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The Technology Valley of Death of Circular Economy Solutions: A System Dynamics Simulation of Business Strategies for the Second-Use Battery Industry

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ABSTRACT

Retired electric vehicle (EV) batteries can be repurposed to stationary storage batteries. While this circularity solution has attracted attention from entrepreneurs, falling battery prices, along with the longer lifetime of new batteries, high consumer expectations and limited governmental support challenge the approach. This paper investigates whether the second-use EV battery industry is at risk of getting trapped in the 'valley of death' (VoD). We developed a system dynamics model and assessed the impact of 12 business strategies. Based on the simulations, some strategies yielded positive returns, while others resulted in a VoD scenario, risking business failure. Subsidising repurposed EV batteries emerged as the most effective strategy to boost commercialisation. Conversely, two plausible and well-intended strategies risk reinforcing VoD conditions: focusing exclusively on the premium end-of-life battery market and relying solely on cooperation with original equipment manufacturers.

1 | Introduction

Circular economy solutions are increasingly recognised as pivotal for achieving climate and sustainability goals (EMF 2014; Geissdoerfer et al. 2016). To realise the potential of circularity, sustainable business models are essential. Developers of circular solutions, however, must adopt new business models (Bocken et al. 2016; Lüdeke-Freund et al. 2019). Commercialising circular business models is a challenge for numerous start-ups as well as incumbents. Providers of new solutions are at risk of getting trapped in the so-called 'valley of death' (VoD), a phenomenon that arises from the failure to transition from the innovation phases of research and development (R&D) to full commercialisation (Grubb 2004; Markham 2002). Circular solutions, on top of this, compete with conventional products and a market environment not yet accustomed to circularity while scaling their business (De Angelis 2024; Hopkinson et al. 2018). The multidimensional interplay between business model innovation, firm performance, consumer demand dynamics and policy initiatives, which determines whether a valley of death situation or a competitive advantage based on circularity emerges, remains an underinvestigated area in the emerging field of circular business model research (Bocken et al. 2021; Ferasso et al. 2020; De Angelis et al. 2023).

This study investigates the technology valley of death of circular solutions related to second-use batteries. As the transportation sector increasingly decarbonises and electrifies, a large number of electric vehicles will be decommissioned in the coming decades (Ai et al. 2019; Niese et al. 2020). At the same time, with the deployment of new renewable energies, storage plays an increasingly important role in the electricity system (IEA 2023, Lund et al. 2016). The circular value retention strategy 'repurposing' (Reike et al. 2018), or giving electric vehicle batteries a second life as stationary storage, is a promising potential solution to the projected demand for storage (Parkinson and Cheung 2024; Jeppe and Proff 2025). However, new battery models and falling costs intensify competition, particularly for safe, long-lasting and affordable home storage batteries (BloombergNEF 2023). This threat is exacerbated by consumer preferences for durable new batteries (Schulz-Mönninghoff and Evans 2023) and policies that implicitly incentivise direct recycling over repurposing through mandatory shares of recycled materials in new batteries (Seika and Kubli 2024). While there are qualitative studies focusing on the challenges within the repurposing market (e.g., Albertsen et al. 2021; Chirumalla et al. 2024; Vignesh et al. 2025; Stefan and Chirumalla 2025) and studies on business model innovations (e.g., Chirumalla et al. 2024; Wellten et al. 2025), the potential systemic impact of key challenges to the market and their long-term impact on profitability are poorly understood.

This paper explores the long-term market dynamics for the second-use EV battery sector from a VoD perspective. We assess the dynamics of repurposing firms in transitioning from the research phase to the commercialisation phase. The VoD, as first described by Markham (2002), serves as a theoretical lens for our analysis. For both phases, research and commercialisation, VoD threats for the second-use battery market are identified and clustered into four pillars: collaboration, demand, price and regulation. Based on this comprehensive picture drawn from the literature review, this paper addresses the following research question: *Under which collaboration, demand and price strategies, as well as regulatory setting, is the battery repurposing sector likely to survive the technology VoD?* We developed a system dynamics (SD) model to simulate the market for repurposed EV batteries, incorporating feedback loops and delay structures. We analyse potential VoD threats and evaluate strategies to overcome them, encompassing stronger collaboration with OEMs, efforts to increase customer value, alternative pricing models and supportive regulatory frameworks.

The findings provide academic contributions in the areas of (1) analysis of sustainable business models, (2) simulation of the long-term effects of consumer demand and business strategies and (3) an integration of business and policy leverage points. The study integrates consumer preference data for repurposed EV batteries with known supplier-side challenges. In doing so, it extends prior simulation models (e.g., Kamath et al. 2023; Seika and Kubli 2024) by integrating empirical customer data and refining findings for the consumer-business dynamics.

This study also offers several practical contributions for battery suppliers and policymakers. Suppliers can use the findings to understand long-term market dynamics and build robust business models in markets characterised by steadily declining prices for new batteries. Policymakers can use the results to determine what governmental support is required to foster a well-functioning circular economy for EV batteries. This is especially important in regions such as Europe, where new battery regulations have been introduced but specific support measures for the repurposing sector are still lacking.

The paper is structured as follows: Section 2 outlines potential threats for the repurposed EV battery market and introduces strategies that could prevent a VoD situation. Section 3 details the methodological approach, including model equations, key dynamics and the 12 strategies assessed. Section 4 presents the simulation results. Section 5 discusses academic and managerial implications, while Section 6 concludes the paper and offers directions for further research.

2 | Literature Review

2.1 | Technology Valley of Death (VoD)

The term ‘valley of death’, first coined by Moore (1991), refers to a critical phase in a company's journey in which early market enthusiasm has faded, but mainstream market adoption has not yet materialise. During this phase, companies often struggle to generate sufficient revenue to sustain operations, and failure to bridge the gap may lead to financial collapse (Gatto and Re 2021). Although originally applied to start-ups, the term has since expanded to describe the challenges entire technologies or sectors may face. In this broader application, it is referred to as the ‘technology valley of death’ (e.g., as in Hockerts and Wüstenhagen 2009), which is the lens adopted in this paper.

The classic visualisation of the VoD, as proposed by Markham (2002), distinguishes between research and commercialisation resources. The gap between declining research resources and a delayed uptake of commercialisation funding is referred to as VoD (Figure 1). If the resource gap between is not addressed on either side, companies or technologies risk entering a VoD, potentially resulting in failure or market exit.

Explanations for the VoD fall into several categories. Financial perspectives attribute the VoD to insufficient funding or poor profitability during the transition from development to market (Gbadegeshin et al. 2022). Examples include inadequate seed investments (Wilson et al. 2018), fund mismanagement (Nnakwe et al. 2018) or lack of cashflow (Wilson et al. 2018).

A situational perspective focuses on broader environmental changes. Economic downturns (Carayannis and Dubina 2014) or sociocultural shifts (Cooper 2013) can delay or halt technology diffusion (Gbadegeshin et al. 2022). Similarly, the resource and competence perspective identifies gaps in collaboration (Ai and Wu 2016; Byrd et al. 2017), insufficient product testing (Jung

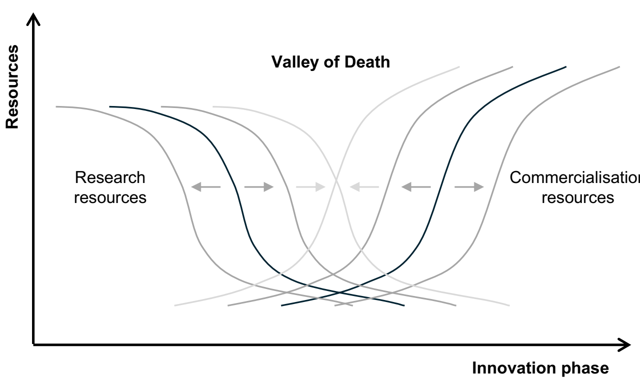

FIGURE 1 | Valley of death emerges from a gap between declining research resources and rising commercialisation resouces (adapted from Markham 2002).

et al. 2015), lack of business development capacity (Leahy and Lane 2010) or structural delays (Brooks 2013) as contributing factors. These failures often stem from the flawed assumption that markets will immediately accept and adopt new technologies (Gbadegeshin et al. 2022).

Besides market risks and uncertainty, the political perspective plays an equally important role in understanding the causes of the VoD problem, due to the lack of governmental support and incentives beyond the R&D phase (Gbadegeshin et al. 2022; Muscio et al. 2023; Norberg-Bohm 2000).

The VoD is especially prominent in industries, where high R&D investments and prolonged commercialisation phases in highly regulated markets increase vulnerability (Gbadegeshin et al. 2022). VoD patterns are evident in several sectors, including renewable energy (Hartley and Medlock 2017; Hockerts and Wüstenhagen 2009; Muscio et al. 2023; Norberg-Bohm 2000); but lack consideration in the new emerging second-use EV battery market.

2.2 | VoD Factors for Second-Use EV Batteries

A range of factors and trends are discussed to influence the availability of the two key resources for (a) research and (b) commercialisation, in the general VoD literature and in the context of second-use EV batteries specifically. Research resources refer to personnel, material and organisational structures necessary for technology development, whereas the commercialisation resources focus on activities to market, sell or distribute technology for market recognition (Markham 2002). VoD factors for second-use EV batteries are assessed based on key barriers assessed for circular economy business models, challenges within the second-use EV battery market and general VoD threats. The dynamic interplay of both resource streams will ultimately determine whether a valley of death situation will materialise.

2.2.1 | Factors Influencing the Availability of Research Resources

Pilot Project Funding: Several barriers are known to hinder the development of circular economy business models, where Geissdoerfer et al. (2022) highlight market and financial factors as relevant, especially for early market entries. Financial barriers, like pre-existing investments or uncertainties, highlight the need for funding before market commercialisation. Funding should extend beyond the R&D funding phase, as the pilot project stage helps attract further investment and field experts with relevant experience, reducing the VoD threat (Gbadegeshin et al. 2022). For example, European governments have invested in the development of second-use EV battery factories in Finland and Norway (European Commission 2023). However, on a more overarching level, new renewable energy solutions face a funding gap when transitioning from the R&D development to commercialisation due to comparatively low EU governmental spendings (Muscio et al. 2023). Also, countries such as Switzerland have been scaling back energy pilot and demonstration grants (Bürer and Wüstenhagen 2009), which hinders market adoption and poses a risk for second-use EV battery companies.

Facilitated Access to Cheap Capital: Access to affordable capital is essential for repurposed EV battery companies to further bridge the funding gap beyond the R&D phase. Without targeted financial support, companies are seen as high risk by investors, resulting in high interest rates and lower investment volumes. Although research grants are available, the lack of support during the product development stage weakens key signalling effects. According to Islam et al. (2018), strong financial signals can increase the likelihood of securing venture capital by 12%. Mechanisms such as low-interest loans or public–private funding can reduce costs and attract investment, helping avoid a VoD situation.

2.2.2 | Factors Influencing the Availability of Commercialisation Resources

Collaboration With OEMs: The EV battery value chain is dominated by OEMs. Vignesh et al. (2025) and Albertsen et al. (2021) identified two business models for OEMs to enter the repurposing market: selling end-of-use batteries and collaborating with repurposing firms. For instance, Renault sells end-of-life batteries for residential use to Powervault and collaborates with Connected Energy (Albertsen et al. 2021; Vignesh et al. 2025). Despite these examples, engagement in repurposing remains rare. Barriers such as data sensitivity, IP constraints and design secrecy discourage deeper collaboration (Albertsen et al. 2021; Vignesh et al. 2025; Stefan and Chirumalla 2025). For circular business models, the collaboration within the value chain network is assessed to be essential in the system. If difficulties and uncertainties pertain, the company can face material flow risks and quantity uncertainties (Geissdoerfer et al. 2022)—both factors that can prevent a long-term robust business model for second-use EV battery companies.

Consumers Willingness to Purchase Repurposed EV Batteries: Consumer demand and acceptance play a key market barrier in implementing circular economy business models (Geissdoerfer et al. 2022; Bocken et al. 2021; Konietzko et al. 2020). When focusing on the second-use battery market, research shows that consumers seek long-lasting, safe and affordable home storage batteries (Seika, forthcoming), providing a potential threat for second-use EV battery companies. In the residential market, consumers tend to favour new or recycled-content batteries over repurposed ones (Albertsen et al. 2021; Seika, forthcoming) and safety concerns—driven by news reports of EV battery fires—are a major issue (Vignesh et al. 2025; Schulz-Mönninghoff and Evans 2023). When consumer demand and market acceptance are not fully addressed, financial and market barriers may hinder the commercialisation of second-use EV batteries, increasing VoD risks.

Competition From New Batteries: Technology learning effects are a key driver in accelerating the adoption of renewable energy technologies (Muscio et al. 2023; Norberg-Bohm 2000). The second-use market must compete with declining new battery prices. Over the past decade, battery prices have fallen dramatically (Figure 2). In 2015, the purchase price for new battery packs was 398.18 EUR/kWh (BloombergNEF 2023). Due to the time lag between initial battery use and repurposing, second-use batteries reflect the technological and cost structures of a previous generation. At present, repurposed batteries can still compete with new ones on price. However, the long-term price dynamics remain uncertain. While second-use batteries may still offer cost advantages, improvements in the longevity, chemical stability and price of new batteries (BloombergNEF 2023) are likely to encourage the adoption of new over repurposed options and may challenge firms to provide competitive costs and benefits in the long run (Toorajipour et al. 2024)—financial uncertainties, which have been categorised as barriers for early entry companies to assess the long-term financial return (Geissdoerfer et al. 2022).

Governmental Support: Geissdoerfer et al. (2022) identified a lack of governmental support and restrictive regulation as barriers for circular business model innovation, and Vignesh et al. (2025), Chirumalla et al. (2023) and Stefan and Chirumalla (2025) even highlight the risk for the battery repurposing industry. Standards, labelling schemes and regulations concerning the handling and remanufacturing of EV batteries are still evolving, leaving repurposing firms with considerable procedural uncertainty (Hua et al. 2021; Vignesh et al. 2025). Furthermore, certain policy frameworks promote direct recycling over repurposing. For example, the EU Battery Regulation (2023/1542, n.d.) includes mandatory quotas that incentivise firms to prioritise recycling to meet the growing demand for recovered battery materials (Seika and Kubli 2024). This policy approach drives up the demand—and therefore the price—of end-of-life EV batteries, undermining the economic viability of repurposing. In sum, regulatory uncertainty and recycling incentives may prove decisive for the prospects of repurposed EV batteries.

2.3 | Strategies to Overcome a VoD in Battery Repurposing

To address a VoD situation, firms must implement business strategies during both the research and commercialisation phases. Drawing on the factors identified in Section 2.2, this

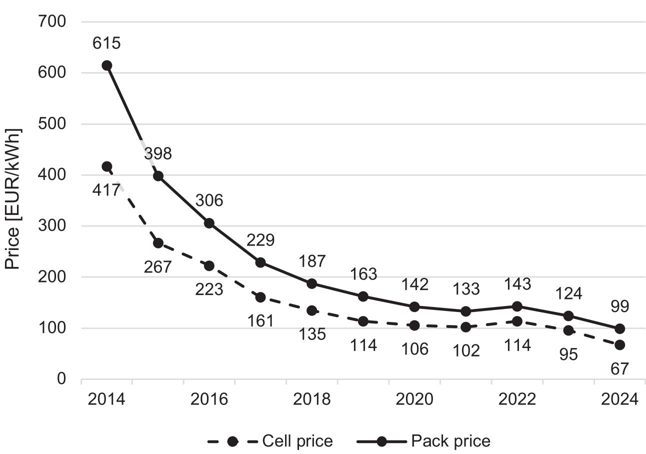

FIGURE 2 | Average lithium–ion battery pack and cell prices, 2014–2024 (BloombergNEF 2023).

section outlines relevant business and policy strategies, which are later incorporated into the experimental design of this study.

2.3.1 | Collaboration

One key strategy for overcoming a VoD is to form partnerships with key strategic stakeholders (Gbadegeshin et al. 2022). Given the prominent role of OEMs, a collaborative business model with second-use EV battery companies appears promising (Chirumalla et al. 2024; Wellten et al. 2025). In the current market, second-use firms can adopt one of three roles: acting as battery owners (C1), acting as service providers to OEMs (C2) or combining both roles (C3). As battery owners, repurposing companies take ownership after the battery's end-of-life phase, making a competitive purchase price crucial for viability. As service providers, repurposing companies collectively work with OEMs, where end-of-life EV batteries are provided, and revenues and costs are equally shared.

2.3.2 | Demand

Understanding consumer demand and testing new circular value propositions is a key task in finding long-term robust business models (Bocken et al. 2021; Konietzko et al. 2020). Based on assessments of consumer preferences (Schulz-Mönninghoff and Evans 2023; Wellten et al. 2025; Seika, forthcoming), three business strategies are identified: pure sale of second-use EV batteries (D1), prioritising premium end-of-life batteries (D2) and offering warranties as part of purchase or leasing agreements (D3).

2.3.3 | Price

Competing with new batteries requires a pricing strategy that aligns with consumer expectations. While most research has focused on the absolute price of second-use EV batteries, little attention has been given to how these prices compare with new alternatives (e.g., Al-Alawi et al. 2022; Vignesh et al. 2025). Drawing on Tomczak et al. (2017), we consider three pricing strategies: demand-oriented pricing (P1), cost-oriented pricing (P2) and competition-oriented pricing (P3).

2.3.4 | Regulation

Bürer and Wüstenhagen (2009) analysed different market pull and push strategies for overcoming a VoD situation. On the research side, the most effective push strategy was for governments to provide demonstration funds to companies. Muscio et al. (2023) advise for additional public grants for the most innovative approach in the energy transition to help bridge development to commercialisation. Accordingly, we identify research funding during product development (R1) and pilot funding beyond development (R2) as relevant policy interventions. On the commercialisation side, subsidies were the second most effective pull strategy (R3), following feed-in tariffs. However, feed-in tariffs tend to support the entire storage market and do not specifically promote second-use batteries and were therefore excluded.

Based on this literature review, this paper analyses the risk of repurposed EV batteries falling into a VoD by testing 12 business strategies. Although existing research addresses challenges in the second-use EV battery market (e.g., Albertsen et al. 2021; Chirumalla et al. 2024; Vignesh et al. 2025; Stefan and Chirumalla 2025), long-term cost- and revenue structures (e.g., Pratap et al. 2024; Alamerew and Brissaud 2020; Shaikh et al. 2023; Kamath et al. 2023) and specific business models (e.g., Chirumalla et al. 2024; Wellten et al. 2025), there is a lack of a quantitative simulation model that integrates regulatory, consumer and pricing strategies. Moreover, few studies have adopted a VoD perspective to assess the long-term viability of the second-use EV battery market. While some simulation models have explored VoD dynamics (e.g., Kubli and Canzi 2021), none have yet done so in the context of second-use EV batteries. This paper fills this gap by simulating profitable business strategies for the second-use EV battery market using a system dynamics approach from a VoD perspective.

This paper builds on the work of Seika and Kubli (2024), who simulated the impact of the EU Battery Regulation (2023/1542, n.d.) on the repurposing and recycling markets. While their model captures battery volumes sent to recycling or repurposing in detail, it overlooks crucial market dynamics specific to the repurposing industry, which can significantly impact the viability of second-use batteries. The integration of empirical customer data and market entry and exit dynamics has not been applied in other simulation models in this field (e.g., Pratap et al. 2024; Alamerew and Brissaud 2020; Shaikh et al. 2023; Kamath et al. 2023). The initial SD model by Seika and Kubli (2024) features 12 feedback loops clustered around price, technology learning and investor decision effects. The enhanced SD model now comprises 25 feedback loops, encompassing key market trends and stakeholder decisions. We also extend the model by incorporating customer data for empirical grounding of behavioural modelling and integrating investor decision-making. To maintain comparability with the original model, we also add one additional feedback loop to the recycling pathway.

3 | Material and Methods

Given the complex market dynamics influencing the success of second-use EV battery companies, we developed a simulation model aimed at identifying a robust, long-term business model. We employ system dynamics (SD) modelling to capture key dynamics, such as feedback loops, delays and ageing chains. SD combines a qualitative perspective—mapping the central market dynamics—with a quantitative layer that integrates these behaviours into a simulation model. SD has been applied across various fields, including the EV battery market (Ginster et al. 2024; Alamerew and Brissaud 2020; Shaikh et al. 2023; Kamath et al. 2023; Pratap et al. 2024) and the stationary battery market (Kubli 2018; Kubli and Canzi 2021). SD modelling has also been the method of choice for assessing various business strategies in the context of the circular economy (Jayarathna et al. 2023; Kazancoglu et al. 2020; Véliz et al. 2024) and sustainability (Abdelkafi and Täuscher 2015; Cosenz et al. 2019).

The simulation model focuses on repurposing applications of batteries from electric vehicles (BEVs) in the passenger car segment to stationary electricity storage in the residential and commercial sectors, covering the period from 2010 to 2050. Switzerland was selected as the empirical context for two reasons: first, the country's regulatory ambition to establish a circular economy for EV batteries and second, the availability of empirical data on customer preferences for repurposed batteries in the Swiss home storage market (Seika, forthcoming).

3.1 | Model Structure

The model features two core stock and flow structures, which crucially connect to the central dynamic structure: (a) the market entry and exit of companies and (b) the battery capacities across different usage and processing stages. Each box represents a stock, while arrows indicate flows within the system. A stock signifies the accumulation of EV battery capacity (EVBC) in kilo-watt hours (kWh) over time.

3.1.1 | Modelling the Market Entry and Exit of Battery Repurposing Companies

To measure whether the repurposing industry is experiencing a valley of death situation or manages to translate circularity into a competitive advantage, we model the market entry and exit of repurposing companies. In our modelling approach, to account for the heterogeneity of the scale of companies, which may also vary over time, we represent the companies through their capacity to repurpose batteries (Figure 3). The market entry is modelled through the investment rate in new repurposing facilities, the capacity currently under development and the completion rate. The repurposing capacity on the market, implicitly representing the number of companies on the market, is measured

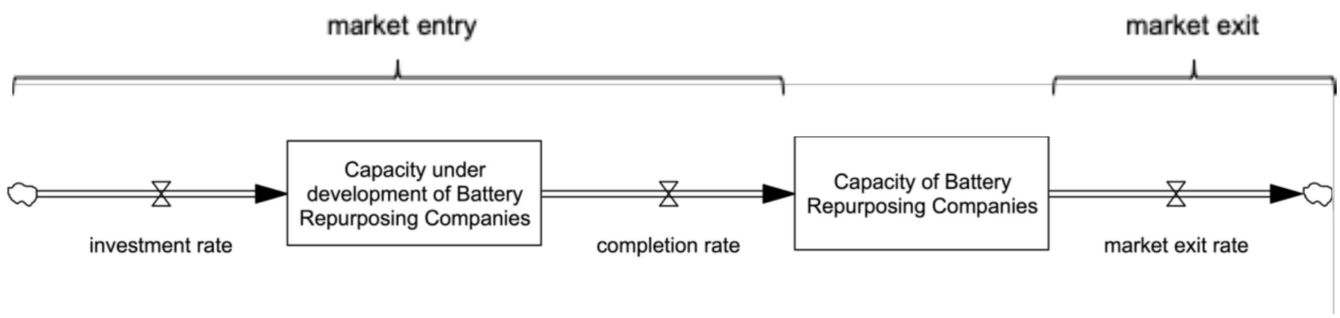

FIGURE 3 | The model structure for market entry and exit of battery repurposing companies.

in how many kilowatt-hours of batteries can be repurposed per year.

3.1.2 | Battery Capacities Across Different Usage and Processing Stages

The model's second core value chain centres on battery capacities across different usage and processing (Figure 4). The first-use, assessment and recycling phases were modelled in detail by Seika and Kubli (2024); for readability, we aggregate these elements here. This study focuses on the market dynamics specific to the repurposing industry.

'EVBC in Assessment for Repurposing' accumulates high-quality batteries, which are assessed for second use. The volume stored for repurposing depends on the profit margin relative to recycling, with respective volumes added accordingly. Within the repurposing market, core dynamics such as the purchase price of high-quality end-of-life EV batteries and the selling price of repurposed stationary batteries are modelled endogenously. The pricing mechanisms function as a policy lever in the simulation. We test demand-oriented pricing, following key SD structures (Sterman 2000), along with cost- and competition-oriented strategies. Both supply and demand are also endogenously integrated based on empirical customer data and factory ramp-up capacities.

'EVBC in Repurposing' quantifies the battery capacities repurposed into stationary batteries. Inflows depend on factory capacities, which reflect the investments and disinvestments of second-use EV battery companies (Figure 3). Based on payback periods, the model simulates investor decisions to ramp up repurposing factories. Cost coverage also influences market exits for second-use EV battery companies. These metrics are detailed in later sections.

'EVBC in Commercial Use' and 'EVBC in Residential Use' represent the capacities adopted by commercial and residential consumers, based on demand. After a time delay—corresponding to the average lifetime of repurposed EV batteries—the model assumes that batteries with a state-of-health below 60% enter the 'Second End-of-Life' stock. These volumes are then directed into the recycling pathway.

3.2 | Central Dynamics

Figure 5 highlights 13 feedback loops relevant to the second-use EV battery market. Each loop is marked with a round arrow, indicating reinforcing (R) or balancing (B) behaviour. Link handles are annotated with (+) or (–) signs to indicate positive or negative causal relationships. To evaluate the VoD situation, we use the profit margin for repurposing and the desired exit rate as key metrics.

Feedback loops are categorised based on their impact on (a) research resources, (b) market entry and exit and (c) commercialisation resources, as explained below.

3.2.1 | Feedback Loops Affecting Research Resources

B1: Loop B1 captures how research resources for battery repurposing change over time. As repurposed battery volumes grow, the technology is increasingly seen as mature, which leads to reduced research funding. With less research funding, profit margins and the share of batteries stored for repurposing decline,

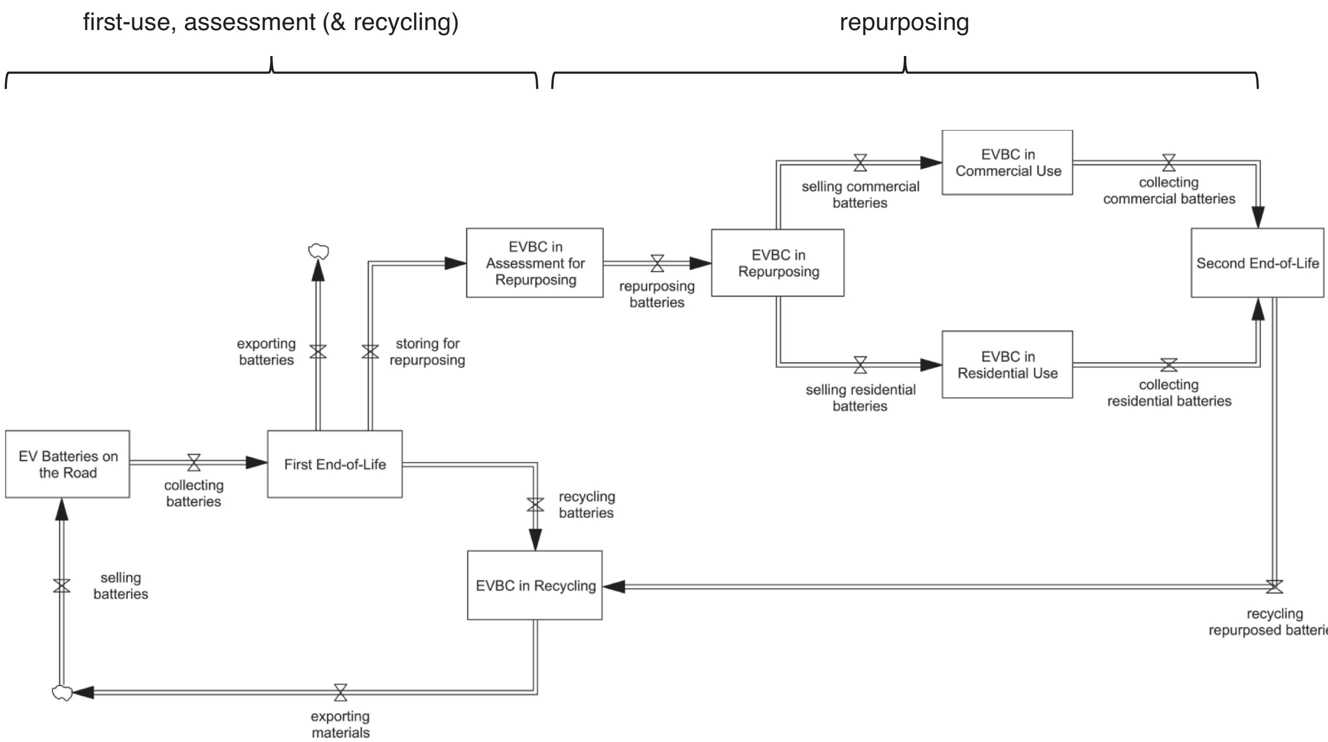

FIGURE 4 | The model structure of battery capacities across different usage and processing stages.

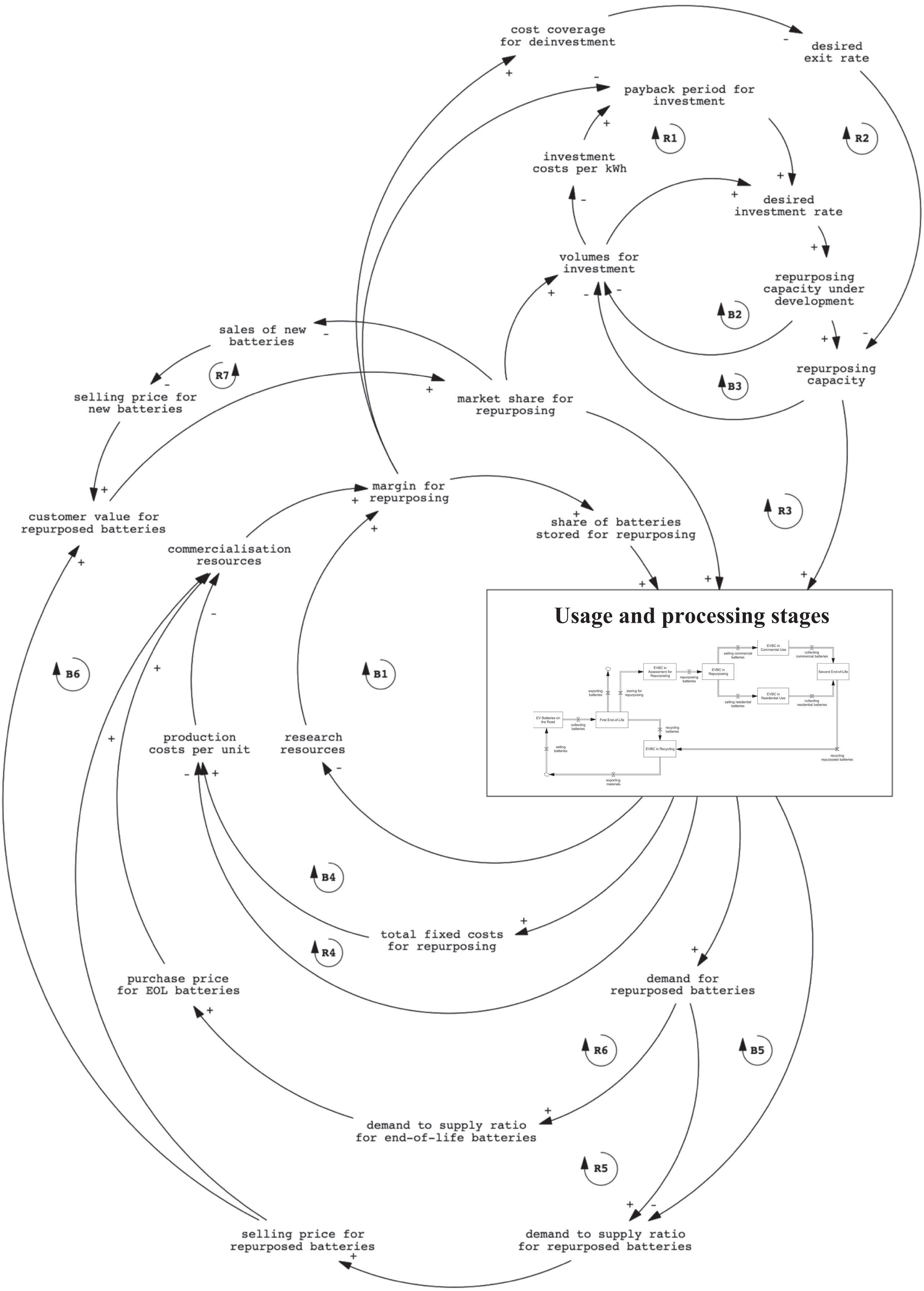

FIGURE 5 | Legend on next page.

FIGURE 5 | Central dynamics in the model. *Note:* Effect on research resources: B1: sales-dependent research resources; effect on market entry and exit: R1: volume-dependent investment costs, B2: market saturation with under development factories, B3: market saturation with built factories, R2: market exit, R3: new investments; effect on commercialisation resources: B4: capacity-dependent fixed costs, R4: technology learning effects on production costs, B5: price effect on repurposed battery supply, R5: price effect on stationary battery demand, R6: price effect on end-of-life EV battery demand, B6: consumer behaviour, $R7_n$: technology learning on new battery prices.

slowing further growth. Thus, Loop B1 represents a balancing dynamic: when sales are low, research funding is high; as commercialisation increases, funding from governments and investors falls.

3.2.2 | Feedback Loops Affecting Market Entry and Exit

Loops R1, B2, B3, R2 and R3 describe the market entry and exit of repurposing companies. Two key drivers—profit margin and market share—shape these dynamics. For market entry, the payback period, determined by profit margin and investment costs, governs the attractiveness of new investments. The level of investment depends on the market share and repurposing capacities. For market exit, the cost coverage impacts the desired exit rate, with repurposing capacities indicating the respective level.

R1: To assess the payback period, we account for factory-size dependent investment costs with Loop R1. As investment volumes rise, scale effects lower costs and shorten the payback period. A shorter payback period attracts more investors, increasing the desired investment rate. To estimate total market entry, the desired investment rate is multiplied by the investment volume.

B2 and B3: Investment volumes depend on the anticipated market share for repurposing, as well as the already planned and existing capacity (Loops B2 and B3). To avoid double-counting, Loop B2 subtracts capacity under development from the total desired capacity, while Loop B3 subtracts capacity already built.

R2: Like market entry, market exit or downsizing of repurposing capacities depends on the profit margin, in particular, the revenues and costs. When the cost coverage of repurposing falls below one, companies begin to consider exiting the market.

R3: This loop links the investment structure to the model's battery usage and processing stages. Changes in repurposing capacity impact overall volumes of repurposed batteries, which consequently influence the market entry and exit of companies.

3.2.3 | Feedback Loops Affecting Commercialisation Resources

Loops R1, B2, B3, R2 and R3 affect commercialisation in the same way as they affect market entry and exit. Loops B4, B5, R4 and R5 incorporate cost and price effects on demand and supply. The underlying assumption is that price is driven by supply–demand dynamics. The price effect is modelled for both the purchase price of end-of-life EV batteries and the selling price of repurposed EV batteries.

B4: Loop B4 impacts commercialisation through its link to fixed costs. It assumes that fixed costs depend on repurposing capacity: The larger the factory capacity, the higher the total fixed costs for the company, and consequently, the greater the commercialisation resources.

R4: Loop R4 captures technology learning effects on production costs. The loop builds on the assumption that every doubling of production volumes decreases operational efforts (Sabel and Weiser 2008). As volumes increase, costs decrease, attracting more volumes into repurposing.

B5: Loop B5 links repurposing volumes to the selling price of repurposed batteries. Following a demand-to-supply structure, higher prices lead, ceteris paribus, to more revenues and hence raise commercialisation resources. This also increases the share of batteries stored for repurposing. As supply grows, the demand-to-supply ratio declines, driving selling prices down again and balancing the system.

R5 and R6: Loops R5 and R6, on the contrary, integrate a reinforcing effect. Higher profits raise the share of batteries entering repurposing, increasing volumes available to consumers. As demand potential grows, the demand-to-supply ratio increases, increasing the selling price for repurposed batteries (Loop R5) and the purchase price for end-of-life batteries (Loop R6).

B6: Loop B6 introduces a balancing effect on consumer demand based on the selling price of repurposed batteries. As prices rise, demand falls, which in turn lowers battery prices. This dynamic allows Loop B6 to counteract the reinforcing effects of purely price-driven loops.

$R7_n$: Loop $R7_n$ integrates an outcrowding effect of repurposed battery demand on new battery sales, where *n* refers to both purchase and selling prices of new batteries. The loop assumes that a high market share for repurposing replaces rather than supplements new battery sales.

The formalisation of the feedback loops to a quantitative simulation model is documented in Appendix S5.

3.3 | Model Validation and Limitations

The 12 validation tests proposed by Sterman (2000) were applied, confirming the suitability of the model for the intended purpose that should though be considered in light of a few model limitations and structural uncertainties that will be discussed subsequently. Furthermore, informal interviews with repurposing and recycling firms in Switzerland and Europe were conducted to validate the underlying mental model and parameter choices.

A CircuBAT consortium workshop titled 'Circular Economy for Batteries – A Swiss Perspective' was also held in May 2025 to validate key findings and model assumptions with relevant battery and energy experts in the Swiss market.

From the validation efforts, four model limitations were identified that should be considered when interpreting the model results. First, the model solely focuses on NMC and LFP batteries, excluding emerging technologies such as sodium-ion batteries due to their current low market share and delayed relevance for the end-of-life battery market. Second, battery exports are treated as an exogenous variable and do not account for OEM contract behaviours with Swiss or foreign partners. This simplification stems from the limited availability of data on OEM contract structures and the decision-making process regarding battery export or retention from the Swiss market. Third, the model assumes that repurposed EV battery supply is limited to domestically sourced batteries within Switzerland, excluding potential imports from the EU or other regions. This assumption reflects the regulatory barriers expected to constrain cross-border battery flows. Fourth, the demand for commercial batteries is based on model assumptions, as empirical customer data—such as that for the residential segment—is lacking.

3.4 | Experimental Setup

An exploratory modelling and analysis (EMA) approach is applied, connecting the SD model with Python. We test 12 business strategies (Table 1). The strategies C1, D1, P1 and R1 are aligned for enhanced comparability of the results. For each strategy, 10 uncertainty parameters are tested. Appendices S3 and S6 explains in detail the variables tested and how the strategies were quantified.

EMA enables computational experiments that help analyse complex and uncertain parameters (Kwakkel and Pruyt 2013). It has been widely applied in SD contexts, including the energy sector (e.g., Auping et al. 2016; Kwakkel and Pruyt 2013; Steinmann et al. 2020). The uncertainty parameters were selected based on a preliminary sensitivity analysis using the sensitivity2all function in Vensim, which identified the variables most strongly influencing the profit margin for repurposing. Ten variables were selected for further assessment, all of which are associated with uncertainty or disagreement in the literature and within the CircuBAT workshop. These variables are listed in descending order of their impact on profit margin and will be introduced in Appendix S3. The following section presents the model results. For enhanced clarity, the analysis focuses on the years 2020–2045.

4 | Results

The analysis compares business and policy strategies considered promising under market uncertainty. All simulations are evaluated based on the annual profit generated by the repurposing industry. The analysis begins with the collaboration strategies C1–C3, followed by the demand-oriented strategies D1–D3, the pricing strategies P1–P3 and the regulatory frameworks R1–R3. Finally, the analysis focuses on the implications of the VoD in the repurposing market.

TABLE 1 | Strategies to overcome a VoD for second-use EV battery companies.

Pillar	Name	Strategy for second-use battery companies
Collaboration	C1	Acting independently as battery owners
	C2	Acting as service providers to OEMs
	C3	Acting as service providers to OEMs and independently as battery owners
Demand	D1	Offering second-use batteries to consumers
	D2	Offering premium second-use batteries to consumers
	D3	Offering second-use batteries with warranties to consumers
Price	P1	Applying a demand-oriented pricing
	P2	Applying a cost-oriented pricing
	P3	Applying a competition-oriented pricing
Regulation	R1	Receiving research and development funds
	R2	Getting more access to research and development funds
	R3	Lobbying for price subsidies to consumers

Across the full set of strategies and uncertainty ranges, the results show scenarios of both strong profitability and zero profit or economic decline (Figure 6). Within each thematic pillar, the strategies C1, D1, P1 and R1 produce the same dynamics, because these strategies were aligned. Throughout the simulation period, the profit envelope remains at or above zero, indicating that the repurposing market maintains economic viability until 2045. Due to the more end-of-(first)-life batteries entering the system, the median annual profit rises sharply until 2033. After this point, growth slows, followed by stagnation and eventual decline.

This turning point is driven by demand constraints. While demand is sufficient to absorb the supply of repurposed batteries until 2033, by 2034 it begins to fall short. Initially, repurposed batteries offer a price advantage, but their value diminishes as new battery prices fall. With stronger market competition, consumer demand declines, capping potential sales. Other contributing factors include shorter expected lifetimes, perceived safety concerns and overall consumer reluctance to adopt repurposed batteries.

The uncertainty envelopes are particularly wide. While some simulations indicate a robust and profitable long-term business, others suggest that the repurposing industry may never

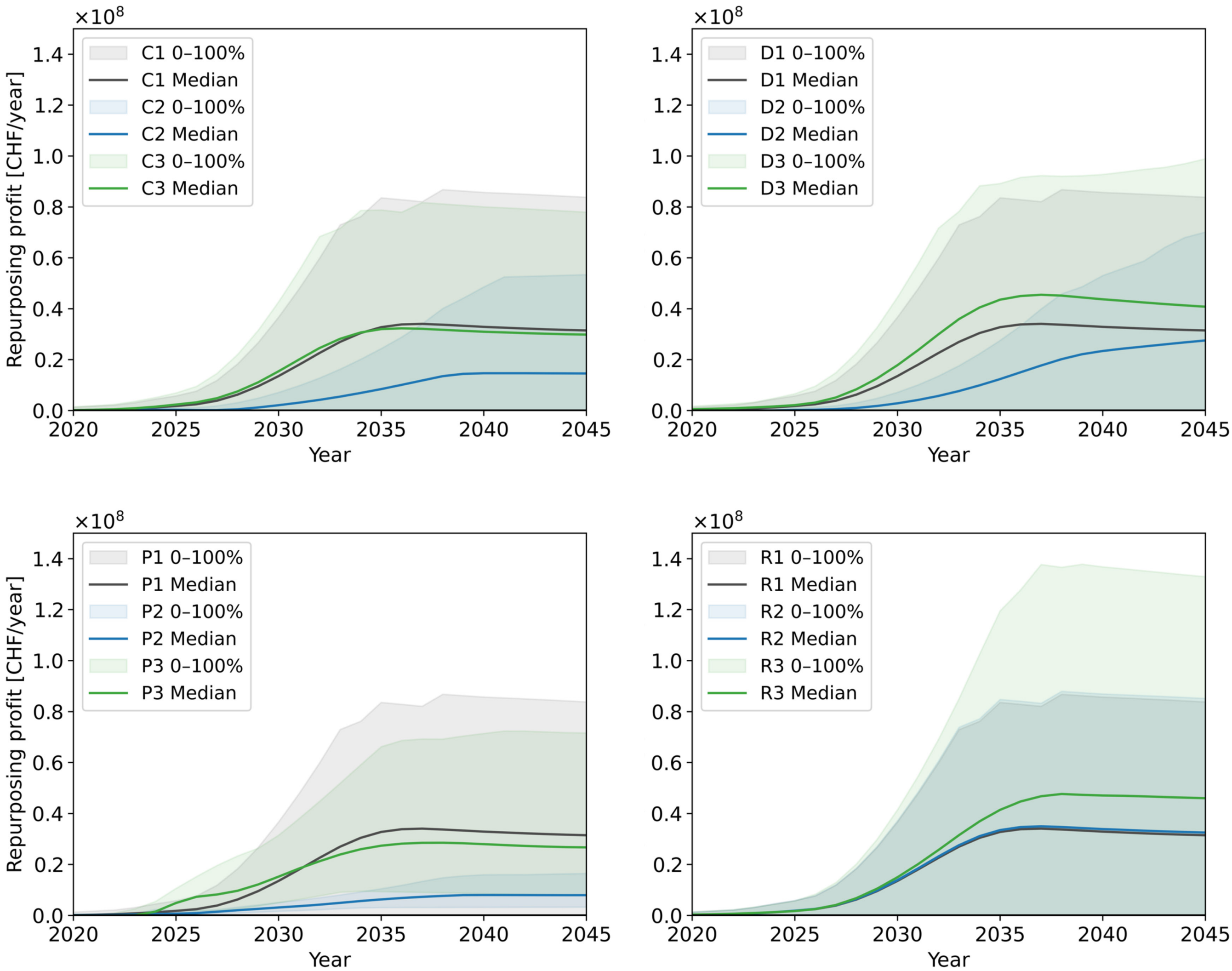

FIGURE 6 | Annual repurposing profit for collaboration strategies C1–C3, demand-oriented strategies D1–D3, price strategies P1–P3 and regulatory frameworks R1–R3.

establish itself or may collapse after initial success. According to sensitivity2all analysis, the new battery selling price and battery lifetime are the most influential variables on the range of possible outcomes. Accordingly, longer battery lifetimes increase the median profit, while shorter lifetimes significantly reduce it.

4.1 | Collaboration

Collaborating with OEMs as service providers proves less profitable than when firms own the batteries. Strategy C2—where repurposing firms act solely as service providers to OEMs—shows the lowest annual profit compared with strategies C1 and C3. In C2, fewer volumes enter the market due to OEMs' internal policies of directly recycling batteries rather than sending them for second use. Consequently, C2 increases the demand-to-supply ratio for the repurposed battery selling price, slowly increasing the price until C2 prices slightly exceed those of C1. Compared with C1, the profit margin in C2 declines more slowly, and while the median line in C2 stagnates, it does not fall as it does in C1. At the lower end of the C2 envelope, annual profit remains at an unprofitable (zero) level. Strategy C3—where repurposing firms act equally as battery owners and service providers to OEMs—yields higher profits in the medium term but slightly lower profits in the long term compared with C1. In C3, demand for repurposed batteries remains at levels comparable to C1 and C2. However, combining ownership and service models increases the supply, which begins to exceed demand slightly earlier than in C1, around 2033. Although supply increases in C3, strategy C1 maintains a higher profit margin, as end-of-life batteries are purchased rather than shared, and revenues and costs are not split with OEMs.

4.2 | Demand

Strategy D2—where repurposing firms offer premium end-of-life EV batteries to consumers—reveals the lowest profit over the simulation period. In D2, lower supply is insufficient to meet rising demand. Consequently, the selling price increases, improving the profit margin relative to D1. However, the ramp-up of factory capacities remains significantly lower, making D2 more suitable for a niche market. Strategy D3—offering warranties to consumers—works effectively in increasing consumer demand. However, the supplied volumes are also increased to the point where supply exceeds demand, which is earlier than in D1. Compared with D1 and D3, strategy D2 yields the strongest demand-pulling effect.

4.3 | Price

The demand-oriented pricing strategy P1 generates the highest annual profits compared with the cost-oriented pricing strategy in P2 and the competition-oriented pricing in P3. A cost-oriented pricing approach results in the highest demand due to its lower selling prices. Strategy P2 effectively maintains a price advantage over new battery models, offering consumers prices of 328.48 CHF/kWh in 2035 and 313.21 CHF/kWh in 2045. From the supplier's perspective, however, reduced prices mean lower profit margins, which in turn suppress annual profits from repurposing. Consequently, profits under P2 remain below those of P1 and initiate lower factory capacities. With reduced factories, supply is insufficient to meet rising demand in strategy P2. With competition-oriented pricing in P3, demand is lower than in P1 and P2, as fewer customers are willing to adopt repurposed batteries when new battery prices are competitive. While P3 outperforms P1 in terms of annual profit at the beginning of the simulation, the resulting oversupply causes profits to decline at a steeper rate. Although P3 begins with higher competitor-aligned prices, from 2030 onwards it offers lower prices than P1—485.91 CHF/kWh in 2035 and 450.48 CHF/kWh in 2045—compared with 532.86 CHF/kWh and 491.56 CHF/kWh under P1.

4.4 | Regulation

All three regulatory frameworks offer profitable business cases for second-use EV battery companies when focusing on the median values in Figure 6. Strategy R2, which involves increased access to R&D funds, closely mirrors R1 but delivers higher profits. While demand and supply dynamics remain the same under R1 and R2, the profit margin is higher in R2 due to increased research resources. However, this higher margin does not lead to further investment, as growth is constrained by limited demand. A comparison of commercialisation and research resources reveals that market-driven profit exceeds that provided by governmental support, explaining the nearly overlapping trajectories of R2 and R1. Strategy R3, which involves lobbying for price subsidies for consumers, has a more pronounced effect on profitability. Under the tested subsidy level, reducing the selling price for second-use batteries by a subsidy level of 30% demand increases to levels where sales are no longer limited by demand due to policy intervention. With high subsidies, the effect increases, while lower rates decrease the pronounced effect on rentability.

4.5 | VoD Assessment

To further assess the VoD scenario, we analyse the firm exit rates in the repurposing industry. Figure 7 illustrates the annual dismantling of capacities due to unprofitable market conditions. The minimum and maximum values of the uncertainty envelopes are displayed alongside the median lines in Figure 7. To remove potential outliers, the 5%–95% range is also presented, helping to better understand VoD risks. Based on the maximum values of the envelopes, 10 out of 12 strategies present a risk of market exit: C1, C2, C3, D1, D2, D3, P1, R1, R2 and R3. However, when focusing on the 5%–95% range, the risk narrows to C2 and D2, which are more likely to result in firms becoming trapped in a VoD scenario. Analysis of the 2–98% percentile range indicates that strategy R2 may also pose an elevated VoD risk.

The primary cause of firms becoming trapped in a VoD lies in the low profits observed at the lower end of the envelopes in Figure 6, which reach zero. Especially during phases where technology learning effects have not yet sufficiently reduced costs, revenues may be insufficient to cover repurposing expenses, forcing firms out of the market. In the higher-risk strategies—C2 and D2—limited supply plays a significant role in increasing VoD risk. Both strategies reduce volume, further weakening the scale effect. Moreover, although strategies D2 and R2 are effective at increasing demand, rapid factory expansion under these conditions results in revenues that remain insufficient to offset costs.

On the contrary, as shown in Figure 7, strategies P2 and P3 do not entail a significant risk of entering a VoD. Even with parameter uncertainties, these strategies generate sufficient revenue to cover repurposing costs over the whole simulation period.

Further reflection on VoD risk within specific market segments reveals a declining market share for residential second-use batteries. As shown in Table 2, profitability in the repurposing industry is largely driven by the commercial consumer segment. While the residential market is initially assumed to have a 34.2% share (Figgener et al. 2020), this figure declines across all strategies except the D2 business case.

5 | Discussion

Reflecting on the potential risk of the second-use EV battery industry getting trapped in a VoD, this study conceptualises and simulates 12 business strategies to identify a long-term, robust business model. The findings offer insights into the annual profitability of each strategy and depict the yearly market exit rate. The academic and managerial implications will be discussed in the following.

5.1 | Academic Implications

The study offers three key academic contributions. First, it provides a detailed understanding of profitable business strategies for second-use EV battery companies. It aligns with research on circular EV battery business models (Albertsen et al. 2021; Olsson et al. 2018; Reinhardt et al. 2020; Wrålsen et al. 2021), particularly those addressing the second-use EV battery market (Chirumalla et al. 2024; Kulkov et al. 2025; Wellten et al. 2025) and links towards the discourse on circular business model experimentation (e.g., Bocken et al. 2021; Konietzko et al. 2020). It builds on existing quantitative studies assessing business strategies (Schulz-Mönninghoff and Evans 2023; Schulz-Mönninghoff et al. 2021) by incorporating regulatory, consumer and pricing dynamics into the model and simulation framework. This offers

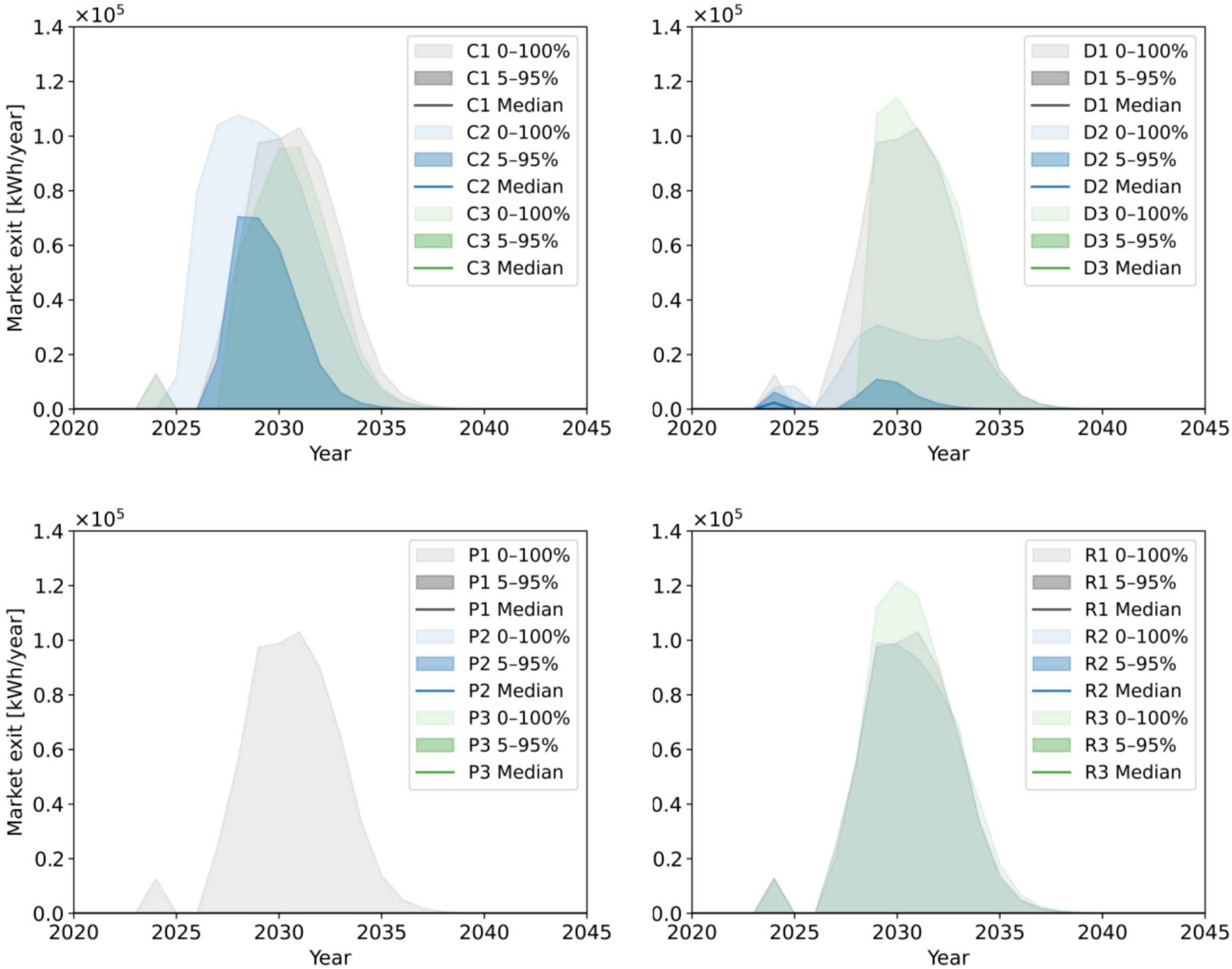

FIGURE 7 | Annual market exit rate for collaboration strategies C1–C3, demand-oriented strategies D1–D3, price strategies P1–P3 and regulatory frameworks R1–R3.

TABLE 2 | Residential market share for collaboration strategies C1–C3, demand-oriented strategies D1–D3, price strategies P1–P3 and regulatory frameworks R1–R3.

		Residential market share per strategy								
		x1[a]	**C2**	**C3**	**D2**	**D3**	**P2**	**P3**	**R2**	**R3**
2035	max	5.2%	5.3%	5.1%	4.6%	21.4%	5.5%	5.3%	5.2%	5.2%
	md.	9.6%	9.6%	9.6%	8.8%	32.3%	9.6%	9.4%	9.6%	9.4%
	min	15.0%	14.9%	14.9%	13.9%	41.0%	14.9%	15.1%	15.0%	14.9%
2045	max	4.6%	4.8%	4.6%	4.4%	18.8%	5.0%	4.8%	4.6%	4.7%
	md.	8.9%	9.0%	8.8%	9.3%	29.5%	9.0%	8.8%	8.9%	8.9%
	min	15.0%	15.3%	15.0%	17.8%	40.1%	14.9%	15.0%	15.0%	14.7%

[a]Values for C1, D1, P1 and R1.

a more holistic evaluation of sustainable business models from both supply and demand perspectives, enriching existing conceptual work with quantitative and dynamic analysis.

Second, the study deepens understanding of long-term supply and demand behaviour within the second-use EV battery market. It presents a quantitative simulation model incorporating 25 feedback loops covering repurposing and recycling dynamics. Our paper aligns with existing circular battery simulation research (Ginster et al. 2024; Hoyer et al. 2011; Kamath et al. 2023; Seika and Kubli 2024) and contributes further by extending techno-economic models for the second-use EV battery market (Pratap et al. 2024; Alamerew and Brissaud 2020; Shaikh et al. 2023; Kamath et al. 2023) to include key, previously neglected stakeholder decisions. These include the integration of empirical customer preference data to assess demand and investor decisions affecting the ramp-up or scale-down of repurposing factories. These enhancements enable simulation of long-term price behaviour and its implications for profitability, particularly by highlighting demand–supply interdependencies and constraints.

Third, this study advances the literature on the VoD, addressing its threats and identifying preventative strategies for the battery repurposing industry. While the concept of VoD originates with Moore (1991) and is commonly applied in R&D-intensive fields, its application to the second-use EV battery market has been lacking. This study fills that gap by examining how companies face VoD risks and evaluating the effectiveness of various business and policy strategies across four thematic pillars. The findings are also applicable to other VoD contexts. Moreover, the study contributes to the discourse on quantifying VoD situations, linking them to technology readiness (Godin 2006; Sadin et al. 1989) and presents a quantitative method for analysing the risk of companies falling into a VoD by simulating their market exit.

5.2 | Managerial Implications

The findings have practical relevance for stakeholders in the EV and stationary battery industries as well as for policymakers addressing retired EV or stationary batteries. First, second-use EV battery companies can use these insights to better understand the long-term profitability of repurposing. The tested strategies—related to collaboration, demand stimulation and pricing—are directly applicable. The results suggest that collaborating with OEMs solely as service providers is not a viable long-term business strategy. Sustaining consumer demand is crucial. While targeting the premium end-of-life battery segment can lead to high short-term profits for some firms, it carries significant uncertainty due to rising market competition. Thus, companies may be better advised to reserve premium batteries for niche markets rather than the mass market. Additionally, from a pricing perspective, demand- and competition-oriented strategies emerged as effective ways to maintain profitable operations, with consumer prices ranging between 485.91 and 532.86 CHF/kWh by 2035. Importantly, profitability is largely driven by the commercial segment, suggesting that second-use EV battery companies should prioritise this market when developing their repurposing strategies.

Second, suppliers of new stationary batteries may benefit from understanding long-term market developments and evaluating opportunities to invest in repurposed battery markets. Although the premium segment may be risky for second-use battery companies, it could provide a testing ground for new battery firms seeking to extend their offerings. These companies could maintain their core business while offering a more sustainable, long-lasting option, potentially reaching new customers and tapping into the upper bounds of the profitability envelope.

Third, policymakers can use these findings to design effective regulatory frameworks that support a circular battery economy. The study identifies OEM policies on direct recycling as a critical lever. In light of the current EU Battery Regulation (2023/1542, n.d.), measures are needed to counteract unintended effects that could undermine the repurposing market. Of the two policy mechanisms tested, subsidies to residential consumers had a much stronger effect on profitability than additional research funding. Thus, supporting repurposed battery adoption through price subsidies may be an effective tool for governments aiming to foster circularity while safeguarding industry viability.

6 | Conclusions

Enabling a circular economy for EV batteries requires companies to avoid the pitfalls of the valley of death. This study has reviewed relevant literature on VoD challenges in the second-use EV battery market and proposed viable strategies to overcome them. Four key strategy pillars—collaboration, regulation, demand and price—were identified, with three strategies tested under each using an SD model tailored to the Swiss market context.

The results indicate that companies face VoD risks when revenues fail to cover repurposing costs, particularly in markets focused solely on premium end-of-life batteries or limited to OEM collaborations. In these scenarios, profit margins are insufficient to sustain a robust, long-term business model. Conversely, a mixed strategy combining partial collaboration with OEMs as service providers with some degree of direct battery ownership offers promising short-term profitability. Over the longer term, three strategies outperformed battery ownership alone: providing product warranties, securing more research and pilot funding and lobbying for consumer price subsidies. Of these, only subsidies posed a notable VoD risk.

As the volume of end-of-life EV batteries continues to grow, these findings carry both academic and practical significance. They contribute to academic understanding of sustainable business modelling and offer guidance for industry stakeholders and policymakers seeking to accelerate second-use EV battery adoption. For society, advancing circularity in battery use is essential to prolong battery life, reduce raw material dependence and lessen reliance on new battery production.

6.1 | Limitations and Further Research

As with any scientific study, this research is subject to limitations, which provide opportunities for further research. Focusing on Switzerland as the methodological context means the study is limited by Switzerland's geographical and institutional context. While the exact annual profit may appear lower than those in neighbouring countries, the qualitative insights and observed market dynamics are likely transferable to other European contexts. Preliminary discussions with companies outside Switzerland suggest that similar dynamics are present elsewhere, underscoring the broader relevance of the findings. Nevertheless, future research could apply the model dynamics used here to non-European countries like Asia, where second-use EV batteries are fully integrated in a closed-loop supply chain or North America, where the electric vehicle market is constrained by political support. Such comparative modelling would allow for a more endogenous perspective on intermarket competition and the export implications of second-use batteries and offer a more nuanced view of Europe's internal competitive landscape. Furthermore, models with a global perspective can contribute to a more holistic understanding of the overarching dynamics of the competition around the scarce materials in EV batteries and the impacts on raw material trade.

On a global scale, there is considerable potential to adapt and apply the proposed model to other regions, particularly Asia and North America. In Asia, the concentration of battery manufacturers heightens the importance of understanding pricing dynamics and lifecycle value capture. Regional adaptations of the model could yield insights into how a European second-use battery ecosystem might position itself in global markets. This, in turn, raises important questions about Europe's future role in the international second-use battery market and the strategic levers available to enhance its competitiveness.

The study is also limited in its treatment representation of the internal decision-making processes of OEMs. There is considerable opportunity to explore the contractual structures and incentive systems that influence OEM participation in the second-use battery market. Future research could build on the findings presented here by conducting targeted interviews or employing group modelling techniques to integrate OEM perspectives more fully into the model. Studies specifically focusing on decision-making processes may also consider employing agent-based modelling. Furthermore, once the second-use battery industry is more advanced, combining System Dynamics modelling with data analytic approaches could be promising.

This work also opens promising opportunities to investigate unintended business and policy effects within the circular EV battery market. One such effect—key stakeholders opting for direct recycling due to internal policies—warrants closer scrutiny to ensure the second-use market is developed in a resilient and coherent manner with positive effects on society and the circular economy. From a policy standpoint, future studies could examine the implications of introducing a mandatory repurposing policy for the European market, particularly in line with the evolving EU Battery Regulation (2023/1542, n.d.). Emerging policy instruments such as the digital product passport (Popowicz et al. 2025) offer new avenues for transparency but may hinder key stakeholders from committing; also, subsidies increase profits but may lead to unintended consequences like market distortion and subsidy reliance. These interconnections between stakeholder interests and regulatory frameworks provide a rich field for further research aimed at supporting the development of a robust second-use battery market.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Appendix S1:** The Technology Valley of Death of Circular Economy Solutions: A System Dynamics Simulation of Business Strategies for the Second-Use Battery Industry.