the localized concentration of resources and capabilities makes the global supply chain vulnerable to price volatility and disruptions, raising concerns about resilience.

2.1.2. The production problem

After resource extraction, the manufacturing process for LIBs begins with the synthesis of active materials, in which raw materials are chemically processed to form electrode materials for cathodes and anodes. This involves mixing active, conductive, and binder materials; preparing the slurry; coating it onto current collectors; and finally drying and treating the electrodes structurally [27]. Following this, electrodes and a porous polymeric material are combined in different layered structures (i.e., cylindrical, pouch, and prismatic) [28]. The battery cells are then organized into modules. A battery pack installed on an EV or coupled with renewables is a set of modules connected in series and parallel [29].

Global LIB capacity is currently 2.8 TWh and is projected to reach 6.5 TWh by 2030 [30]. Pack production is usually close to where the EV is assembled [24]. Therefore, China leads, with over 70% capacity, followed by the EU, USA, South Korea, and Japan [31]. The production of large-scale batteries can leverage economies of scale; however, the initial stages necessitate substantial capital investments, resulting in elevated LIB costs [32]. The EU's LIB production is limited, primarily concentrated in specific nations and plants [33]. Europe hosts approximately 252 GWh of nominal LIB cell production capacity as of the end of 2025. The production is concentrated in Poland (86 GWh) and Hungary (78 GWh), primarily operated by South Korean manufacturers LG Energy Solution, Samsung SDI, and SK On, which together account for 164 GWh. France (42 GWh) and Germany (40 GWh) follow, with European players such as ACC and PowerCo increasingly contributing to domestic capacity. Chinese CATL operates a 14 GWh facility in Germany. Notably, Northvolt AB filed for bankruptcy in late 2024, and its Swedish gigafactory production has been suspended, significantly reducing effective European capacity [34].

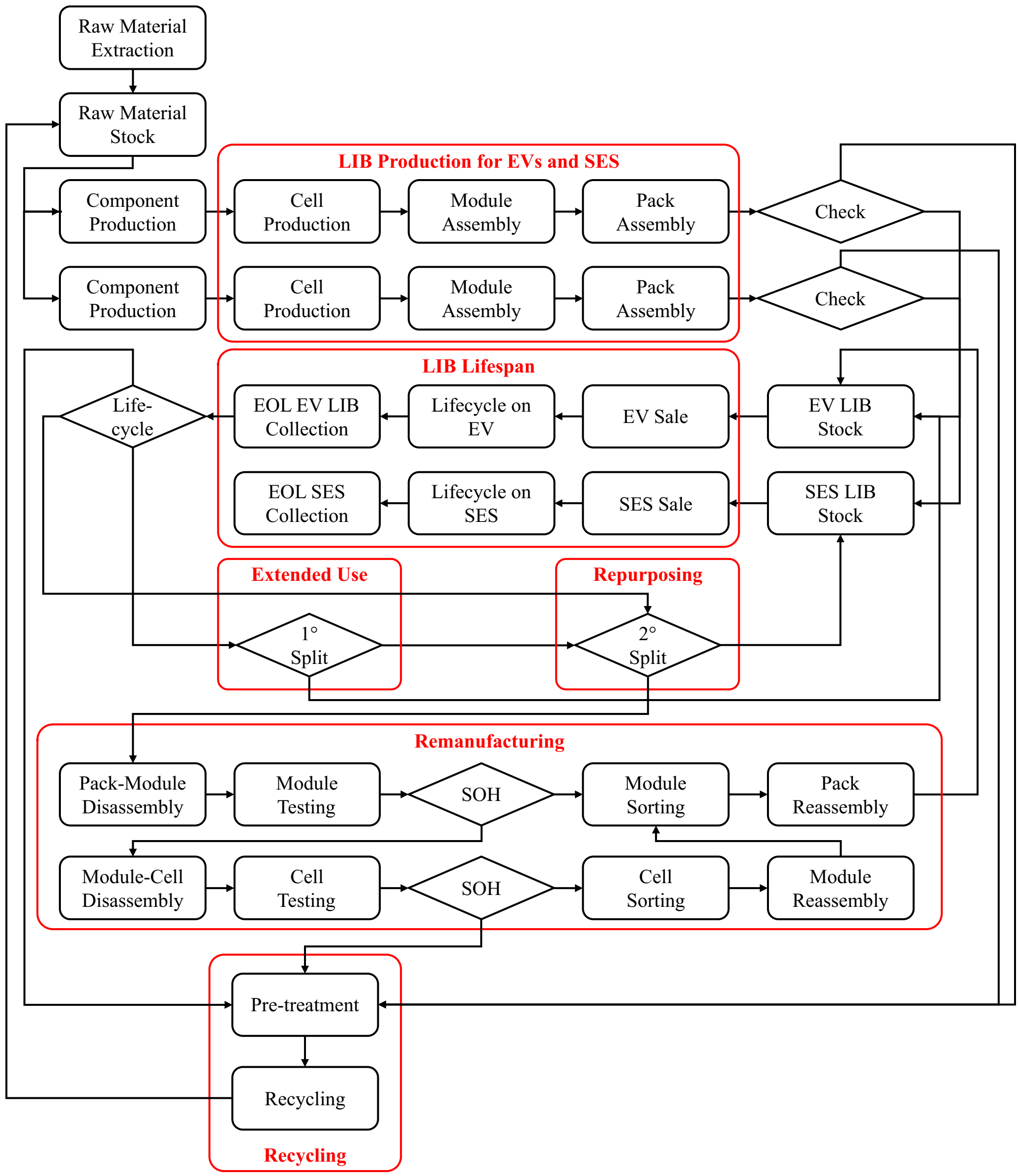


Fig. 1. A flowchart of the main LIB lifecycle steps.

2.1.3. End-of-life options for batteries

Upon reaching the EOL after initial utilization in an EV (or secondary utilization if directly reused), the battery can be ranked according to the principles of the circular waste management hierarchy: remanufacturing, repurposing, and recycling [35,36]. Remanufacturing restores used batteries to their original performance, retaining the highest value [37]. Repurposing adapts batteries for new, less-demanding applications, extending the batteries' service life. Remanufacturing and repurposing effectively extend the lifespan of LIBs, while recycling ultimately helps close the loop of material reuse. Therefore, direct recycling immediately following vehicular use is considered less favorable due to diminished lifecycle benefits and potential material losses [38].

Extended use. This refers to exploiting EOL LIBs in the same vehicle, even if their performance is compromised. This is only feasible when the LIB's state of health (SOH) has not yet reached substitution thresholds [39]. The term SOH refers to the degradation processes that occur in batteries as they age, including capacity loss and increased internal resistance [40–42]. Other use cases that might extend battery life beyond substitution limits include less demanding daily travel needs of EV users or early vehicle failure. Saxena et al. [43] suggest that improving the diffusion of charging stations can extend battery life and necessitate redefining retirement criteria based on travel needs. The lack of appropriate applications, however, has limited attention to the direct reuse of EOL batteries [44]. Moreover, the reliability of these batteries and the incompatibility between different brands remain major concerns for second-life EV applications [45,46].

Remanufacturing. This refers to the recovery of batteries that have been collected after a first use (i.e., first EOL) or after a direct reuse in an EV (i.e., second EOL). Remanufacturing entails restoring batteries to their original condition so they can be reused in their original applications [33]. At the collection facility, LIBs must be visually assessed to separate damaged batteries, which are sent to the recycling facility, from undamaged ones, which proceed to further testing [47]. This testing evaluates their SOH. This performance indicator usually guides the decision about whether a battery should be remanufactured or repurposed, as both routes are generally viable if the SOH is close to 80%. Whenever the battery does not meet the SOH threshold for some cells, but the full pack still functions well, the LIBs are first disassembled and then tested at the module and cell level [48]. Disassembly involves separating modules and cells. Acceptable cells can be reassembled into modules after passing the strict original equipment manufacturer (OEM) standards. Reassembled packs then undergo another testing phase, where electrical performance, thermal stability, and reliability are checked.

Repurposing. Repurposing involves using EV batteries for less-demanding applications, such as SES systems. Second-life EV batteries are well-suited for renewable power storage, energy trading, and grid reserve capacity [49,50]. Reaching net-zero targets depends on renewable energy sources (RES), including solar and wind. Given their variability, SES require storage of surplus energy, but a major obstacle is the high cost of battery storage [51]. Therefore, second-life batteries offer a cost-effective solution for SES. These batteries can support the electrification of emerging sectors and facilitate the broader integration of RES [20,52]. Moreover, battery repurposing can significantly boost resource circularity [53]. Despite the proven benefits of extending battery lifetimes and reducing environmental impact, a major concern remains regarding market potential, given the projected decrease in LIB prices [54].

Recycling. This entails disassembling the battery to the cell level and then extracting metals and critical materials for use in the production of future batteries [55]. Through recycling, valuable critical materials, such as lithium, cobalt, nickel, copper, and aluminum, can be recovered [48]. Pre-treatment is the first step and involves dismantling, comminution, classification, separation, dissolution, and thermal treatment [56]. Currently, pyrometallurgy, hydrometallurgy, and direct recycling are the three primary methods for recycling LIBs. The battery is smelted using pyrometallurgy to separate different materials. Acid (or base) leaching, concentration, and purification constitute hydrometallurgy. Finally, direct recycling is currently only available at the lab or pilot scale and attempts to recover active materials while preserving their compound structure [38].

The EU Battery Directive mandates extended producer responsibility, requiring automakers to handle EOL battery waste, set ambitious recycling targets, and provide robust infrastructure. As of 2020, the EU's LIB recycling was about 28.5 kt annually [57]. Recycling is evenly split among pyrometallurgical, hydrometallurgical, and mechanical firms, each contributing a third of the capacity. However, hydrometallurgical recycling in Europe is expected to rise to 82%, with the rest divided between pyrometallurgy (10%) and mechanical treatment (8%) [58].

2.2. Modeling efforts

Research on EOL LIB projections has employed a variety of modeling approaches. SD has become a notable tool for simulating and analyzing the impacts of circular strategies and future stock development. Alongside SD, other methods have also been widely applied, including Material Flow Analysis (MFA), Substance Flow Analysis (SFA), scenario-based forecasting, and economic–environmental modeling. The following sections organize these contributions around four thematic clusters: critical raw material demand and recycling feasibility; second-life strategies and their trade-offs with recycling; SD models for battery circularity; and MFA/SFA approaches for Europe.

2.2.1. Critical raw material demand and recycling feasibility

Studies in this cluster converge on the conclusion that near-term recycling capacity is structurally insufficient to close the material supply gap, while diverging on its primary driver. Maisel et al. [13] estimated raw material demand through 2040, comparing it with current production levels and emphasizing the urgent need to upscale recycling capacity. Specifically, Bruno and Fiore [23] project that existing European recycling plants will be unable to process over 78% of the forecast EOL volumes in 2030. Zeng et al. [15] simulate global cobalt cycles from 2020 to 2050 with regional resolution, finding that cobalt supply shortages are inevitable in the short- to medium-term (2028–2033) even under the most technologically optimistic scenario, and that battery technology and recycling alone cannot close the gap without a simultaneous expansion of primary supply. Wesselkämper et al. [8] found that Europe will achieve full circularity more than ten years later than China for lithium and nickel, and seven years later for cobalt. Where Bruno and Fiore [23] identify physical capacity as the binding constraint, Xu et al. [14], Maisel et al. [13], and Zeng et al. [15] emphasize that long battery lifetimes and slow chemistry transitions delay the return of recyclable material, structurally limiting secondary supply regardless of installed capacity. These studies share a static treatment of capacity: none models its endogenous expansion in response to regulatory targets or market signals.

2.2.2. Second-life strategies: resource benefits and trade-offs with recycling

Research on second-life pathways produces directly conflicting results, arising from differences in system boundaries and in the demand sectors considered. Bobba et al. [18] found that second-use can improve LIB utilization while delaying the recovery of vital elements like cobalt and lithium. According to Abdelbaky et al. [21] and Abdelbaky et al. [22] the EU could exploit up to 3 million EOL batteries annually with a 125 GWh capacity, offsetting between 10% and 300% of raw material demand. However, the expansion of battery chemistries and second-life adoption are sources of significant uncertainty. Kastanaki and Giannis [19] revealed that Germany and France alone could cover significant national energy storage demand with second-life batteries by 2040. Aguilar Lopez et al. [20] assessed the role of vehicle-to-grid and second-life batteries in reducing both material demand and geopolitical risks, quantifying a reduction in cumulative primary demand of up to 7.5% through 2050. Zhou et al. [17] argued that the EU's recycled content targets may inadvertently undermine circularity by encouraging waste generation and discouraging battery life extension or repurposing. The conflicting conclusions of this cluster arise because no study models the full feedback between second-life deployment, SES demand, and recycling capacity simultaneously: each fixes one or more of these dimensions as exogenous, preventing identification of the net system effect.

2.2.3. System dynamics models for battery circularity

SD is a widely recognized approach developed by Forrester [59] to study complex systems. SD incorporates feedback loops and delays, which can be extremely useful for modeling non-linearities, which are frequent in complex systems [60].

SD has been applied to battery circularity at national and global scales, though its application to the EU-27 under the EU Battery Regulation is limited to a single study. Idjis and Da Costa [61] analyzed the cost effects of different circular strategies for EOL management of LIBs, comparing repurposing and recycling. Alamerew and Brissaud [45] presented a model to visualize the interactions among costs, revenues, and regulatory decisions, and identified the main enablers and barriers in reverse logistics. Yang et al. [62] studied the intertwined effects of reuse and recycling in China's EV sector. In this paper, they suggested that, with high levels of cooperation, the recycling sector could be boosted. Still, they did not consider EOL batteries suitable for use in low-speed EVs and other markets. Volan et al. [63] estimated the EOL battery flow in China to 2040, considering SES for photovoltaic and wind system enhancement. In this study, second-life applications were found to reduce pressure on recycling facilities while supporting the expansion of RES. Volan et al. [64] forecasted EOL batteries up to 2050, suggesting various management strategies, such as recycling and repurposing; highlighting their benefits; and emphasizing the need for supportive regulations. Tao et al. [65] combined scenario analysis and life cycle simulation to design a sustainable circulation system of second-life traction batteries in Japan, developing a market model that considers customer behaviors and preferences for demand estimation; their results show that reusing LIBs in the new EV assembly process could reduce life cycle CO_2 emissions by 5.76% compared to a baseline scenario. Kamath et al. [66] used a SD model to assess the stock of EOL EV batteries in the United States from 2020 to 2050. The authors studied battery flows considering recycling and remanufacturing, but only for second-life adoption in stationary applications (i.e., repurposing in our context). Shafique et al. [67] tested different growth scenarios in Asia through 2030, considering various battery chemistries for recycling and material recovery. Shaikh et al. [68] explored the cost dynamics behind EV battery refurbishment. Bhanu et al. [69] accounted for various features, such as cost, battery chemistry, and range anxiety, to quantify their effects on market demand and costs. Cui et al. [70] used an SD approach to analyze the business model for batteries in Japan, considering circular manufacturing, repurposing, and recycling. Mohamad-Ali et al. [71] explored the multi-stakeholder interrelation of the automotive EV recovery market in Malaysia, using interviews and a dynamic hypothesis. Ojha and Agarwal [72] tested behavioral dynamics and offered practical recommendations, such as the need for a strategic adoption of Industry 4.0 technologies, increased awareness of the circular economy, improved end-of-life battery collection, optimized battery lifespan, and early investment in recycling and refurbishment. Pratap et al. [73] performed a 180-month simulation to improve the efficiency of EOL management of EV batteries in India by studying collection rates, LIB chemistry, and the allocation between repurposing and recycling. Seika and Kubli [74] developed a model to assess the impacts of the EU Battery Regulation on repurposing and recycling in Switzerland up to 2050. In this study, the new regulations reduced the attractiveness of repurposing, potentially limiting the benefits it offers for lifespan extension—particularly in scenarios with a high share of LFP batteries. Finally, Ren and Eveleigh [75] simulated the impacts of regulations, incentives, and technology investments for the US market. The study recommended investing in advanced recycling technologies, supporting cost-efficient battery repurposing, optimizing logistics, and implementing regulatory policies that align battery design with recycling and manufacturing requirements to enhance economic and environmental sustainability.

Ginster et al. [76] integrate an SD market model with process-level models for battery production and recycling, embedding Life Cycle Assessment (LCA) to quantify both material flows and greenhouse gas impacts of circular battery production in the EU-27 under the EU Battery Regulation. Covering ten scenarios over the period 2020–2050, their study finds that post-consumer waste alone is structurally insufficient to meet the minimum recycled-content thresholds due to long battery lifetimes, and that cobalt targets are particularly ambitious. Ginster et al. [76] is the only SD model applied to the EU-27 under the EU Battery Regulation prior to the present study. Structurally, their model fixes the second-life usage share as a single exogenous parameter, holds the geographic distribution of recycling capacity static after 2030, and excludes the SES sector as a coupled demand driver.

Across the SD literature, three structural characteristics recur: the number of circular pathways modelled is typically limited, with most studies including recycling and one form of second life but omitting remanufacturing and extended use; the geographic scope is either a single country or an aggregated EU-wide estimate; and infrastructure capacity is treated as a static exogenous parameter or modelled without country-level disaggregation.

2.2.4. MFA, SFA, and scenario-based approaches for Europe

In addition to SD, several approaches have been adopted in the recent literature to assess the effects of EOL management of spent batteries in Europe, such as MFA, SFA, scenario-based forecasting, and economic–environmental modeling. These methods are well-suited to steady-state or scenario-specific snapshots and provide robust forecasts of material flows while considering policy implications. Nevertheless, they often fail to capture feedback loops, time delays, and dynamic interactions among technological, economic, and regulatory factors.

Abdelbaky et al. [21,22] combine distribution-delay forecasting and SFA models to forecast waste volumes and second-life capacity by 2040. Similarly, Bobba et al. [18] simulated reuse, repurposing, and recycling paths using a dynamic-parametrized MFA model, as did Zhou et al. [17]. Furthermore, Maisel et al. [13] employed a scenario-based modeling approach. Bruno and Fiore [23] revealed that current EU capacity will be insufficient by 2030 with a process-based MFA, promoting hydrometallurgy as the most promising recycling method for economic and environmental performance. On the other side, Kastanaki and Giannis [19] showed that Germany and France alone could cover significant national energy storage demand with second-life batteries by 2040. Moreover, Aguilar Lopez et al. [20] used a dynamic MFA. Wesselkämper et al. [8] calculate the regional break-even points for lithium, cobalt, and nickel in China, Europe, and the US. Rossi et al. [77] integrated MFA and LCA into an optimization model to identify the optimal environmental options for the EU's future battery industry, emphasizing the importance of battery mix and recycling performance. None of these approaches endogenises the feedback between collection rates, infrastructure capacity, and market dynamics that SD enables.

The review reveals three zones of convergence across the literature: (i) near-term recycling capacity is insufficient to meet demand; (ii) second-life pathways carry both benefits and costs for material recovery, with conflicting conclusions arising from differences in system boundaries and demand sectors considered; and (iii) the EU-27 context is under-modelled at a country-disaggregated, feedback-rich level. At the same time, a methodological gap is shared by all studies reviewed: no model simultaneously tracks the full set of circular pathways (extended use, remanufacturing, repurposing, and recycling), couples the EV and SES sectors, disaggregates infrastructure capacity at the Member State level, and evaluates pathway interactions through a full-factorial scenario design. Ginster et al. [76] and Zhou et al. [17] advance the field in complementary directions: Ginster et al. [76] demonstrate that post-consumer waste insufficiency is a structural feature of the EU circular battery system; Zhou et al. [17] show that recycled-content regulation can generate perverse incentives against life extension and repurposing. The present study builds on both findings by quantifying, through an 864-scenario SD model resolved at the individual Member State level, how the dynamic interplay between circular pathway allocation, infrastructure constraints, chemistry transitions, and regulatory targets shapes the conditions under which self-sufficiency targets can be achieved, and at what systemic cost.

3. Literature gaps and research contribution

The review of the existing literature reveals three zones of convergence across modeling approaches. First, near-term recycling capacity is structurally insufficient to meet projected demand for critical raw materials, regardless of the modeling method adopted [8,13,15,23]. Second, second-life pathways carry both resource benefits and costs for material recovery: studies consistently find that repurposing delays the return of recyclable material, yet disagree on whether this delay is outweighed by the displacement of new stationary batteries, a conflict that arises because each study fixes at least one of the interacting demand sectors as exogenous [17,18,20,22]. Third, the EU-27 context remains under-modelled at a country-disaggregated, feedback-rich level: most studies aggregate infrastructure capacity at the EU-wide level or focus on single Member States, preventing the identification of cross-border compliance bottlenecks [19,23,76].

Table 1 synthesizes the key structural characteristics of the most directly relevant studies alongside the present work, covering the modeling approach, geographic scope, circular pathways included, whether SES is coupled, infrastructure treatment, and scenario design.

Existing research analyzes circular strategies for EOL management of LIBs through SD, MFA, SFA, and scenario-based models. Nevertheless, several gaps remain. Many existing studies treat recycling and repurposing as separate processes, overlooking the need to balance them to maximize resource recovery efficiency. Moreover, remanufacturing and

Table 1
Comparative overview of key modeling studies on EOL LIB circularity.

Study	Method	Scope	Ext. use	Remanuf.	Repurpos.	Recycling	Chem. trans.	Infra. delays	2 L vs. recycling	SES coupled	Scenario design
Xu et al. [14]	MFA/SFA	Global			✓	✓	✓		✓		3 scenarios
Abdelbaky et al. [21]	Dist.-delay	EU + EFTA	✓		✓	✓			(✓)	(✓)	Parametric
Abdelbaky et al. [22]	SFA	EU + EFTA+TR	✓		✓	✓	✓		✓		3 scenarios
Bobba et al. [18]	dMFA	EU	✓		✓	✓			✓		Parametric
Bruno and Fiore [23]	MFA	EU				✓					3 strategies
Maisel et al. [13]	Scenario	Global				✓	✓				6 scenarios
Kastanaki and Giannis [19]	Weibull	EU-27		✓	✓	✓	✓		(✓)	(✓)	4 scenarios
Aguilar Lopez et al. [20]	dMFA	EU			✓	✓			✓	✓	4 scenarios
Zhou et al. [17]	dMFA	EU			✓	✓	✓		✓	(✓)	108 scenarios
Wesselkämper et al. [8]	dMFA	EU/CN/US			✓	✓	✓		✓	(✓)	5 levers
Zeng et al. [15]	dMFA	Global/regional				✓	✓				7 scenarios
Idjis and Da Costa [61]	SD	France			✓	✓			✓		6 scenarios
Yang et al. [62]	SD	China			✓	✓			(✓)		2 scenarios
Volan et al. [63]	SD	China			✓	✓			✓	✓	3 scenarios
Volan et al. [64]	SD	Brazil			✓	✓			(✓)	(✓)	2 scenarios
Tao et al. [65]	LCS	Japan	✓		✓	✓			✓		Qualitative
Kamath et al. [66]	SD	US		✓	✓	✓	✓	(✓)	✓		Parametric
Shafique et al. [67]	SD	Asia				✓	✓				3 scenarios
Shaikh et al. [68]	SD	Pakistan		✓		✓			(✓)		3 scenarios
Bhanu et al. [69]	SD	India					✓				3 scenarios
Cui et al. [70]	SD	Japan			✓	✓			✓		3 scenarios
Ojha and Agarwal [72]	SD	India/Global		✓		✓					5 scenarios
Pratap et al. [73]	SD	India			✓	✓	✓		✓	✓	Parametric
Seika and Kubli [74]	SD	EU (CH)			✓	✓		✓	✓		4 scenarios
Ren and Eveleigh [75]	SD	US			✓	✓		(✓)	(✓)		4 scenarios
Ginster et al. [76]	SD + LCA	EU-27			✓	✓	✓	(✓)	(✓)		10 scenarios
This study	**SD**	**EU-27**	✓	✓	✓	✓	✓	✓	✓	✓	**864 scenarios**

Notes. Ext. use = extended use; Remanuf. = remanufacturing; Repurpos. = repurposing; Chem. trans. = chemistry transitions modelled dynamically; Infra. delays = endogenous capacity ramp-up with commissioning delays; 2 L vs. recycling = second-life vs. recycling trade-off explicitly quantified; SES coupled = stationary energy storage as a coupled demand driver. dMFA = dynamic MFA; LCS = life cycle simulation; Dist.-delay = distribution-delay forecasting; (✓) = partial coverage only.

user-driven lifetime extension have received limited attention. Most research focuses on non-European areas such as China, the US, and Japan, under-representing EU-27 cross-country dynamics. Consumer behaviors, infrastructure readiness, and market expansion trajectories across Europe are underexplored.

Although SD has been applied to EU battery circularity, existing models share structural limitations that constrain the scope of their policy inference. Four gaps remain unaddressed in the literature:

1. Few studies simultaneously endogenise the full spectrum of post-consumer circular pathways: extended use, remanufacturing, repurposing, and recycling. The substitution effect between second-life deployment and recycling feedstock availability is central to assessing recycled-content compliance under regulation.
2. Existing EU-level models do not identify interaction effects between pathway shares, chemical transitions, infrastructure delays, and market dynamics. A full-factorial scenario design with pathway allocation as an independent parameter dimension is absent from the literature.
3. SES has not been integrated as a coupled demand driver in EU-level battery circularity models, omitting this coupling produces an incomplete picture of the material flow implications of second-life policies.
4. Existing EU-level dynamic models aggregate recycling and collection capacity at the EU-wide level. Country-level infrastructure disaggregation with endogenous capacity expansion and intra-EU sharing dynamics is absent, preventing the identification of Member State-specific compliance trajectories.

These four gaps are interdependent: a model addressing only a subset cannot represent the interaction effects between pathway allocation, sector coupling, chemistry transitions, and infrastructure disaggregation that determine net system behavior, as opposed to first-order effects alone. Closing them jointly is therefore a methodological requirement. This study contributes an eight-module system dynamics modeling architecture that jointly represents post-consumer battery pathway allocation and the coupling between the EV and SES sectors, evaluated through a full-factorial scenario design. Its module structure and feedback logic are transferable to other multi-country battery systems, subject to re-parameterization with local data; the country-level infrastructure disaggregation and intra-EU trade mechanism (gap 4) are specific to a multi-region setting and would not apply to a single-country application. The EU-27, assessed here over 2020–2050 under the EU Battery Regulation, is the multi-country setting in which we apply and test this architecture.

4. Methodology

4.1. System scope and boundaries

The model analyzes the evolution of EVs and SES LIBs in the EU-27 countries from 2020 to 2050 using AnyLogic. Within the system boundary, the model includes the following:

- Adoption of battery and plug-in hybrid EVs across passenger cars; light-, medium-, and heavy-duty vehicles; and buses at a country level, with inflows from new sales and repurchases, and outflows governed by average vehicle lifetime (the model also tracks the substitution rate of batteries).
- Adoption of SES at a country level, across grid-scale and behind-the-meter applications. SES-driven demand can be reduced by repurposing EV batteries.
- Flows of batteries from in-use stock to end-of-life, with subsequent pathway allocation into collection, extended use, remanufacturing, repurposing, or recycling.

- Collection, remanufacturing, and recycling capacity expansion driven by targets, projections, and commissioning delays.
- Different battery types, focusing on LIB cathode chemistries, including lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide in 1:1:1/5:3:2/6:2:2/8:1:1 ratios (NMC111/532/622/811), lithium nickel cobalt aluminum oxide (NCA), lithium manganese oxide (LMO), and lithium manganese nickel oxide (LMNO). Chemistries differ in their raw material composition.
- Recovery of lithium, nickel, and cobalt through recycling with specified efficiencies.
- Imports of LIBs whenever EU production is insufficient, and raw material exploitation when stocks cannot meet demand.
- Export of batteries that cannot be recycled domestically. Since the EU aims to avoid leakages to non-EU countries, the model redistributes EOL volumes from capacity-constrained Member States to those with spare recycling headroom, using a proportional allocation rule based on each constrained country's share of the total exportable EOL buffer.

The model is resolved at the individual Member State level. Vehicle ownership is projected separately for each country using a Gompertz function fitted to national historical data (Supplementary Material), while SES demand is allocated via country-specific renewable capacity proxies. Recycling, remanufacturing, and collection capacities are computed independently per country, driven by national EOL flows. As a result, the model captures cross-country heterogeneity in fleet size, economic development, energy mix, and infrastructure readiness. The scenario parameters are instead applied uniformly across countries to isolate system-level effects within a tractable factorial design; full country-level trajectories are reported in the Supplementary Material.

Outside the boundary, the model simplifies operational-level techno-economic aspects (e.g., transport costs and permitting timelines) and environmental LCA factors, focusing on aggregated parameters such as efficiencies, delays, and targets. Consumer and OEM behavior is similarly simplified to adoption shares and resistance factors. In particular, repurposing and recycling ratios are modeled as exogenous policy parameters since there are no harmonized, country-level empirical data on second-life market prices, cohort distributions, and national incentive structures across the EU-27. The main goal of this study is to analyze system-level dynamics of battery flows, infrastructure bottlenecks, and material recovery. Process-level recycling efficiency is parameterized at the material level using the minimum recovery rates mandated by EU Regulation, without disaggregation by recycling route as discussed in the Supplementary Material.

4.2. Causal loop diagram

Decision-making in complex environments is particularly challenging, especially when decisions entail indirect, delayed, non-linear, and multifaceted feedback effects [78]. A causal loop diagram (CLD) is a representation of the structure of the system, presenting causal interactions between variables, and constitutes the foundation of the SD model [60]. The causal relations of variables are presented in this section in Fig. 2.

As is common in a CLD representation, variables are system elements that change over time (e.g., inventory level, demand rate), and arrows indicate hypothesized cause–effect relationships among these elements [79]. Specifically, every arrow-shaped link has a positive or negative sign that denotes its influence type [80]. A positive link means that if the cause variable increases (or decreases), the effect tends to increase (or decrease) above (or below) what it would otherwise have been, whereas a negative link means the effect changes in the opposite direction. Causal loops can have two effects on system behavior: reinforcing (positive) or balancing (negative) loops, marked with “R” and “B” in the figure, respectively. In a balancing loop, a change in one variable leads to an opposite change in another. Conversely, in reinforcing loops, a change in a variable causes a similar change in the same direction.

Vehicle replacement depends on lifespan: a larger stock leads to higher outflows, stimulating repurchases and further growth [81,82] (R1). In many EU countries, internal combustion engine (ICE) vehicles often exceed their expected lifespan, staying in service for over 20 years [83]. This trend may suggest a similar pattern for EVs remaining in use beyond the 80% SOH threshold in the future. Despite reduced capacity, most EVs still cover common trips [84], leading to an asymptotic limit on extended-use growth, which slows as saturation occurs [14,19,85] (B2). Cultural and economic resistance to replacement, as seen with ICEs used beyond 20 years, slows reuse as saturation approaches [83,84] (B3). Extended use balances demand by avoiding new batteries [39,43] (B1). Remanufacturing and repurposing lower new demand and raw material use [17,33,45,86,87]. Their growth increases recycled supply, easing material pressure and reducing incentives for collection and processing (B6, B8–B11). Ultimately, higher remanufacturing needs trigger

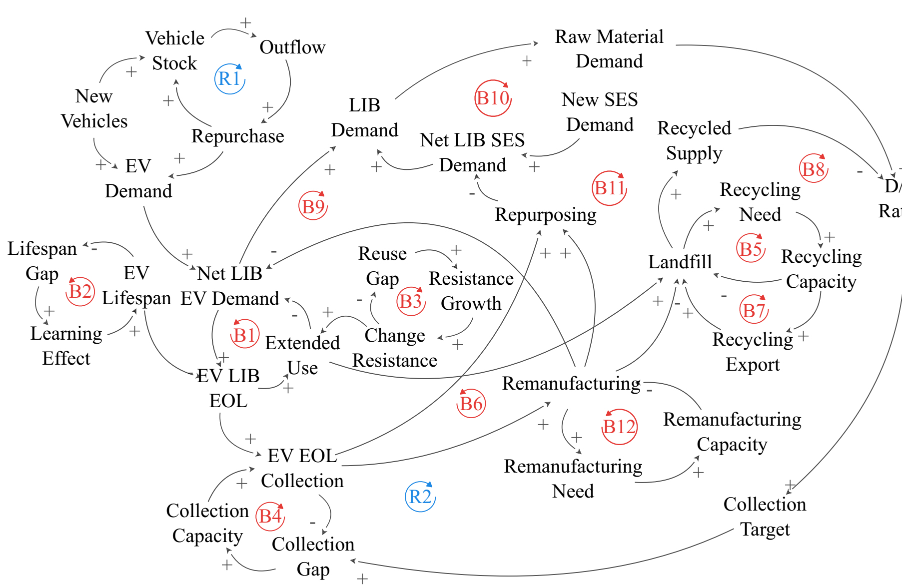


Fig. 2. CLD.

Table 2
A summary of reinforcing (R) and balancing (B) feedback loops.

Loop	Feedback structure
R1	Outflow ↑⇒ Repurchase ↑⇒ Vehicle Stock ↑⇒ Outflow ↑
R2	EV LIB EOL ↑⇒ Extended Use ↑⇒ Landfill ↑⇒ Recycled Supply ↑⇒ D/S Ratio ↓⇒ Collection Target ↓⇒ Collection Gap ↓⇒ Collection Capacity ↓⇒ EV EOL Collection ↓⇒ Remanufacturing ↓⇒ Net LIB EV Demand ↑⇒ EV LIB EOL ↑
B1	EV LIB EOL ↑⇒ Extended Use ↑⇒ Net LIB EV Demand ↓⇒ EV LIB EOL ↓
B2	Learning Effect ↑⇒ EV Lifespan ↑⇒ Lifespan Gap ↓⇒ Learning Effect ↓
B3	Resistance Growth ↑⇒ Change Resistance ↑⇒ Reuse Gap ↓⇒ Resistance Growth ↓
B4	Collection Gap ↑⇒ Collection Capacity ↑⇒ EV EOL Collection ↑⇒ Collection Gap ↓
B5	Recycling Need ↑⇒ Recycling Capacity ↑⇒ Landfill ↓⇒ Recycling Need ↓
B6	EV LIB EOL ↑⇒ EV EOL Collection ↑⇒ Remanufacturing ↑⇒ Net LIB EV Demand ↓⇒ EV LIB EOL ↓
B7	Recycling Need ↑⇒ Recycling Capacity ↑⇒ Recycling Export ↑⇒ Landfill ↓⇒ Recycling Need ↓
B8	Remanufacturing ↑⇒ Landfill ↑⇒ Recycled Supply ↑⇒ D/S Ratio ↓⇒ Collection Target ↓⇒ Collection Gap ↓⇒ Collection Capacity ↓⇒ EV EOL Collection ↓⇒ Remanufacturing ↓
B9	LIB Demand ↑⇒ Raw Material Demand ↑⇒ D/S Ratio ↑⇒ Collection Target ↑⇒ Collection Gap ↑⇒ Collection Capacity ↑⇒ EV EOL Collection ↑⇒ Remanufacturing ↑⇒ Net LIB EV Demand ↓⇒ LIB Demand ↓
B10	Repurposing ↑⇒ Net LIB SES Demand ↓⇒ LIB Demand ↓⇒ Raw Material Demand ↓⇒ D/S Ratio ↓⇒ Collection Target ↓⇒ Collection Gap ↓⇒ Collection Capacity ↓⇒ EV EOL Collection ↓⇒ Repurposing ↓
B11	Remanufacturing ↑⇒ Repurposing ↑⇒ Net LIB SES Demand ↓⇒ LIB Demand ↓⇒ Raw Material Demand ↓⇒ D/S Ratio ↓⇒ Collection Target ↓⇒ Collection Gap ↓⇒ Collection Capacity ↓⇒ EV EOL Collection ↓⇒ Remanufacturing ↓
B12	Remanufacturing Need ↑⇒ Remanufacturing Capacity ↑⇒ Remanufacturing ↓⇒ Remanufacturing Need ↓

capacity investment, but once processing expands, further need declines [66,88,89] (B12). Collection and recycling are self-regulating: increasing EOL stock widens the collection gap, driving capacity expansion until targets are met [73,88] (B4). Rising landfill volumes, here defined as the stock of EOL material awaiting processing, not irreversible disposal, increase recycling needs, prompting investment that channels waste and reduces disposal [11,90]. EU regulation supports closed-loop recovery, while intra-EU exports may alleviate landfill pressure [12] (B5, B7). EOL batteries diverted to extended use eventually exit their secondary service life and accumulate in the landfill stock. Higher volumes in this buffer feed recycling, increasing recycled supply and lowering the demand-to-supply ratio, which reduces collection targets and capacity, thereby decreasing remanufacturing and raising net demand (R2). Table 2 summarizes the main reinforcing and balancing feedback loops.

4.3. Stock-and-flow diagram

The stock-and-flow diagram serves as an instrument within SD to formulate mathematical interrelations among variables, thereby translating the model dynamics identified in the CLD. A simplified version of this diagram is presented in Fig. 3, while the comprehensive model developed using AnyLogic is detailed in the Supplementary Material. The diagram is divided into modules to enhance interpretability, covering the following domains: (i) circular pathways, (ii) EV and SES market, (iii) product lifetime, (iv) collection processes, (v) extended usage, (vi) remanufacturing, (vii) recycling, and (viii) raw material sourcing.

The interaction across these domains is fully detailed and formalized in the Supplementary Material. The foundational mathematical structures underlying these equations, together with an illustrative example, are presented in Appendix A.

4.4. Model validation

The model was validated following the structured protocol of Sterman [60]. Structural validity was confirmed by verifying the dimensional consistency of all stock-flow equations and the analytical coherence of all 12 feedback loop polarities. Parameter validity was established by tracing all inputs to peer-reviewed literature or official EU and international institutional sources (Supplementary Material, Section 1). For behavior reproduction, the modelled EU-27 EV fleet stock for 2020–2024 was compared against ACEA data [91]; reproduction of EOL battery volumes and recycling throughput was not attempted for this period, as first-generation EV battery retirements are expected to reach industrial scale only from approximately 2025–2030 onward, and harmonized EU-27 EOL/recycling time series of sufficient resolution are not yet available. Extreme-condition tests confirmed physically plausible model behavior at boundary parameter values. Full validation results are reported in Supplementary Material.

5. Analysis outline

5.1. Input data

This study integrates inputs from both the literature and official EU and international reports. Road transport market growth is modeled using country-level Gompertz car ownership curves calibrated on historical ownership and GDP (Eurostat) and projected GDP growth (OECD) [92–96]. EV shares follow different scenarios described in Section 5.2, with battery EVs (BEVs) and plug-in hybrid EVs (PHEVs) splits derived from international projections [2,74,97,98]. SES demand (grid-scale and behind-the-meter) is derived from long-term Joint Research Centre (JRC) outlooks using piecewise compounded annual growth rate (CAGR) trajectories and allocated across Member States using market shares and a renewable capacity proxy [99–101]. EU battery production capacity combines data from the European Court of Auditors and recent assessments [99,102–104]. Technological parameters include battery lifetime evolution (S-curve with uncertainty bounds) and average pack capacities by vehicle class [2,14,15,18,19,23,105,106], cathode mix trajectories for EVs and SES [13,99], material intensities, and specific energies (Li, Co, Ni) by chemistry [13,14,73,107–110]. Recycling parameters reflect EU Battery Regulation targets, efficiencies (with interpolation rules), and country-level announced or operational capacities from industry and academic sources [12,17,111,112]. Complete datasets, assumptions, and country-level time series are provided in the Supplementary Materials.

5.2. Scenario description

Future dynamics related to EOL LIBs are uncertain. Therefore, a scenario analysis was developed to test different policy outcomes.

The scenarios are structured around eight central variables that influence the electrification expansion time and scale, EOL flow cycles, and technology evolution: EV share growth, SES demand, repurposing ratios, recycling ratios, EV battery lifetime, battery chemistry mix, extended-use, and infrastructure capacity delay. Table 3 summarizes the input variables used to generate the scenarios.

The scenario setting was developed by combining the values of each factor, resulting in a full factorial design of 864 scenarios ($2 \times 2 \times 3 \times 3 \times 3 \times 2 \times 2 \times 2$). The eight scenario parameters are applied uniformly across countries to isolate system-level effects within a tractable factorial design. Country-level heterogeneity enters the model through the structural inputs described in Section 4.1. Different structural sources of uncertainty are accounted for: demand-side dynamics, EOL pathway allocation, and technology and infrastructure evolution. Ranges are drawn from published sources where available. Parameters lacking direct empirical estimates (repurposing ratio, recycling ratio, and extended-use adoption rate) are varied across the full structurally feasible range.

5.3. Experimental outcomes

Each scenario is presented in aggregate form at the EU-27 level to ensure readability and highlight insights that apply to the entire region.

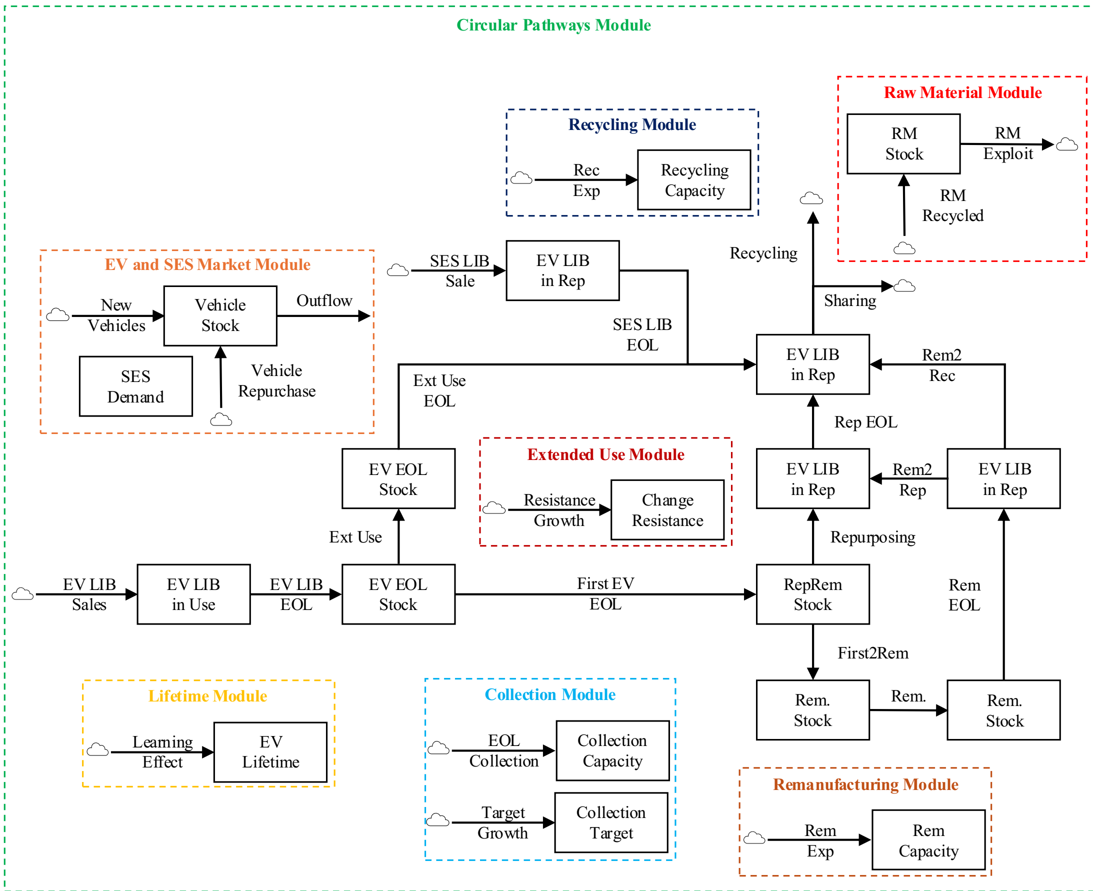


Fig. 3. A simplified stock-and-flow diagram and modules.

Additional country-level trajectories, sensitivity plots, and complete time-series tables are reported in the Supplementary Material, which expands the main results with full-resolution model outcomes. The following indicators were chosen to present the results of this analysis, grouped into clusters.

1. EV and SES battery demand, total storage demand, internal production capacity, and import dependency.
2. Installed collection capacity and targets, recycling and remanufacturing capacities, landfill disposal, and intra-EU export utilization.
3. EOL flows, extended use, remanufactured and repurposed batteries, and their respective contributions to circularity.
4. Critical raw material demand, material recovery, circularity rate, net primary extraction requirements, and EU recycling target achievement.

6. Results

The 864-scenario analysis yields four overarching findings. First, EU-27 LIB demand grows substantially across all scenarios, reaching approximately 105 kt of lithium and 239–502 kt of nickel by 2050, with battery chemistry (NMC vs. LFP) and EV growth trajectory as the dominant drivers. Second, second-life deployment is highly sensitive to the repurposing ratio: shifting it from 0.25 to 0.75 increases repurposed stock by + 54.43% while cutting remanufacturing output by −62.94%, revealing a structural trade-off between pathways. Third, recycling infrastructure remains a binding constraint: a delay of 8 versus 5 years in capacity commissioning reduces self-sufficiency by approximately −16.1% across all three target materials, and only a handful of Member States concentrate the majority of recycling capacity. Fourth, secondary material recovery can meet EU 2036 targets for lithium and nickel and, under high-recycling scenarios, for cobalt, but only if the recycling ratio is maximized and infrastructure delays are avoided. The following subsections provide the full quantitative evidence underlying these findings. A consolidated cross-parameter sensitivity decomposition is presented in Appendix B.

6.1. Demand and supply

In this section, projections of net LIB demand for EVs and SES in the EU-27 from 2020 to 2050 under multiple scenarios are presented. Each chart illustrates the distribution of model outputs across all variations for selected years. While the 2020 values are nearly identical across scenarios—reflecting the shared historical baseline—the dispersion becomes substantial after 2030.

For EVs (Fig. 4), the median net LIB demand rises to 3052.5 kt in 2030, 6592.6 kt in 2040, and 13,320 kt in 2050. The lowest-demand trajectory reaches 2745.1 kt, 4778.8 kt, and 9815.1 kt, while the maximum trajectory exceeds 3345.6 kt, 9214.1 kt, and 18,538 kt over the same years.

Among all parameters, the BAU (no phase-out) scenario reduces net demand by −17.09% relative to the BAN scenario. Similarly, the Ni-dominant scenario results in a reduction of −9.66%. The repurposing ratio is another influential driver. Increasing it from 0.25 to 0.5 raises the projected demand by approximately +5.16%, and increasing it to 0.75 raises demand by +10.82%. Technological improvements in EV lifetime also have a measurable impact: raising the lifetime parameter from 0.04 to 0.07–0.1 reduces demand by approximately −3.01%–4.71%, respectively.

Table 3
Key factors and scenario settings.

Factor	Description	Reference
EV growth	EV shares vary by policy: share slightly below 100% by 2050 in the ICE EU BAN by 2035 (*BAN*) vs. 50% after 2035 in the business-as-usual scenario (*BAU*)	[17,74,95]
SES growth	CAGR growth baseline assumptions: 40% (2020–30), 10% (2030–40), 3% (2040+) for grid-scale and BTM, varied between ±20% after 2030 (*low* and *high penetration*)	[99,101]
Repurposing ratio	Share of EOL EV batteries directed to stationary repurposing instead of remanufacturing varied between 25%, 50%, and 75% (*low*, *mid*, and *high*)	Own assumption [12,17,73]
Recycling ratio	Share of second-use EOL batteries sent directly to recycling instead of being used in second-life applications varied between 25%, 50%, and 75% (*low*, *mid*, and *high*)	Own assumption [17,19,87]
Tech growth	Three scenarios are considered: the *baseline* shows steady improvements aligned with literature estimates, the *low-growth* (−50%) assumes slower progress, and the *fast-growth* (+50%) faster innovation effect	[14,15,19,21]
Chemistry mix	In the *NMC-dominant* scenario, the EV LIB market shifts to nickel-rich cathodes, such as NMC811, while in *LFP-dominant* scenario, the market favors iron-phosphate (i.e., LFP) cathodes well suited for both EV and SES	[13,17,99,110,113]
Extended-use adoption rate	Annual rate at which the share of EV LIB retained beyond their standard replacement lifetime increases toward a country-specific saturation level. Varied between *low* (0.05) and *high* (0.10).	Own assumption [83,84]
Recycling delay	Technical and financial uncertainty can lead to project delays; we considered a baseline and delayed scenario of 5 and 8 years for capacity building	[74,112,114]

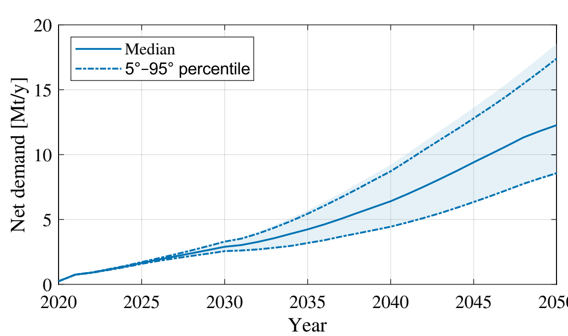


Fig. 4. Net EU LIB demand for EVs.

For SES applications (Fig. 5), the median projection reaches 59.07 kt in 2030, 146.45 kt in 2040, and 81.12 kt in 2050. The minimum configuration yields 13.46 kt, 23.98 kt, and 15.27 kt, while the maximum trajectory achieves 134.6 kt, 420.67 kt, and 534.25 kt in 2030, 2040, and 2050, respectively.

Expanding the SES deployment range results in a 121.84% increase, while the BAU scenario increases SES demand by +13.28% relative to the BAN scenario, as fewer repurposed EV batteries are available for stationary storage. The Ni-dominant scenario further increases SES demand by +85.56%, as the shift away from LFP chemistry reduces the pool of EOL batteries suitable for repurposing. Among user behavior drivers, technological growth shows a moderate positive effect: increasing it from 0.04 to 0.07–0.1 raises demand by approximately +17.72%–32.36%, respectively. In contrast, the repurposing ratio exerts the strongest negative effect. Raising the proportion from 0.25 to 0.5 results in a −34.29% decrease in net demand, while increasing it to 0.75 results in a −50.76% decrease. The recycling ratio shows an opposing but smaller influence: increasing it to 0.5 or 0.75 raises demand by +3.58% and +7.72%, respectively.

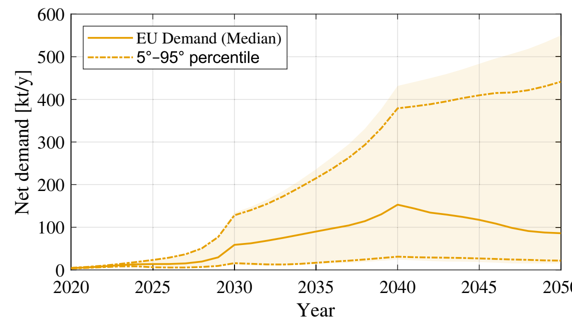


Fig. 5. Net EU LIB demand for SES.

Fig. 6 presents the evolution of EU LIB import volumes and domestic production under varying parameter combinations. Total demand reaches 1.56/0.96/0.53 TWh in 2050 (max/median/min). The acceleration after 2040 (0.85/0.42/0.05 TWh in 2045) is dominated by LFP and nickel-rich NMC chemistries (particularly NMC811 and NMC622), while other types, such as NMC111, LMO, and NCA, progressively phase out.

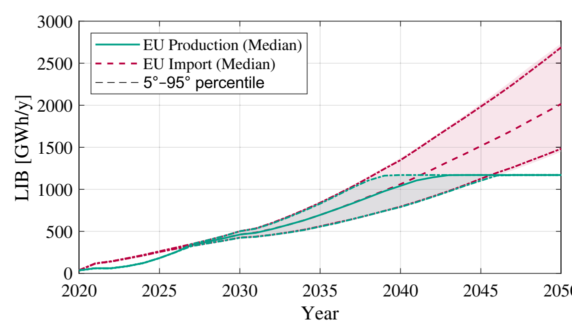


Fig. 6. EU LIB production and imports (2020–2050).

The LFP chemistry contributes the largest share to system totals, increasing from 202 GWh in 2030 to 1.8 TWh in 2050 on the upper trajectory, and from 102 GWh to 614 GWh on the median. NMC811 follows with 131/620/1406 GWh (2030/2040/2050) in the maximum trajectory. NMC622 remains the third contributor, reaching 293 GWh at the upper bound in 2050, while LMNO, NCA, and NMC532 contribute only marginally (less than 350 GWh combined in the maximum scenario). Chemistries such as NMC111 and LMO show negligible activity beyond 2030 due to their decommissioning.

Higher technological growth rates consistently reduce the total import requirement by a maximum of −16.84% on average. Increasing the repurposing ratio from 0.25 to 0.5 and 0.75 raises imports by +53.89% and +150.94%. In contrast, a higher recycling ratio leads to minor increases (+0.37% to +0.77%). The BAU scenario reduces imports by −40.70% relative to the BAN scenario, while the Ni-dominant scenario increases them by +5.81%. The SES range adds a smaller effect (+5.68%).

6.2. Infrastructure capacities

Fig. 7 illustrates the magnitude in terms of collection capacity needed for EOL LIB in aggregated EU-27 countries. The results show a sharp increase after 2030, with the median capacity rising from 0.14 kt in 2020 to about 763.12 kt in 2030, 2.38 Mt in 2040, and nearly 5.20 Mt in 2050. The maximum trajectory reaches about 7.89 Mt, while the lowest-performing scenario reaches 3.62 Mt by 2050.

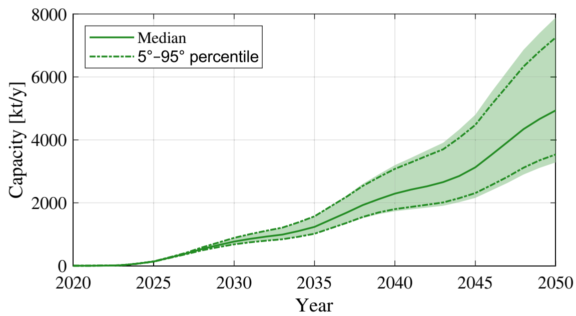


Fig. 7. EU collection capacity (2020–2050).

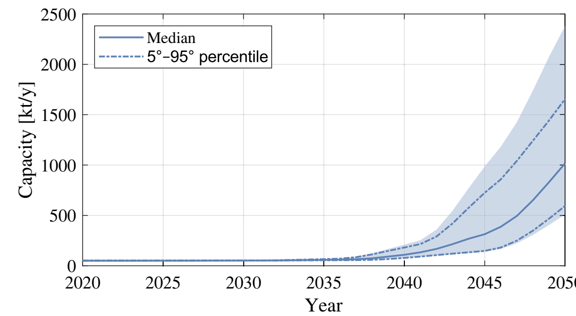


Fig. 9. EU recycling capacity (2020–2050).

The expansion of the EU's collection capacity is evidently influenced by demand-side factors associated with EVs. The BAU scenario reduces collection capacity by −9.40% relative to the BAN scenario. Adopting a nickel-dominant mix lowers the result by −6.45%. Among policy parameters, the repurposing ratio exerts the strongest positive influence. Increasing it from 0.25 to 0.50 results in an increase of 2.79%, while raising it to 0.75 yields an increase of 5.76%. Conversely, improving battery lifetime decreases the 2050 capacity by −11.13% and −17.51% on average.

Fig. 8 shows the projected evolution of EU-27 remanufacturing capacity. The results indicate a clear growth pattern starting after 2030, with the median capacity rising from 103.8 kt in 2030 to approximately 1390 kt in 2040, and 2.63 Mt in 2050. The maximum scenario reaches 6.04 Mt by 2050, while the lowest-performing configuration attains only 926.6 kt.

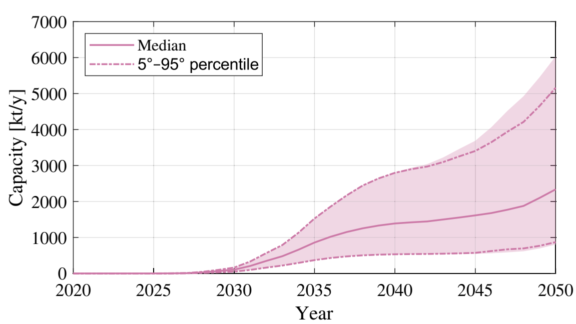


Fig. 8. EU remanufacturing capacity (2020–2050).

The evolution of EU remanufacturing capacity is driven by technological growth, which reduces the 2050 expected capacity by −12.21%–19.49%, accelerating efficiency improvements, delaying battery replacement, and lowering EOL inflows. The repurposing ratio exerts the most pronounced effect among policy variables. Increasing it from 0.25 to 0.50 reduces remanufacturing capacity by −33.02%, while raising it to 0.75 yields a stronger decrease of −66.17%, as more batteries are diverted toward second-life applications rather than remanufacturing. Regarding demand factors, the BAU scenario reduces remanufacturing capacity by −7.49% relative to the BAN scenario. The nickel-dominant chemistry similarly decreases results by −18.51%.

Fig. 9 shows recycling capacity growing moderately compared with other lifecycle stages. Median capacity remains nearly flat from 2020 to 2030 (50.1 kt to 51.5 kt), as countries with limited infrastructure rely on surplus capacity already available elsewhere. Growth then accelerates to 108.8 kt in 2040 and 1.02 Mt in 2050. The maximum configuration reaches about 2.38 Mt per year by 2050 (209.1 kt in 2040, 52.3 kt in 2030), while the lowest scenario reaches only 510.3 kt (75.4 kt in 2040, 51.1 kt in 2030), mirroring increases in total EOL battery volumes driven by EV uptake and prior second-life use.

Increasing the repurposing ratio from 0.25 to 0.50 and 0.75 reduces recycling capacity by −4.46% and −9.05%, respectively, as more batteries are retained for second-life applications rather than entering recycling streams. In contrast, raising the recycling ratio enhances capacity by +6.51% at 0.50 and +13.05% at 0.75. Demand-related parameters also exert a marked influence. Expanding the SES growth range increases recycling capacity by +19.17%, while the BAU scenario produces a marginal reduction of −0.35%. Increasing technological growth from 0.04 to 0.07 and 0.10 decreases capacity by −4.14% and −6.34%. A delayed recycling acquisition further lowers capacity by −15.00%.

Fig. 10 shows the distribution of recycling capacity across EU-27 countries. High-capacity countries include Germany (249.8 kt) and Italy (178.7 kt), which together represent over 40% of the EU's total requirement. They are followed by Spain (80.5 kt), the Netherlands (55.5 kt), and France (45.4 kt), indicating that these nations would need to host major recycling hubs to sustain future EOL flows.

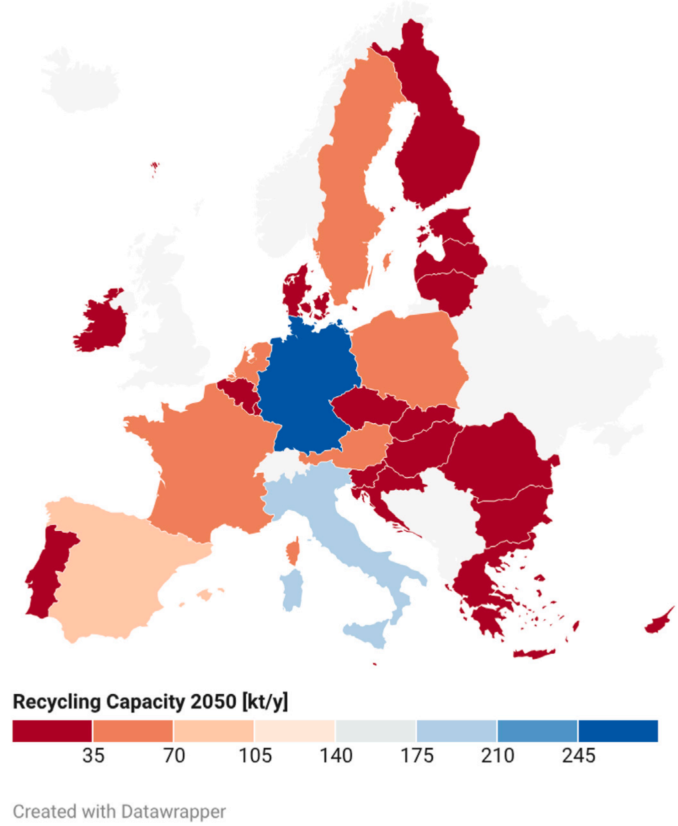


Fig. 10. Projected EU-27 recycling capacity by 2050.

Medium-capacity countries such as Poland (51.0 kt), Austria (47.4 kt), and Sweden (38.8 kt), range between 35 and 55 kt. In contrast, low-capacity countries, including most Eastern and smaller Southern European states (e.g., Bulgaria (7.8 kt), Lithuania (5.9 kt), Slovenia (5.1 kt), Cyprus (1.0 kt), and Malta (0.9 kt)), would require less than 10 kt. Overall, the simulated distribution implies a strong concentration of recycling demand in Central and Western Europe.

6.3. End-of-life pathways

In Fig. 11, extended-use LIBs in the EU increase from 0.08 kt in 2020 to 1.15 kt in 2030, 6.83 kt in 2040, and 30.36 kt in 2050, reflecting a gradual but consistent expansion of second-life use before EOL. In the maximum-demand case, the stock grows much faster, reaching 1.76 kt in 2030, 14.67 kt in 2040, and 84.67 kt in 2050, while in the minimum-demand case, extended-use volumes remain modest, peaking at 9.16 kt in 2050. The increase in reuse is the most significant positive factor influencing growth, increasing extended-use stocks by +157.48% on average. The repurposing ratio also exerts a strong positive influence, with gains of +3.86% and +7.97% when increased from 0.25 to 0.5 and 0.75, respectively. Conversely, technological growth reduces extended-use potential (−6.97% to −11.28%). The BAU scenario reduces extended-use stocks by −12.87% relative to the BAN scenario.

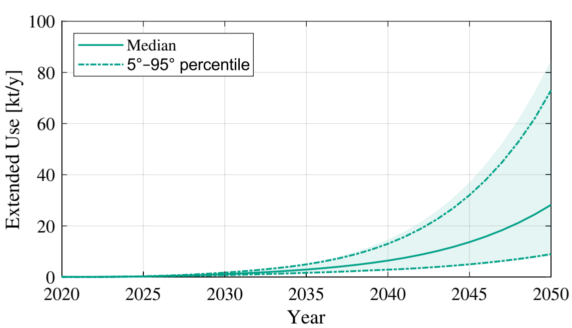


Fig. 11. EU LIB in extended use (2020–2050).

Fig. 12 illustrates the projected evolution of remanufactured LIBs in use. Under the median scenario, remanufactured LIBs in use increase substantially to 90.77 kt by 2030, reaching 707.86 kt in 2040, and peaking at 1537 kt in 2050. The maximum-demand scenario follows a similar pattern, rising to 147.87 kt in 2030, 1259.9 kt in 2040, and 3061 kt by 2050, while the minimum scenario achieves only 638.9 kt of remanufactured LIBs in use. Among parameters, the repurposing ratio has the strongest negative effect: increasing it to 0.50 cuts output by −30.06% and to 0.75 by −62.94%. The BAU policy reduces remanufacturing by −15.93% relative to the BAN scenario, and high-tech growth by −8.96%–13.74%.

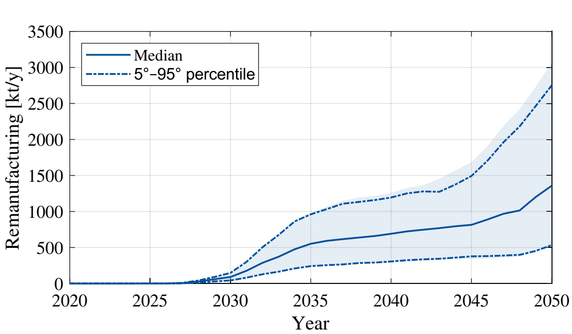


Fig. 12. Remanufactured EU LIBs in use (2020–2050).

Fig. 13 shows the evolution of repurposed LIBs in use under maximum, median, and minimum scenarios. Repurposing flows rise sharply from negligible levels in 2020 to about 88.6 kt by 2030, 244.4 kt by 2040, and stabilize near 269.3 kt by 2050 in the median case. The maximum scenario reaches 437.8 kt by 2050, while the minimum case remains limited to roughly 125.3–160.9 kt by 2040–2050. Across parameter effects, the repurposing ratio is the most influential driver, increasing the mean outcome by +54.43% when raised from 0.25 to 0.75. Higher SES growth also exerts a strong positive effect (+29.30%). Conversely, BAU reduces the mean output by −4.21%, while the Ni-dominant scenario further decreases it by −16.27%.

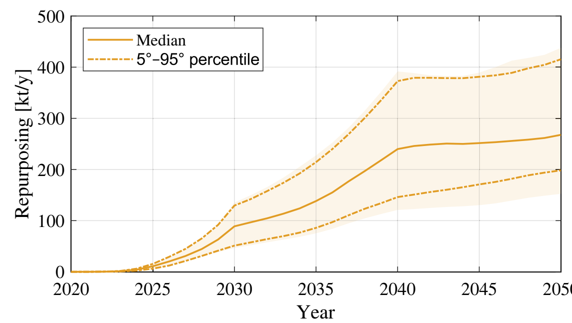


Fig. 13. EU LIB use in repurposing (2020–2050).

EU recycled LIBs in Fig. 14 increase to 6.9–11.5 kt in 2030, 68.8–209.1 kt in 2040, and 465–1685 kt by 2050. The recycling ratio is the main driver, raising output by +9.49% and +18.83% for 0.5 and 0.75 levels. SES growth adds +40.06%, and infrastructure delay subtracts −11.11%. Negative effects come from repurposing (−6.32% to −13.07%), the BAU scenario (−0.94%), and high-tech growth (−5.85%–8.97%).

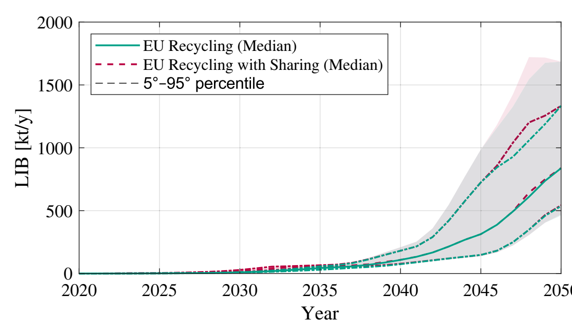


Fig. 14. EU LIB in recycling and sharing (2020–2050).

Moreover, stronger cooperation and coordination among EU countries can unlock additional recycling capacity via intra-EU recycling sharing, allowing nations with limited facilities to send end-of-life LIBs to those with advanced processing infrastructure. In the maximum scenario, such shared recycling flows can add over 20 kt of extra capacity between 2030 and 2035, and more than 100 kt by 2046–2047.

6.4. Materials and targets

6.4.1. Demand and EU targets

Under the median scenario, EU lithium demand increases from 3.49 kt in 2020 to 44.23 kt in 2030, 97.82 kt by 2040, and 105.74 kt by 2050. In the maximum-demand scenario, this demand level is reached already by 2040 (106.49 kt), constrained by EU internal battery production capacity, as illustrated in Fig. 15. Conversely, in the minimum-demand scenario, lithium demand grows to 42.07 kt in 2030, 76.12 kt by 2040, and 104.99 kt by 2050. Compared with the EU recycling targets (6% by 2031 and 12% by 2036), the median scenario requires 2.65 kt of lithium in 2030, 11.74 kt in 2040, and 12.69 kt in 2050, with negligible variation across the extreme scenarios (2.52–2.84 kt in 2030). The repurposing ratio exerts the strongest positive influence: increasing it from 0.25 to 0.75 increases lithium recovery potential by +1.28%–2.63%. Moreover, technological growth and the BAU scenario both strongly reduce lithium demand, by −1.50%–2.48% and −8.33%, respectively.

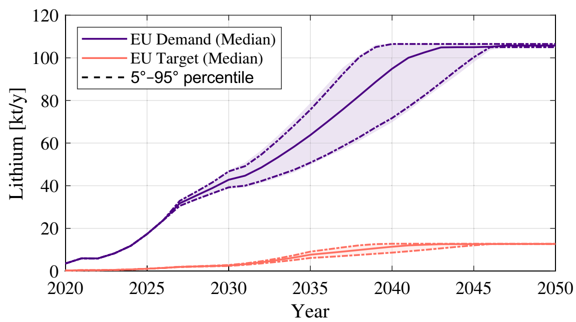


Fig. 15. Lithium demand and EU recycling targets (2020–2050).

Nickel exhibits the steepest growth among the analyzed elements, increasing from 12.91 kt in 2020 to 158.4 kt in 2030 and 294.01–370.34 kt by 2040–2050 under the median scenario (Fig. 16). The maximum-demand configuration reaches 501.87 kt by 2040, while the minimum scenario yields 238.81 kt by 2050. By 2036, the EU regulatory target of 15% recycled nickel would correspond to approximately 26.15 kt, 44.10 kt, and 75.28 kt under the minimum, median, and maximum scenarios, respectively, by 2040. Ni-dominant scenarios increase material demand by an average of +64.92%, while technological growth and BAU scenarios decrease demand by −1.65%–2.72% and −8.41%, respectively, similar to the trend observed for lithium. An increase in the repurposing ratio increases demand by approximately +1.71%–3.39%.

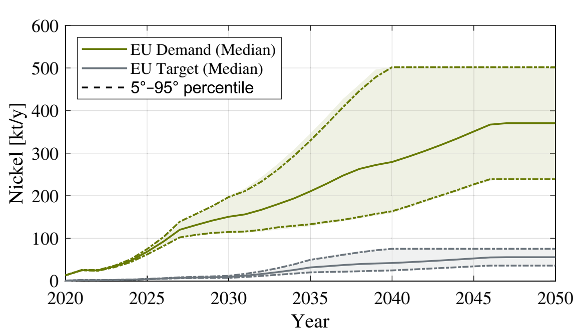


Fig. 16. Nickel demand and EU recycling targets (2020–2050).

Under the median scenario, EU cobalt demand rises from 3.22 kt in 2020 to 30.28 kt in 2030 and 47.84–58.83 kt by 2040–2050, as shown in Fig. 17. In the maximum-demand scenario, demand reaches 74.76 kt by 2040, while the minimum-demand configuration yields 24.98 kt in 2030, 31.62 kt by 2040, and 42.90 kt by 2050. Increasing the repurposing ratio from 0.25 to 0.75 raises median cobalt recovery potential by 3.90%. Conversely, technological growth reduces demand by −2.95%, and the BAU scenario cuts it by −7.93%.

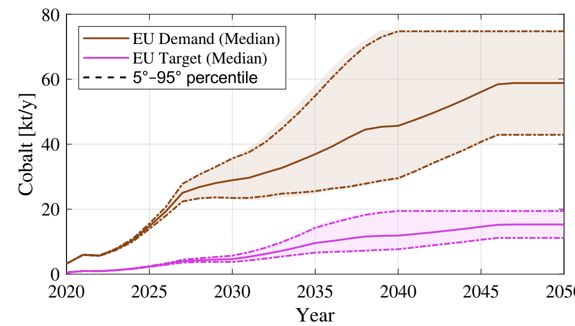


Fig. 17. Cobalt demand and EU recycling targets (2020–2050).

6.4.2. Extraction and recycling

Under the median scenario, EU lithium extraction required to sustain internal LIB production grows from 3.49 kt in 2020 to 44.12 kt in 2030, reaching 96.72 kt by 2040 and stabilizing around 97.70 kt by 2050 (Fig. 18). The maximum configuration attains similar levels earlier, peaking at 105.79 kt already by 2040, while the minimum scenario reaches 41.98 kt in 2030, 75.11 kt by 2040, and 87.51 kt in 2050. Increasing the repurposing ratio from 0.25 to 0.75 raises extraction by 3.50%. Conversely, the BAU scenario decreases extraction by roughly −8.33%.

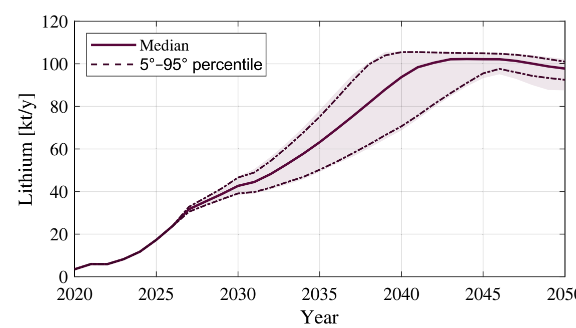


Fig. 18. Lithium extraction (2020–2050).

Nickel extraction demand increases from 12.91 kt in 2020 to 157.91 kt in 2030, and reaches 291.15–327.10 kt by 2040–2050 under the median scenario (with a peak of 352.53 kt in 2045) (Fig. 19). The maximum scenario surges to 199.62 kt in 2030 and over 490–500 kt by 2040–2050, while the minimum scenario remains lower at 122.4 kt, 171.28 kt, and 186.43 kt in the same years. Ni-dominant production grows extraction (+67.37%), while BAU configurations reduce it by −8.38%. Raising the repurposing ratio from 0.25 to 0.75 increases nickel extraction by +4.53%, whereas higher recycling rates alleviate it (−0.55%–1.09%).

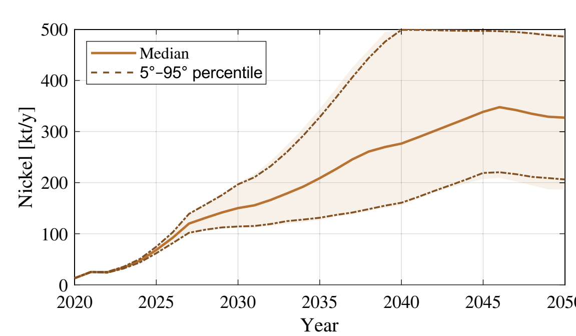


Fig. 19. Nickel extraction (2020–2050).

For cobalt, the median scenario foresees an increase from 3.22 kt in 2020 to 30.17 kt in 2030 and 47.27–50.90 kt by 2040–2050 (with a peak of 55.38 kt in 2045) (Fig. 20). The maximum-extraction case accelerates to 36.13 kt in 2030 and 74.39 kt by 2040, whereas the minimum trajectory remains more moderate at 24.89 kt, 30.94 kt, and 32.05 kt, respectively. Enhancing the repurposing ratio from 0.25 to 0.75 raises extraction by +5.34%, while increasing the recycling ratio significantly mitigates it (−0.69%–1.38%). Technological improvements reduce extraction modestly (−1.22%–2.10%), and the BAU condition dampens extraction by −7.89%, consistent with the trend observed for nickel and lithium.

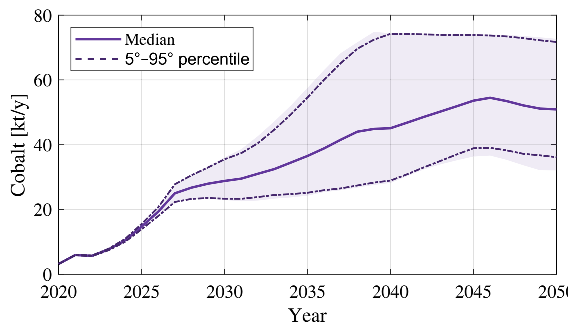


Fig. 20. Cobalt extraction (2020–2050).

6.4.3. *Recycling self-sufficiency*

Finally, this section quantifies how much of the EU's future target-bound battery metal demand can be met through domestic secondary recycling streams, thereby defining recycling self-sufficiency.

Under the maximum-demand scenario, the recycled share of lithium rises from negligible levels in 2020 to 5.63% in 2030, 18.83% in 2040, and 141.82% by 2050, exceeding EU targets. The median scenario reaches 4.42%, 8.74%, and 62.96%, while the minimum scenario peaks at 33.63% (Fig. 21). The recycling ratio is the strongest positive driver (+9.49%–18.99%), and the BAU scenario improves self-sufficiency by +13.37% relative to the BAN scenario. Longer infrastructure delays cut self-sufficiency (−16.08%), and a higher repurposing ratio further limits recycling (−7.74%–15.60%). SES growth yields moderate benefits (+34.82%).

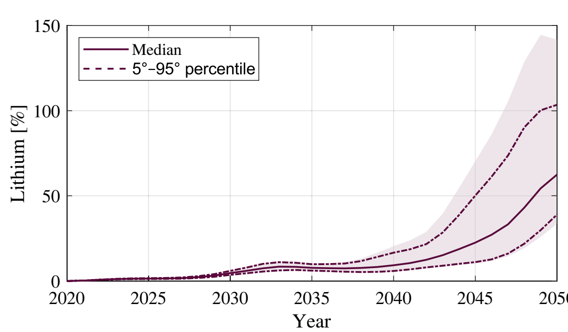


Fig. 21. Lithium recycling self-sufficiency (2020–2050).

Nickel recycling grows to 7.87% in 2030, 19.37% in 2040, and 146.22% by 2050 under the maximum scenario, with median and minimum cases reaching 46.83% and 14.85%, respectively (Fig. 22). The recycling ratio drives the largest increase (+15.69%–31.03%), and the BAU scenario improves self-sufficiency by +13.22% relative to the BAN scenario. Infrastructure delays sharply reduce results (−16.41%), while higher repurposing ratios hinder recycling (−10.70%–21.62%). SES growth supports outcomes (+31.12%), whereas tech growth slightly lowers recyclable mass (−6.28%–9.37%).

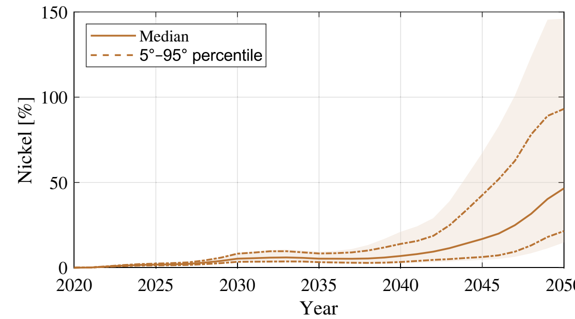


Fig. 22. Nickel recycling self-sufficiency (2020–2050).

Cobalt recycling climbs from near zero to 3.14% in 2030, 13.32% in 2040, and 97.26% by 2050 under the maximum scenario, approaching EU targets. The median and minimum cases reach 31.21% and 10.75%, respectively (Fig. 23). The recycling ratio shows the highest impact (+17.10%–33.76%), followed by SES growth (+30.16%) and BAU scenario improvements (+12.24% relative to BAN). In contrast, infrastructure delays (−16.05%), the repurposing ratio (−11.38%–23.21%), and tech growth (−6.30%–9.46%) constrain performance.

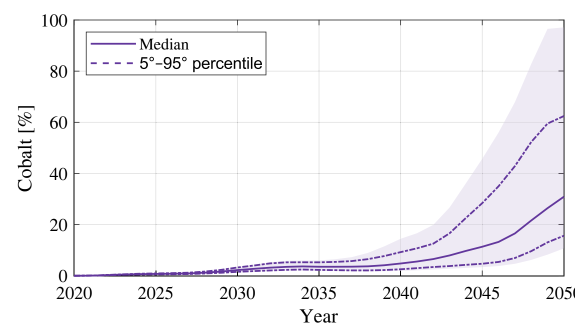


Fig. 23. Cobalt recycling self-sufficiency (2020–2050).

7. Discussion

The results highlight how the evolution of EU-27 LIB demand, infrastructure capacity, and material flows are strongly path-dependent.

Several of the findings reported below are directionally consistent with results established in the MFA literature. The repurposing–recycling feedstock trade-off is documented in Zhou et al. [17] and Bobba et al. [18]; the insufficiency of post-consumer waste flows to meet recycled-content targets under realistic battery lifetimes is the principal finding of Ginster et al. [76]; and the geographic concentration of recycling infrastructure in a small number of Member States appears in Bruno and Fiore [23] and Kastanaki and Giannis [19]. The present model does not contradict these findings. Rather, it extends them along four structural dimensions that are inaccessible to static MFA: (i) temporal compounding of infrastructure capacity shortfalls through an explicit investment-delay feedback structure, which produces bottleneck timing estimates across the full 864-scenario space; (ii) endogenous modeling of remanufacturing as a demand-suppression pathway, which is absent from all cited MFA studies including Zhou et al. [17] and Ginster et al. [76]; (iii) country-level disaggregation across EU-27, enabling identification of the specific national capacity gaps that bind EU-aggregate throughput under high-demand scenarios; and (iv) full-factorial joint sensitivity analysis, revealing interaction effects between parameters that are invisible to one-at-a-time or reduced scenario designs. Each policy direction below identifies which of these structural dimensions produces the reported result and why it could not have been derived from the cited prior studies.

Xu et al. [14] estimated global 2050 demand at 620–770 kt of Li, 250–620 kt of Co, and 1.5–3.7 Mt of Ni, values larger than EU-27 projected here (105.74 kt of Li, 58.83 kt of Co, and 370.34 kt of Ni). Abdelbaky et al. [22] predicted that European recycling in 2040 could meet 10–30% of Li, 36% of Ni, and 67% of Co. Here, similar results are reached by 2045. Bruno and Fiore [23] identified a 2030 recycling bottleneck with existing recycling capacity (48.8 kt/y). Similarly, Abdelbaky et al. [21] projected a recycling capacity need of 150 kt/y by 2040 for EU + EFTA + Turkey. Despite the broader geographic scope that requires additional capacity, our EU-27 median estimate reaches the same order of magnitude and extends to 1.02 Mt/y by 2050. Kastanaki and Giannis [19] estimated that repurposed batteries could cover 28–60% and 26–87% of German and French SES demand by 2030. Our results suggest that at the EU-27 level, repurposing policy could cut SES demand by −34.29%–50.76% on average. However, Bobba et al. [18] demonstrated that second-life use can reduce recycling flows by 23–60% and delay material recovery; our model found that higher repurposing and lower recycling ratios lower recycling throughput and self-sufficiency.

The main results of this study reveal issues that could constrain EU battery circularity and self-sufficiency. The following policy directions emerge from the 864-scenario analysis and are organized around the two research questions formulated in Section 1.

Addressing RQ1, the model identifies four interconnected levers shaping how dynamic EOL pathway allocation affects battery demand, infrastructure requirements, and EOL flows. Excessive emphasis on repurposing increases overall EV battery demand and imports, since it cuts remanufacturing output while reducing recycled volumes: raising the repurposing ratio from 0.25 to 0.75 increases net extraction demand by + 3.50% for lithium, +4.53% for nickel, and + 5.34% for cobalt; on the other hand, higher recycling ratios raise recovered output but increase demand for new SES LIBs. Compounding this, recycling capacity remains a critical bottleneck since delays in facility commissioning reduce recycling and self-sufficiency by approximately −16.1% across all three target materials. This bottleneck is moreover geographically concentrated: a few countries (i.e., Germany, Italy, Spain, France, and the Netherlands) comprise the majority of recycling capacity, largely due to the projected expansion of the LIB market, while most EU-27 member states may lack sufficient infrastructure due to their smaller markets. Conversely, remanufacturing and lifetime extension driven by technological advancements, combined with extended use, can reduce primary demand.

These findings reveal a structural tension within the circular economy framework. Lifetime extension and second-life deployment reduce primary demand and preserve material value, consistent with the waste management hierarchy. Yet over-retention of batteries in service delays the return of critical materials to the recycling stream, eroding the feedstock base on which recycling infrastructure depends. A well-functioning circular system therefore requires that upper-hierarchy activities do not undermine the operational continuity of lower-hierarchy ones: recycling capacity must be sustained even as second-life markets expand. Identifying the optimal balance between service-life extension and timely material recovery is both an operational research challenge and a policy design question concerning how regulatory instruments can simultaneously incentivize second-life deployment and protect feedstock adequacy for recyclers.

Turning to RQ2, the recycling ratio remains a strong policy lever, enhancing self-sufficiency by + 9.49%–18.99% for lithium and + 15.69%–33.76% for nickel and cobalt. However, delayed capacity rollout (−16.1%), BAN-type phase-out policies (−10.9%–11.8%), and excessive second-life deployment (−7.7%–23.2% depending on the material) counterbalance these benefits. Chemistry trajectories introduce a further dimension of variability: the Ni-dominant scenario intensifies raw material pressure, amplifying extraction needs by + 67.37% relative to Fe-based pathways; in contrast, Fe-based pathways reduce dependency but require larger pack sizes, increasing total battery mass in EOL flows and the volumetric throughput required from collection and recycling infrastructure. Across all pathway and chemistry configurations, technological growth in battery lifetime has a direct mitigation effect, lowering total import needs.

The sensitivity of extraction demand to chemistry trajectories reflects a “refuse” logic at the top of the circularity pyramid: substituting nickel- and cobalt-intensive cathodes with iron-based alternatives reduces critical material dependence upstream of any end-of-life strategy, and lifetime extension acts at an even earlier stage by lowering total material throughput through product design. Both levers are quantifiable only through a chemistry-aware framework, and together reinforce the case for chemistry-specific regulatory pathways calibrated to the technological availability of alternative cathode materials, rather than uniform recycling mandates applied independently of product design trajectories. More broadly, higher-hierarchy pathways do not contribute to recycled-content compliance under Regulation (EU) 2023/1542, but batteries entering extended use, remanufacturing, or repurposing retain their lithium, nickel, and cobalt within functioning EU assets. The apparent conflict between the waste management hierarchy and the recycled-content targets is therefore an artifact of the metric’s definition: both recycling and second-life pathways protect EU material security, through supply recovery and material deferral respectively.

8. Conclusions

The present study simulated multiple possible scenarios for the EU-27 battery market development at the country level up to 2050. An SD model was developed integrating technological, behavioral, infrastructural, and policy drivers. The model simulated different automotive and stationary market LIB forecasts, desired capacities, resource usage, and material recovery. This document outlines a strategic framework to address future EU electrification transition challenges related to the LIB market.

A balanced mix of waste management strategies, supported by coordinated infrastructure, is suggested to meet EU circularity and sustainability targets. On the other hand, excessive focus on second-life applications postpones material recovery, whereas increased recycling enhances self-sufficiency but elevates short-term demand for storage. Recycling capacity is limited to a few countries, highlighting the need for flexible, chemistry-specific, and regionally integrated policies linking product design, collection, and recycling.

These findings motivate several implementation-level directions. The trade-off between repurposing and recycling feedstock availability suggests the need for flexible EOL allocation mechanisms that adjust pathway priorities dynamically in response to material recovery targets and market saturation. The concentration of recycling capacity in a small number of Member States, and the sensitivity of throughput to commissioning delays, point to coordinated intra-EU logistics and accelerated permitting as enabling conditions for meeting EU targets. The remanufacturing-feedstock tension identified by the model is consistent with a multi-stakeholder governance structure combining lifetime optimization incentives, early collection schemes, and digital traceability instruments such as the battery passport. The sensitivity of self-sufficiency to chemistry trajectories motivates chemistry-specific regulatory pathways. The role of the recycling ratio as the dominant lever, conditional on investment timing, is consistent with extended producer responsibility as a complementary instrument. These directions are inferences motivated by the simulation results; their economic and organizational feasibility lies beyond the scope of the present model.

The system-level approach adopted in this study simplifies the representation of economic and environmental impacts by abstracting behavioral and market dynamics. Limitations include technological and policy uncertainties. There are also challenges in data collection in certain countries and the use of our own assumptions, as no published empirical estimates are currently available. The model further abstracts economic and cost dynamics, a deliberate choice to maintain the focus on physical and regulatory feasibility across the 864-scenario space. As a result, findings should be interpreted as identifying pathway configurations that are physically feasible and compliant with the regulatory framework, not economically optimal: high-repurposing scenarios may become commercially unviable under continued LIB price deflation, and recycling capacity trajectories reflect regulatory targets rather than market equilibria driven by commodity price signals. Future research should integrate environmental and economic assessment modules, including commodity price feedbacks on recycling investment, utilize empirical behavioral data, incorporate stochastic policy and investment dynamics, and partially endogenise these allocation decisions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Mathematical foundations of the model

A.1. Foundational structures

Two generic mathematical structures generate the module-level equations reported in the Supplementary Material. First, every stock variable $\mathrm{Stock}(t)$ evolves according to the standard SD accumulation principle (Eq. A.1).

$$\mathrm{Stock}(t) = \int_{t_0}^{t} [\mathrm{Inflow}(s) - \mathrm{Outflow}(s)]\, ds + \mathrm{Stock}(t_0) \tag{A.1}$$

Second, cohort-driven retirement and infrastructure-commissioning lags are represented through a bounded third-order material delay (`delay3`). Cascading delays in continuous series are equivalent to the Erlang family of distributions [60]: given an input rate $\mathrm{IN}(t)$ and a delay time D, three auxiliary stages (stocks) L_1, L_2, L_3 evolve as in Eqs. (A.2)–(A.4).

$$\frac{dL_1}{dt} = \frac{3}{D}\left(\mathrm{IN}(t) - L_1\right) \tag{A.2}$$

$$\frac{dL_2}{dt} = \frac{3}{D}\left(L_1 - L_2\right) \tag{A.3}$$

$$\frac{dL_3}{dt} = \frac{3}{D}\left(L_2 - L_3\right) \tag{A.4}$$

This structure concentrates the outflow distribution around the mean delay D, reproducing the cohort-based clustering of retirement and commissioning events.

A.2. Illustrative example: circular pathways module

Both structures are instantiated below for the circular pathways module (Supplementary Material), which governs the partitioning of end-of-life battery flows across circular strategies.

Eq. (A.5) applies the generic accumulation principle of Eq. (A.1) to the landfill stock, which accumulates collected end-of-life material awaiting processing:

$$\frac{d\mathrm{Landfill}_{c,k}}{dt} = \mathrm{EV\_LIB\_EoL}_{c,k} - \mathrm{Recycling}_{c,k} - \mathrm{Export}_{c,k} \tag{A.5}$$

Eq. (A.6) applies the generic delay structure of Eqs. (A.2)–(A.4) to the generation of end-of-life batteries for country c and cathode chemistry k:

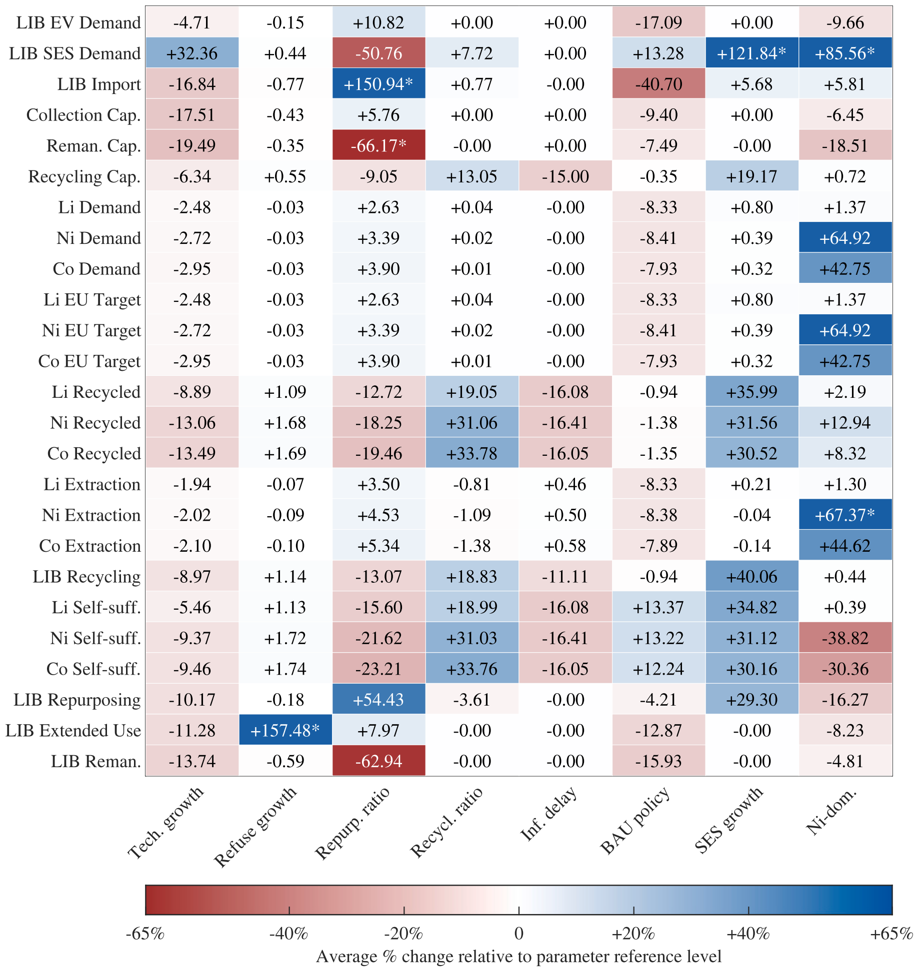
$$\mathrm{EV\_LIB\_EOL}_{c,k} = \min\Big(\mathrm{delay3}\Big(\mathrm{EV\_LIB\_sales}_{c,k}, \mathrm{EV\_lifetime}, \frac{\mathrm{EV\_LIB\_in\_use}_{c,k}}{\mathrm{EV\_lifetime}}\Big), \frac{\mathrm{EV\_LIB\_in\_use}_{c,k}}{\mathrm{EV\_lifetime}}\Big) \tag{A.6}$$

The same accumulation principle governs every other stock in the model, from vehicle fleets to installed collection, remanufacturing and recycling capacities. The delay3 structure recurs, with module-specific variables and delay times, in the extended-use, remanufacturing and recycling modules described in the Supplementary Material.

Appendix B. Sensitivity analysis

For each scenario parameter p and system variable Y, the effect reported in Fig. B.24 is the average percentage deviation of Y at the highest-magnitude non-reference level of p from its value at the reference level, averaged across all scenario configurations and simulation years. The formal derivation of this metric is provided in the Supplementary Material; the complete level-by-level decomposition across all 25 system variables and the 42 two-way interaction figures are reported in Supplementary Table 12 and Supplementary Figs. 16–57, respectively.

Each cell reports the average percentage change in the system variable when the parameter is moved from its reference level to the level with the highest absolute effect, averaged over all 864 scenario configurations and simulation years. Grey cells indicate the absence of a structural pathway between the parameter and the variable. The color scale is capped at ±65 %; values beyond this range are marked with an asterisk. BAU policy values are expressed relative to the BAN reference; a positive value indicates that BAU conditions improve the variable relative to BAN.



* Value exceeds the color scale (> 65%); the actual magnitude is shown in the cell label.

Fig. B.24. Sensitivity analysis decomposition.

Appendix C. Supplementary data

Supplementary data for this article can be found online at doi:10.1016/j.rser.2026.117363.

Data availability

The model file and the complete raw output dataset are available on Zenodo at https://doi.org/10.5281/zenodo.20691883. The repository includes the executable model and scenario-level output tables.

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