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Repurpose or recycle? Simulating end-of-life scenarios for electric vehicle batteries under the EU battery regulation

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ABSTRACT

A high number of electric vehicles (EVs) are expected to reach end-of-(first)-life during the mobility transition, leaving large volumes of scarce materials behind. At the same time, shortages are expected in the supply chain for battery materials, emphasising the urgency to develop a circular economy for EV batteries. In this study, we investigated the market formation of repurposing and recycling by simulating long-term market dynamics. We quantitatively assessed the reinforcing and counteracting impact of the newly introduced EU battery regulation (2023/1542). We built a system dynamics model to capture the decision factors for repurposing or recycling end-of-life EV batteries. Our findings reveal that the EU battery regulation is effective when it comes to building the required recycling capacities. Our simulations highlight that the current recycling capacities are insufficient to meet the growing demand, thereby highlighting the need for investors to expand the current facilities. On the other hand, the EU battery regulation, which promotes recycling with mandatory recycling shares, leads to a considerable dropping of shares in the emerging repurposing market. Our study concludes that, to achieve a circular economy for EV batteries, balanced support for recycling and repurposing is needed. We call for a complementary policy framework that ensures that repurposing is an integral part of the closed-loop system.

1. Introduction

Electrifying vehicle fleets plays a key role in reaching climate goals at the EU and national levels. Lithium-ion batteries, in particular, are crucial drivers of this transition, as they carry high energy densities (Ai et al., 2019; Harper et al., 2019). When reaching end-of-life (EOL), electric vehicle batteries retain high residual values—approximately 70 % to 80 % of their initial capacity—rendering them suitable for being repurposed in non-automotive sectors. This coincides with a surge in demand for battery materials in the automotive sector, which necessitates the need for closed-loop EV batteries following the recycling approach.

The dual objectives of extending battery lifespans and recovering materials underscore the circular strategies of repurposing and recycling. These two strategies, though they can be competing at times, could be combined to a two-loop system. Parallel developments in the energy market have bolstered the viability of the repurposing approach. Notably, stationary storage applications have emerged as a promising repurpose strategy, as EOL batteries carry sufficient capacities to sustain industry standards and prolong the average battery lifetime by ten years (Nurdiawati and Agrawal, 2022; Neubauer et al., 2015). Consequently, there is an increasing demand for home and community storage battery systems driven by consumers' growing desire for self-sustaining energy solutions (Kubli and Canzi, 2021; Kubli, 2018).

In a singular strategy, recycling is the focus of the one-loop system by providing the opportunity to close the material loop and returning valuable battery materials to the system for new EV production. Successful business models for EV batteries are assessed, incorporating a combined approach of both strategies (*two-loop system*) over direct recycling (*one-loop system*) when today's lack of available end-of-(first)-life materials is overcome (Wrålsen et al., 2021; Olsson et al., 2018).

To stimulate the market development for circularity in the EV battery industry, the EU introduced a battery regulation (2023/1542), obligating producers to produce new EV batteries with recycled content by defining minimum recycling shares. With increasing shares from 2031 to 2036 onward, an impact on the demand for recycled materials is assumed, which strengthens the economic value towards a one-loop system (Albertsen et al., 2021). Moreover, Richter (2022) and Wasesa et al. (2022) argued that political incentives and critical battery materials incentivise a one-loop approach, which focuses on direct recycling

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and neglects the environmental and economic benefits of repurposing batteries first.

Incentivising closed-loop EV batteries while not hampering repurposing activities is a crucial challenge for establishing a well-functioning circular economy solution. This research focused on the long-term market dynamics of end-of-life batteries by exploring the following question: How do mandatory recycling shares within the EU battery regulation affect the market formation of EOL solutions for used EV batteries? A system dynamics (SD) model was built to simulate the EOL scenarios that impact the number of batteries entering a one-loop or two-loop pathway. The model was then used to assess the effects of the new EU battery regulation.

Our research contributes to the literature in three aspects. First, by conducting a simulation assessment of the EU battery regulation's impact, we offer a quantitative perspective that expands the current qualitative considerations (Richter, 2022; Albertsen et al., 2021). Second, we provide long-term profitability and market dynamics estimations for repurposed and recycled products. Third, we highlight the leverage points and feedback effects for developing a circular value chain for EVs.

Our findings, which illustrate the long-term effects of the EU battery regulation, are particularly relevant for EU policymakers. Moreover, for non-EU actors faced with the question of adopting similar policies on a national level, our findings offer a crucial basis to understand market formations. Business owners and investors can also estimate respective market volumes and profitability using our model simulations.

This paper is structured into five parts. After the introduction, Section 2 provides a literature review on the key concepts used in this study, the drivers and barriers for one-loop and two-loop approaches and highlights future battery trends. Section 3 introduces the methodological approach, explaining the SD model structure and crucial equations. Section 4 reveals insights into the model simulations and discusses the key research findings. The paper concludes in Section 5.

2. Literature review

2.1. Pathways and definitions

EOL strategies for EV batteries are an emerging topic in scientific literature. According to Zhu et al. (2021), an EV is classified as EOL when its battery capacity can no longer satisfy the industry's use standards. A widely used criterion is the State-of-Health (SoH) assessment, which assigns the EOL status to a battery with a 20 % capacity loss (Zhu et al., 2021). Currently, despite residual values, most EOL materials from EVs follow a linear path to the final disposal (Harper et al., 2019) or inventories, where the batteries are stored until suitable EOL treatments are available.

A circular economy aims to achieve economic values and environmental benefits by bringing back used materials into the system and reducing the demand for virgin materials (Kirchherr et al., 2017). There are two approaches to a circular economy: *slowing* and *closing* approaches. The former extends the lifetime of materials by reusing them, while the latter focuses on recycling activities (Albertsen et al., 2021).

The emerging EOL industry for EV batteries could develop into a one-loop or two-loop system. Subsequently, we elaborate on the definitions of the pathways and the relevant steps. Fig. 1 illustrates the distinction between a one-loop system and a two-loop system, considering potential changes in battery ownership within one use phase.

The one-loop approach focuses on *closing* solutions by recycling EOL materials. It builds the foundation for both one-loop and two-loop systems to establish a circular economy.

Recycling attempts to close the loop of lithium-ion batteries by recovering the essential valuable materials for new battery production (Neumann et al., 2022). By discharging and disassembling EOL batteries to the cell level, the active materials are separated from metallic components and further processed into a black mass product (Neumann et al., 2022). Based on metallurgy methods, the active materials—such as lithium, nickel, and cobalt—are extracted (Neumann et al., 2022; Yu et al., 2021). Despite high recovery rates, expensive and energy-

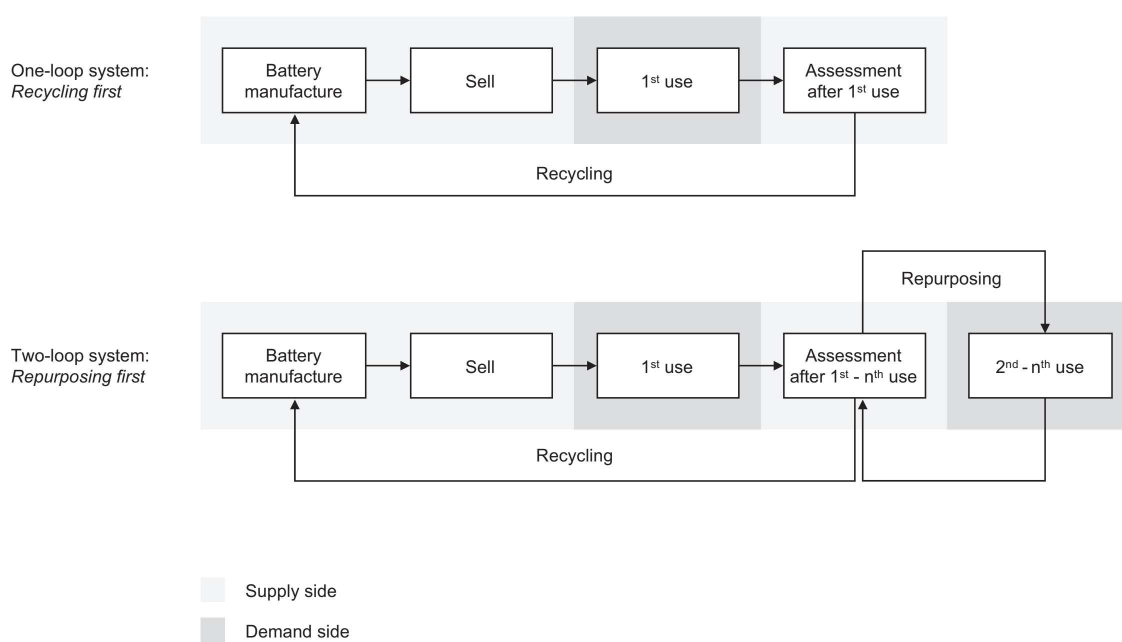


Fig. 1. One-loop and two-loop system (adjusted from Gonzalez-Salazar et al., 2023).

demanding processes still mitigate diffusion (Ferrara et al., 2021; Hua et al., 2021). Thus, direct recycling as an alternative method is focused on and tested on a laboratory scale (Yu et al., 2021). Direct recycling involves bypassing chemical destruction, resetting the lifecycle, and adding lithium to EOL materials (Neumann et al., 2022). Compared to commercialised metallurgy methods, direct recycling is low in energy consumption, pollution, and costs (Hua et al., 2021).

For EV batteries, a two-loop approach, which combines the *slowing* and *closing* solutions, has been deemed to be promising (Albertsen et al., 2021; Wrålsen et al., 2021; Olsson et al., 2018). The reuse of EV batteries follows different strategies depending on their battery capacity and preferred market: (i) direct reuse, (ii) remanufacture, or (iii) repurpose. Arguing against *direct reuse* and *remanufacture* in the end-of-life phase, higher operational efforts are needed to sustain battery performance in automotive applications. Hence, repurposing seems a promising strategy for a two-loop system to extend the battery lifetime while closing the material loop (Olsson et al., 2018). Fig. 1, therefore, integrates *direct reuse* and *remanufacture* within the 1^{st} use phase, focusing on repurposing in the two-loop approach.

Direct reuse is applied after vehicle failures or crashes. The batteries are drawn from the system before they reach EOL with a 20 % capacity loss. The materials can then bypass the disassembly process and are directly reused in an additional automotive application (Alamerew and Brissaud, 2020).

Remanufacturing targets automotive markets by refurbishing and repairing EV batteries (Hua et al., 2021). In both cases, appropriate pretreatment steps—testing, disassembly, identification, removal, and reassembly activities—are essential to assess the optimal path (Zhang et al., 2014).

Repurposing defines second-use applications of EV batteries in non-automotive markets, where end-of-(first)-life capacities are sufficient to meet industry standards (Kamran et al., 2021). The prominent applications of repurposing are battery storage solutions in the energy market—for example, peak shaving, residual home storage, grid stability, and EV charging (Hua et al., 2021; Harper et al., 2019; Olsson et al., 2018).

2.2. Drivers and barriers

One key parameter guiding the decision between a one-loop and two-loop system is the SoH assessment, clustering high-quality batteries (80 % $\geq$ SoH $\geq$ 50 %) and low-quality batteries (SoH < 50 %) (Al-Alawi et al., 2022). Despite low-quality batteries directly entering the recycling path, different drivers and barriers become relevant for assessing the one-loop or two-loop path for high-quality batteries.

Returning critical raw materials for EV production is a driver of a one-loop system. In the hydrometallurgy process, high qualities of lithium, nickel, and cobalt are preserved (Neumann et al., 2022; Yu et al., 2021). The ongoing discussions surrounding the current technologies indicate recovery rates ranging from 90 % to 98 % (Santos et al., 2021). Consequently, the one-loop system is advantageous for its environmental benefits and its capacity to facilitate the reintegration of materials into the production system. Noteworthy is the observation that, while the pyrometallurgical process falls short in preserving all active materials, it does, however, contribute to the conservation of aluminium and binder materials. These resources are relevant for producing new batteries and mitigating the dependence on virgin materials (Bhuyan et al., 2022). Furthermore, the one-loop system seems a convincing way to counteract the time-sensitive material shortage problem of lithium and cobalt (Rajaeifar et al., 2022).

The move towards a one-loop system faces various barriers related to politics, economics, technology, and the environment. On the political side, there is a lack of rules and standards to guide the design of recyclable batteries across the industry (Bhuyan et al., 2022; Zhang et al., 2014). Economically, high costs and low EOL volumes make it hard to expand recycling efforts (Kamath et al., 2023; Sopha et al., 2022). The complexity of different battery designs strengthens this barrier (Azadnia et al., 2021). From a social perspective, consumer awareness about the importance of recovering EV batteries is lacking, impacting EOL volumes and acceptance (Sopha et al., 2022; Azadnia et al., 2021). Furthermore, insufficient cooperation in the supply chain hinders access to battery data (Bhuyan et al., 2022; Azadnia et al., 2021). Additionally, concerns about the toxicity of metals in batteries challenge the scalability of recycling (Bhuyan et al., 2022; Alamerew and Brissaud, 2020). On the technological side, inefficient recycling processes and uncertainties concerning battery lifespan and volumes impede the establishment of a one-loop system (Sopha et al., 2022; Albertsen et al., 2021; Azadnia et al., 2021; Bobba et al., 2018). Finally, from an environmental standpoint, metallurgical processes use energy-intensive procedures, thereby reducing the environmental efficacy of recycling techniques (Bhuyan et al., 2022).

Prolonging the lifespan of batteries, and thus enhancing their environmental values, is a compelling driver for the two-loop system (Ali et al., 2021). With minor remanufacturing steps needed to repurpose a battery, manufacturers can increase revenues across its entire lifecycle (Júnior et al., 2023). Repurposed batteries typically reach higher selling prices than recycled materials (Kamath et al., 2023; Gu et al., 2018). Despite these economic benefits, repurposing can address the current barriers in the one-loop system by postponing the recycling step, allowing recycling entities and researchers to refine technologies and enhance their efficiency (Júnior et al., 2023; Richter, 2022). Without maturity and efficiency in the market, the relevant resources, such as energy, materials, and labour, might be wasted in the one-loop system (Júnior et al., 2023).

A two-loop system is also hindered by several barriers. First, there is a prominent security concern regarding the toxic materials in batteries (Bhuyan et al., 2022; Rajaeifar et al., 2022; Hua et al., 2021; Alamerew and Brissaud, 2020). Handling these batteries poses social risks to human health, necessitating specialised knowledge, qualified personnel, and dedicated equipment for disassembling and transporting retired batteries (Hua et al., 2021). Consequently, liability regulations and standards are currently lacking for the treatment and installation phase (Schulz-Mönninghoff and Evans, 2023). Moreover, uncertainties about battery ageing after the end-of-(first)-life hinder the adoption of the two-loop approach (Azadnia et al., 2021; Alamerew and Brissaud, 2020; Harper et al., 2019). Additionally, a lack of transparency regarding first-usage data limits an accurate assessment (Júnior et al., 2023).

2.3. Market developments and research gap

As of today, few full-scale recycling and repurposing business models exist in the market with OEMs or third-party operators as battery owners (Albertsen et al., 2021). The majority of these initiatives are pilot projects aimed at acquiring expertise in EOL battery management, awaiting an exponential increase in end-of-(first)-life volumes and prioritising economic parameters in their decision (Rallo et al., 2020).

The EU battery regulation, which was introduced in August 2023 and will be implemented in a staged approach (Regulation 1542/2023), is expected to significantly impact future developments. The regulation focuses on lithium-ion batteries and considers specific requirements for EV batteries, aiming to make recovered batteries competitive, promote circular value chains, and reduce environmental impacts along the supply chain (Regulation 1542/2023). The assigned target groups are manufacturers or importers who introduced the batteries to the European market. These actors have extended producer responsibility, providing a collection and recovery system for used EV batteries (Olsson et al., 2018). Specific recycling shares in newly sold batteries are relevant to the one-loop system, affecting EV batteries that contain cobalt, lead, lithium, or nickel as active materials (Regulation 1542/2023). From 2031 onwards, those batteries require a minimum share of 16 % cobalt, 6 % lithium, and 6 % nickel from recycled content, obligating importers for each battery model per year and manufacturing plant

(Regulation 1542/2023). From 2036 onwards, the required shares will increase up to 26 % for cobalt, 12 % for lithium, and 15 % for nickel.

Following the argumentation of several authors, the EU battery directive is assumed to incentivise firms to prioritise recycling after the end-of-(first)-life phase (Albertsen et al., 2021; Kotak et al., 2021). With growing demand for battery materials compared to constant supply, suppliers can increase market prices, thereby impacting recycling returns. Sterman (2000) refers to this phenomenon as the price effect, mapping the reinforcing and balancing effects of a demand-to-supply ratio in the market. As firms scale up to meet demand, operational costs are expected to decrease, leading to a technology learning effect. According to Sabel and Weiser (2008), production costs decrease with each doubling of production volumes, thereby impacting factory utilisation and economic returns (Thies et al., 2018; Hoyer et al., 2015). Moreover, rising profitability impacts the construction of new factories in the market (Thies et al., 2018), increasing supply and strengthening the discussed price dynamics. Hereby, an increase in value is hypothesised to drive the system towards a one-loop approach (Richter, 2022; Kotak et al., 2021).

A two-loop system may experience a push through technology substitution: replacing the current battery chemistries with lithium iron phosphate (LFP) batteries. Overall, the market follows the trend of replacing cobalt with alternative elements, such as nickel, manganese, or iron phosphate, as cobalt represents a critical and costly factor in battery production processes (Kotak et al., 2021). As a consequence of the material substitution, the recycling value of LFP batteries diminishes (Wasesa et al., 2022) and higher LFP repurposing values are expected.

Previous studies that investigated the different factors that influence the one-loop or two-loop approach predominantly undertook qualitative assessments to analyse the influence of the EU battery regulation on the market (Richter, 2022; Albertsen et al., 2021; Kotak et al., 2021). Given the analysed risk of incentivising a one-loop prematurely or promoting a two-loop without compliance with EU policy, assessing the impact of long-term dynamics quantitatively gains high practical relevance.

3. Methods

To investigate the market formation of repurposing and recycling solutions for EV batteries, we developed a simulation model focused on the long-term market dynamics, integrating feedback loops and decision delays. The model focused on a one-loop and two-loop structure and considered the economic incentives when deciding between a repurposing or recycling application.

SD modelling was selected as the simulation method, given the complex nature of ageing chains, delay structures, and market dynamics present in the system for EOL solutions for EV batteries. It provides an impactful methodology to analyse future scenarios and support the system's complexity, which could not be conducted mentally (Sterman, 2000). SD, prominently known because of the 'The Limits to Growth' simulations, has been applied to various business and political fields, with several studies specifically addressing the EV battery context (Kamath et al., 2023; Wasesa et al., 2022; Li et al., 2020; Alamerew and Brissaud, 2020; Gu et al., 2018; Farel et al., 2013; Hoyer et al., 2011).

The model focused on EVs in the passenger car segment, and Switzerland was chosen as the empirical context to derive policy recommendations for both non-EU and EU stakeholders. Switzerland is a particularly interesting case for the research question since the country is yet to decide whether it will adopt the EU battery directive. Simulations were performed for the period between 2010 and 2050 to measure the impact of the EU regulation. To this end, the model integrated twelve feedback loops into its structure, which will be introduced sequentially.

The model's central feedback structure was developed in a two-fold process. First, the literature on drivers and barriers, discussed in Section 2.2, was reviewed to define the stimuli relevant to establish a circular economy solution for EV batteries. Second, a conference workshop titled 'Closing the loop of EV batteries' was conducted in June 2023 to prioritise these stimuli according to their relevance with experts from the EV battery and energy industry. The workshop results showed that the volume of returned end-of-life materials was highlighted as crucial for enhancing scalability and reducing operational costs. Moreover, national regulations can orchestrate a pulling price effect for recycling, thereby supporting a one-loop approach. For the two-loop system, increased cooperation among stakeholders was ranked high, pulling the market towards repurposing (s. supplementary material for more details on the workshop).

3.1. Model structure

The core part of the model captures the circular pathways for EV batteries in Switzerland by integrating a stock and flow structure. Each stock, illustrated as a box in Fig. 2, measures the accumulated battery capacity (kWh) at a specific point in time (t). Each flow, illustrated as pipes with a valve, captures the stock's inflow and outflow. The structure is divided into four phases: i) first-use, ii) assessment, iii) repurposing and iv) recycling:

First-use is defined by two stocks: 'EV batteries on the road' and 'first end-of-life'. The 'EV batteries on the road' stock captures the electric vehicle fleet in Switzerland based on retailers selling EVs on the market and collecting from customers retired batteries with a SoH below 80 %. The 'first end-of-life' stock captures end-of-(first)-life volumes based on batteries being collected by retailers before being transported for further recovery.

Assessment is determined by three stocks: 'EV battery capacities (EVBC) in assessment', 'high-quality batteries', and 'low-quality batteries'. The current pilot projects in the market indicate that OEMs do not directly undertake recycling but rely on third-party operators (Albertsen et al., 2021). These recycling or repurposing firms operate independently as battery owners or service providers to OEMs. The first stock involves end-of-(first)-life capacities remaining in Switzerland and being collected for further recovery. In this context, third-party operators distinguish between batteries under OEM and non-OEM ownership. For batteries with non-OEM ownership, third-party operators predominantly apply a SoH assessment, categorising them as high-quality (SoH $\geq$ 50 %) and low-quality batteries (SoH $<$ 50 %). For batteries with OEM ownership, third-party operators are subject to internal OEM policies defining the performance of a SoH assessment or the direct recycling of batteries.

Repurposing is presented by two stocks: 'EVBC in repurposing' and 'second end-of-life'. For high-quality batteries, an economic assessment is conducted to decide whether to choose the two-loop structure or the one-loop structure. Having high economic margins for the two-loop system, the 'EVBC in repurposing' stock accumulates battery capacities that were repurposed and are now in use for stationary storage applications. The 'second end-of-life' stock then captures the retired batteries from repurposed applications before storing them in the 'low-quality batteries' stock. The model assumes that second end-of-life materials are directly integrated into the recycling path, excluding any subsequent use phases and reflecting the current industry structure in Switzerland, where repurposing firms mainly collaborate with recycling firms to provide shared value in a circular economy.

Recycling is presented by one, the 'EVBC in recycling' stock, which incorporates the capacities successfully recycled into black mass products by reducing the number of exported materials.

3.2. Central dynamics

The model considered twelve feedback loops to capture the impact of the EU battery regulation. The feedback loops are highlighted with round arrows in Fig. 4. The reinforcing loops are visualised with the polarity identifier R, whereas a balancing behaviour is described with the abbreviation B in the graph (Sterman, 2000). The feedback loops can be grouped based on their thematic proximity into three subgroups: *price*

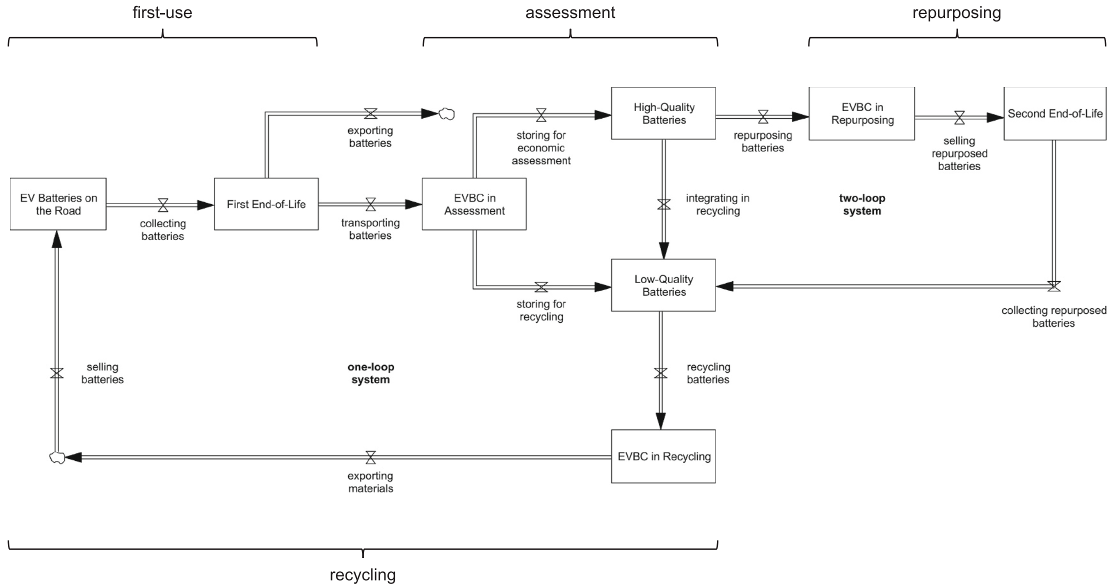


Fig. 2. The model structure for EV batteries' end-of-life paths.

effect (Loop $B_{1a\text{-}c}$ and $B_{2a\text{-}c}$), *technology learning* (Loop R_1 and R_2), and *investor decision* (Loop R_3 and $B_{3\text{-}5}$).

Loop $B_{1a\text{-}c}$ and $B_{2a\text{-}c}$ integrated the *price effect* emerging from the dynamics of demand and supply, a key aspect of SD in market analysis (Sterman, 2000). In alignment with the EU battery regulation, the model focused on modelling the price effect of recycled lithium (B_a), cobalt (B_b), and nickel (B_c). The material prices for virgin materials were modelled endogenously. Balancing loop B_1 adjusts the product prices in response to demand shifts, leading to price increases during demand surpluses, which, in turn, reduce demand and restore equilibrium. Conversely, balancing loop B_2 regulates prices in reaction to supply imbalances, causing price adjustments to stabilise the market and restore equilibrium.

Loop R_1 and R_2 modelled the *technology learning effects* on the production costs of recycling and repurposing. These loops are structured to address the exponential decay characteristic inherent in this phenomenon, whereby operational costs diminish with each doubling of production volumes (Sabel and Weiser, 2008). Reinforcing loop R_1 specifically considers the learning effect in relation to recycling costs, while reinforcing loop R_2 integrates this reinforcing behaviour within the framework of the repurposing system.

Loop R_3 and $B_{3\text{-}5}$ captured the *investor decision* process based on a common stock management structure of SD modelling (Sterman, 2000). The underlying assumption is that firms' increasing capacities need to await construction due to an administration and construction delay. The model distinguished two stocks: 'capacity of recycling factories' and 'factory capacity under construction'. The model captured endogenous investment decisions and integrated investments already planned by industry actors of 8.700 t/year, which were modelled exogenously (Soldan et al., 2023). The construction stock was increased by an investment rate and decreased by the acquisition (Fig. 3).

Within the *investor decison* process, Loop R_3 integrated *new investments* based on the calculation of payback periods. As the market experiences higher investments, the technology learning effect on recycling costs is enhanced, thereby augmenting economic margins and, consequently, positively influencing the payback period. This reinforcing effect is, however, balanced out by the free volumes for investments, upon which two feedback loops are oriented. Loop B_3 incorporated a *market saturation* effect on investment volumes, which diminished the investment rate. Similarly, Loop B_4 also considered *market saturation with under-construction factories* to prevent the market from reconsidering already made investments. The reduction of investment volumes based on Loop B_3 and Loop B_4 increased the investment costs, leading to a decrease in profitability and further balancing new investments with Loop B_5: *volume adjusting of investment costs*.

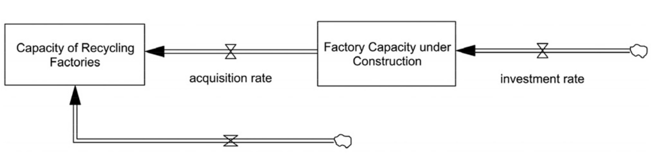


Fig. 3. The investor decision structure for recycling plants.

Table 1
Data for market volume and EV market share (data source: BFS and ASTRA, 2023; Prognos et al., 2021).

Time	Market volume	EV Market share[a]		
		BAU scenario	ZERO scenario	ICE BAN scenario
2010	296'597	0 %	0 %	0 %
2015	327'143	1 %	1 %	1 %
2020	239'887	4 %	4 %	4 %
2025	248'401	12 %	15 %	15 %
2030	256'212	21 %	35 %	35 %
2035	262'824	30 %	60 %	100 %
2040	266'121	38 %	80 %	100 %
2045	268'440	46 %	85 %	100 %
2050	270'172	55 %	90 %	100 %

[a] Market share of battery electric vehicles (BEV) in the passenger car segment.

3.3. Model equations

Here, we present a selection of equations central to the model dynamics. We start with the fundamental framework of the model and continue with the key equations used for quantifying the feedback loops. A complete overview of all the model variables and equations is listed in the supplementary material.

The fundamental framework of this model was organised around ageing chains, a conventional structure in SD modelling that incorporates various stocks with specific delay times (Sterman, 2000). Given the pivotal role of material delay times in this model, particular emphasis was placed on their accurate representation. Two relevant factors contributed to the portrayal of delay behaviour: (1) length of

Table 2
Weibull and optimisation values for EV retirement (data source: Ai et al., 2019).

Purchase year of EV	Weibull values[1] *Based on* Ai et al. *(2019)*		Optimisation values[2] *Based on optimisation*	
	Scale *[Year]*	Shape *[Dmnl]*	Delay time *[Year]*	Delay order *[Dmnl]*
2010–2014	5.5	3.5	5.23	5.0
2015–2019	7.5	3.5	7.12	5.0
2020–2024	9.5	3.5	9.02	5.0
2025–2029	11.0	3.5	10.44	5.0
2030–2034	12.0	3.5	11.41	5.0
2035–2040	12.5	3.5	11.88	5.0

[1] The relative magnitude of lifespan was assumed to equal the average EV lifespans (Barré et al., 2013), and the pattern of retirement was assumed to equal the pattern of Nickel-cadmium (Ni-Cd) batteries with a scale parameter of 3.5.
[2] In system dynamics, a higher-order delay is implemented using a technical function characterised by two variables: delay time and delay order. The delay time constitutes the average length of the delay (Sterman, 2000). The delay order indicates the shape of distribution around the delay time (Sterman, 2000). With the optimisation, both parameters were determined to best align the model's output with the Weibull curves reported by Ai et al. (2019). The details of the optimisation procedure are documented in the supplementary material.

delay and (2) distribution, which is reflected in the delay order (Sterman, 2000). However, an exception occurred for the *first-use* phase, capturing the 'EV batteries on the road' stock and the 'first end-of-life' stock.

The 'EV batteries on the road' stock was measured based on the EV sales data in Switzerland. The market volume of passenger cars in Switzerland between 2010 and 2050 period was modelled using the data of Prognos et al. (2021) (Table 1). To calculate the respective EV market share, three different scenarios were used: business as usual (BAU), reaching net zero by 2050 (ZERO), and reaching net zero by 2050 with a fade-out of internal combustion engines (ICEs) by 2035 (ICE Ban) (Prognos et al., 2021).

The 'first end-of-life' stock was captured using the EV retirement rate as an inflow. In the literature, Weibull distributions have emerged as a recognised method for measuring product life cycles and retirement (Rinne and Mittag, 1995). Applied to EV batteries, Ai et al. (2019) presented data on the ageing process of EV batteries along Weibull parameters. The accurate delay time and order values were determined using a payoff optimisation to approximate the Weibull parameters (s. supplementary material for more details) (Table 2).

For other material delays where no detailed information was available, a third-order material delay was assumed to be a prevalent practice in SD.

The key equations in quantifying the feedback loops were categorised into three subgroups: *price effect*, *technology learning*, and *investor decision*.

Price effect was applied to the material prices affected by the EU battery regulation, where m = nickel, lithium, and cobalt. The structure was predicated upon the demand-to-supply ratio, representing the quotient of demand and supply (Sterman, 2000). Here, demand refers to the proportion of battery materials required to comply with the EU battery regulation (V_{demand_m}). Conversely, supply pertains to the batteries recycled within the boundaries of the model (V_{supply_m}). By introducing mandatory recycling shares ($V_{\text{demand}_m} > 0$), the price effect (p_{effect_m}) becomes active by the subsequent equation, where s is the sensitivity of price to a change in the demand-to-supply ratio, which was assumed to be 0.05 (Sterman, 2000):

$$\text{Price effect}: P_{\text{effect}_m} = \text{if } (V_{\text{demand}_m} > 0) \text{ then} \left(\frac{V_{\text{demand}_m}}{V_{\text{supply}_m}}\right)^s \text{else } (0) \tag{1}$$

The initial prices ($P_{m_{t_0}}$) for nickel (11.4 CHF/kg), lithium (61.8 CHF/kg), and cobalt (43.1 CHF/kg) were captured for the stock (Kamath et al., 2023; Trading Economics, 2022; U.S. Geological Survey, 2022). Multiplying the current price with the price effect (P_{effect_m}) forms an indicated price ($P_{\text{indicated}_m}$). If the indicated price exceeds the marginal prices (P_{marginal_m}) for nickel, lithium, and cobalt, the stock price adjusts to the indicated price with a delay time of 1 month, capturing the time for the market to incorporate the new price (Li et al., 2020; Sterman, 2000):

$$P_m = \text{INTEG}\left(\left(\frac{P_{\text{indicated}_m} - P_m}{dt_{\text{price adjustment}}}\right) P_{m_{t_0}}\right) \tag{2}$$

with $P_{\text{indicated}_m} = \mathit{MAX}\left(P_m {*} P_{\text{effect}_m} P_{\text{marginal}_m}\right)$

The final recycling price considers the material prices (P_m) of nickel, lithium, cobalt, steel, manganese, iron, copper, and aluminium. The values were aggregated based on their material fraction within the two modelled battery types (s. supplementary material), thereby integrating the prices for LFP and NMC811 batteries. The model assumes NMC batteries to hold a dominant position in the market, constituting 93 % of the share, with a projected decrease to 65 % by 2030 (Bianchetti et al., 2023; IEA, 2022).

Since the model excluded black mass treatment, the recycling price was further multiplied by a black mass fraction of 0.65, capturing the quotient of the average recycling price of 5′901 CHF/t (Kamath et al., 2023) with the average black mass price of 4′000 CHF/t (No Canary, 2022).

Technology learning incorporated a scaling effect on the annual fixed costs (c_{fixed_i}), where i considered the recycling or repurposing pathways (Rosenberg et al., 2023; Dai et al., 2019). The equation is based on initial costs ($c_{\text{fixed}_{i_{t_0}}}$), production volumes ($V_i$), and a learning coefficient (b) (Sabel and Weiser, 2008):

$$\text{Technology learning}: c_{\text{fixed}_i} = c_{\text{fixed}_{i_{t_0}}} \cdot V_i^{-b} \tag{3}$$

For recycling, the technology learning effect was applied to the starting costs of 406 CHF/t, considering the annual fixed costs of 4.06 Mio CHF for a large factory size of 10′000 t/year (Rosenberg et al., 2023; Neometals Ltd., 2021). For repurposing, the starting costs of 1′510 CHF/

Table 3
Experimental setup for analysis.

		Policy sphere	
	Base assumptions (EV = ICE BAN, EXP = 40 %, OEM = NONE, LFP = ON)	BR OFF_{base}	BR ON_{base}
Scenario sphere	EV market share (EV = BAU, ZERO, ICE BAN)	BR OFF_{EV}	BR ON_{EV}
	Export share (EXP = 0 %–80 %)	BR OFF_{EXP}	BR ON_{EXP}
	OEM batteries in 100 % recycling policy (OEM = NONE, ALL)	BR OFF_{OEM}	BR ON_{OEM}
	LFP battery substitution (LFP = OFF, ON)	BR OFF_{LFP}	BR ON_{LFP}

t were assessed, integrating the fixed costs of 1.1 Mio. CHF/year with a plant capacity of 115 MWh/year (Kamath et al., 2023).

The production volumes were captured with the accumulation of battery capacities entering the recycling ($V_{i=\text{recycling}}$) and repurposing ($V_{i=\text{repurposing}}$) pathways (Fig. 2). The learning coefficient was set to 0.32, integrating a learning effect of 20 % for every doubling of volume (Sabel and Weiser, 2008).

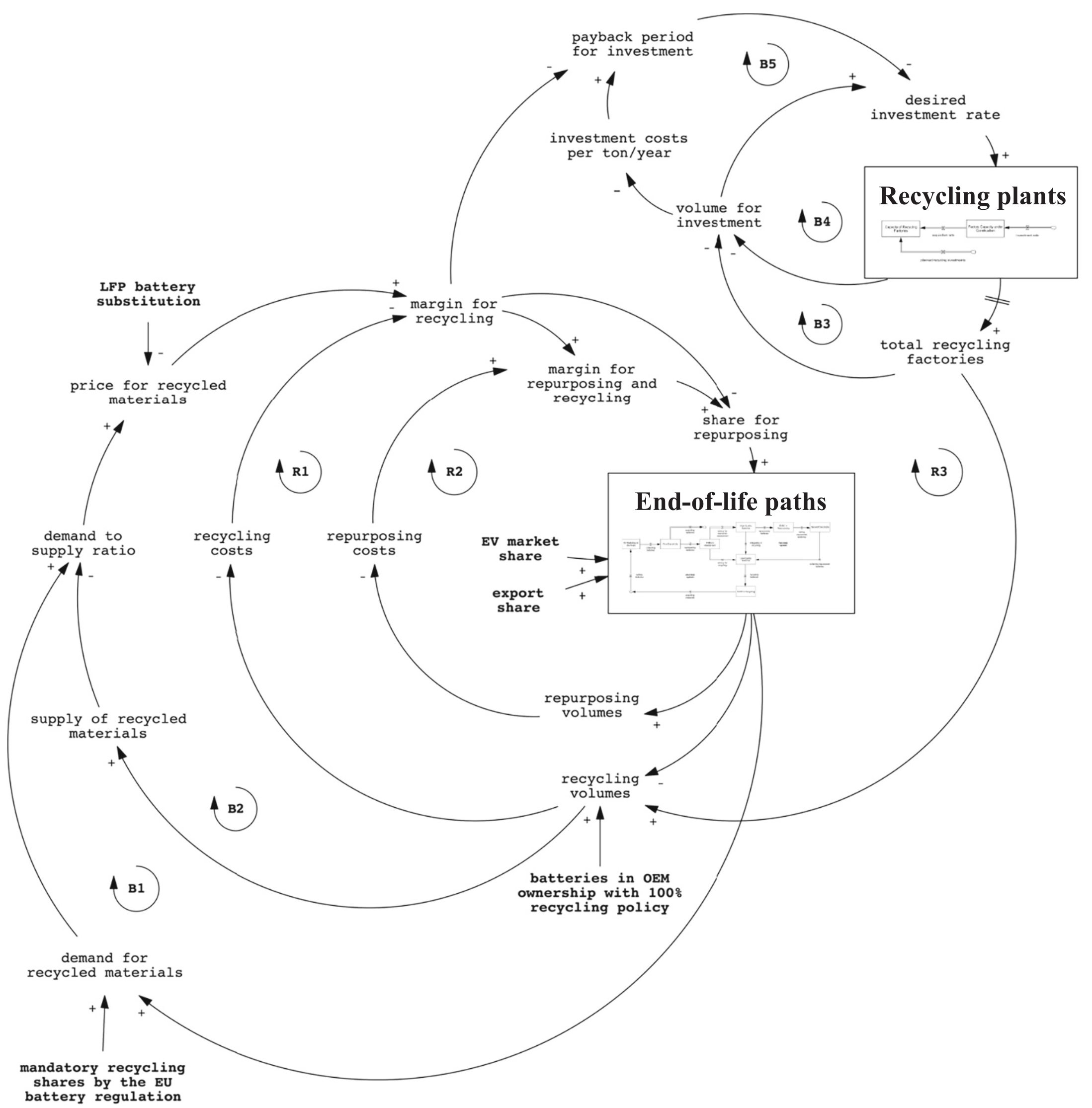
The total costs accumulated the annual fixed costs with the respective variable, transportation and battery purchasing costs. The variable costs for recycling (1268 CHF/t) and repurposing (848 CHF/t) were subdivided into labour, energy, material, and disposal costs (Kamath et al., 2023; No Canary, 2022; Byland, 2022). By excluding black mass treatment, the variable costs for recycling were reduced to 495 CHF/t (No Canary, 2022). The transportation costs were assumed to have minor disparities between recycling and repurposing and were therefore excluded. The battery purchasing costs were assumed to be 0 CHF/t (Albertsen et al., 2021).

Investor decision incorporated four feedback loops: *new investments*, *volume adjusting of investment costs*, *market saturation*, and *market saturation with under-construction factories*.

New investments was grounded in the stock management structure of commodity markets, where the recycling factories were increased by a desired investment rate (ir_{desired}) (Sterman, 2000):

$$\text{New investments} : ir_{\text{desired}} = PP_{\text{tolerance}} {}^{*} V_{\text{invest}} \quad (4)$$

The profitability of a new investment was determined by calculating the payback period. The key driver was the economic margin for recycling ($u_{i=\text{recycling}}$), comprising the black mass price, black mass costs, and an advanced recycling fee of 1600 CHF/t (Bianchetti et al., 2023). This value was multiplied by an expectation growth factor of 1.1, forming



Price effect: $B_{1a\text{-}c}$ = Price effect on demand, $B_{2a\text{-}c}$ = Price effect on supply

Technology learning: R_1 = Technology learning for recycling, R_2 = Technology learning for repurposing

Investor decision: R_3 = New investments, , B_3 = Market saturation, B_4 = Market saturation with under-construction factories, B_5 = Volume adjusting of investment costs

Fig. 4. Central dynamics in the model.

long-run margin expectations ($u_{expected_{i=recycling}}$). For the calculation of payback periods (PP_{invest}), the investment costs (s. Eq. (6)) were divided with the expected economic margin:

$$PP_{tolerance} = \text{Lookup } PP_{tolerance}(PP_{invest}) \quad (5)$$

$$\text{with } PP_{invest} = c_{invest_V} \Big/ u_{expected_{i=recycling}}$$

Reflecting the investor preferences for payback periods involved considerations by Kubli (2018) and Helms et al. (2015), which helped us cluster the payback periods along a descending S-curve: the Lookup $PP_{tolerance}$ assumed 50 % of institutional investors in the renewable sector to invest within a period of 5 years, 80 % within a payback period of 3 years and 100 % within a payback period of 0 years (Fig. 5).

Volume adjusting of investment costs considered three levels of plant sizes. The model divided small (2′500 t/year), medium (5′000 t/year), and large capacities (10′000 t/year) with costs of 45 Mio. CHF, 68 Mio. CHF, and 103 Mio. CHF (Rosenberg et al., 2023; Neometals Ltd., 2021). Dividing the total investment costs with the annual production capacity formed the annual investment costs per tonne. These values were integrated into the lookup function (Lookup c_{invest}), which adjusted the investment costs based on the respective investment volumes (V_{invest}):

$$\text{Volume adjusting of investment costs: } c_{invest_V} = \text{Lookup } c_{invest}(V_{invest}) \quad (6)$$

The investment volumes (V_{invest}) play a crucial role in shaping investment decisions. The model posited that investors determine their desired investment rate based on long-term volume expectations. The EV sales data ($V_{EV\ sales}$) served as a key metric for this assessment, offering insights into the expected EOL volumes. When multiplied by the share of expected exports (s_{export}), only the portion of volumes remaining in the system was considered. To assess the expected needed recycling capacity ($V_{expected\ capacity}$), the model employed a common SD modelling method using the SMOOTH function. The method utilises first-order adaptive expectations and employs exponential smoothing to incorporate historical behaviour (Sterman, 2000). The model set a formation horizon of three years to guide long-term investment decisions (s. Eq. (7)).

Market saturation and *market saturation with under-construction factories* exerted a balancing effect on the investment volumes. In this process, the volumes anticipated from EV sales ($V_{expected\ capacity}$) were diminished by the existing recycling factories (F_{done}) and factories under construction (F_{build}) to prevent the investments already made from being overly considered due to the construction delay. The disparity of these determinants was designated as residual volumes for investment (V_{invest}) based on the following equation:

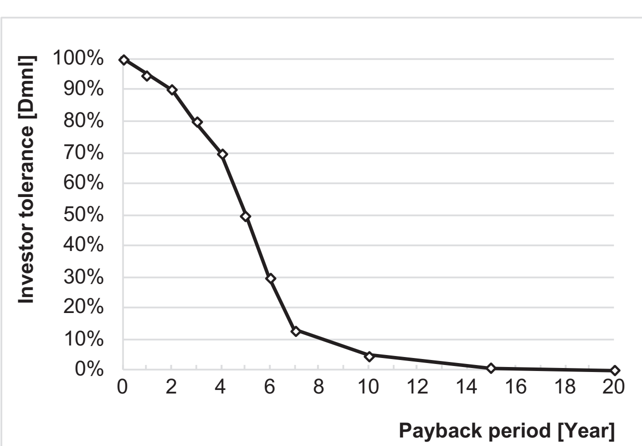


Fig. 5. The lookup function for the tolerance of payback periods (adjusted from Kubli, 2018; Helms et al., 2015; Ebers and Wüstenhagen, 2015).

$$\text{Market saturation}: V_{invest} = max\left(V_{expected\ capacitiy} - F_{done} - F_{build}, 0\right) \quad (7)$$

$$\text{with } V_{expected\ capacity} = \text{SMOOTH}\left(V_{EV\ sales} * (1 - s_{export}), 3\right)$$

3.4. Model validation and limitations

For validation, the twelve tests for assessing dynamic models by Sterman (2000) were performed, which included and extended the procedure from Forrester and Senge (1980). We placed particular emphasis on including the expertise of industry experts. During the model development, workshops with the CircuBAT consortium comprising energy and EV battery experts were held to validate the causal loop structure. Furthermore, meetings with project partners from CircuBAT were performed to validate the structure and behaviour of the model. In addition, discussions with recycling and repurposing companies in Switzerland and the Netherlands were orchestrated to align the model structures with real-world dynamics.

The model's validation revealed five central limitations that should be kept in mind when interpreting the simulation results. First, the scope of the study was limited to Switzerland, but the model considered the price and technology learning effects that are, to a large extent, steered by European or even global dynamics. To still consider these aspects in their dynamic structure, we took the simplifying assumption that surrounding countries are developing in a similar manner and, therefore, the price and technology learning can be approximated by the Swiss market. Second, the study focused predominantly on black mass production, as black mass treatment and cell production are increasingly outsourced beyond Europe. Third, our dataset was primarily limited to the passenger car segment, which dominates the EOL market. Fourth, our study focused on NMC and LFP batteries. While we did explore technological advancements in LFP batteries, other battery technologies, such as solid-state, were excluded due to their limited scalability. Finally, the model primarily considered economic factors when assessing the share of batteries entering the one-loop or two-loop structure. Ecological factors were excluded.

3.5. Experimental setup

We tested the policy simulation of the EU battery regulation using our model (Table 3). The simulation *BR ON$_{base}$* introduced the mandatory recycling shares for lithium, cobalt, and nickel as foreseen by the European policy framework. The model compared the results with the no policy simulation *BR OFF$_{base}$*, capturing the system without the EU battery regulation. Here, the *technology learning* and *investor decision* loops were active, whereas the average black mass price was applied for the *price effect.*

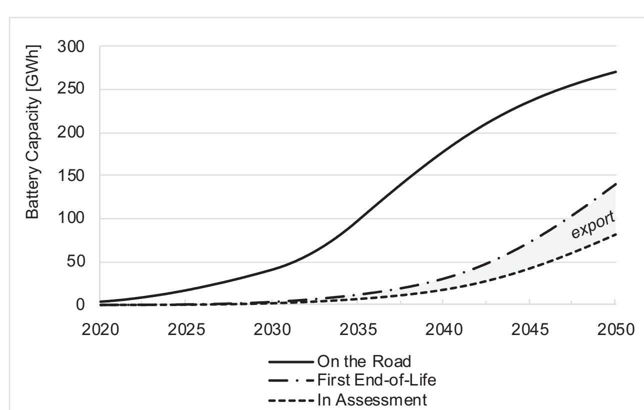


Fig. 6. Battery capacities 'On the Road', reaching 'First End-of-Life' and 'In Assessment' under base assumptions.

The policy simulations were further tested against four scenario domains: (1) *EV market share*, (2) *export share*, (3) *OEM batteries in 100 % recycling policy*, and (4) *LFP battery substitution* (s. variables in bold in Fig. 4). The EU market share was subdivided into BAU, ZERO, and ICE BAN scenarios, whereas the ICE BAN scenario was integrated into the base assumptions (s. Section 3.1). *Export share* was tested with a value range of 0 % to 80 %, whereas the first reflects legislation to declare EOL batteries as waste, requiring materials to stay in Switzerland. The latter incorporates an expectation by Bianchetti et al. (2023) concerning the export of EV batteries in Switzerland. In the base assumptions, the average value from both metrics ($EXP = 40$ %) is chosen. *Batteries in 100 % recycling policy* were tested for a value range of 0 % to 100 %. *LFP battery substitution* simulated a partial substitution of NMC batteries with LFP batteries. Based on Bianchetti et al. (2023) and IEA (2022), LFP shares were assumed to gradually increase from 0 % (year 2010), to 7 % (year 2020), to 15 % (year 2021), and to 35 % (year 2030).

4. Results and discussion

For our analysis, we simulated a base run without the EU battery regulation ($BR\ OFF_{base}$) and a policy run with the regulation ($BR\ ON_{base}$) activated (Table 3). The subsequent section will focus on the key findings, starting with the results of the EOL calculations and the base runs ($BR\ OFF_{base}$ & $BR\ ON_{base}$). It continues with the scenario simulations ($BR\ OFF_{scenarios}$ & $BR\ ON_{scenarios}$, where *scenarios* = EV, EXP, OEM, LFP) to test for policy robustness. A detailed overview of the scenario runs is presented in the supplementary material.

4.1. End-of-life volumes

The EOL volumes determine the flow towards repurposing and recycling. The simulation considered under the base assumptions an ICE ban in Europe and an increase in the EV market share to 100 % after 2035. The simulations indicated 74′000 EOL vehicles by the year 2030 in Switzerland with an increase to 2.38 Mio EOL EVs in the year 2050. This translates to 3.6 GWh (year: 2030), resp. 139.2 GWh (year: 2050) of end-of-(first)-life battery capacities (Fig. 6). With 40 % of batteries being exported, the battery capacities that remain in Switzerland and assessed and treated locally was reduced to 2.1 GWh (year: 2030) and 82.3 GWh (year: 2050).

4.2. Simulating the effect of the EU battery regulation

To assess the impact of the EU battery regulation, simulations without and with the activated policy were compared ($BR\ OFF_{base}$ and $BR\ ON_{base}$). The analysis focuses on identifying the impacts on the share of high-quality batteries being repurposed or recycled. The main results are visualised in Fig. 7.

The $BR\ OFF_{base}$ simulation resulted in 62.6 % (year: 2030) and 63.5 % (year: 2050) of batteries repurposed for stationary use (Fig. 7). The reciprocal of these values indicates the volumes stored for recycling. The repurposing share visualised in Fig. 7 comprises (1) a SoH assessment and (2) an economic assessment. In the first step, 80 % of batteries were classified as high-quality batteries, whereas 20 % were batteries with insufficient quality for repurposing and therefore must be recycled immediately. In the second step, the high-quality batteries underwent an economic assessment for repurposing, reflecting the tension between a one-loop and two-loop system. The $BR\ OFF_{base}$ simulation thus indicates an economic incentive for the two-loop system, revealing higher economic margins for the two-loop system compared to the one-loop approach. Hence, the economic shares of 78.9 % (year: 2030) and 79.9 % (year: 2050) for high-quality batteries being repurposed reflect this behaviour.

In the $BR\ OFF_{base}$ simulation, therefore, the majority of EV batteries were repurposed into stationary batteries (Fig. 7). The run indicates 1.3 GWh (year: 2030) and 52.2 GWh (year: 2050) of battery capacities being repurposed and 0.78 GWh (year: 2030) and 30.0 GWh (year: 2030) being stored for recycling. The slight increase in repurposing is attributed to the technology learning effect, where higher repurposing volumes enhance scale effects and positively impact the economic value of the two-loop system.

In the policy simulation $BR\ ON_{base}$ with the EU battery regulation activated, 62.6 % (year: 2030) and 49.0 % (year: 2050) of batteries were repurposed (Fig. 7). The values until 2030 aligned with the $BR\ OFF_{base}$ simulation; thereafter, the mandatory recycling shares are introduced in 2031.

Driven by the dynamics of the price effect, the $BR\ ON_{base}$ simulation reveals an imbalance in the demand-to-supply ratio after 2031, indicating greater demand for recycled battery materials relative to the available supply. It takes until 2038 for the ratios of nickel and lithium to be rebalanced with supply; stricter regulations for cobalt delay the

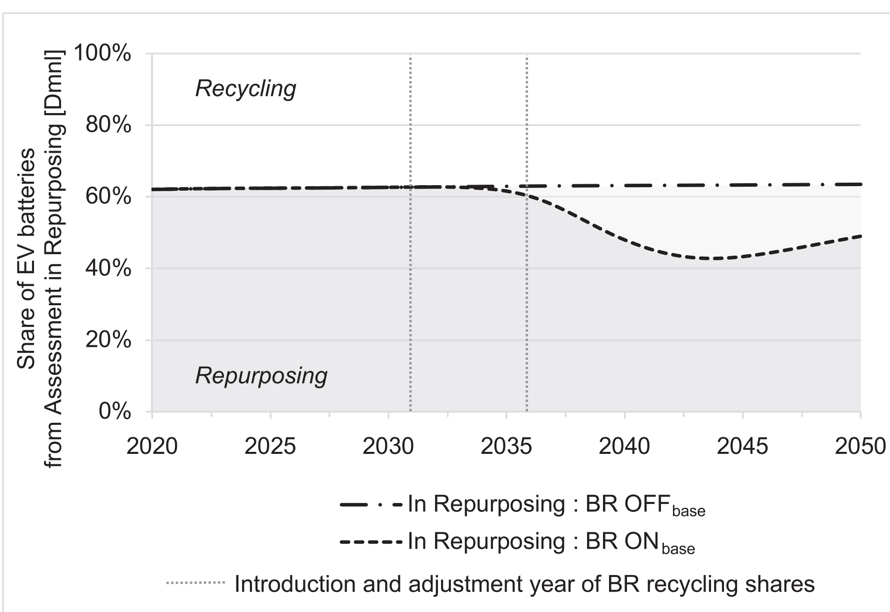


Fig. 7. The share of EV batteries from assessment 'In Repurposing' or 'In Recycling' under base assumptions.

rebalancing effect until 2041. The relatively long persistence of a demand surplus is attributed to an increase in recycling shares in 2036, reinforcing the effect of exceeding demand despite rising supply.

As a result, the *BR* ON_{base} simulation began with 78.9 % (year: 2030) of high-quality batteries repurposed before mandatory recycling shares within the EU battery regulation are introduced. With the increased prices for recycled material, the share of the economic assessment fell, as direct recycling is more attractive. It reduced to the lowest share of repurposing of 41.1 % in year 2039, reflecting the demand surplus for nickel and lithium until 2038 and cobalt until 2041. After this period, a rebalanced demand-to-supply ratios is captured, reflecting the equilibrium-seeking nature of the price effect based on investments in recycling facilities.

The *BR* ON_{base} simulation indicates a turning point after 2043, where the economic share surpassed the threshold of 0.5, redirecting the majority of high-quality batteries for repurposing. The overall repurposing share follows similar dynamics when multiplying economic behaviour with the SoH ratio of 80 %. As a result, the overall share indicates 62.6 % (year: 2030) of batteries in assessment to repurposing and falls to a minimum value of 42.9 % (year: 2043) before rebounding to 49.0 % (year: 2050). When applying the overall shares to batteries in assessment and considering production delays, the *BR* ON_{base} simulation indicates 1.3 GWh (year: 2030) and 40.3 GWh (year: 2050) battery capacities being repurposed and 0.78 GWh (year: 2030) and 41.6 GWh (year: 2030) stored for recycling.

Based on Fig. 8, the *BR* ON_{base} simulation foresaw more recycling at an earlier stage, where, in comparison to the *BR* OFF_{base} simulation, the recycling volumes arrived delayed due to the slowing function of repurposing. Consequently, the annual recycling inflow for the *BR* OFF_{base} run was diminished for large periods of the simulation, resulting in recycling capacities of 8′614 t/year (year: 2040), but then increased to 28′874 t/year (year: 2050). In the *BR* ON_{base} run, there were higher inflows of 13′479 t/year result (year: 2040); thereafter, the development was slower, leading to 27′263 t/year (2050). The flattening of the *BR* ON_{base} curve after 2043 was caused by the *price effect*, which initiated a turning point in battery volumes being stored for recycling. After the 2043 period, more batteries were repurposed, which reduced the annual inflow curve. Although the annual *BR* OFF_{base} inflow exceeded the *BR* ON_{base} inflow after 2048, the accumulated recycling volumes for *BR* ON_{base} are higher compared to *BR* OFF_{base} by the end of the simulation. The late uptake of recycling in BR OFF_{base} is explained by the second EOL volumes nourishing the inflow of recycling capacities.

With the current and planned recycling capacities of 8′700 t/year in Switzerland, our results reveal that further investments will be needed to satisfy the annual inflow of recycling volumes. The simulations expect that the new investments of 32′316 t/year (year: 2050) recycling capacities for the *BR* ON_{base} run (Fig. 8) and 31′360 t/year (year: 2050) for the *BR* OFF_{base} run will be realised based on volume and economic considerations. For both simulations, this value is more than a tripling of current capacities. Assuming a factory size of 10′000 t/year, this expansion would equal three large factories.

4.3. *Testing policy robustness*

The impacts of the EU battery regulation were further tested against four scenarios designated to a maximum and minimum variable range. This section focuses on the core elements related to the share of batteries in assessment being repurposed or recycled, starting with the *BR* $OFF_{scenarios}$ followed by the *BR* $ON_{scenarios}$ runs. The analysis centred on comparing the runs with the base assumptions by analysing the deviation from the *BR* ON_{base} simulations (Fig. 9). Based on previous findings, the year 2043, where the most extreme effects of the EU battery regulation were observed in the simulations, was chosen as the cross-section for this comparison. The detailed results of the scenario runs are listed in the supplementary material.

The results of the BR $OFF_{scenarios}$ simulations indicate that scenarios three and four significantly deviate from the *BR* OFF_{base} simulations, while the first two scenarios show minor deviations (< 1 %). For scenarios one and two, this implies that EV market shares and export behaviour have limited impacts on the share of batteries repurposed. Here, the economic assessment is still dominated by the incentive for the two-loop approach. However, neglecting the export of batteries (export = 0) leads to increased recycling volumes, thereby providing additional investments in new recycling factories. With an annual recycling inflow of 48′064 t/year (year: 2050) within the ‘no export’ scenario, an expansion of 59′153 t/year (year: 2050) capacities to the current values was assessed, indicating six new factories of large size.

In scenario three, where OEMs act along an internal policy for direct recycling, a notable shift towards the one-loop system is revealed. Notably, the simulations show a 50 % deviation from the *BR* OFF_{base} run, when internal policies are defined, reflecting the proportion of batteries under OEM ownership. The finding underscores the significant role of

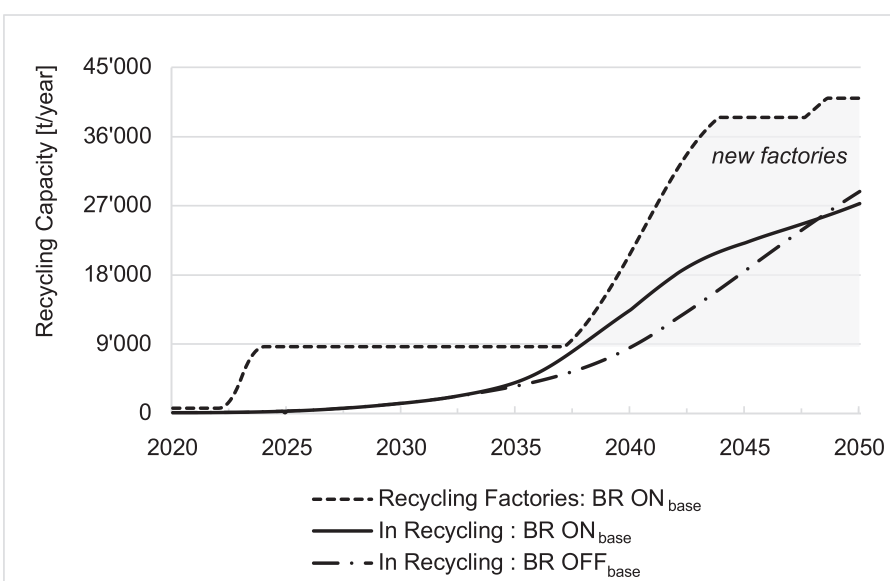


Fig. 8. Recycling capacities and battery capacities ‘In Recycling’ under base assumptions.

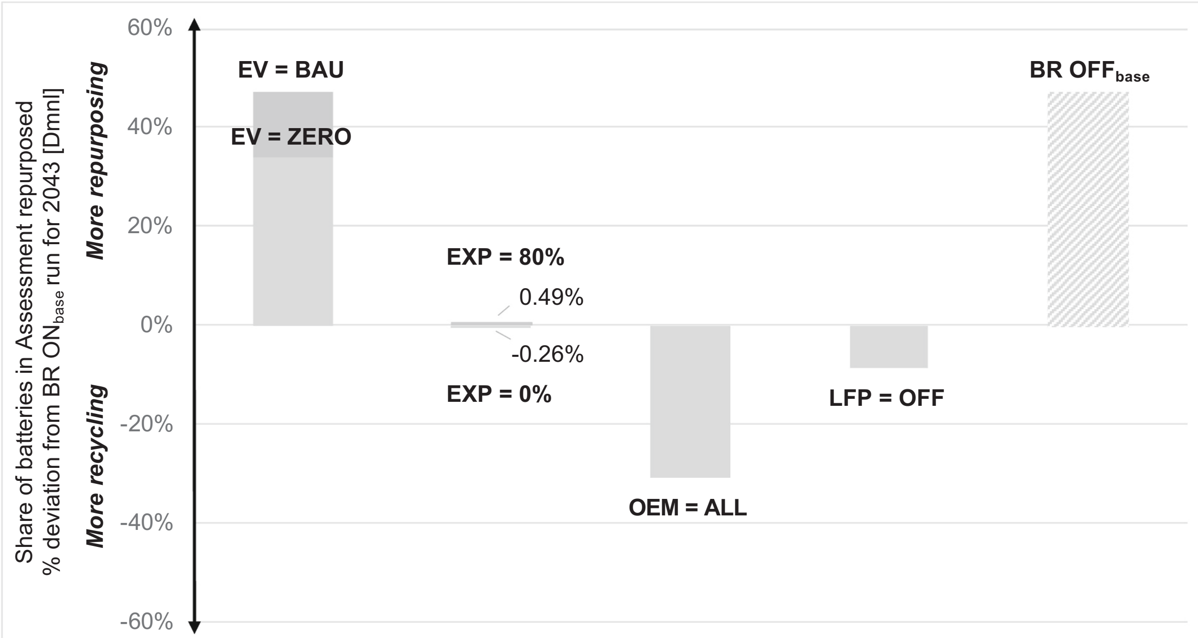


Fig. 9. Share of batteries in assessment repurposed compared to *BR ON$_{base}$* simulation for 2043.

OEMs in building a circular EV system. This scenario can be driven by rising material prices, unecological linear value chains, and customer demands, which could motivate OEMs to recycle batteries directly, even in the absence of the EU battery regulation.

On the contrary, scenario four reveals a slight increase (a deviation of 1 % from *BR OFF$_{base}$* run) in repurposing volumes when considering an LFP substitution. As discussed in Section 2.2 and consistent with Kamath et al. (2023) and Gu et al. (2018), an LFP substitution has emerged as a relevant driver affecting repurposing attractiveness due to the lower prices of black mass. Our results indicate that a higher presence of LFP batteries in the market promotes a two-loop approach.

The results of the *BR ON$_{scenarios}$* simulations indicate similar behaviour for the export scenario, while the other three scenarios (EV, OEM and LFP) differ in the magnitude of divergence (Fig. 9).

In the first scenario, our findings suggest that the fluctuations in EV market shares have a notable impact on the proportion of repurposed batteries. When compared to the *BR ON$_{base}$* run, which incorporated an ICE BAN scenario, both the ZERO and BAU scenarios capture a stronger tendency towards the two-loop system. It becomes apparent that, since the EV market share is lower (e.g., in the ZERO and BAU scenarios), the demand for recycled materials is on lower levels as well to align with EV sales. Despite lower supply, the demand-to-supply ratio remains below one for the BAU scenario (Fig. 9). Similarly, in the ZERO scenario, the lower demand is almost entirely compensated for by the lower supply, preserving the economic incentive of the two-loop approach. This highlights the necessity for additional incentives to bolster the two-loop approach, especially in the context of political support for EV sales, which increases the demand for recycled materials and strengthens the price effect observed in this study.

The third scenario analyses the introduction of a 100 % recycling policy for batteries under OEM ownership. Upon comparing the two scenarios, OFF (OEM = 0) and ON (OEM = 1), we observe more batteries directly entering the recycling pathway. The supply of recycled materials thus increases and impacts the demand-to-supply ratio. Given the same demand in the OFF and ON scenario, the surge in supply leads to a faster rebalancing of the demand-to-supply ratio and, consequently, an increase in high-quality batteries being repurposed. This indicates that OEMs can reduce the price effect by introducing a 100 % recycling policy. Consequently, our findings suggest that the tendency of the EU battery regulation towards a one-loop system would be reinforced by internal OEM policies. While factors such as material prices, value chains, and customer demands were previously named as potential drivers in the *BR OFF$_{OEM}$* simulation, in this context, the EU battery regulation itself can act as an incentive for OEMs, thus promoting the one-loop approach.

In the fourth scenario, an LFP substitution was tested with an ON (LFP = 1) and an OFF (LFP = 0) scenario. Similar to the results of the *BR OFF$_{LFP}$* run, the lower shares of LFP batteries reduce the ratio of cobalt to nickel in battery chemistries and, therefore, impact the black mass selling price after recycling. The economic margin for the one-loop system is reduced, incentivising a two-loop approach. However, it becomes clear that the *BR ON$_{LFP}$* scenario shows higher divergence compared to the *BR OFF$_{LFP}$* results due to material prices rising in line with the EU battery regulation. Particularly notable is the surge in cobalt price due to mandatory recycling shares, which is not factored in for LFP batteries. This suggests that a flattening LFP substitution could support the dynamics of the EU battery regulation. Our findings thus imply that a stronger LFP substitution counteracts the BR policy effects.

5. Conclusions

In this study, we addressed the tension between a one-loop system based on only recycling and a two-loop system that first repurposed and then recycled used EV batteries. By simulating long-term market dynamics, we explored how mandatory recycling shares within the EU battery regulation affect the system of used EV batteries. Our findings suggest that there is an economic incentive favouring the two-loop approach in the absence of the regulation. Consequently, most EOL materials are initially repurposed for secondary applications. However, the implementation of the EU battery directive enhances the recycling value through mandatory recycling shares, thereby increasing the demand for recycled materials. This surplus in demand is expected to raise market prices, providing manufacturers with greater incentives to prioritise the recycling of EOL materials. Moreover, an active price effect may encourage OEMs to implement internal policies for direct EV battery recycling, thereby strengthening the dynamics of the regulation. As a consequence of the pulling effect of the regulation, repurposing solutions that contribute to expand the lifetime of lithium-ion batteries are disadvantaged. Only the increased substitution of LFP batteries may help repurposing systems regain their attractiveness, though it cannot mitigate the full effect of the regulation and provide a lifetime expansion of ten years.

The results suggest three policy recommendations. First, mandatory recycling shares strongly impact the system dynamics favouring recycling. While building up a recycling industry for EV batteries is urgently needed, it should not be at the cost of sacrificing the currently emerging repurposing market in the long term. Establishing complementary supporting mechanisms for the repurposing segment, offering an avenue to strengthen the slowing approach of EV batteries within the two-loop system. This would ensure that both recycling and repurposing contribute to a sustainable battery industry. Potential policies could consider introducing mandatory shares of repurposed batteries for the stationary battery market or a minimum achieved battery age before a (not damaged) battery may be recycled. Second, manufacturers play a pivotal role in the decision concerning repurposing or recycling and can be incentivised through regulatory frameworks and financial incentives to adopt a two-loop system in the long run. Finally, promoting research and development efforts can help reduce the reliance on cobalt in new battery materials, thus consequently advancing the establishment of a two-loop system for EOL EV batteries.

Our study contributes to the theoretical discussion on finding a circular economy solution for EV batteries. By using a quantitative assessment, it extends the current qualitative works on the impact of the EU battery regulation (Albertsen et al., 2021; Rallo et al., 2020). Integrating the current qualitative considerations (Gu et al., 2018; Kamath et al., 2023) in a dynamic simulation model allows the provision of long-term profitability simulations for both repurposing and recycling approaches. Moreover, our simulation assessment highlights several leverage points in the system for developing a circular value chain at both the EU and Swiss levels.

Our findings are particularly relevant for four stakeholders. First, they offer relevant volume estimations for business owners entering the recycling or repurposing market. Our simulations may serve as an important input for business case calculations for companies selling repurposed batteries or black mass products. Second, our findings capture the market potential of investing in new recycling facilities by considering the different market scenarios relevant to European and non-European investors. Third, our findings help EU policymakers understand the long-term market effects of the EU battery regulation. This seems particularly relevant for the discussion on reviewing the current targets within the EU battery regulation, which is foreseen in 2028. Furthermore, our study helps to avoid pitfalls in the long term, such as insufficient recycling facilities for a well-functioning circular economy solution. Fourth, from our findings, we can also derive recommendations for non-EU policymakers in the European market, which can guide the discussions on the adoption of similar policies at the national level.

Though our study is one of the early contributions that aims to quantify the effects of the EU battery regulation, it is subject to limitations that indicate avenues for further research. The model limitations, elaborated in the methods section, may be addressed by expanding the model scope to a European or even global level by integrating refined structures to model technology learning and price effects. Studies interested in assessing the very long-term dynamics should also take into account novel battery technologies, such as solid-state batteries. Widening the scope, however, also comes at the trade-off of concreteness. On the contrary side, we also expect that more refined simulation models to assess business strategies for companies operating in a circular economy will be of great value for practitioners as well as for business model research. Especially relevant, in our view, are business models integrating the environmental perspective, assuming that companies will be increasingly incentivised to extend current economic parameters with ecological measures. Moreover, our analysis is limited in the extent to which we considered the consumer perspective, while it is expected that consumers will play a central role in implementing a circular economy. In this regard, analysing end-consumer preferences seems crucial for defining optimised offers, pricing strategies, and potential rebound effects. Finally, our study suggests complementary policy support for the market formation of repurposing. Further studies are needed to analyse a set of policies and test their effectiveness in contributing to a slow and closed loop for EV batteries.

CRediT authorship contribution statement

Juliane Seika: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Merla Kubli:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.09.023.

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