Rebound Effects in the Circular Economy for EV Batteries

Master Thesis

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Executive Summary

The production of carbon dioxide (CO_2) is the largest contributor to global warming. The primary source of these emissions is petroleum-derived fuel used in transportation, specifically in internal combustion engine vehicles. In response, the European Union (EU) has implemented a low-emission mobility strategy, aiming to shift towards low-carbon transportation. This strategy includes ambitious targets for electric vehicle (EV) adoption with at least 30 million zero-emission vehicles expected to be on European roads by 2030. This push towards EVs is driving up demand for lithium-ion batteries (LIBs).

While efforts to improve efficiency in EV battery production and use are intended to reduce environmental impacts, they might potentially lead to unintended consequences known as rebound effects. Rebound effects occur when efficiency improvements result in increased consumption or production elsewhere in the system, negating the expected benefits. These effects can arise from both behavioural and systemic responses to efficiency gains. Current discussions and policy frameworks often overlook the potential rebound effects in CE activities, particularly concerning EV batteries. This oversight poses a significant risk to the effectiveness of initiatives aimed at reducing CO_2 emissions and advancing CE practices. Therefore, it is crucial to investigate these rebound effects within the CE context for EV batteries to develop effective mitigation strategies.

There is a noticeable gap in the existing literature regarding the interconnected dynamics of CE practices and rebound effects in the context of EV batteries. While some studies have explored rebound effects in other sectors, limited research examines how CE practices for EV batteries contribute to rebound effects across different lifecycle stages. To ensure the sustainability of CE initiatives, it is essential to adopt a systemic view that considers these effects. By doing so, businesses can develop strategies that not only focus on recycling and efficiency but also address broader systemic impacts, ensuring that increased demand does not negate the benefits of circular practices.

The research employs qualitative SD to examine potential rebound effects in the CE system for EV batteries. This approach allows for a comprehensive understanding of the system's dynamics by identifying causal relationships between physical and behavioural components. The study uses CLDs to represent the interconnections and feedback processes within the circular economy of EV batteries, helping to identify reinforcing and balancing feedback loops that drive system behaviour. The initial phase involves identifying key variables that influence the system's behaviour. These variables include economic incentives, technological advancements, regulatory frameworks, consumer behaviour, and environmental impacts. The relationships between these variables are mapped to create CLDs, which are then iteratively refined based on expert feedback to ensure accuracy and relevance.

Expert interviews are conducted to validate and refine the constructed CLDs. Professionals with in-depth knowledge of the circular economy and EV batteries provide insights that help verify the model's assumptions, structure, and behaviour. This validation process includes discussions on potential oversights or nuances that the initial model may not fully capture. The methodology also involves developing Circular Business Models (CBMs) as strategies to mitigate rebound effects. A review of existing business model innovations in the CE context is conducted to identify patterns relevant to EV batteries. These business model patterns are categorized to align with the rebound mechanism categories, facilitating a cohesive analysis.

The study identifies key mechanisms within the EV battery lifecycle that can lead to rebound effects, particularly during the usage phase. Three significant mechanisms—Income, Substitution, and Demand Adjustment by Efficiency—were found to be most prominent in this phase. To mitigate these effects, the research proposes various strategies. Dynamic Pricing emerges as the most effective strategy, capable of addressing all three mechanisms by adjusting prices in response to real-time market conditions, thereby preventing excessive consumption and production. Alternative strategies such as Pay per Use and Subscription models also show promise in mitigating rebound effects by promoting efficient use and reducing the need for outright ownership.

The research highlights the importance of understanding these mechanisms and selecting suitable strategies to mitigate rebound effects. Firms must focus on the identified mechanisms and integrate appropriate strategies into their business models to ensure sustainable practices. Furthermore, the study underscores the necessity of engaging a diverse range of stakeholders, including consumers, policymakers, and industry practitioners, to develop comprehensive and inclusive CE strategies. Future research should continue to refine these strategies and explore the dynamic interactions within the EV battery lifecycle to enhance the effectiveness of CE initiatives.

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Abbreviations

Abbreviation	Definition
BD	Improving Battery Design for End-of-Life
BL	Improving Battery Design for Longevity
CBM	Circular Business Model
CE	Circular Economy
CI	Improving the Number of Charging Infrastructure
CLD	Causal Loop Diagram
CO2	Carbon Dioxide
EoL	End of Life
EU	European Union
EV	Electric Vehicle
ICE	Internal Combustion Engine
LIB	Lithium-ion Battery
PP	Improving Production Process
RE	Rebound Effect
RL	Improving Reverse Logistics
RP	Improving Recycling Process
SD	System Dynamics

1 Introduction

1.1. Background and Context

The production of carbon dioxide (CO2) is the biggest source of global warming (EC, 2016). Global CO2 emissions have increased rapidly over the last 50 years and in 2023, the overall CO2 emissions grew by 1.1%, reaching a new record high of 37.4 Gt (IEA, 2023). Petroleum-derived fuels, which have been the primary source of energy in the transportation sector for powering internal combustion engine vehicles, contribute substantially to CO2 emissions. In addition to the rapid growth of CO2 emissions globally, the European Union (EU) has been addressing the issue by implementing low-emission mobility strategies aimed at shifting towards a low-carbon (European Commission, 2016). The low-emission mobility strategies have resulted in a shift away from traditional internal combustion engine (ICE) vehicles to electric vehicles (EVs). The EU also sets a target for the adoption of EVs. According to the Sustainable and Smart Mobility strategy, at least 30 million zero-emission vehicles will be in operation on European roads by 2030 (European Commission, 2021). This push towards EV adoption is increasingly gaining momentum, with electric car sales increasing by over 15% in 2022 (IEA, 2023), indicating a growing commitment to reducing CO2 emissions in the transportation sector.

The increasing demand for EVs is driving demand for batteries. Lithium-ion batteries (LIBs) are commonly used in the battery storage system of EVs because of their high energy and power densities (Wralsen, 2021). In 2022, the manufacturing capacity for LIBs for automotive was approximately 1.5 TWh for the year, and the demand is predicted to rise significantly by 2030, reaching over 3 TWh (IEA, 2023). Furthermore, The EU proposed the Net Zero Industry Act in March 2023, to have battery manufacturers within the EU meet approximately 90% of the yearly demand for batteries by 2030, with a minimum manufacturing capacity of 550 GWh (IEA,2023). With the growing demand for LIBs, there is also a corresponding increase in the number of batteries that will be discarded as the EVs reach their end-of-life (EoL). EV battery lifespan is highly uncertain and dependent on many factors, but the majority of previous studies put the average EV's LIB life between 8 and 10 years (Skeete et al., 2020). Richa et al. (2014) projected that global annual EV battery waste flows will be 340,000 metric tonnes by 2040. If these batteries are not recycled or reused at their EoL, the result would be the generation of millions of tons of spent LIBs, causing significant environmental pollution and a substantial waste of resources.

Notably, LIB waste not only contains hazardous materials but also contains rare and precious materials such as lithium, cobalt, and graphite (Ahuja, 2020). These materials are essential for manufacturing new batteries but are difficult to obtain due to their limited availability on Earth. Therefore, there is an urgent need for safe, environmentally friendly, and economically viable disposal methods to handle battery waste. Transitioning from a linear economy to a circular economy (CE) offers a solution by minimizing waste and reducing the need for extracting virgin raw materials. This approach allows resources to move continuously in a loop through the EV life cycle stages, promoting sustainability in battery production and disposal. To achieve this goal, the EU has implemented various regulations, including the Net Zero Industry Act, Critical Raw Material Act, and the Battery Directive, which play significant roles in shaping policies and practices related to sustainable battery management, such as setting collection and recovery targets for batteries waste and critical materials like lithium (European Commission, 2006; European Commission, 2023).

The increasing demand for EVs and LIBs, coupled with the EU's initiatives indicates a growing focus on sustainable practices within the transportation sector, including CE. In practice, CE can be promoted and sustained through the development of new and innovative business models that include CE principles in their value propositions throughout the value chain, which is the Circular Business Model (CBM) (Manninen et al., 2018). However, CE does not always lead to a positive contribution to the triple bottom line (i.e., environmental, social, and economic dimensions) (Geissdoerfer, 2017). By excluding large parts of the social dimension, emphasising economic benefits, and simplifying the environmental perspective, CE can lead to sustainability trade-offs (Geissdoerfer, 2017; Metic and Pigosso, 2022). In a study conducted by Padilla-Rivera et al. (2020), it was found that overlooking the social dimension in the CE concepts can lead to insufficient stakeholder engagement. This can result in decisions that fail to consider the needs and inputs of all affected parties, potentially leading to resistance or failure in policy implementation. Furthermore, the analysis of CE frequently neglects consumer behaviour. This oversight can lead to an inadequate understanding of consumer needs and preferences, potentially resulting in lower adoption of circular practices by consumers. (Padilla-Rivera et all., 2020).

The CE, recognized for its potential to enhance resource efficiency, has brought theoretical advancements that benefit both practice and policy, but implementing this still requires addressing significant challenges, including the rebound effect (RE) (Figge and Thorpe, 2019). Energy economist Daniel Khazzoom defined rebound effects as “increased consumption induced by the reduction in price due to enhanced energy efficiency” (Khazzoom, 1980). However, in a study by Vivanco et al. (2016), the concept of the RE is introduced as a concept that expands from focusing solely on energy to considering a wide array of environmental impacts, including water usage, waste generation, and other ecological footprints. Additionally, Edgar Hertwich (2005) defines RE as a “behavioural or other systemic response to a measure taken to reduce environmental impacts that offsets the effect of the measure.” According to Zink and Geyer (2017), the RE happens when “the efficiency of a productive system is offset by an increase in production or consumption”. This effect can arise from CE activities for EV batteries, such as the increase in material consumption per product for battery manufacturing that occurs when recycled material is used, resulting in more waste being produced at the EoL.

In this research, rebound effects are focused on as unintended side effects of well-intended sustainability actions, where efforts to enhance efficiency or reduce environmental impacts may lead to increased consumption or production (Guzzo et al., 2024). To enhance the effectiveness of the CE practice for EV batteries, it is crucial to address and minimize RE. This involves implementing strategies to mitigate unintended consequences and ensure that sustainability efforts can create long-term positive impacts.

1.2. Problem Statement

Research has shown that implementing new solutions to improve energy and process efficiency almost unavoidably results in negative unintended consequences known as RE which occur not only because of behavioural, but also systemic responses (Zink and Geyer, 2017). Sorrell (2009) defines the rebound effect as “the broader and often unintended economic and behavioural responses by various actors within an economic system to efficiency improvements that can reduce or negate the expected outcome”. RE involves changes in the overall economic structure and productivity that can further influence resource consumption across sectors and markets, often leading to unexpected increases in total resource use, sometimes even exceeding the savings from efficiency gains (backfire). Gillingham (2016) discusses the RE as a concept that extends beyond mere consumer behaviour due to its wide-reaching implications on the economy, environment, and policy. Greening (2000) also mentions that RE captures broader economic responses that go beyond individual consumer behaviour, involving market and economic dynamics that can significantly alter the supply and demand dynamics across different sectors. Vivanco et al. (2016) address the factors that drive RE include not only economic factors, but also psychological and environmental variables that might influence consumption patterns.

According to Zink and Geyer (2017), RE may occur in the context of CE and significantly reduce the expected environmental benefit because the theory of CE focuses more on material resource flow and often ignores the inclusion of behavioural economic and market forces. Therefore, incorporating the RE into CE practices ensures more accurate projections and effectively mitigates unintended increases in resource consumption and associated environmental impacts. This approach aims to prevent RE by designing systems and business models accordingly. This aligns with Vivanco et al. (2016), who emphasize the importance of understanding the potential for negative rebounds in designing interventions that genuinely reduce overall environmental impacts.

Despite the EU's proactive measures to promote sustainable mobility and address the environmental impact of transportation, there is a significant gap in recognizing and addressing the potential RE associated with the CE activities that focus on EV batteries. The implications of RE within this context have been overlooked in current discussions and policy frameworks (Metic and Pigosso, 2022). This gap should be addressed to prevent the failure of the implementation of initiatives aimed at reducing CO2 emissions and advancing CE practices for EV batteries.

CE practices for EV batteries are still emerging and are currently in the early stages of development. Despite being in its infancy, the significance of implementing CE for EV batteries has motivated several publications to define the stages involved in the circular value chain. For instance, Kubli et al. (2023) have proposed a conceptual model for this value chain, where numerous stages will be involved, ranging from raw material extraction to EoL management. Each of these stages will present unique challenges and opportunities for implementing CE principles and reducing environmental impacts. The complexity of the CE system creates the possibility of RE occurring at different stages of the EV battery lifecycle. However, because it is still in the early stages of development, it is challenging to evaluate RE. Yet, this also presents an opportunity to proactively design systems that can prevent RE from arising initially.

According to Remme (2023), despite the success in EV adoption and the plan of implementation of CE strategies for EV batteries, the downsides of this approach have been largely overlooked by failing to address the full scope of its impact. Further study is still needed to fully comprehend the dynamic complexity of the RE phenomenon and possible mitigation strategies (Metic and Pigosso, 2022). Moreover, further elaboration about the factors that contribute to the likelihood of RE occurring, as well as the reasons why RE occurs within the CE transition is required (Metic and Pigosso, 2022).

With the potential RE associated with CE practices for EV batteries, businesses that operate under the CE paradigm and are based on the CBMs should carefully evaluate the true environmental benefits of circular business (Siderius and Poldner, 2021). This evaluation is particularly crucial in the context of EV batteries, where the interconnectedness of the battery supply chain and market dynamics can amplify RE. A more comprehensive understanding of what the RE means in relation to CE will help avoid the overstatement of environmental benefits and generate meaningful criticism of CE strategies and CBM (Siderius and Poldner, 2021). By integrating considerations of RE into the evaluation of CBM, businesses can ensure that their circular initiatives effectively mitigate unintended consequences of CE practices. Therefore, understanding the specific stages in the EV battery value chain in which RE are most likely to occur is important for effectively mitigating their impact and ensuring the effectiveness of circular economy initiatives. By identifying the specific stages in which these effects are likely to occur more frequently, stakeholders can develop targeted strategies to minimize their occurrence and maximize the environmental benefits of circular economy practices for EV batteries.

1.3. Research Gap

The integration between the CE for EV batteries and RE themes lies in their common goal of promoting sustainability in the transportation sector. The CE for EV batteries aims to solve environmental issues related to battery production and disposal by optimizing resource utilization, minimizing waste, and extending product lifecycles. However, the implementation of CE practices may unintentionally lead to RE, where the environmental benefits of sustainable actions are offset by increased consumption or production elsewhere in the system. Therefore, it is necessary to investigate the RE of CE actions for EV batteries to ensure that the objectives of these actions can be achieved. The emergence of systemic challenges and behavioural shifts in the CE indicates the importance of exploring existing strategies to effectively address RE (Laurenti et al., 2015).

Despite the growing interest in the CE for EV batteries and RE, there remains a research gap in understanding their interconnected dynamics. While some studies have explored the potential for RE within specific sectors or sustainability initiatives (Guzzo et. al, 2024), there is limited research examining how CE practices for EV batteries may contribute to RE across different stages of the battery lifecycle. It is essential for businesses adopting circular models for EV batteries to incorporate a systemic view that considers these effects. By doing so, the businesses can develop strategies that not only focus on recycling and efficiency but also address the broader systemic impacts, ensuring that increased demand does not negate the benefits of circular practices. Addressing this research gap is important so CBMs can more effectively contribute to sustainable development goals while avoiding the unintended consequences of RE.

1.4. Research Objectives

This research aims to investigate where rebound effects are potentially emerging in the CE practices for EV batteries, their possible implications, and potential measures to address them. The study will analyse the EV battery value chain to understand its relationship with CE principles and illustrate system behaviour in CE practices for EV batteries, particularly focusing on behaviours leading to RE. By analysing feedback loops and critical factors influencing system dynamics, the research aims to uncover the underlying mechanisms driving RE within the CE framework.

First, this research will examine the lifecycle of LIBs used in EVs, emphasizing the need for a circular approach to minimize environmental impact and maximize resource efficiency. Understanding the entire lifecycle, from production to EoL, is crucial for implementing effective CE practices. Second, the research will investigate the unintended consequences that are likely to occur when implementing CE practices, including how both systemic and behavioural changes in response to CE initiatives can negate the benefits of efficiency improvements. The study aims to identify these rebound effects and understand their impacts on sustainability efforts. Third, the study will illustrate system structures in CE practices for EV batteries, particularly focusing on behaviours leading to rebound effects. This involves analysing feedback loops and critical factors influencing system dynamics to uncover the underlying mechanisms driving rebound effects within the CE framework. The goal is to provide insights into how both systemic and behavioural changes in response to CE initiatives can counteract the intended benefits. Lastly, the research will develop and evaluate strategies for mitigating RE and integrating them into circular economy business models for EV batteries.

The focus of the mitigation strategies is on a micro level, showing how focal companies can create value through implementing CE approaches. Focal companies hold the power to influence the entire value chain through their decisions and actions. Their direct control over business processes allows them to implement CE approaches in a way that aligns with their core competencies and strategic objectives. Therefore, the goal is to inform focal companies about practical measures and interventions that can address rebound effects effectively while ensuring continued progress toward circularity in the EV battery industry.

1.5. Research Question

Building upon the identified research gap and objectives, it is crucial to define the specific questions that will guide this research. The integration of CE practices with the EV battery lifecycles presents both opportunities and challenges, particularly in mitigating RE. To address these challenges effectively, the following research question and sub-questions will guide the exploration of these critical issues:

RQ: Which stages in the circular economy for EV batteries are prone to lead to rebound effects, and what managerial strategies and circular business models can be effectively integrated to mitigate them?

SQ1: What are the key components of the current EV battery value chain, and how do they relate to circular economy principles?

SQ2: What are the dynamics of system structure within the circular economy of EV batteries that contribute to the emergence of rebound effects?

SQ3: What managerial strategies are most effective in mitigating rebound effects when integrated into the circular business model for EV batteries?

1.6. Relevance with MoT

The relevance of this research to the Management of Technology (MoT) program is underscored by its alignment with some concepts taught within the program, which are the organization's focal point, core competencies, dynamic capabilities, and stakeholder engagement. Within the MoT program, the importance of directing an organization's focus toward innovation and sustainability is taught. This research reflects this concept by addressing the need for biases and inertia that hinder progress to be overcome by organizations. By concentrating on sustainable practices in the lifecycle of EV batteries, the alignment with the MoT teachings on driving long-term success and sustainability through a clear and strategic organizational focus is demonstrated.

The MoT curriculum teaches the development and harmonization of multiple abilities to create a sustained competitive advantage. This research draws on this concept by exploring how unique skills and knowledge can be leveraged by organizations to implement effective recycling practices for EV batteries. Moreover, the necessity of being agile and responsive to change is also taught. This research incorporates the concept of dynamic capabilities by examining how opportunities can be sensed by organizations and operations transformed to mitigate rebound effects in the circular economy for EV batteries. This focus on adaptability and proactive transformation aligns with the dynamic capabilities taught in the MoT program, emphasizing the importance of resilience and the ability to capitalize on emerging opportunities.

The importance of engaging stakeholders in implementing sustainable practices is also taught. This research highlights stakeholder engagement by stressing the need for the active involvement of consumers and other stakeholders in the decision-making processes related to EV battery recycling. By fostering trust and collaboration, the alignment of strategies with stakeholder needs and expectations, mirroring the stakeholder engagement principles taught in the MoT curriculum, is ensured.

2 Theoretical Background

2.1. EV Adoption and EV Batteries

EVs have received considerable attention as a potential solution to solve the current environmental problems such as climate change and air pollution caused by conventional internal combustion engine vehicles (Woo and Magee, 2020). To reduce CO2 emissions, the adoption of electric vehicles is increasing globally as countries around the world are setting EV adoption targets. Although there remains uncertainty regarding the trajectory of the e-mobility sector within the national markets, battery electric vehicles and plug-in hybrid electric vehicles are projected to dominate the European EV market, following trends observed in other regions (European Commission, 2023). Europe accounted for 10% of global growth in new electric car sales, with electric car sales increasing by more than 15% in 2022 relative to 2021 to reach 2.7 million (IEA, 2023).

In the development and market penetration for EVs, the technological readiness of batteries as the energy storage system is important. Several battery technologies that are suitable to be used to power the EV are Lead-Acid, Nickel-Cadmium, Nickel-Metal-Hydride, Lithium-Ion, and Sodium-Nickel-Chloride (Manzetti and Mariasiu, 2015). Because of the high energy density, relatively long lifecycle, and lightweight, LIBs have become the most widely used power battery technology in EVs (Jin et al., 2022). However, due to their presence in the Earth's crust and varied availability across different regions, LIBs encounter a unique challenge in the supply of critical metals such as Lithium, Cobalt, Nickel, and Manganese (Chen et al., 2020). While LIB costs have decreased by a factor of 5 over the past 10 years (~$1,000/kWh in 2005 to ~$200/kWh in 2016), the critical materials costs have been fluctuating due to the uncertainty in their value chain (Chen et al., 2019).

Concerns regarding the environmental, economic, and ethical consequences of accelerated mining operations, geopolitical instability, global quantities of natural metal sources, and hazardous working conditions have also been heightened in connection to ensuring worldwide access, sourcing, and secure supply chains for these metal materials (Zhao et al, 2021). On the other hand, these materials are also considered as toxic heavy metals (Zhao et al. 2021), that can contaminate soil, air, and water and can cause serious impacts on human health as well as other living things. The hazards coming from LIBs include the release of vapours, gases, metal nano-oxides, degradation products of the electrolyte, and potential traces of additives (Mrozik et al., 2021).

Typically, LIBs have an average lifespan of 8–10 years, so failure to recycle or reuse them at the end of their life could result in the generation of tons of spent LIBs, leading to significant environmental pollution and a substantial waste of resources (Jin et al., 2022). With the high rates of EV adoption, global demand for LIBs has approximately doubled every 5 years, and it is predicted that global LIBs capacities will reach 390 GWh in 2030 (Ding et al. 2019). This high demand for LIBs by the EV market will be translated into a large number of spent LIB packs, estimated at 1 million in 2030 and 1.9 million in 2040 (Chen et al., 2019). Therefore, the potentiality of a circular approach for LIBs recycling together with reuse and remanufacturing should become a concern. Recycling, along with reducing and reusing battery materials, is a core principle in transitioning from a linear battery economy to a circular economy, aiming to sustainably maintain value and promote economic, environmental, and social benefits. (Wesselkamper and van Delft, 2024).

2.2. Circular Economy and Circular Business Model

The circular economy (CE) is an economic system aimed at creating a regenerative and sustainable system by minimizing waste and maximizing the utilisation of resources (Ellen MacArthur Foundation, 2013). Over the past decade, there has been a remarkable increase in research on the CE, aligning with the increased global focus on sustainability driven by the United Nations (UN) and the European Union (EU) (Geissdoerfer, 2017).

Geissdoerfer et al. (2017) have comprehensively examined the key components of the CE and its potential as a new sustainability framework. They redefined circular economy as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops". The CE involves shifting from the traditional linear model of "take-make-dispose" to a model that focuses on a regenerative system (Geissdoerfer et al., 2017). According to Korhonen et. al (2018), the objective of CE is to reduce the expenses associated with raw materials and energy consumption, waste management, and emission control within the production-consumption system. Additionally, CE seeks to mitigate risks arising from environmental legislation and taxation, improve public perception, and foster innovation in product design to create new market opportunities for businesses.

However, the complete implementation of the CE requires a more holistic approach that takes into account the interconnections between economic, social, and environmental factors (Geissdoerfer et al., 2017). The research from Korhonen et al. (2018), emphasized the importance of taking a holistic approach to CE as it involves complex interdependencies between economic sectors and environmental systems.

The CE is gaining increasing attention as a strategy for achieving sustainable resource management. This approach emphasizes the importance of restoring product value at the EoL when products are no longer usable or have become damaged (Geissdoerfer et al., 2017). By extending the product life cycle, the CE aims to reduce waste and address resource scarcity (Alamerew & Brissaud, 2019).

Waste streams should be recovered and processed for use as inputs into production processes (Bocken et al., 2016). Ideally, waste loops can be completely closed by using waste from a product as a resource for the production of the same product (Ellen MacArthur Foundation, 2015). In cases where this is not possible, resources can flow across industries in an open-loop cycle. EoL products can be used as an input for a different loop to delay waste, although this may result in a loss of value (Geissdoerfer et al., 2017).

Overall, the CE emphasizes restoring product value at the end of life to extend product life cycles, reduce waste, and address resource scarcity. Disassembly compatibility, waste recovery, and closed-loop production processes are key strategies for achieving these goals. However, to enable the shift to a CE, with reuse and recycling, specific business models are required (Bocken et al., 2016). A business model is "the representation of the underlying core logic of the company for the creation and capture of value within a broader value network" (Teece, 2010). A business model requires a broader value-network perspective for innovation and model transformation because it does not only have a company focus but involves a wider set of stakeholders (Bocken et al., 2014). To address the urgent challenges of a sustainable future, innovation at the core of the business model should be introduced (Bocken et al., 2014). In the implementation of CE principles, circular business models (CBMs) are needed. Mentink (2014) defines a CBM as "the rationale of how an organization creates, delivers and captures value with and within closed material loops". CBM can create value among the four dimensions, which are reduce, reuse, recycle, and recover, so that economic value is captured by reducing costs through reusing materials, on the other hand, environmental values are enhanced by reducing the environmental footprint and the use of virgin materials (Bocken et al., 2014). In the EU, the European Commission states that they will help businesses shift to CBM, with the transition to CE will be driven by private firms and consumers, and regulatory bodies taking part in promoting the concept by creating regulatory frameworks (European Commission, 2016).

In the context of circular EV batteries, numerous studies have been conducted in this field. For instance, Kubli et al. (2023) developed a conceptual model for the EV battery value chain. This model visually represents the essential elements of a CE practice for LIBs, such as material flows, use cases, and business strategies. This model is developed to provide a common understanding and framework for all parties involved in a project named CircuBAT. Figure 1 shows the conceptual model created by Kubli et al. (2023). The diagram outlines the traditional linear economy model for the EV battery supply chain that starts with material extraction until batteries are in disassembly, which is highlighted in grey. On the other hand, the path that reflects the circular economy, symbolizing the closed-loop approach to material flow, is shaded in green (Kubli et al., 2023).

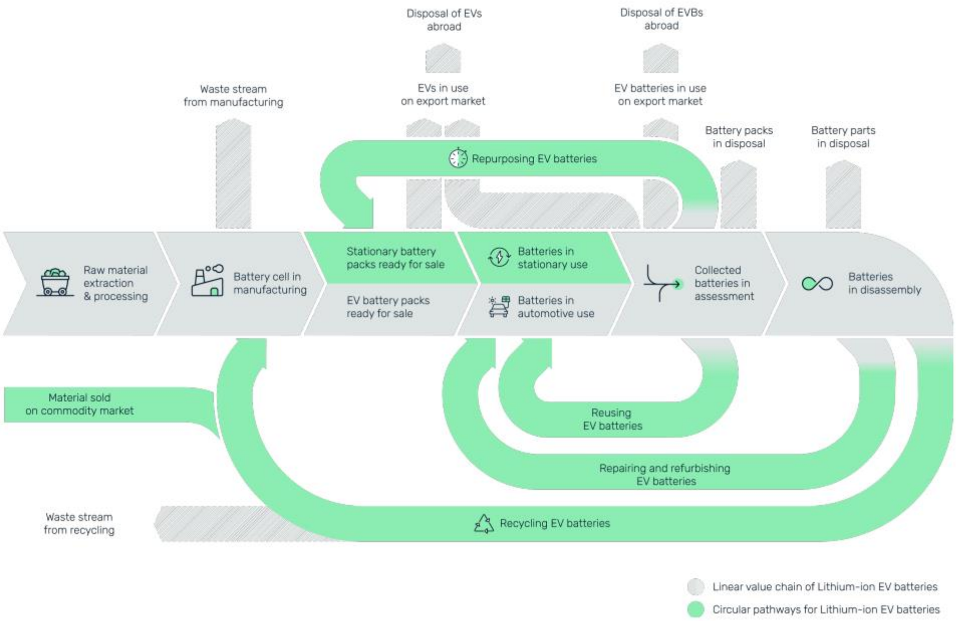

Figure 1 Conceptual Model for EV Battery Value Chain (Kubli et al., 2023)

2.3. Rebound Effect

Initially, the classical RE theory emerged from energy economics by examining how energy efficiency impacts the power system by estimating changes in energy demand based on price elasticity and efficiency improvements (Castro et al., 2022). The RE refers to the phenomenon where the expected energy savings from energy efficiency improvements are partially or fully offset by behavioural or other systemic responses that increase energy consumption (Lange et al., 2021). This means that while energy efficiency measures are intended to reduce overall energy consumption, the actual savings can be less than anticipated due to these REs. Empirical studies reviewed by Lange et al. (2021) demonstrate significant variability in the size of the RE, with estimates ranging from small offsets to cases where energy consumption actually increases—known as "backfire." Brockway et al. (2021) emphasize that failing to account for REs can lead to an overestimation of the potential energy savings from efficiency improvements and an underestimation of future demand. This can result in energy policies that are less effective than intended.

The RE is gaining increasing attention in research within the field of transportation, as current scientific literature indicates its potentially significant magnitude (Greening et al., 2000; Sorrell et al., 2009). For conventional ICE vehicles, the RE refers to the increase in vehicle usage resulting from the reduced per-mile fuel cost of driving that is caused by technical improvements that enhance fuel efficiency (Greening et al., 2000). The RE for ICE vehicles is typically defined in terms of an exogenous change in fuel efficiency, where fuel consumption and vehicle miles travelled are inversely related, measured by the elasticity of vehicle miles travelled concerning the per-mile fuel cost (Small and van Dender, 2007).

However, as the automotive industry transitions from traditional ICE vehicles to EVs and adopts CE principles, the RE is now recognized as the circular rebound effect rather than only the energy rebound.

2.3.1 Circular Economy Rebound

According to Zink and Geyer (2017), the CE has faced some criticism regarding whether the CE activities actually reduce or displace the primary production, because connecting waste streams from one process to inputs in another does not automatically assure reductions in environmental impact. Increasing overall product production and consumption, and consequently, environmental effects is one way the circular economy can backfire (Zink and Geyer, 2017). Furthermore, CE can also result in sustainability trade-offs by excluding large parts of the social dimension, emphasizing economic benefits, and simplifying the environmental perspective (Metic and Pigosso, 2022). Previous studies have shown that implementing new practices to increase efficiency almost unavoidably results in negative unintended consequences known as RE (Zink and Geyer, 2017). RE is a systemic response that offsets the initial intentions of sustainability-oriented actions, hindering the achievement of the full potential of sustainable solutions (Guzzo et.al, 2024). The Jevon's Paradox, which explains the rise in coal consumption caused by increased energy efficiency, served as the foundation for the study of RE (Sorrell et al., 2009).

While energy rebound emerges because of the increase in use-phase efficiency that is offset by increased use, circular economy rebound occurs when increases in production or consumption efficiency are offset by increased levels of production and consumption (Zink and Geyer, 2017). In other words, energy rebound focuses more on the use phase, as can be seen in the use of ICE vehicles, whereas circular economy rebound extends beyond that, emphasizing efforts to enhance production or consumption efficiency within CE practices. Recently, research on RE within CE has emerged by criticizing closed-loop solutions (e.g., the reduced cost of recycled materials leads to an increase in total material consumption) (Dace et al., 2014). This RE in the CE suggests that while CE strategies have the potential to lower the environmental impact per unit of production, the total environmental gains can be reduced if these strategies lead to an increase in total production or consumption, therefore integrating CE strategies with broader environmental policy and market regulation is needed to ensure that the potential benefits of CE are fully realized and not undermined by increased overall consumption (Siderius and Poldner, 2021).

2.3.2 Rebound Mechanism

The research about the RE continues to evolve. Numerous studies have explored rebound mechanisms in the context of energy efficiency. A mechanism is a frequently used concept denoting a group of interconnected elements responsible for initiating an activity or process, so the rebound mechanism explains how the RE occurs (Castro et al., 2022). Colmenares et al. (2020) identify that rebound mechanisms are driven by factors like market dynamics, consumer behaviour, and technological advancements, categorizing them into four dimensions: level of aggregation, actors involved, income levels, and timeframes. Lange et al. (2021) review how these mechanisms link energy efficiency improvements to changes in energy demand, organizing them across different economic levels—micro, meso, and macro—and timeframes. Brockway et al. (2021) highlight that rebound mechanisms are key to understanding how energy efficiency improvements interact with the broader economy, identifying direct, indirect, and macroeconomic mechanisms. Metic and Pigosso (2022) discuss how these mechanisms, operating at micro, meso, and macro levels, can lead to behavioural or economic changes that partially or fully offset the anticipated environmental benefits of efficiency improvements.

More recently, a comprehensive categorization of the mechanisms that lead to RE was developed by Guzzo et al. (2024). In their research, Guzzo et al. (2024) mapped the causal structures that support the occurrence of RE to explore how feedback thinking can help explain these mechanisms. This research will use the rebound mechanisms identified in their study. The rebound mechanisms defined by Guzzo et al. (2024) are shown in Table 1. The mechanisms that are most relevant to the CE for EV batteries should be carefully selected. These selected mechanisms are then modelled to illustrate how various factors interact within the system, potentially creating unintended consequences that can either amplify or mitigate the intended effects of sustainability initiatives. The complexity and interconnectivity of these mechanisms highlight the challenge of managing RE effectively within sustainability transitions.

Table 1 Rebound Mechanism Overview (Adapted from Guzzo et al., 2024)

Rebound Mechanism	Overview
Income Mechanism	Increased disposable income due to cost savings from efficiency improvements leads to increased consumption.
Consumption Time	Time savings from efficiency improvements increase consumption opportunities.
Motivational Consumption	Behavioural changes influenced by the perceived benefits of efficiency lead to increased consumption.
Re-spending	Monetary savings are redirected towards other goods and services, potentially increasing overall consumption.
Re-spending with Limited Income	Income constraints affect the extent to which savings are re-spent.
Output	Improved efficiency in production increases output.
Production Time	Time savings in production processes enable more production.
Re-investment	Savings are reinvested into productive capacity leading to greater output.
Cost-dependent Output	Reduction in production costs increases output.

Substitution	Switching between products due to changes in their relative costs.
Motivational Substitution	Changes in consumer preferences influence substitution.
Factor Substitution	Substitution among production inputs based on efficiency improvements.
Composition Substitution	Shifts in industry composition due to changes in relative advantages.
Sectoral Allocation	Redistribution of investments across sectors influenced by efficiency gains.
Demand Adjustment by Sufficiency	Efforts to reduce demand fundamentally through sufficiency strategies.
Demand Adjustment by Efficiency	Efficiency improvements modify demand patterns.
Demand and Investment Adjustment	Adjustments in both demand and investment are driven by changes in efficiency.
Re-design	Product redesign to optimize resource use can alter consumption patterns.
Supply Adjustment	Adjusting supply levels in response to efficiency changes.
Producer-induced Demand Adjustment	Producers manipulate demand in response to changes in supply conditions.
Sector-induced Demand Adjustment	Sector-wide adjustments in demand due to external factors.
Economies of Scale	Efficiency gains lead to larger production scales, affecting prices and consumption.
Market Price	Changes in market prices due to efficiency improvements.
Labour Income	Increases in labour income from productivity gains can lead to increased consumption.
Labour Income with Limited Labour Supply	The interaction between increased income and constrained labour supply.
New Economic Activity	Generation of new economic activities as a result of efficiency improvements.

In the context of the circular business model for EV batteries, the CE aims to extend product lifecycles, enhance recycling processes, and reduce waste, ideally minimizing environmental impacts, and by employing the SD approach from the Guzzo et al. (2024) study, the potential rebound effects and how it occurs can be identified. The feedback loops identified might show that while EV battery efficiency increases, the aggregate effect on resource consumption might grow, an escalation in resource use contrary to the intentions of circular economy practices. For example, understanding the interactions between improved battery technology (which encourages more EV usage) and the resulting increase in resource extraction for batteries due to market growth.

2.3.3 Evidence of Rebound Effect in CE Practices

Even though the CE practices for EV batteries are still about to develop, some studies already prove the presence of rebound effect in CE practices in another sector. The study by Makov and Vivanco (2018) examines the potential negative impact of RE in the CE on smartphone reuse. The study highlights that reused smartphones do not always directly replace the demand for new ones on a one-to-one basis. Instead, the substitution is often imperfect, which means reused smartphones can stimulate additional demand rather than solely displacing new products. Moreover, economic savings from buying reused smartphones lead to additional consumption (re-spending), which can further diminish the environmental benefits. Consumers often use the savings from purchasing cheaper, reused phones to buy other goods and services, potentially increasing overall environmental impacts.

The research by Kara et al. (2022) also discusses various cases related to RE in the context of circular economy initiatives, particularly focusing on the manufacturing sector. For example, in the case of LED lighting, significant energy savings are achieved due to the higher efficiency of LEDs compared to traditional incandescent bulbs. However, the rebound effect is observed when the reduced costs and improved performance of LED lighting lead to increased usage. For instance, more areas are lit than before, and lights are left on for longer durations, which can potentially offset the energy savings. The other case is in the context of material efficiency in manufacturing, where the use of more efficient manufacturing processes and the recycling of materials can lead to a reduction in the consumption of raw materials. However, the lower costs associated with these efficiencies can lead to increased production and consumption, which may result in a RE by increasing overall material usage across the industry.

Empirical evidence on the RE also highlights its significant and variable impact across different sectors and contexts. The review by Colmenares et al. (2020) reveals that the rebound effect varies across different types of energy services. For example, efficiency improvements in heating and transportation tend to exhibit higher RE due to the direct relationship between cost savings and increased usage. The magnitude of the RE can range widely, with reported values from -22% to 334%, and on average, the median rebound effect is estimated to be around 31%, suggesting that nearly one-third of the anticipated energy savings are lost due to increased energy consumption following efficiency gains (Colmenares et al., 2020). According to Lange et al. (2021), the RE in households can range from 10-30% for certain energy-efficient appliances, indicating that a small portion of the expected energy savings is lost due to increased usage, while in more energy-intensive appliances, the RE can be much higher, potentially reaching 50% or more. Brockway et al. (2021) also reviewed that studies using computable general equilibrium models estimate rebound effects of around 50% or more in many cases, where 13 out of 21 studies provided baseline estimates of approximately 50% or more, with some even approaching 100%.

3 Methodology

3.1. Research Design

The research design employs a systematic approach to address and mitigate rebound effects within the CE framework for EV batteries. Utilizing qualitative System Dynamics (SD) and Causal Loop Diagrams (CLDs), the study thoroughly explores and analyses the complex interactions and dynamics within the system. The process begins with building CLDs specifically tailored to the context of EV batteries, involving a detailed review of relevant literature and the adaptation of general rebound mechanisms to this specific context. This approach allows for a detailed examination of how different components influence each other and contribute to the overall system structure. The CLDs are then validated through expert input to ensure their accuracy and relevance, providing a robust foundation for understanding and addressing rebound effects in the CE for EV batteries.

This research employs qualitative SD to investigate the potential occurrence of RE in the CE system for EV batteries. SD offers a better understanding of complex systems comprising several feedback loops by identifying the causal relationships between the physical and behavioural components of the system (Auping et al., 2023). The primary factors influencing system structure are feedback loops, which offer the strongest leverage points for intervention because they explain why certain behaviours occur and predict future effects. In the context of RE, these feedback loops are crucial as they can either amplify or mitigate the unintended consequences of efficiency improvements, revealing how well-intended sustainability actions may lead to increased consumption or production.

CLD is an essential tool in the SD methodology that helps visualize the structure of complex systems. These diagrams will be used to represent the interconnections and feedback processes within the CE for EV batteries. Building CLDs involves identifying variables that significantly impact the system and connecting them through arrows that denote causal relationships, showing how each variable affects others (Laurenti et al., 2015). This visualization aids in understanding how positive (reinforcing) and negative (balancing) feedback loops drive system behaviour, including the generation of RE.

Following the CLD development, the research shifts focus to developing Circular Business Models (CBMs) as strategies to mitigate the identified rebound effects. This involves mapping existing mitigation strategies from the literature and aligning them with innovative business models that have proven effective in other CE contexts. This matching process analyses how these strategies can be effectively integrated into business models to mitigate the identified rebound mechanisms. The aim is to develop a cohesive framework that integrates these strategies into practical business models tailored to the EV battery sector. The most relevant business models are then selected based on their effectiveness in addressing the significant rebound mechanisms identified. These models are chosen for their ability to provide practical and sustainable solutions within the circular economy for EV batteries.

3.2. Incorporating Qualitative SD Modelling

To thoroughly understand and address the rebound mechanisms, this research applies SD, a methodology that incorporates feedback thinking to model complex systems dynamically. SD is a powerful tool for visualizing and analysing how decisions made today will influence outcomes in the future, acknowledging that "today's problems often result from yesterday's solutions," as noted by Sterman (2002). This approach is particularly useful in studying rebound mechanisms because it allows for the depiction of accumulations, delays, and non-linear feedback mechanisms that define the behaviour of complex systems (Dace et al., 2014). The SD models help trace the intricate cause-and-effect relationships within these systems, which are critical for understanding how and why RE occurs.

A qualitative SD approach will be employed to develop a framework for rebound mechanisms using CLDs. In CLD, the loops can either reinforce behaviour that amplifies resource use (reinforcing feedback loops) or attempt to balance and mitigate increased consumption (balancing feedback loops). The research will illustrate two primary generic mechanisms. The first generic mechanism is characterized by actions that are intended to decrease resource consumption in a local system but may increase the supply or demand for those systems, leading to a net increase in general resource consumption. The second mechanism involves actions that reduce supply or demand but trigger compensatory reactions from other actors, aiming to maintain their levels of consumption or production. By mapping these mechanisms, the research clarifies the dynamic interplay between different economic, social, and environmental factors in sustainability actions. It also emphasizes the importance of anticipating and mitigating rebound effects by understanding the systemic responses that drive them, fostering a multi-disciplinary approach to sustainability transitions that integrates economic, social, and environmental perspectives. This holistic approach highlights the necessity of considering all aspects of system behaviour to effectively manage and reduce unintended negative outcomes in sustainability initiatives.

Qualitative SD modelling has been employed to examine RE arising from sustainability-focused actions within a particular system (Guzzo et al., 2024). Qualitative SD modelling has been useful in identifying specific structures that contribute to RE. For instance, lower driving costs can lead to more driving (Stepp et al., 2009), increased recycling can reduce costs and boost demand for materials (Dace et al., 2014), and social norms can reinforce higher levels of transportation (Freeman et al., 2016). Researchers often analyse these qualitative models to pinpoint leverage points that can lead to better sustainability outcomes (Laurenti et al., 2016; Stepp et al., 2009), which is a recognized advantage of using CLDs (Lane, 2008).

3.3. Building CLDs for Rebound Mechanisms

Initially, a comprehensive review of the rebound mechanisms related to the CE for EV batteries is conducted. This involves studying the potential occurrence of these mechanisms and identifying the actors, causes, effects, triggers, drivers, and archetypes associated with them. The rebound mechanisms will be translated from the paper by Guzzo et al. (2024), which outlines rebound mechanisms in a general context. Concurrently, existing literature on the CE for EV batteries is reviewed, including academic papers, industry reports, and case studies. The findings from the literature review are then compared with the identified rebound mechanisms to determine their applicability.

Once the relevant rebound mechanisms have been identified and reviewed, the next step is to adapt these mechanisms to the specific context of the circular economy for EV batteries using the methodology depicted in the picture. This process begins by listing all relevant variables from CLDs for each mechanism. These variables are then modified to accurately reflect the mechanisms within the CE context for EV batteries, ensuring that all feedback loops and causal links are contextually accurate. Adjustments are made to the interactions in the CLDs to ensure that all feedback loops and causal lines are accurate and relevant to the specific context of EV batteries.

Using VENSIM software, a new CLD for the context of EV batteries is created based on the adapted variables and interactions. The most significant mechanisms are then identified through an analysis of the CLDs and a review of literature that explains specific mechanisms. Finally, these mechanisms within the CLDs are validated through expert interviews. Selected experts from academia, industry, and relevant stakeholders are interviewed to gather insights and suggestions for refining the CLD. Their feedback is crucial in ensuring the accuracy and relevance of the CLD to real-world dynamics and interactions. This entire process of translating the CLD is depicted in Figure 2.

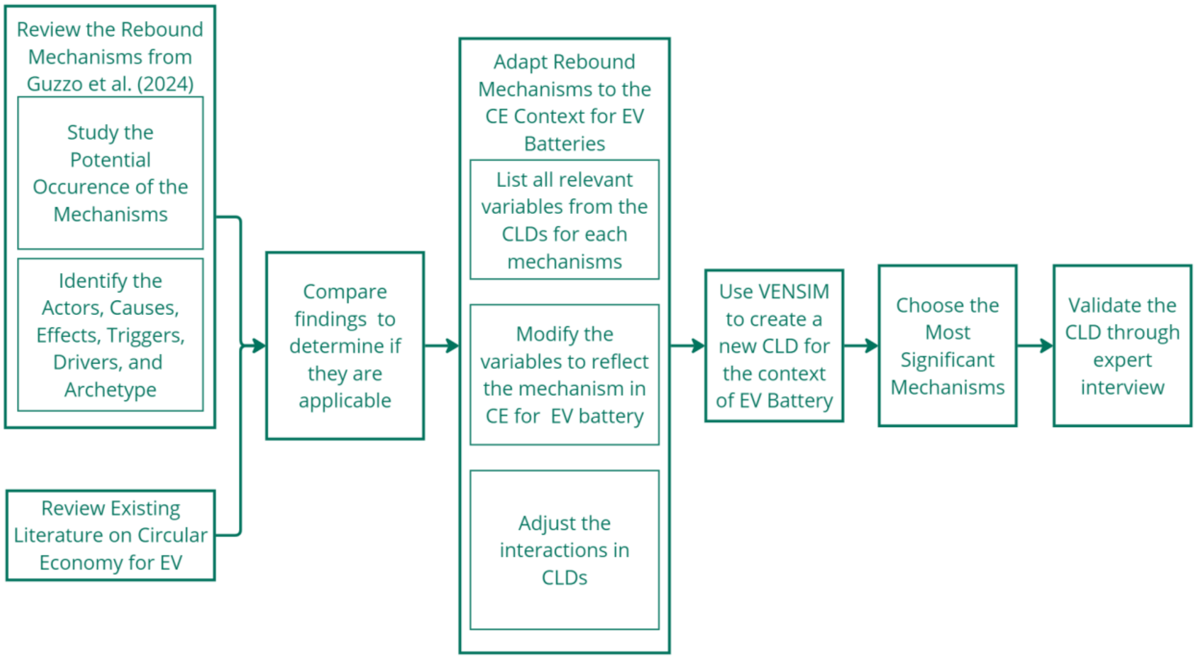

Figure 2 Method for Translating CLDs

3.4. Circular Business Model as Mitigation Strategy

The methodology for developing a CBM as a strategy to mitigate the rebound effects in the context of EV batteries involves the integration of CE principles and the mitigation of RE. The first step involves a comprehensive review of existing literature focused on mitigation strategies for rebound effects. In this research, papers by Font Vivanco et al. (2016) and Maxwell et al. (2011) are used for mapping the mitigation strategies. Concurrently, the methodology involves reviewing existing business model innovations within the CE that could be applied to EV batteries. This step aims to identify innovative business models that have been successfully implemented in other CE contexts and could potentially be adapted for the EV battery sector. In this research, paper by Takacs et al. (2020) will be used to define which business models that are relevant to circular EV batteries.

The next step is to match the identified mitigation strategies with business models that are relevant to the CE for EV batteries. This involves analysing how different strategies can be integrated into specific business models to effectively address the identified rebound mechanisms. The goal is to create a cohesive framework that aligns the mitigation strategies with practical business model implementations.

Finally, the methodology involves selecting the most relevant business model as the strategy to mitigate significant rebound mechanisms identified in the research. This selection is based on the effectiveness of the business model in addressing the significant mechanisms that were previously selected. The chosen business model should offer practical and sustainable solutions to mitigate the rebound effects within the circular economy for EV batteries. This process is illustrated in Figure 3.

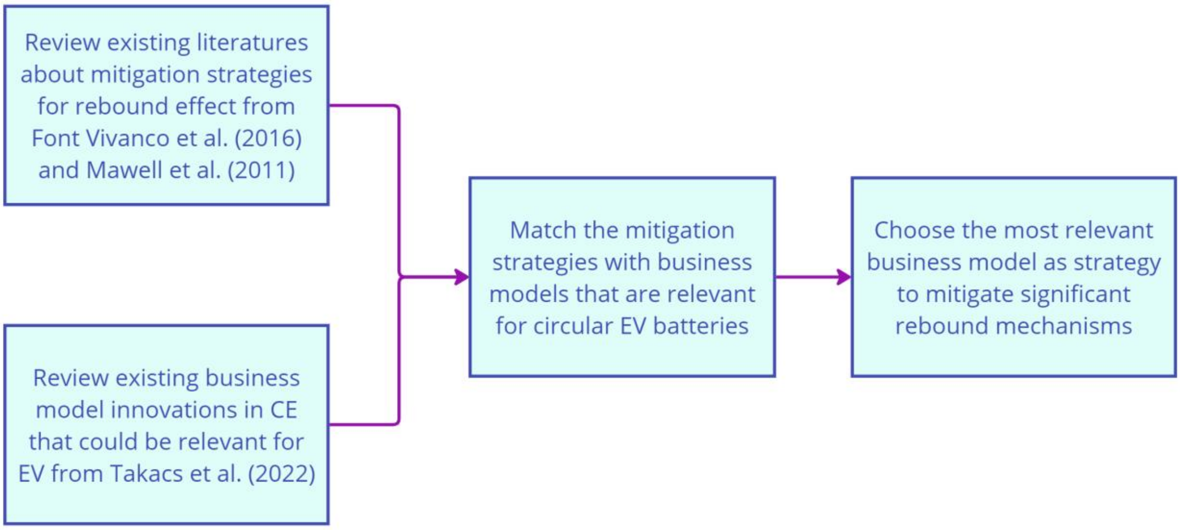

Figure 3 Method for Strategy Selection

3.5. Validation Interviews

According to Luna-Reyes et al. (2012), interviews are important for incorporating qualitative data and human judgment, which are often as crucial as quantitative data in modelling complex systems. Through interviews, expert insights can be accessed that are essential for verifying the accuracy and relevance of a model's assumptions, structures, and behaviours. Experts can confirm or refute the assumptions underlying a model, ensuring that the model accurately represents the real-world phenomena it aims to simulate. By discussing model outputs and scenarios with experts, the model's predictions can be checked whether it is aligned with expert expectations and experiences. Feedback from experts during interviews can lead to adjustments in the model's structure, making it more robust and reflective of complex dynamics. The interview framework is structured into several steps to ensure efficient and organized data collection, as detailed in Figure 4.

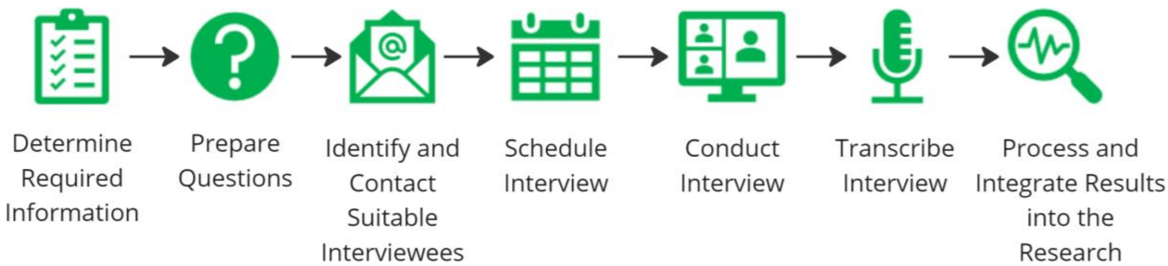

Figure 4 Interview Methodology

The first step is to **Determine Required Information** where the critical information required for the research is identified through desk research, aligning with the research objectives and findings from the analysis model. This helps to determine the key areas to focus on during the interviews. The second step is to **Prepare Questions**, which involves creating relevant interview questions based on the insights from the CLD model, ensuring that the questions are appropriate and targeted to gather meaningful feedback for validation.

The third step is to **Identify and Contact Suitable Interviewees.** Expert interviews involve consulting with academia, specifically researchers and professors who possess in-depth knowledge and experience in the field of circular economy and EV batteries. These experts are recruited through a targeted approach, leveraging academic connections to ensure a diverse and knowledgeable group. A few candidates are recommended by the thesis committee based on the conducted research. Potential interviewees are contacted via email and invited to participate, outlining the research requirements and describing the ideal interview candidate's field of expertise and academic background. Once they agree to participate in an interview, the fourth step is to **Schedule Interview**, where practical arrangements are made, including scheduling and specifying the length and setup of the interview. It is also crucial to obtain the respondents' permission to record the interviews for accurate transcription and analysis. The list of interviewees along with their backgrounds and expertise is tabulated in Table 2.

Table 2 List of Experts Interviewed

Expert	Role/ Academic Background	Expertise
A	Researcher at the Department of Civil and Mechanical Engineering Design for Sustainability, Technical University of Denmark	• Circular Economy • Rebound Effect • System Dynamics • Sustainability Transitions • Product Service System
B	Research Associate and PhD Candidate at the Institute for Economy and the Environment at the University of St-Gallen	• Circular Business Model • Lithium-Ion Battery • Repurposing and Recycling of EV Battery • System Dynamics
C	Assistant Professor of Circular Economy, Operations, and System Dynamics at Technical University of Eindhoven	• Circular Economy • System Dynamics • Rebound Effects • Digital Economy • Circular Product Design

The fifth step is to **Conduct Interviews**. Interviews are made semi-structured to allow for both guided discussions and the flexibility to explore additional relevant topics that arise during the conversation. During the introduction, the purpose and objectives of the interview are clearly explained to the interviewees, highlighting the importance of their expertise and insights for the research. Interview questionnaires, included in Appendix B, serves as a guide to ensure that all critical areas are covered. Some questions are asked in every interview, based on the results from the analysis model. Additional questions are tailored to the academic and professional expertise of each interviewee. Other questions are more detailed, specifically relating to papers the interviewees had written or topics they had expertise in or knowledge about. These interviews are conducted via video conferencing to facilitate detailed discussions and accommodate the experts' schedules.

The sixth step is the **Transcribe Interview**, where each interview is recorded and transcribed for thorough analysis, ensuring that the content is accurately captured and interpreted. The interview transcripts can be found in Appendix C. A systematic thematic analysis is performed on the transcripts to identify key themes and insights. The interviews are intended to be anonymous, so each interviewee is assigned a code (experts A, B, and C). Finally, in the **Process and Integrate Results into the Research** step, insights gained from the interviews are then integrated into the research findings and discussed. This is done by first summarizing the insights obtained from each interview. The responses are coded and categorized to extract information on reinforcing and balancing loops, interactions between mechanisms, and real-world examples. This qualitative analysis helped refine the CLDs by incorporating expert feedback, ensuring that the models accurately reflected the complexities of the CE for EV batteries.

The insights gained from these interviews are systematically integrated into the CLDs to enhance their accuracy and robustness. By validating and refining the models with expert feedback, the research aims to develop a comprehensive and reliable framework for addressing rebound effects within the circular economy for EV batteries. The detailed evaluation and incorporation of expert insights ensure that the models are well-grounded in real-world dynamics and stakeholder perspectives, ultimately supporting more effective and sustainable circular economy practices.

4 Modelling Rebound Mechanisms

4.1. Overview of Rebound Mechanisms in Circular EV Battery

In this section, the system dynamics models for the rebound mechanism in Circular EV Battery are described, and all of the detailed CLDs are presented in Appendix A. The model consists of the Base Structure and the Rebound Mechanisms. The Base Structure is presented in the form of a stock-flow diagram, while the rebound mechanisms are presented using the CLDs.

4.1.1. Recycling as a Key Intervention

In the context of the CE for EV batteries, multiple interventions can be implemented to promote sustainability and reduce environmental impact. These interventions include repurposing, reusing, repairing and refurbishing, and recycling EV batteries. Each pathway offers distinct advantages and faces unique challenges, as illustrated in the value chain diagram. However, for the purpose of this research, the focus will be exclusively on the recycling of LIBs.

Recycling is the process of collecting, processing, and using waste materials to create new materials or products (Alamerew and Brissaud, 2020). Recycling is a popular method to recover valuable materials like cobalt and lithium from the EoL of EV batteries (Winslow et al., 2018). Focusing on recycling as a primary intervention within the circular economy framework for EV batteries is justified due to the significant environmental and economic benefits it offers. Recycling LIBs from EVs can serve as an important alternative source of materials, which is crucial as the demand for these materials continues to rise with the growth of the EV market. According to Harper et al. (2019), recycling helps to address the serious waste-management challenges presented by the increasing number of EoL EV batteries, while also ensuring a stable supply of strategic elements and critical materials necessary for battery manufacturing. According to Huang et al. (2018), the recycling of spent LIBs helps in recovering these valuable metals, thereby reducing the need for virgin material extraction and minimizing the environmental impact associated with mining activities.

Moreover, the recycling process can substantially reduce the environmental footprint associated with the extraction of raw materials, which has been shown to have considerable environmental impacts, including the depletion of water tables and the generation of significant waste streams (Harper et al, 2019). By recovering materials such as lithium from spent batteries, recycling not only mitigates the need for new mineral extraction but also enhances the sustainability of the automotive industry.

Another key point is the economic aspect. Recycling spent LIBs provides an economic incentive by reducing the dependency on raw material imports and stabilizing supply chains for critical materials. With the European Union's emphasis on achieving a circular economy and the establishment of regulations like the Battery Directive and the Critical Raw Material Act, recycling is positioned as a strategic intervention to ensure resource security and economic stability (Huang et al., 2018).

4.1.2. Base Structure

The CLDs for rebound mechanisms will be created using a base structure derived from a stock and flow diagram adapted from Kubli et al., (2023). This structure has been adjusted to focus exclusively on recycling, with the exclusion of reuse, repurpose, and refurbish interventions to align with the research scope. It will be used to visually illustrate the material flow of EV batteries, providing a comprehensive view of their lifecycle stages from production through to disposal. Furthermore, a standardized conceptual model for circular EV batteries will be established, ensuring coherence and transparency across different analyses and applications. As the base structure is expanded, each identified rebound mechanism will be incorporated, enabling a comprehensive exploration of how these mechanisms interact within the circular economy framework for EV batteries. The base structure can be seen in Figure 5.

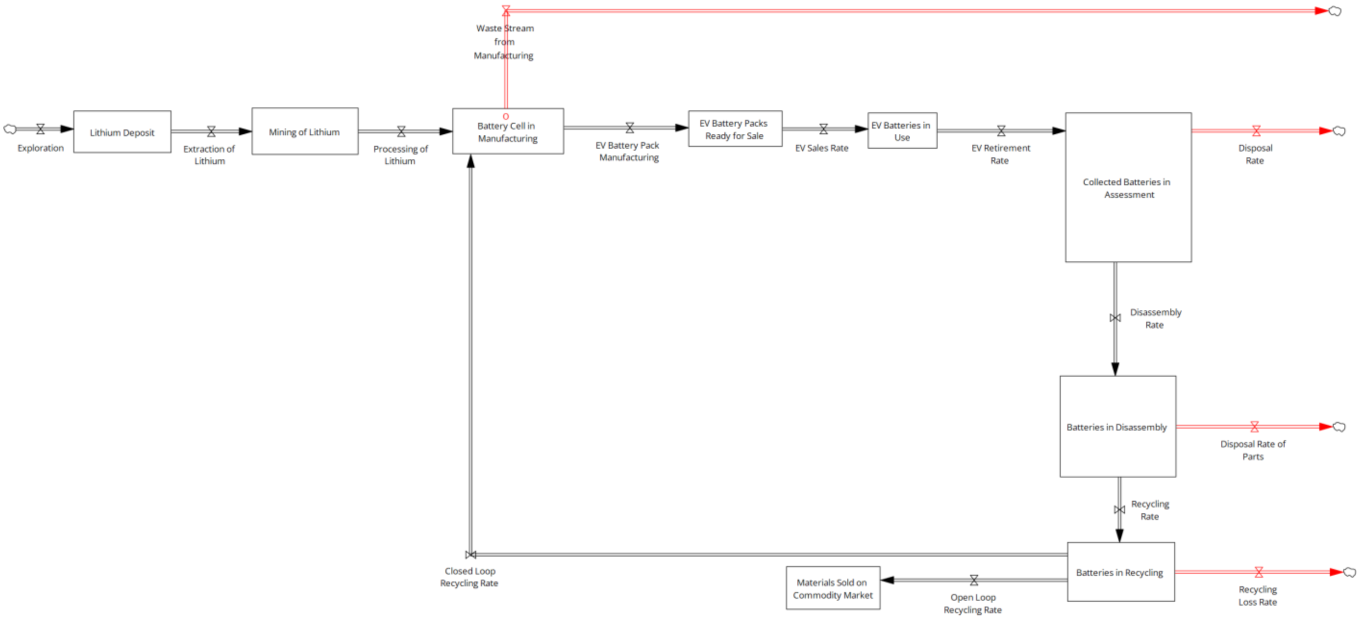

Figure 5 Base Structure for Circular EV Batteries

The primary flow starts from lithium exploration, goes through mining, processing, and manufacturing, and ends with the batteries being used in EVs. After their useful life, batteries are collected, assessed, disassembled, and recycled or disposed of. The closed-loop recycling rate indicates materials from recycled batteries being reused in manufacturing new batteries, promoting sustainability. There are also points in the process where materials are lost or disposed of, which are tracked through various disposal rates.

In this structure, the material flow starts with the Exploration of Lithium, resulting in Lithium Deposits, which are defined as the natural occurrence of lithium-bearing minerals or brines in sufficient quantity and quality to make their extraction economically viable for mining operations (Weimer et al., 2019). The existence of lithium deposits allows for more mining of lithium through the Extraction process. Mining of lithium activities allows for the processing of lithium and leads to the Manufacturing of LIBs. This allows for EV Battery Packs Ready for Sale, which results in EV Batteries in Use according to the EV Sales Rate. The EoL of EV Batteries starts when the battery is retired, resulting in Collected Batteries in Assessment, where they are tested for their state of health and assessed for further potential usage (Kubli et al., 2023). These batteries are then inspected in more detail and prepared for either repairing, refurbishing, or recycling. Because this study focuses on recycling, the intervention included in this structure is only for Recycling. Therefore, the Batteries in Recycling will depend on the Recycling Rate, which then goes back to the Battery Cell in Manufacturing through the Closed Loop Recycling Rate.

4.2. Adaptation of Rebound Mechanisms for Circular EV Batteries

Guzzo et al. (2024) have developed a comprehensive catalogue of rebound mechanisms within a general context, identifying 26 distinct mechanisms using qualitative SD modelling and CLDs. These mechanisms highlight the complex feedback loops and systemic responses that can hinder the effectiveness of sustainability interventions by generating unintended consequences.

However, not all of these mechanisms are directly applicable to the specific context of circular economy for EV batteries. The unique characteristics of EV batteries and the application of circular economy principles to them require adapting these general rebound mechanisms to fit the context. In this research, the rebound mechanisms identified by Guzzo et al. (2024) will be reviewed and translated to fit the context of circular EV batteries. This involves a detailed examination of each mechanism to determine its relevance and applicability. Key actors, causes, effects, triggers, drivers, and archetypes within the EV battery lifecycle will be identified and mapped onto the general rebound mechanisms to ensure contextual accuracy.

Based on the definition provided by Guzzo et al., (2024), **key actors**, such as firms, consumers, and policymakers play significant roles in the EV battery lifecycle and influence rebound mechanisms and their interactions within the system. The **causes** of rebound effects include technological advancements, policy changes, consumer behaviour, and market dynamics, which initiate or contribute to these effects. The **effects**, whether positive or negative, impact the sustainability and efficiency of the circular economy for EV batteries, such as increased resource consumption, changes in consumer demand, or shifts in environmental impact. **Triggers**, including regulatory changes, economic shifts, technological innovations, or changes in consumer preferences, activate or intensify rebound mechanisms. The **drivers** of these mechanisms include economic incentives, technological improvements, regulatory frameworks, and societal trends. Additionally, **archetypes**, which are recurrent patterns or models, describe common dynamics and structures within the system.

There are 2 archetypes present in these mechanisms. The first one is Fix That Fail which occurs when a sustainability action serves as a quick fix, enhancing resource consumption in the local system but also triggering the rebound mechanism. This may cause overall resource consumption to revert to its previous level or even increase (Braun, 2002). The second one is the Escalation archetype which occurs when two or more actors feel pressured or threatened by each other's actions. One actor's action prompts a counteraction from the other, increasing the sense of threat (Braun 2002).

Rebound Mechanisms are feedback structures that are initiated by triggers and influenced by drivers that result from a sustainability intervention being implemented in the analysed system that negate the potential sustainability goals and maintain the need for action to relieve societal pressure for sustainability (Guzzo et al., 2024).

The sustainability intervention can be in the form of efficiency or sufficiency actions such as:

- Improving battery design for EoL (abbreviated as BD), involves creating batteries that can be easily disassembled. This design approach facilitates the efficient separation and recovery of valuable materials like lithium, making the recycling process less costly. Simplified disassembly reduces the number of steps and techniques required for recycling, leading to lower processing costs.

- Improving reverse logistics (abbreviated as RL), which focuses on enhancing the efficiency and cost-effectiveness of managing returned products. This involves better planning of transportation routes and consolidating shipments, which reduces transportation and handling costs. Such optimizations are particularly important in the logistics of returning unused batteries, and the resulting cost savings can be passed on to consumers.
- Improving the battery production process (abbreviated as PP) involves streamlining manufacturing techniques to enable higher volume production more efficiently. This increase in production volumes achieves economies of scale, reducing the per-unit cost of batteries.
- Improving the recycling process (abbreviated as RP) increases the availability of recycled materials, boosting supply and potentially lowering raw material costs. This allows manufacturers to produce new batteries at a lower cost.
- Improving battery design for longevity (abbreviated as BL) by designing batteries that are more durable and less prone to failure, reducing the frequency of repairs or replacements. This saves consumers significant costs associated with battery replacements and maintenance.
- Increasing the number of charging infrastructure (abbreviated as CI) reduces wait times and optimizes charging patterns, enhancing the convenience and effectiveness of electric vehicle use. This promotes greater adoption of EVs, leading to more efficient energy usage and reduced reliance on fossil fuels.

The societal pressure for sustainability can be in the form of:

- Battery Collection Target
- Material Recovery Target
- Carbon Footprint Requirement
- Battery Efficiency target
- EV Adoption Target

These targets are outlined in various EU documents and regulations. The new EU Battery Regulation (2023/1542) sets specific collection targets for different types of batteries (European Commission, 2023). This regulation also establishes ambitious recovery targets for materials such as lithium, cobalt, nickel, and copper. Additionally, it mandates that battery production must include a carbon footprint declaration. Performance and durability metrics for batteries must be disclosed, and manufacturers are expected to meet specific standards to ensure long-term sustainability and efficiency according to this regulation. Furthermore, the EU Regulation on CO2 emissions sets specific CO2 emission targets, necessitating a significant increase in the uptake of electric vehicles to achieve these goals (EU, 2019).

To better organize all the rebound mechanisms, a classification will be made based on their structural and dynamic characteristics, as illustrated by their causal loop diagrams. Each class will represent a specific type of feedback mechanism that can lead to rebound effects and this results in 5 distinct classes. The classification follows the framework provided by Guzzo et al. (2024), however, the specific criteria and justifications for the classification have been developed independently. The classes are: 1) Consumption-Induced Mechanisms; 2) Production-Driven Mechanisms; 3) Substitution Dynamics Mechanisms; 4) Demand Response Mechanisms; and 5) Combined Income-Output Mechanism with Delay.

4.2.1 Consumption-Induced Mechanisms

This class of mechanism involves efficiency actions that reduce the cost of consuming a product or service. These mechanisms have a direct effect on the same good or process. The main actors in these mechanisms are consumers, who experience increased disposable income due to cost savings. This class operates at the micro level, focusing on individual decisions. The primary triggers are economic or financial, such as cost savings, and the drivers include the elasticity of demand for the product or service, which determines how much additional income influences consumption. The CLDs typically show a reinforcing feedback loop where cost savings lead to increased disposable income, which then drives higher consumption. This class of mechanisms employs the "Fix that Fails" archetype, where short-term solutions lead to long-term problems. In this context, consumers are the primary actors causing the rebound effect. By responding to increased efficiency with higher consumption, they inadvertently negate the intended benefits of resource savings. The translated mechanisms for this class can be found in Table 3. The red-coloured texts refer to the feedback loop in the CLDs for these mechanisms, which can be seen in Figure 6.

Table 3 Consumption-Induced Mechanisms

Rebound Mechanism	Actor	Cause	Trigger	Driver	Effect
Income Mechanism	Consumer	Efficiency Actions: • BD • RL • RP • PP • BL	Economic (Budget available for consumption)	Economic (Income Elasticity of Demand)	Reduced total cost of EV → increased disposable income → increased EV demand (R1)
Consumption Time Mechanism	Consumer	Efficiency Actions: • BD	Physical Constraint (Time Available for Using EV)	Economic (Time Elasticity of Demand)	Increased EV life → EVs are available to be used more often → increased EV demand (R2)
Motivational Consumption	Consumer	Efficiency Actions: • RP • BL • CI	Consumer Choice (Positive Perception towards EV)	Consumer Choice (Fraction of Change in Behaviour)	EVs are preferred → increased EV demand (R3)
Re-Spending	Consumer	Efficiency Actions: • BD • RL • RP • PP • BL	Economic (Budget available for consumption)	Economic (cost of consuming other goods)	Increased budget for consumption → Increased demand for other goods (R4)
Re-Spending with Limited Income	Consumer	Efficiency Actions: • BD • RL • RP • PP • BL	Economic (Budget available for consumption)	Economic (cost of consuming other goods)	Increased budget for consumption → Increased demand for other goods (R5), but the budget is limited (B5)

In the **Income** mechanism, the cost savings are transferred to consumers, lowering the total cost of EVs and freeing up budget for additional consumption. This triggers RE, where increased disposable income leads to higher demand for EVs due to the income elasticity of demand. Consequently, this increased demand escalates the resource consumption, driving societal pressure to meet battery efficiency, material recovery, carbon footprint, and collection targets. These pressures further amplify efficiency actions, reinforcing the cycle (R1). As demand for EVs increases, the demand for critical materials also rises, which can lead to environmental degradation and increased energy use in mining operations (Alonso et al., 2012). While EVs reduce CO2 emissions, the total environmental impact depends on the source of the electricity used to charge them. In regions where electricity is generated primarily from fossil fuels, increased use of EVs may not significantly decrease emissions and might even increase total energy consumption (Hawkins et al., 2012).

In the **Consumption Time** mechanism, improvement in battery design so that it can be used in a longer period of time makes EVs being more readily available for use without maintenance, thereby increasing the demand for EVs. This increased demand drives resource consumption, prompting societal pressures to meet battery performance standards. These pressures, in turn, reinforce efficiency actions, completing the cycle (R2). With the ability to drive longer distances without the need for recharging, users may choose to use their EVs for trips they might not have considered before, thus increasing total driving distance and energy consumption (Greene et al., 2012). A typical EV battery might last several years before needing replacement. However, increased usage can shorten this expected lifespan, leading to more frequent replacement cycles (Ambrose and Kendall, 2016).

In the **Motivational Consumption** mechanism, positive perceptions of EV batteries among consumers lead to an increased preference towards EVs, encouraging more consumers to adopt them, thus increasing the demand for EV batteries. As demand rises, there is an increase in general resource consumption. The reinforcing loop (R3) highlights how positive perceptions can perpetuate increased demand. Consumers increase their consumption because they believe the new technology or product, which is EV, is better, more sustainable, or offers improved performance that justifies increased use (Horner et al., 2016). This perception can lead to a behavioural change where users take longer trips or use their EVs more frequently, believing that the environmental benefits justify the increased usage (Borenstein, 2015).

In the **Re-Spending** mechanism, reduced costs of EVs lead to increased budgets available for consumption, which in turn drives demand for other goods such as upgrades to EV features, green investments, and other sustainable technologies, thereby potentially increasing overall resource consumption (Mokhtarian and Chen, 2004). The reinforcing loop (R4) is driven by the efficiency improvements that reduce the costs of using EV batteries, leading to increased demand for other goods such as green investments and sustainable technologies (Gillingham et al., 2013).

In the **Re-Spending with Limited Income** mechanism, as consumers save money due to efficiency improvements, they may reallocate their budget towards other expenditures, including alternative products such as public transportation or other sustainable solutions. This dynamic is captured in the reinforcing loop (R5), where efficiency improvements lead to reduced costs, increasing the available budget and potentially boosting demand for EV batteries. The balancing loop (B5) is that the additional demand for EV batteries and other products is limited by consumer budgets (Borenstein, 2015).

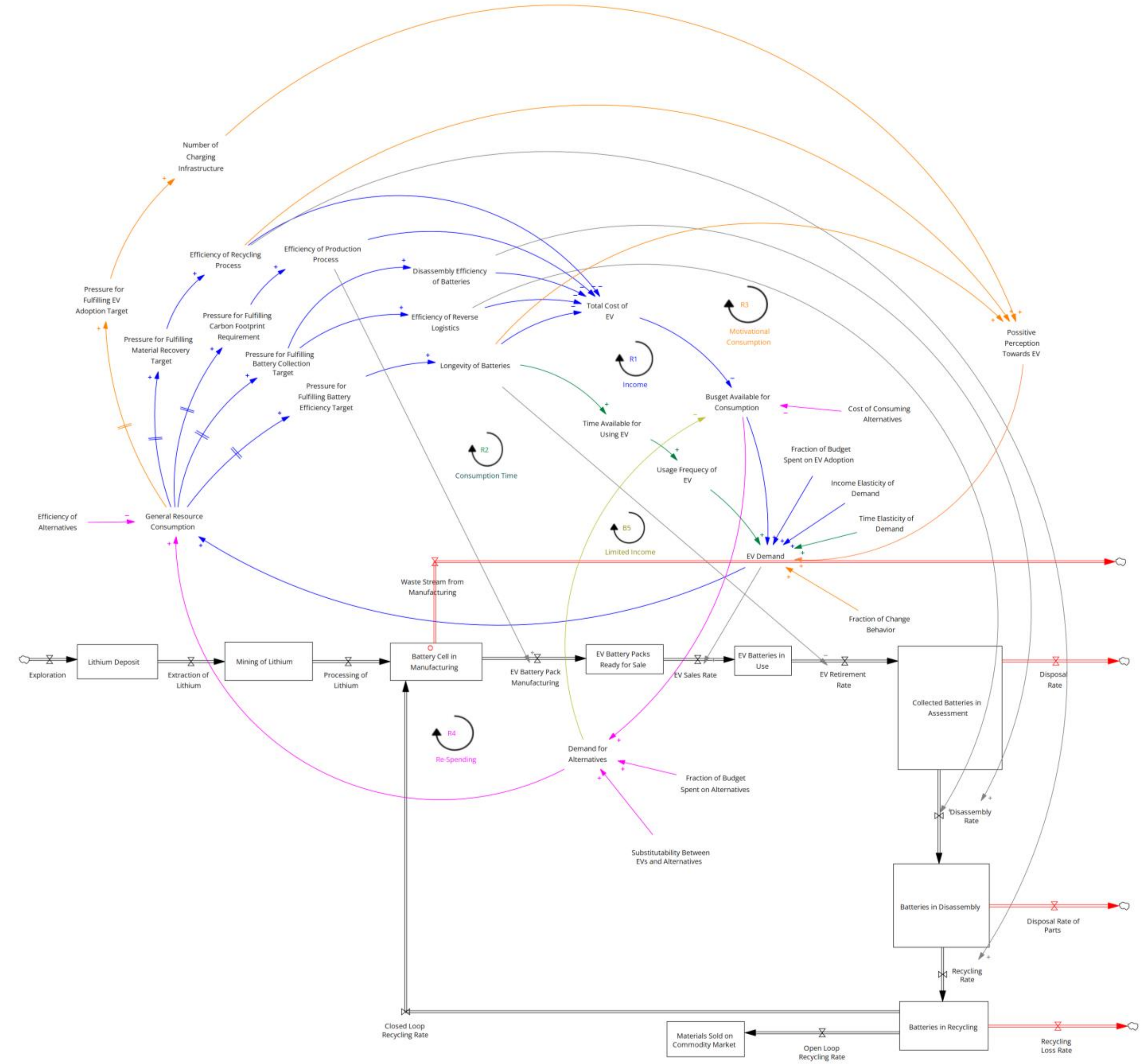

Figure 6 Consumption-Induced Mechanism

4.2.2 Production-Driven Mechanisms

This class of mechanism focuses on efficiency actions in production processes that lower production costs. These mechanisms have a direct effect on production output and potentially indirect effects on related goods and processes. The main actors are firms or producers who reinvest cost savings into increased production. This class operates at both micro and meso levels, focusing on firm-level decisions and interactions within supply chains. The primary triggers are economic or financial, such as reduced production costs and increased profits. Market demand and the elasticity of supply, which determines how much production increases in response to lower costs, act as the main drivers. In the CLDs, the diagrams illustrate a feedback loop where reduced production costs lead to increased production, which can lower prices and boost consumption. This set of mechanisms exemplifies the "Fix that Fails" archetype, where firms, as the primary actors, inadvertently trigger rebound effects. When companies implement efficiency improvements, they often unintentionally stimulate increased demand for their products, which can offset the benefits of those efficiencies. The translated mechanisms for this class can be found in Table 4. The red-coloured texts refer to the feedback loop in the CLDs for these mechanisms, which can be seen in Figure 7.

Table 4 Production-Driven Mechanisms

Rebound Mechanism	Actor	Cause	Trigger	Driver	Effect
Output	Firm	Efficiency Actions: • BD • RL • RP • PP	Economic (Company profits)	Company Choices (fraction of profits reinvested)	Reduced cost of battery production → increased company profit → increased battery production (R6)
Production Time	Firm	Efficiency Action: • BD • PP	Physical Constraint (Time constraint in the process)	-	Reduced time constraint in production process → increased battery production (R7)
Re-Investment	Firm	Efficiency Action: • RL • RP • PP	Economic (company profit)	Company choices/ economic, Good Attributes (fraction of profit reinvest, cost of advance process)	Increased company profit → reinvest in alternative process (R8).
Cost-Dependent Output	Firm	Efficiency Action: • RL • RP • PP	Economic (company profit)	Company Choices, Good Attributes (fraction of profit reinvested)	Increased company profit → invest in new process →reduced profit → reinvest in the more efficient process (R9).

In the **Output** mechanism, As the efficiency of these processes improves, the costs associated with battery production decrease, which means higher profit margins for companies, as they can produce batteries more cheaply while maintaining or increasing sales prices. This increase in profitability provides companies with additional capital to reinvest in their processes that can be used to further scale their production capabilities or to invest in even more advanced efficiency measures (Nykvist and Nilsson, 2015), creating a reinforcing loop (R6).

In the **Production Time** mechanism, as the time constraints decrease, the production of batteries increases. This increase in production capacity leads to a higher output of EV batteries, which in turn can drive down costs due to economies of scale and more efficient use of resources (Nykvist and Nilsson, 2015). The reinforcing loop (R7) depicts the increased production capacity leads to further efficiency improvements.

In the **Re-Investment** mechanism, the actions reduce the costs associated with battery production, and the decreased costs increase company profits, which are then partially reinvested into more advanced processes (R8). The production of batteries then increases, resulting in higher output and potentially lower prices for consumers, driving higher demand and reinforcing the cycle of production and reinvestment (Sheldon and Deshazo, 2017). This increased efficiency and reinvestment cycle can lead to higher production and consumption of batteries, thereby potentially increasing overall resource consumption.

In the **Cost-Dependent Output** mechanism, actions lead to a reduction in the costs associated with these activities, such as lower expenses in battery production and recycling. With these cost reductions, it can then be transferred to the advanced processes (lower cost for this advanced process), making the companies that use this advanced process gain more profit (Nykvist and Nilsson, 2015), creating a reinforcing cycle of continuous efficiency improvements and cost savings (R9). This leads to a significant increase in the production and consumption of EV batteries.

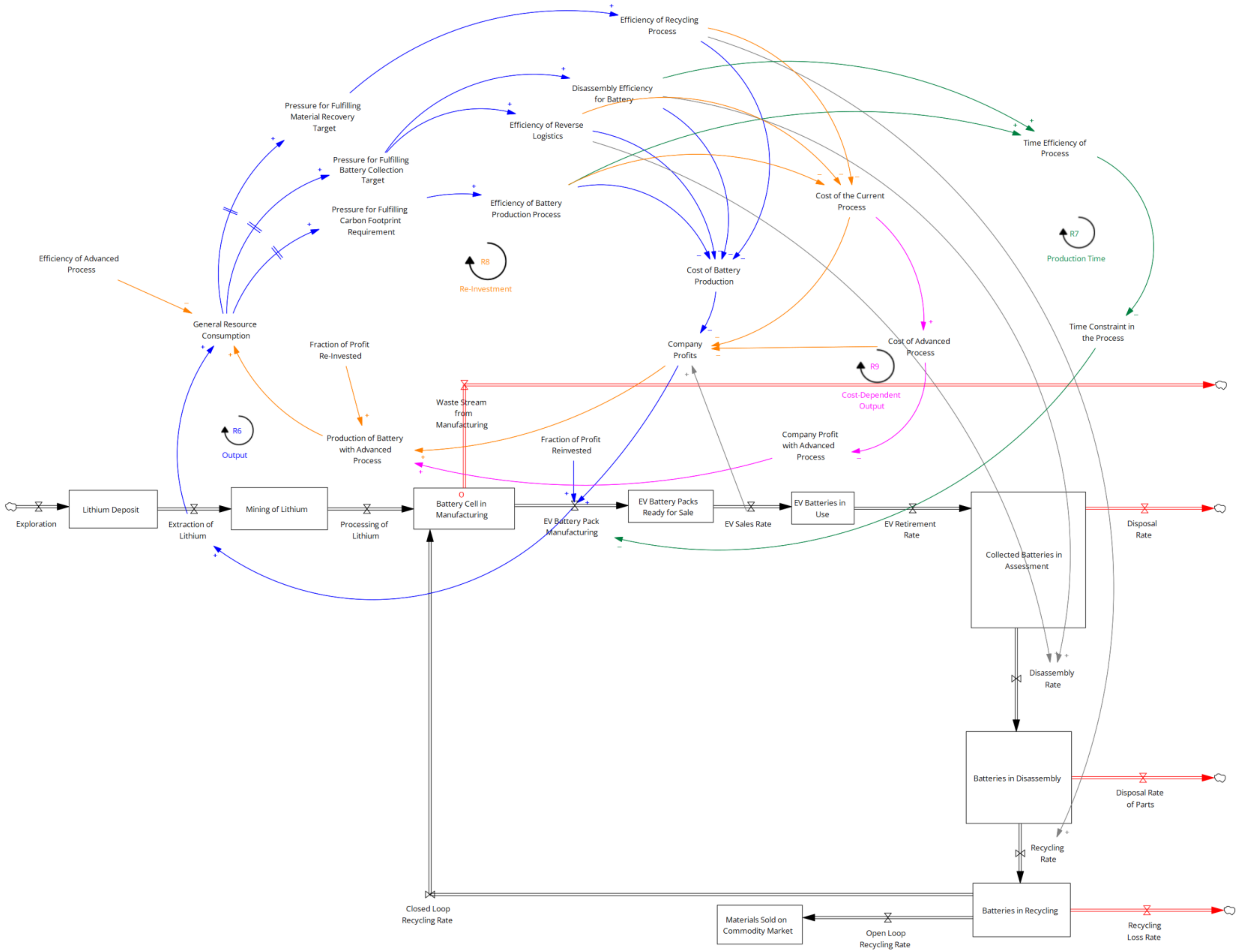

Figure 7 Production-Driven Mechanisms

4.2.3 Substitution Dynamics Mechanism

This class of mechanism involves efficiency actions that alter the relative costs of different products or services, prompting consumers to switch preferences. These mechanisms have an indirect effect on other goods or processes. The actors involved can include both consumers and firms, depending on whether the substitution is in consumption or production. This class operates at micro to macro levels, as substitution can affect individual choices as well as broader market trends. The triggers involve changes in the relative costs of products or services, and the drivers include the substitutability and relative efficiency of the products or services involved. The CLDs show how changes in the relative costs of products lead to substitution effects, with feedback loops reflecting changes in demand for both the original and substituted products. The "Fix that Fails" archetype highlights mechanisms where attempts to solve a problem end up exacerbating it over time. In this scenario, both consumers and firms can be the actors causing the rebound effect. The translated mechanisms for this class can be found in Table 5. The red-coloured texts refer to the feedback loop in the CLDs for thess mechanisms, which can be seen in Figure 8.

Table 5 Substitution Dynamics Mechanisms

Rebound Mechanism	Actor	Cause	Trigger	Driver	Effect
Substitution Mechanism	Consumer	Efficiency Actions: • RP • PP • CI • BL • RL	Economic (Total cost of EV)	Economic (Substitutability between EVs and Alternatives, total cost of consuming alternative vehicles)	Lower total cost of EV → EVs are more preferred compared to alternatives → increased EV demand (R10)
Motivational Substitution	Consumer	Efficiency Actions: • RP • CI • BL	Consumer Choices (favouring of EV instead of alternatives)	Consumer Choices, Good Attributes (perception towards alternatives, substitutability between EV and alternatives)	Positive perception towards EV → increased EV demand compared to alternatives (R11)
Factor Substitution	Firm	Efficiency Actions: • RL • RP • PP	Economic (cost of Advanced Process)	Economic, Good Attributes (substitutability between Advanced Process and Traditional Process)	Advanced Process becomes more favorable → increased demand for Advanced Process (R12)

In the **Motivational Substitution** mechanism, the improvement enhances the positive perception of EV batteries, making them more attractive to consumers (Gaines, 2014). As a result, the demand for EV batteries rises, reinforcing the efficiency loop (R11). To balance this effect, efficiency improvements in alternative products (B11) such as public transportation or biofuels are also necessary. If these alternatives become more efficient, they can act as substitutes for EV batteries, potentially reducing the overall demand for batteries and mitigating consumption.

In the **Factor Substitution** mechanism, as the efficiency of the advanced process improves, the costs of this process decrease, making it more attractive compared to current processes (less efficient process) (Nykvist and Nelsson, 2015). Consequently, there is a shift in favour of advanced processes over the current process (B12), leading to an increased demand for advanced processes. The reinforcing loop (R12) shows how improved efficiency and reduced costs of advanced processes can enhance its attractiveness, leading to higher demand, stimulating further improvements and investments in this process, perpetuating a cycle of efficiency gains and cost reductions, and can also lead to increased general resource consumption.

There is a mechanism called the **Composition** mechanism, but this mechanism is irrelevant to this research. This mechanism shows how efforts to enhance the efficiency of processes in Sector A can influence its costs, thereby affecting its competitiveness and demand relative to Sector B. Circular EV battery systems are focused on a single sector, which is the lifecycle of batteries from production to recycling. There will be no direct relevance to a competing sector, making the two-sector model less applicable. Diekmann et. al. (2021) highlight efforts regarding circular economy strategies specifically within the EV battery sector to improve recycling technologies, material recovery, and the design of batteries for easier disassembly, emphasizing sector-specific advancements rather than cross-sector interactions. The circular EV Batteries also focus on internal sector improvements such as the development of efficient recycling processes, second-life applications for used batteries, and the economic implications of these advancements within the battery sector, rather than referencing other competing sectors (Harper et. al., 2019).

The other mechanism is **Sectoral Allocation**. Sectoral allocation involves redistributing resources, investments, or activities across different sectors to achieve overall economic or environmental goals. CE for EV batteries focuses on deepening investments within the battery sector to support sustainable practices, such as developing advanced recycling techniques, improving battery design for disassembly, and facilitating second-life applications. The aim is to create a sustainable and self-sufficient ecosystem within the sector. Hannan et. al (2021) explore the lifecycle management of EV batteries and highlights the need for investments to improve recycling and sustainability within the battery sector. It emphasizes enhancing circularity within this sector instead of shifting resources to other sectors.

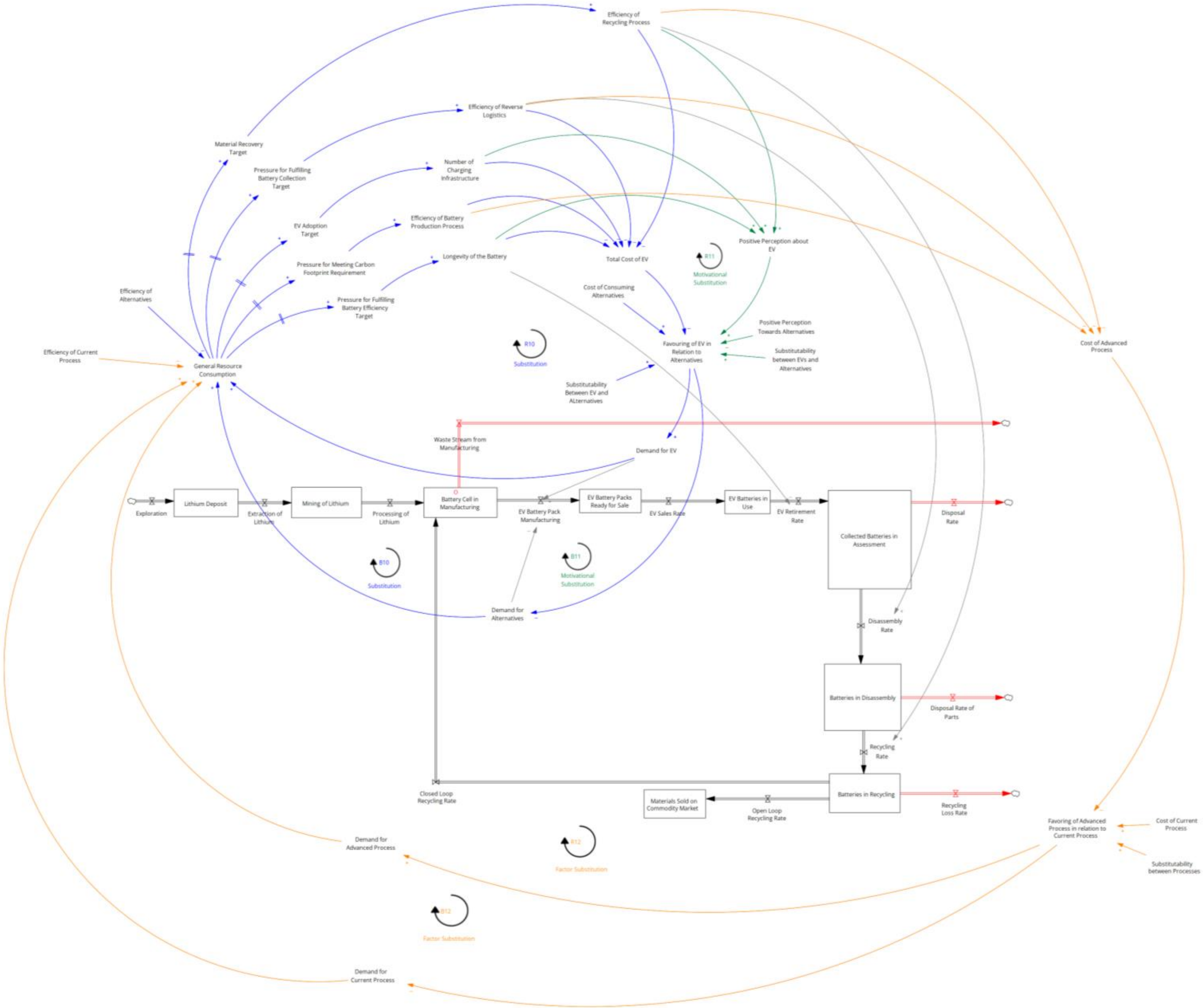

Figure 8 Substitution Mechanisms

4.2.4 Demand Response Mechanism

This class describes how demand adjusts in response to changes in supply or efficiency, often leading to increased overall consumption. These mechanisms can have direct, indirect, or economy-wide effects, depending on the nature of the demand adjustment. The actors include multiple entities such as consumers, firms, and sectors. This class operates at meso to macro levels, influencing sectoral or national consumption patterns. The triggers are a combination of economic or financial factors, consumer choices, and company choices. The drivers include market dynamics, societal pressures, and the responsiveness of supply to changes in demand. The diagrams typically depict feedback loops where increased efficiency leads to lower costs, which then drive higher demand and consumption, counteracting the initial efficiency gains. In this context, the archetype at play is "Escalation," where the interaction between consumers and firms drives the rebound effect. As firms enhance efficiency and consumers adjust their usage patterns, each party's actions lead to increased demand and consumption, creating a cycle that escalates resource use rather than reducing it. The translated mechanisms for this class can be found in Table 6. The red-coloured texts refer to the feedback loop in the CLDs for these mechanisms, which can be seen in Figure 9.

Table 6 Demand Response Mechanisms

Rebound Mechanism	Actor	Cause	Trigger	Driver	Effect
Demand Adjustment Mechanism by Sufficiency	Consumer, Firm	Sufficiency Actions: • BL	Economic (EV Demand)	Economic (Supply of EV Battery)	excess supply relative to the demand → increased other's demand for EVs (B13)
Demand adjustment initiated by efficiency	Consumer, Firm	Efficiency Actions: • BL • BD • RP	Economic (EV demand)	Economic (supply of EVs with Current Technology)	excess supply vs lower demand for EV → reduced price for EV → attract additional demand for EV → increased demand for EV (B14)
Demand adjustment with investment adjustment	Consumer, Firm	Efficiency Actions: • BL • BD • RP	Economic (profit from additional demand)	Company choices (fraction of profit reinvested)	excess supply relative to demand → decrease in battery prices → further stimulate additional demand for the batteries → higher profits for manufacturers → reinvested in expanding manufacturing capacity → increased EV production (B15a)
Re-Design	Firm	Efficiency Actions: • BL • BD	Economic, Good Attributes (Efficiency, cost)	Good Attributes (Design of Additional Feature for Product)	Lower cost anticipated to use EVB →drive design opportunity for EVB because of cost savings → increased design for additional feature → Reduced efficiency of EVB because the additional feature might consume more energy (B16)

Rebound Mechanism	Actor	Cause	Trigger	Driver	Effect
Supply Adjustment	Consumer, Firm	Sufficiency Actions: • BL • RL	Economic (supply)	Economic, Company Choices (demand for product, choice of other companies to fight for excess demand)	excess demand vs supply for EV Batteries → other companies will try to give additional supply of EVB to accommodate the demand → Increased supply (B17)
Producer-induced demand adjustment	Firm	Efficiency Actions: • RL • RP	Economic (demand of process)	Economic (supply of process)	Reduced price of the process → additional demand for the process (B18)

In **Demand Adjustment initiated by Sufficiency**, sustainability actions lead to a smaller gap between current and intended individual resource consumption, promoting more sustainable behaviour. As individuals consume fewer resources, the demand for new EV batteries decreases, resulting in an excess supply relative to the demand (Nykvist and Nilsson, 2015). This surplus supply of EV batteries causes market prices to drop and may trigger other consumers to purchase EV batteries, partially counteracting the initial reduction in individual consumption (Holland et al., 2016). This dynamic is represented by the balancing loop (B13), where the drop in demand leads to excess supply and reduced prices, which then stimulates additional demand from other consumers.

In **Demand Adjustment** initiated by Efficiency, the improvements reduce the operational and production costs associated with batteries, making EV batteries more attractive to consumers, thus increasing the demand for batteries. As the demand increases, the supply also increases to meet this higher demand. If the supply exceeds the demand, this creates an excess supply in the market. To balance this excess, companies may lower the prices of EV batteries. The reduced prices then further stimulate additional demand from other consumers who were previously unable or unwilling to purchase at higher prices (Gillingham et al., 2013), leading to a potential rebound effect. The balancing loop (B14) in this mechanism illustrates how the initial increase in efficiency and subsequent cost reductions can lead to an increase in demand.

In **Demand Adjustment with Investment Adjustment**, the efficiency actions improve the overall efficiency of EV batteries, making them more attractive to consumers by lowering operational costs. This drives up demand for EV batteries, and so does the supply of EV batteries to meet this demand. The balancing loop (B15) shows that excess supply relative to demand results in a decrease in battery prices, which can further stimulate additional demand for the batteries. The reinforcing loop (R15) highlights the role of profits from increased demand. As additional demand for EV batteries generates higher profits for manufacturers, a fraction of these profits are reinvested in scaling up production processes, which includes investing in further efficiency improvements and expanding manufacturing capacity (Gaines, 2014), leading to higher consumption.

In the **Re-Design** mechanism, improved EV battery efficiency reduces costs, allowing for innovation and enhanced features. However, new features may consume more energy (Holland et al., 2016), reducing overall battery efficiency and increasing operational costs, potentially making EVs less appealing and affecting market competitiveness. A balancing loop (B16) shows that while new features enhance products, they also raise costs. This cycle can lead to rebound effects, where increased efficiency and added features may raise overall resource use.

In the **Supply Adjustment** mechanism, as the efficiency actions take effect, they improve the overall efficiency of EV batteries, thereby reducing individual resource consumption and increasing firm sustainability. This enhancement leads to sufficiency actions, where the demand for EV batteries is adjusted based on sustainable practices. Increased efficiency in EV battery production also leads to a rise in supply (Gaines, 2014). The balancing loop (B17) indicates that excess demand relative to supply can drive up prices, which in turn encourages other companies to enter the market and increase the overall supply.

In the **Producer-induced Demand Adjustment** mechanism, because of increased efficiency in the EV production-related processes, more EV batteries will be produced, which will eventually lead to a reduced demand for further production processes, leading to an excess supply relative to demand. This excess supply will result in a reduction in the price of the processes. As the price of the process decreases, it will stimulate additional demand for the process in other companies. However, this additional demand will eventually balance out with the increased supply (B18). When the demand for EV batteries increases, manufacturers ramp up production to meet this demand (Nykvist and Nilsson, 2015). If the supply of EV batteries exceeds the demand, it leads to a decrease in prices. Lower prices can stimulate additional demand, helping to balance the market. As more companies adopt efficient processes, the competition increases, potentially driving prices down further and increasing demand even more.

The other mechanism is **Sector-induced Demand Adjustment**. This mechanism is not relevant for analysing circular EV batteries due to its emphasis on interactions with other sectors, which is not relevant to the focus of circular economy strategies for EV batteries. Circular EV battery strategies are concerned with maximizing the lifecycle of specific materials. Instead, the focus is on intensifying investments within the battery sector to enhance circularity and integrate sustainable practices, such as developing advanced recycling techniques, improving battery design for disassembly, and facilitating second-life applications.

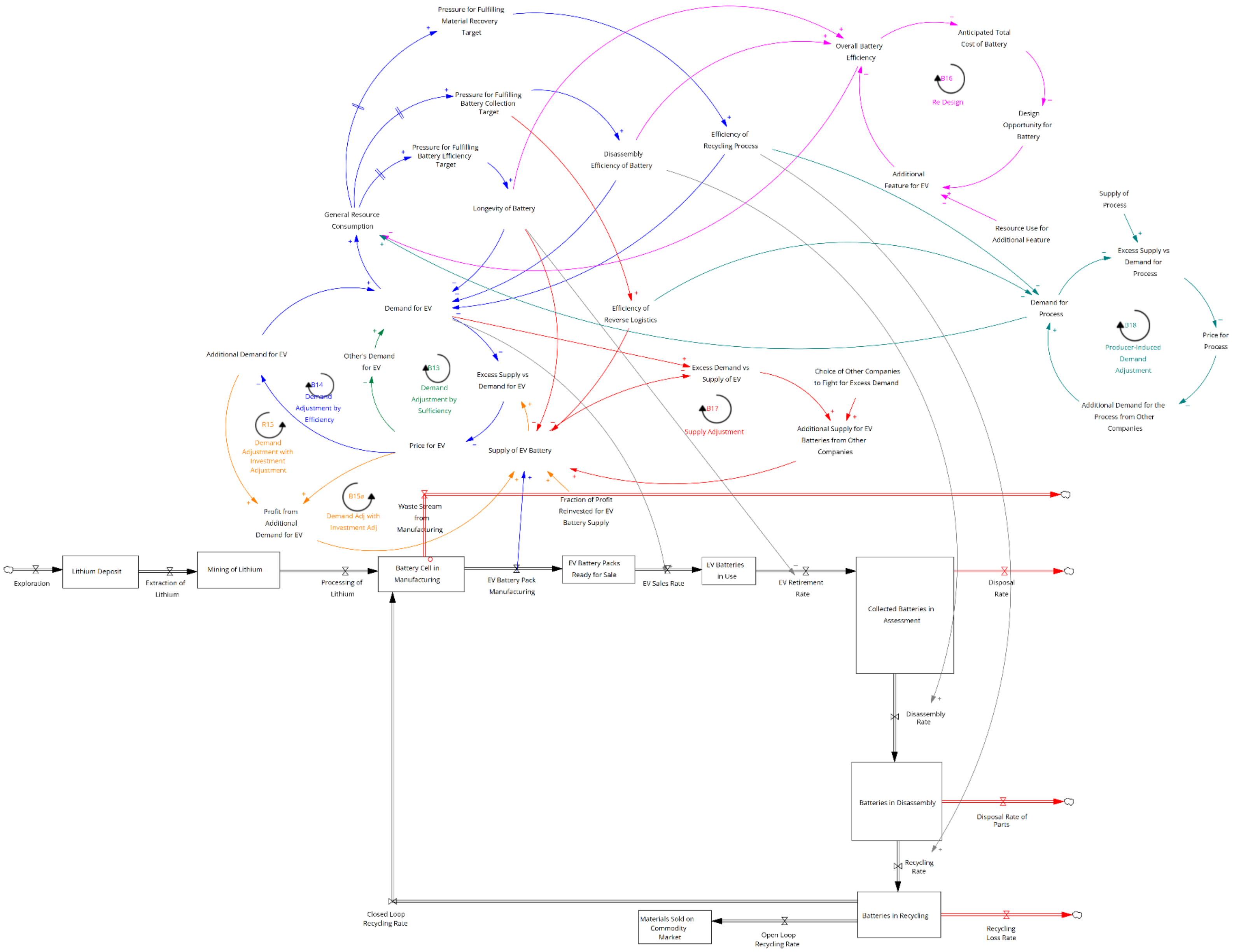

Figure 9 Demand Response Mechanisms

4.2.5 Combined Income-Output Mechanism with Delay

This class involves the interaction of income and output mechanisms with time delays, leading to more complex and delayed rebound effects. These mechanisms are characterized by initial efficiency improvements that result in cost savings or increased income, which are then reinvested into expanding production or consumption capacity over time. This delayed response can lead to increased resource consumption in the long term, counteracting the initial benefits of the efficiency improvements. The CLD involves multiple feedback loops with time delays. There are reinforcing loops where initial savings or efficiencies lead to reinvestment and subsequent increases in production or consumption. These diagrams also include balancing loops that reflect the delayed responses in the system, such as the time it takes for reinvested savings to result in increased production capacity or for consumers to change their consumption patterns. In this scenario, the "Fix that Fails" archetype is evident, characterized by the interplay between consumers and firms. When firms enhance efficiency, and consumers adapt their behaviours, their interactions can inadvertently lead to increased overall consumption. The translated mechanisms for this class can be found in Table 7. The red-coloured texts refer to the feedback loop in the CLDs for these mechanisms, which can be seen in Figure 10.

Table 7 Combine Income-Output

Rebound Mechanism	Actor	Cause	Trigger	Driver	Effect
Economies of Scale	Consumer, Firm	Efficiency Actions: • RL • RP • PP	Economic (budget available for consumption)	Economic, Company choices (income elasticity of demand, fraction of profit reinvested)	Increased budget available for consumption → increased demand for EV (R19a), at the same time increase company profit → as the efficiency increases over time, it further reduces the total cost of EVs (R19b)
Market Price	Consumer, Firm	Efficiency Actions: • RL • RP • PP	Economic (cost of the process)	Economic, Company choices Good Attributes (cost of consuming, fraction of profit reinvested, efficiency of alternative process)	Reduced cost of the current process → increased profit for investing in the advanced process (R20a); at the same time, reduced total cost of EV from current process → increased budget available for consumption → increased demand for EV from (R20b)

In the **Economies of Scale** mechanism, the increased efficiency makes the supply of batteries more attractive. As the supply increases to meet demand, other companies might also step in to supply this process, aiming to capture the excess demand. The reinforcing loop (R19a) shows how the increased efficiency and reduced costs of the product lead to higher demand for

EV batteries, resulting in higher profits for companies due to cost savings and potential market advantages which are then partially reinvested into further scaling and improving the product. The reinforcing loop (R19b) highlights how increased production due to higher demand can lead to economies of scale in the processes used for EV batteries.

In the **Market Price** mechanism, as the efficiency of EV batteries increases, the costs of consuming them decrease, making EV batteries more attractive compared to other products or processes. Consequently, there is a shift in favour of EV batteries, leading to increased demand for them. The reinforcing loop (R20a) depicts how improved efficiency and reduced costs of EV batteries enhance their attractiveness, leading to higher demand and generating higher company profits. A portion of these profits is reinvested into further scaling and improving the processes used for EV batteries. Reinforcing loop (R20b) shows how increased company profits from EV batteries are reinvested in scaling the processes used for EV batteries. This reinvestment leads to economies of scale, further reducing the costs of consuming EV batteries and increasing their demand.

In the **Labor Income** mechanism, the mechanism is caused by productivity gains that lead to higher labour income, which subsequently increases consumption across various sectors. Circular EV battery strategies concentrate on improving the lifecycle of battery materials within the sector, rather than broad economic impacts like labour income and consumption patterns. Therefore, this mechanism is irrelevant to this context.

In **Labor Income with Limited Labor Supply** mechanism, the mechanism highlights the interaction between increased labour income and a limited supply of labour, potentially affecting production and economic activity. Circular EV battery initiatives are primarily concerned with material recovery, recycling technologies, and extending battery life, which does not directly relate to the broader economic dynamics of labour supply and income. Harper et. al (2019) discusses the specific challenges and technological advancements within the battery sector, underlining the focus on sector-specific improvements rather than labour market dynamics. Therefore, this mechanism can be considered irrelevant in the context of circular EV batteries.

In the **New Economic Activity** mechanism, the mechanism occurs when efficiency improvements lead to new economic activities and industries emerging as a result. However, circular EV battery strategies aim to enhance sustainability and efficiency within the battery sector, including developing advanced recycling processes and second-life applications for batteries. This is distinct from generating new economic activities in other sectors. Gaines et al. (2020) highlight the importance of specific recycling and reuse strategies within the battery sector, emphasizing sector-specific circular practices over broad economic activities.

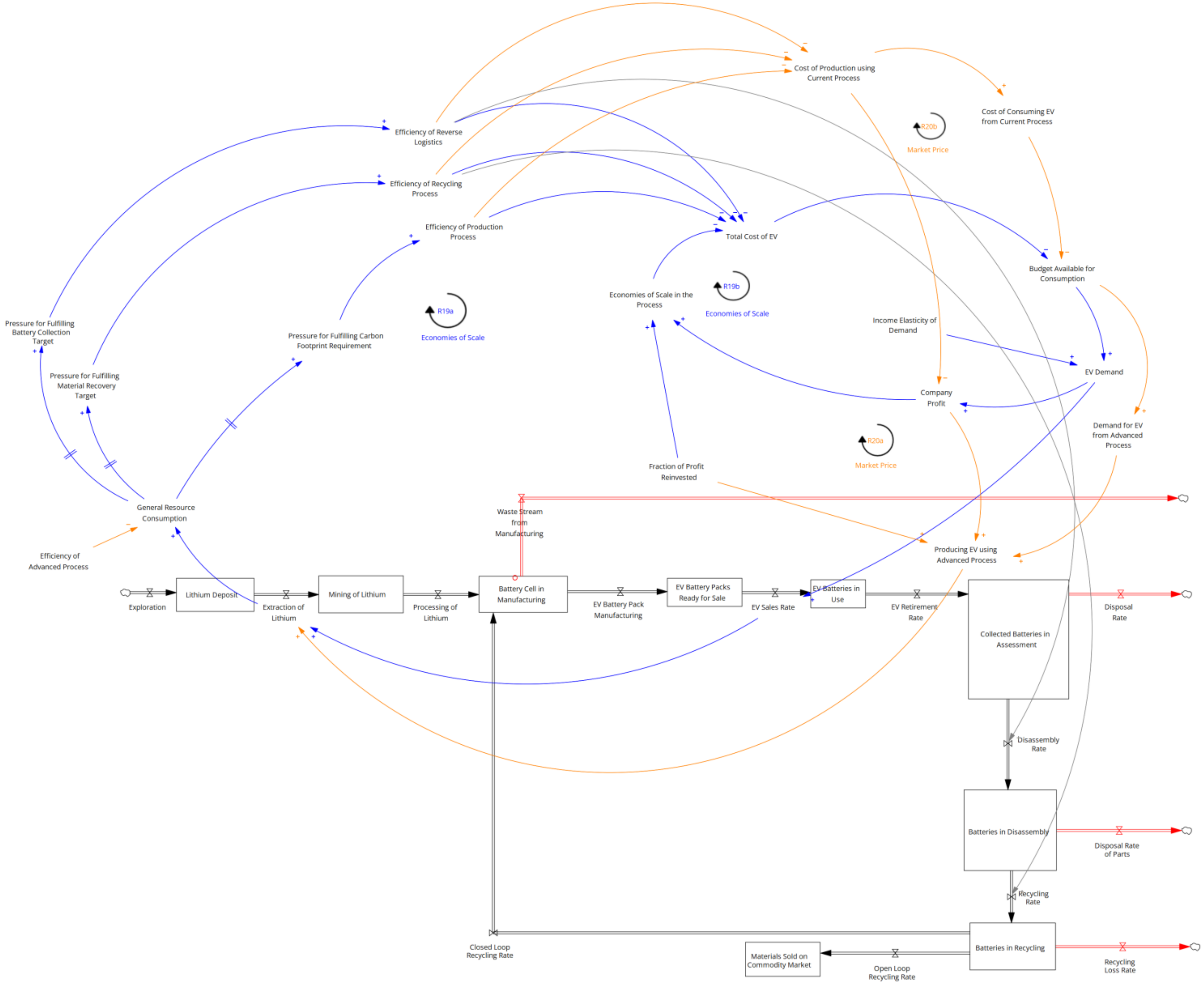

Figure 10 Combined Input-Output Mechanism

4.3. The Most Significant Rebound Mechanisms

The selection process for choosing the most significant rebound mechanism will involve analysing the created CLDs and integrating them with insights gained from the literature review. The literatures used for this selection are:

- Colmenares et al. (2020): The paper provides an extensive review and analysis of the rebound effect (RE) in the context of energy efficiency improvements. The study synthesizes findings from 118 studies on the RE, including 61 empirical studies conducted between 2016 and 2018, and presents a detailed examination of both ex-post and ex-ante studies.
- Brockway et al. (2021): The paper reviews the role of efficiency and the potential for economy-wide rebound effects in global energy consumption scenarios. It explores the historical relationship between energy consumption and GDP, the impact of improved energy efficiency, and the extent to which rebound effects are included in integrated assessment and global energy models.
- Lange et al. (2021): The paper provides an extensive review and analysis of the RE in the context of energy efficiency improvements. The study develops a novel typology to address the diverse and ambiguous definitions of RE, distinguishing between rebound mechanisms and rebound effects across micro, meso, macro, and global economic levels, and over short and long time frames. It systematically integrates findings from existing classifications and empirical estimates, highlighting the complexities and discrepancies in RE research, and emphasizes the need for targeted policies to mitigate rebound effects.
- Metic and Pigosso (2022): The paper provides an extensive review and analysis of the RE within the context of the CE. The study systematically examines the definitions, triggers, types, mechanisms, and measurement approaches of RE, proposing a conceptual framework to address the complexities of these effects. This comprehensive review highlights the intricate interplay between CE initiatives and RE, underscoring the necessity for informed policies to mitigate adverse impacts and enhance sustainability outcomes.
- Zink and Geyer (2017): The paper provides an extensive review and analysis of the RE in the context of CE initiatives. It introduces a novel typology to address diverse definitions of CE rebound, distinguishing between direct and indirect effects across various economic levels. The study systematically integrates findings from existing classifications and empirical estimates, highlighting the complexities and potential unintended consequences of CE activities.
- Sorrell (2009): This paper focuses on defining the direct rebound effect, addressing conceptual and empirical challenges in its estimation, and highlights the potential overestimation in previous studies due to methodological issues. The paper emphasizes the importance of understanding the rebound effect to ensure effective efficiency policies.

4.3.1. Consumption-Induced Mechanisms

Income Mechanism

In the CLD for the Income mechanism in Figure 6, the trigger of this mechanism is the budget available for consumption, and the driver is income elasticity of demand. This mechanism is also influenced by an external factor, which is the fraction of the budget spent on EV adoption. This external factor can be considered uncertain because this fraction can be influenced by other factors that are not analysed in the CLD. This mechanism also has a strong relation to CE Principles, especially the intervention that is analysed in this research, which is recycling. This is because, in the CLD, it can be seen that the efficiency actions of this mechanism have a direct impact on the EV retirement rate, disassembly rate, and recycling rate.

From the literature, there are sources that mention the significance of this mechanism. Colmenares et al. (2020) and Brockway et al. (2021) mentioned that the income effect significantly contributes to the direct rebound effect, and empirical studies indicate that the income effect can be substantial, often underestimating the net savings achieved by energy efficiency measures. Schmitz and Madlener (2020) provide estimates where income effects are shown to be smaller in magnitude than substitution effects, but still significant enough to warrant attention in policy design. Lange et al. (2021) reviewed empirical studies that highlight the significance of income effects as a major driver of rebound effects, consistently pointing to the importance of understanding how increased income from energy efficiency improvements influences consumption behaviours. Sorrell (2009), Zink and Geyer (2017), and Metic and Pigosso (2022) highlight how efficiency improvements can lead to lower prices and increased disposable income, which in turn can drive higher overall consumption, counteracting the intended sustainability benefits of such improvements.

Consumption Time

In the CLD for the Consumption Time mechanism in Figure 6, the trigger is the time available for using an EV, and the driver is the time elasticity of demand. There is no other external factor that might influence this mechanism. However, this mechanism does not directly affect the Recycling phase, which is the main intervention analysed in this research. The time available for using an EV can influence the EV lifetime, which also has a direct impact on the EV retirement rate, but this mechanism does not highlight how to close the loop and only highlights how to slow the loop.

From the literature, Colmenares et al. (2020) highlighted that time savings can significantly impact energy consumption patterns, which can result in behavioural changes that have to be considered to accurately estimate the overall energy savings from efficiency improvements. Metic and Pigosso (2022) also mentioned how improvements in efficiency that save time can paradoxically increase overall consumption, thereby diminishing the expected sustainability gains from such efficiencies.

Motivational Consumption

In motivational consumption in Figure 6, the efficiency action directly impacts the positive perception towards EVs. Compared to the variable Budget Available for Consumption, this perception is more abstract and harder to measure. Motivation involves a complex interplay of factors, including psychological, social, and environmental influences, which complicates the measurement process (Sekhar et al., 2013). The driver of this mechanism is the Fraction of Change in Behaviour, which is also intangible and uncertain compared to a factor like Income Elasticity of Demand. In relation to the Recycling intervention, the efficiency action has a direct impact on the recycling rate, so this mechanism is integrated with CE principles.

From the literature, Lange et al. (2021) reviewed studies indicating that preference changes are a significant driver of rebound effects, and in the long run, this mechanism shifts consumer behaviour and market dynamics over time. Metic and Pigosso (2022) stated that motivational change is crucial as it can significantly diminish the anticipated sustainability benefits of efficiency improvements.

Re-Spending

In Re-Spending depicted in Figure 6, the driver of this mechanism is the same as the Income mechanism, which is Budget Available for Consumption; however, the trigger is the Fraction of Budget for Alternatives and Substitutability between EVs and Alternatives, which are both external factors that can be influenced by variables outside the analysed CLD. Moreover, there is also an additional external variable that is considered in this mechanism, which is the Efficiency of Alternatives. These external factors can change unpredictably if they are part of other loops that are not analysed, introducing uncertainty into the system. Additionally, this mechanism involves Demand for Alternatives, which means that the focus will extend beyond EVs. In relation to CE principles, this mechanism also has a direct influence on the EV retirement rate, recycling rate, and disassembly rate.

From the literature, Colmenares et al. (2020) and Brockway et al. (2021) stated that cost savings from energy efficiency improvements spent on other goods and services result in additional consumption, so this effect has to be considered to accurately estimate the overall rebound effect of efficiency policies as empirical evidence regarding this effect has also been reviewed. Ignoring this effect can lead to an overestimation of the net energy savings from efficiency improvements (Colmenares et al., 2020). Metic and Pigosso (2022) also highlighted that the re-spending effect is significant because it demonstrates how savings from efficiency improvements in one area can lead to increased consumption in other areas.

Re-Spending with Limited Income

In the CLD for this mechanism shown in Figure 6, the structure is almost the same as the Re-Spending mechanism. However, there is an additional balancing loop that reflects the limitation of the budget for consumers to spend their income. This constrained budget makes the magnitude of the rebound effect from this mechanism less than the Re-Spending mechanism because the balancing loop will counteract the reinforcing loop. Even though this cannot be quantified since this study only involves qualitative analysis, the effect can be considered lower than that of Re-Spending.

The only literature that includes budget limitations is Colmenares et al. (2020), which suggests that under fixed income scenarios, expenditure on energy-efficient goods reduces the budget available for other goods, leading to a redistribution effect that may influence overall energy savings and environmental influences, which complicates the measurement process (Sekhar et al., 2013). The driver of this mechanism is Fraction of Change in Behaviour, which is also intangible and uncertain compared to a factor like Income Elasticity of Demand. In relation to the Recycling intervention, the efficiency action has a direct impact on the recycling rate, so this mechanism is integrated with CE principles.

Choosing the Most Significant Mechanism

The process for selecting the most significant rebound mechanisms involves analysing the created CLDs and integrating insights from the literature review. This is illustrated in Table 8.

Table 8 Most Significant Consumption-Induced Mechanisms

	Consumption Time	Motivational Consumption	Re-Spending	Re-Spending with Limited Income	Income
CLD Findings	Not relevant to the CE principle	Involve intangible variable	Many external factors	Balancing in forms Limited income leads to insignificant than Re-Spending	• Relevant to CE • Does not involve intangible variable • Less external factors
Number of Literature	2	2	3	1	6
Most Significant?	❌	❌	❌	❌	✓

The number of literature discussing the Income mechanism underscores its importance as a significant rebound mechanism requiring mitigation. The CLD analysis highlights relatively lower uncertainty regarding external factors and direct alignment with CE principles.

In contrast, literature addressing the Consumption Time mechanism is less abundant compared to the income effect. Regarding CE principles, this mechanism shows less direct influence, as it does not significantly affect recycling or disassembly rates. Therefore, this mechanism is considered less significant compared to the Income mechanism.

The Motivational Consumption mechanism involves more challenging-to-measure variables, such as the Consumer Perspective of EV, compared to the Budget Available for Consumption, which is more straightforward to quantify. There is also less literature focusing on this mechanism compared to the income mechanism Therefore, this mechanism is also considered less significant compared to the Income mechanism.

The Re-Spending mechanism is considered important due to its frequent mention in literature. This mechanism is also linked to Income, as the fraction of the available budget can determine allocation towards either increased EV adoption or alternative options. However, this mechanism involves several external factors beyond the scope of this analysis. Therefore, this mechanism is regarded as less significant compared to Income mechanism.

Re-Spending with Limited Income shares the same structure as Re-Spending, but its magnitude of rebound effect may be lower. Given the limited literature addressing this mechanism, it can be considered relatively less significant.

Based on these considerations, it can be concluded that the most significant mechanism for this class is the **Income** mechanism.

4.3.2. Production-Driven Mechanisms

Output Mechanism

In the CLD for the Outcome mechanism in Figure 7, the trigger of this mechanism is the company profit, and the driver is the fraction of profits that will be reinvested. This mechanism influences the EV sales rate, which means it has a direct impact on increased EV usage, as the profit will be used to increase the manufacturing of batteries. This mechanism also has a strong relation to CE principles, especially the intervention analysed in this research, which is recycling. This is because, in the CLD, it can be seen that the efficiency actions of this mechanism have a direct impact on the EV disassembly rate and recycling rate.

From the literature, there are sources that mention the significance of this mechanism. Colmenares et al. (2020) and Lange et al. (2021) described that efficiency improvements lead to an increase in production output and higher overall energy consumption, potentially offsetting some of the energy savings. Colmenares et al. (2020) and Brockway et al. (2021) emphasize the importance of considering the direct rebound effect in both consumption and production contexts to accurately assess the net impact of energy efficiency policies, avoiding the underestimation of rebound effects and overestimation of energy savings. Lange et al. (2021) stated that effective policies need to address these dynamics to ensure that efficiency improvements lead to real reductions in energy use. Metic and Pigosso (2022) highlighted that the output effect is critical because it directly ties the increased efficiency in production to a corresponding increase in resource use and environmental impact. Similarly, Sorrell (2009) also stated that this mechanism is important due to the higher levels of output that will increase consumption.

Production Time

In the CLD for the Production Time mechanism in Figure 7, the trigger is the time constraint in the battery production process, and there is no driver or exogenous factor that influences this mechanism. There is no other external factor that might influence this mechanism. However, this mechanism does not directly affect the Recycling phase, which is the main intervention analysed in this research. This mechanism is too focused on the production side, neglecting the direct influence on the EoL of the battery. This mechanism might have a direct influence on the disassembly rate, as this concerns the design improvement of the battery to be easily disassembled, but this mechanism does not highlight how to close the loop.

There are only a few literature found that describe this mechanism. Metic and Pigosso (2022) highlight that if producers can produce a product in less time, they are more likely to produce more of it, leading to higher resource use, which underscores the complexity of achieving sustainability goals.

Re-Investment

In Reinvestment mechanism in Figure 7, the driver of this mechanism is the same as the Output mechanism, which is company profits. However, the trigger is the fraction of profit reinvested for more advanced processes and the cost of these advanced processes, which are both external factors that can be influenced by variables outside the analysed CLD. Moreover, there is also an additional external variable considered in this mechanism, which is the efficiency of the advanced process. These external factors can change unpredictably if they are part of other loops that are not analysed, introducing uncertainty into the system. This mechanism highlights that while efficiencies in the current process improve, the decision to reinvest profits into advanced processes is a separate, strategic decision, not an automatic consequence of efficiencies in the current process. In relation to CE principles, this mechanism also has a direct influence on the EV recycling rate and disassembly rate.

From the literature, Colmenares et al. (2020), Brockway et al. (2021), and Metic and Pigosso (2022) highlighted that efficiency improvements can reduce production costs, increasing profit, which in turn can be reinvested in other production factors, leading to more resource consumption. Metic and Pigosso (2022) stated that this mechanism is significant because it potentially negates the environmental benefits of the initial efficiency improvements. Colmenares et al. (2020) and Brockway et al. (2021) also stated that ignoring these effects can lead to an overestimation of net savings.

Cost-Dependent Output

In Cost-Dependent Output mechanism depicted in Figure 7, the driver is the same as the Reinvestment mechanism, which is company profits, and the trigger is the fraction of profit reinvested for a more advanced process. However, the cost of the advanced processes is considered in the loop rather than only as an exogenous factor, indicating a more immediate and direct relationship between the efficiencies of different processes. Improvements in one process directly reduce costs in another process, showing a tightly coupled system where changes in one process have direct and measurable impacts on the other. In relation to CE principles, this mechanism also has a direct influence on EV recycling and disassembly rate.

From the literature, Lange et al. (2021) and Metic and Pigosso (2022) mentioned that efficiency improvements in production are often accompanied by improvements in and between different production factors, such as capital, leading to increased demand. The cross-factor mechanism is crucial because it highlights how interconnected improvements in various production factors (e.g., labor, capital, materials) can collectively contribute to increased economic activity and resource use (Metic and Pigosso, 2022). Brockway et al. (2021) also highlighted that cost savings from efficiency improvements are spent on other energy-consuming activities, so failure to account for this effect can lead to over-optimistic projections of energy savings and insufficient policy measures.

Choosing the Most Significant Mechanism

The process for selecting the most significant rebound mechanisms is illustrated in Table 9.

Table 9 Most Significant Production-Driven Mechanisms

	Production Time	Reinvestment	Cost-Dependent	Output
CLD Findings	Does not have a direct connection with Recycling	There are some external factors	Emphasize more on advancing to the new production process	• Direct influence on increased consumption • Alignment with CE principles
Number of Literature	1	3	3	4
Most Significant?	✗	✗	✗	✓

The number of literature discussing the Output mechanism is greater than for other mechanisms in this class, indicating that it is a significant rebound mechanism requiring mitigation. The CLD analysis highlights its direct influence on increased consumption and its strong alignment with CE principles.

There is only a few literature about the Production Time mechanism, suggesting that it is less significant compared to other mechanisms in this class. The CLD also shows that this mechanism does not have a direct connection with the Recycling phase, which is the main intervention analysed in this research.

There is considerable literature on the Re-Investment mechanism. However, this mechanism involves exogenous factors that introduce uncertainty into the analysed system. It relates to more advanced production processes compared to the current ones, which extends the focus to the variance in recycling and production processes. Similarly, the Cost-Dependent Output mechanism is well-documented but emphasizes the immediate and direct relationship between the efficiencies of different processes. In CE practices for EV batteries, the focus is more on how firms adopt and implement production and recycling processes rather than advancing to new processes. Therefore, this mechanism may be less relevant compared to the Output mechanism.

Based on these considerations, it can be concluded that the most significant mechanism for this class is the **Output** mechanism.

4.3.3. Substitution Dynamics Mechanisms

Substitution

In the CLD for the Substitution mechanism in Figure 8, the trigger of this mechanism is the total cost of EVs, and the drivers are the total cost of consuming alternatives and the substitutability between EVs and alternatives. This mechanism is also influenced by another external factor, which is the efficiency of alternatives that can be impacted by factors outside the analysed system. This mechanism has a strong relation to CE principles, especially the intervention analysed in this research, which is recycling. In the CLD, it is evident that the efficiency actions of this mechanism directly impact the EV disassembly rate and recycling rate. Moreover, this mechanism also influences the EV retirement rate, which means it also considers slowing the loop.

In several literatures, the substitution mechanism is regarded as the most significant rebound effect in the system. Zink and Geyer (2017) mentioned that increased consumption is not limited to secondary goods but extends to other goods and services, driven by extra disposable income and the relative attractiveness of cheaper products. Sorrell (2009) also stated that substitution can occur when cheaper products replace other products while maintaining a constant level of utility. Colmenares et al. (2020) and Metic and Pigosso (2022) highlighted that substitution effects are a critical aspect of the rebound effect that must be considered to accurately assess the net impact of efficiency improvements, as these effects capture shifts in consumption patterns that can either enhance or undermine the net savings. Colmenares et al. (2020) also stated that the magnitude of the substitution effect is a key determinant of the overall rebound effect, influencing how much of the energy savings from efficiency improvements are offset by increased consumption.

Brockway et al. (2021) emphasized that both direct and indirect substitution effects are part of the broader category of rebound effects that must be considered to accurately estimate the net impact of efficiency improvements. Lange et al. (2021) highlighted studies showing that substitution effects can significantly contribute to the rebound phenomenon, and therefore, policymakers need to consider this effect.

Motivational Substitution

In Motivational Substitution depicted in Figure 8, the efficiency action directly impacts the positive perception of EVs. Compared to variables like the total cost of EVs, this perception is more abstract and harder to measure. Moreover, this mechanism is also driven by the positive perception of alternatives, which is also an abstract factor. Similar to the substitution mechanism, this mechanism is influenced by an exogenous variable: the efficiency of alternatives, which can be affected by factors outside the analysed system. In relation to CE principles, this mechanism has a direct impact on the recycling rate.

Some literature mentions the importance of this mechanism. Metic and Pigosso (2022) describe that as a product or service becomes more efficient, consumers' preferences, perceptions, and behaviour change, leading to increased consumption of other products or services. This is crucial because it shows how consumer perceptions and behaviours, influenced by efficiency gains, can lead to unintended increases in consumption. Colmenares et al. (2020) state that the indirect behavioural effect is crucial for understanding the full impact of efficiency improvements, and accounting for behavioural changes is essential for the realistic modelling of the rebound effect.

Factor Substitution

In Factor Substitution from Figure 8, instead of focusing on the substitution of products, such as EVs, this mechanism focuses on the processes related to battery production. This mechanism involves the demand for both the current process and the advanced process. The cost of current and advanced processes, efficiency of processes, and substitutability between the processes are presented as external variables. These external variables introduce uncertainty, as they can be influenced by other unanalysed factors.

Many literatures mention the importance of this effect. Metic and Pigosso (2022) noted that due to efficiency improvements and reduced costs of particular products or services, producers may substitute the consumption of one resource for another. This effect is significant as it leads to increased use of another resource. Studies reviewed by Lange et al. (2021) show that the substitution of production factors is a significant driver of the rebound effect in various sectors. Brockway et al. (2021) highlighted the critical need to consider both direct and indirect substitution effects for producers to ensure realistic projections and effective policy interventions. Lastly, Colmenares et al. (2020) discussed the broader concepts of factor substitution within the context of rebound effects, emphasizing that recognizing these effects is crucial for accurate policy assessment and effective energy management.

Choosing the Most Significant Mechanism

The process for selecting the most significant rebound mechanisms involves analysing the created CLDs and integrating insights from the literature review. This is illustrated in Table 10.

Table 10 Most Significant Substitution Dynamics Mechanisms

	Motivational Substitution	Factor Substitution	Substitution
CLD Findings	Involve abstract/intangible variable	Not focus on addressing the demand for the product	• Least uncertainties • Align with CE
Number of Literatures	2	4	6
Most Significant?	✗	✗	✓

In the CLD, the Substitution mechanism plays a crucial role in CE principles as it shows actions for both slowing and closing the loop. The focus of this mechanism is on how consumers change their behaviour to substitute EVs with alternatives. There may be external factors in this mechanism, but compared to other mechanisms in this class, it has the least uncertainty. Numerous studies mention the importance of this mechanism, with the highest number of references compared to other mechanisms. Some literature even suggests that the magnitude of this mechanism is the largest compared to others.

In the CLD for the Motivational Substitution mechanism, there are some hard-to-measure variables related to perception. Some papers highlight that these behavioural effects are difficult to quantify accurately. In relation to CE principles, this mechanism is related to the recycling rate. However, not many studies indicate that this effect needs to be considered.

The Factor Substitution mechanism involves behavioural changes by the producer to change the factors of production. However, in this research about CE for EV batteries, the emphasis is placed on addressing the demand for the product itself rather than focusing on the demand for production processes or related activities. This means efforts are directed towards optimizing the product's lifecycle, enhancing its usability, and ensuring its efficient recycling and reuse, rather than primarily concentrating on improving or changing production methods.

Therefore, based on these considerations, it can be concluded that the most significant mechanism for this class is the **Substitution** mechanism.

4.3.4. Demand Response Mechanisms

Demand Adjustment Initiated by Sufficiency

In the CLD in Figure 9, this mechanism is driven by the supply of EVs, which has a direct connection with the base structure. The demand for EVs also directly influences the EV sales rate, indicating its potential significance in impacting consumer behaviour as the main actor creating the rebound effect. In relation to CE principles, this mechanism only directly impacts the EV retirement rate but does not directly influence recycling.

There is literature that highlights this mechanism. Metic and Pigosso (2022) state that sufficiency strategies while aiming to reduce consumption and promote sustainability, can have unintended rebound effects if not adopted widely. Therefore, this mechanism is crucial because it emphasizes the need for collective action and widespread adoption of sufficiency strategies to ensure their effectiveness in reducing overall resource consumption and achieving sustainability goals.

Demand Adjustment Initiated by Efficiency

The CLD for this mechanism in Figure 9 clearly shows the relationship between supply and demand for EVs, involving variables for excess supply versus demand. This mechanism also directly affects the EV sales rate, indicating that it is driven by both producers and consumers as actors. Additionally, it influences the EV retirement rate and, in relation to CE principles, directly impacts the disassembly and recycling rates.

Several literatures mention the importance of considering this effect. Metic and Pigosso (2022) and Lange et al. (2021) emphasize that improvements in resource efficiency at the market level can lead to lower prices, which in turn can stimulate higher demand for the resource. This effect is crucial because it demonstrates how market dynamics can lead to increased overall resource consumption, counteracting the intended sustainability benefits of efficiency improvements (Metic and Pigosso, 2022). Lange et al. (2021) also state that lower prices make these goods and services more accessible to a broader range of consumers, thereby increasing consumption. Brockway et al. (2021) describe that changes in prices due to shifts in demand can have significant ripple effects across the economy, affecting both consumers and producers. Including this effect is important to avoid underestimating rebound effects and overestimating savings. Colmenares et al. (2020) mention that understanding this effect is essential for accurately modelling the net effects of policies.

Demand Adjustment with Investment Adjustment

The CLD for this mechanism in Figure 9 is quite complex as it involves how firms may invest the profit from additional demand. This mechanism includes an external variable, which is the fraction of profit that will be reinvested to increase the supply of EVs. There are two balancing loops and one reinforcing loop creating this mechanism, adding to its complexity. This mechanism also directly influences the disassembly rate, retirement rate, and recycling rate, ensuring its alignment with CE principles.

From the literature, Colmenares et al. (2020) refer to this effect as disinvestment, which is the reduction or withdrawal of investments in certain sectors or technologies. The potential for disinvestment effects should be considered in models assessing the rebound effect, as these effects can influence the overall economic landscape (Colmenares et al., 2020). Brockway et al. (2021) mention that this effect occurs when reductions in energy demand and lower prices lead to reduced profitability for producers. It stresses the importance of including disinvestment effects in economic models to avoid underestimating future demand and overestimating the stability of supply.

Re-Design

In the CLD for this mechanism in Figure 9, the driver is the design of additional features for EV batteries, and this mechanism also involves an external variable, which is resource use for additional features. The other variable, which is the design opportunity for EVs, can be seen as uncertainty because the design opportunity is relative, so each firm might see this opportunity differently. In relation to CE principles, this mechanism only has a direct influence on the retirement rate and disassembly rate, while the influence on the recycling rate is missing.

Some literature mentions the rebound effect associated with the redesign. Colmenares et al. (2020) mention that when producers redesign products to enhance features or improve performance, the additional functionalities may increase consumption and offset the savings.

Lange et al. (2021) note that when firms redesign their products to be more efficient, they may add new features or increase the size and capacity of the products, leading to higher energy consumption. This form of rebound effect is often seen in sectors where technological advancements and consumer preferences drive the continuous improvement and enhancement of products, and the magnitude can be substantial (Colmenares et al., 2020). Lange et al. (2021) state that redesign is often a long-run mechanism, as it involves substantial changes in production processes and consumer preferences, so understanding this effect is crucial for developing effective efficiency policies.

Supply Adjustment

In the CLD from Figure 9, this mechanism treats demand for EVs as an external factor that influences the excess demand vs. supply. It also involves the additional supply of EV batteries by other companies, influenced by the external factor of companies choosing to fight for excess demand. This mechanism is quite complex, involving conflicting interests between firms on whether to add supply or not, adding uncertainty to the analysed system. In relation to CE principles, this mechanism only has a direct influence on the retirement rate and disassembly rate, while the influence on the recycling rate is missing.

Based on the literature, there is a paper that mentions this effect. Metic and Pigosso (2022) highlight that sufficiency strategies at the producer level are crucial for reducing overall resource consumption and promoting sustainability. However, if only a few producers adopt sufficiency measures, the resulting reduction in supply can lead to increased production by other producers, thereby negating the environmental benefits. This underscores the need for collective action and industry-wide adoption of sufficiency strategies.

Producer-Induced Demand Adjustment

The focus of this mechanism is on the production process rather than the product itself. In the CLD depicted in Figure 9, the demand is analysed as the demand for the process, involving the variable of excess supply vs. demand of the process. This mechanism also involves an external variable, which is the supply of the process, adding uncertainty to the system as it can be influenced by factors outside the analysed system. This mechanism is aligned with CE principles since it has a direct influence on the disassembly rate and recycling rate.

From the literature, there is a paper that mentions this effect. Lange et al. (2021) highlight that when efficiency improvements lead to a reduction in demand, the price may decrease, making the product more attractive and leading to increased consumption by other users who benefit from the lower prices. This effect is important because lower prices can influence the demand and supply dynamics of related markets, potentially leading to changes in overall energy consumption patterns. Therefore, this effect should be understood for developing comprehensive policies that effectively mitigate rebound effects (Lange et al., 2021).

Choosing the Most Significant Mechanism

The process for selecting the most significant rebound mechanisms involves analysing the created CLDs and integrating insights from the literature review. This is illustrated in Table 11.

Table 11 Most Significant Demand Response Mechanisms

	Demand Adjustment Initiated by Sufficiency	Demand Adjustment Initiated by Efficiency	Demand Adjustment with Investment Adjustment	Redesign	Supply Adjustment	Producer-Induced Demand Adjustment
CLD Findings	Does not have a direct influence on Recycling	• Have a direct influence on the Recycling rate • Align with CE	Many external factors	Adding complexity and unpredictability to the overall system	External factors Conflicting interests among actors	Focus on the production process
Number of Literatures	1	4	2	2	1	1
Most Significant?	❌	✓	❌	❌	❌	❌

In Demand Adjustment Initiated by Sufficiency, the CLD shows the interaction between producers and consumers as actors who create the rebound mechanism. There is also less uncertainty in this mechanism as it involves no external factors. However, in relation to CE principles, this mechanism does not show alignment with recycling, which is the intervention analysed in this research. Moreover, there is only one literature source found mentioning this mechanism.

In Demand Adjustment Initiated by Efficiency, the CLD also shows that the rebound mechanism can be caused by both producers and consumers. Compared to Demand Adjustment Initiated by Sufficiency, this mechanism is more aligned with CE principles as it has a direct influence on the recycling rate. This mechanism offers a more tangible approach to achieving sustainability by focusing on technological improvements. It emphasizes measuring and enhancing the efficiency of products and services (such as through advancements in technology), which provides concrete, observable metrics. In contrast, Demand Adjustment Initiated by Sufficiency focuses on promoting sufficiency among consumers, a more abstract concept that involves changing consumer behaviour and attitudes towards resource consumption. Moreover, the literature explicitly stating the importance of Demand Adjustment Initiated by Efficiency is more prevalent than that for Initiated by Sufficiency.

In Demand Adjustment with Investment Adjustment, the CLD introduces additional complexity by incorporating the external variable of the fraction of profits reinvested, which adds uncertainty. This complexity arises from the involvement of two balancing loops and one reinforcing loop. The balancing loops regulate the system by adjusting demand and supply, while the reinforcing loop amplifies the effects of profit reinvestment on supply. Managing these intertwined feedback loops requires more assumptions, increasing the uncertainty of outcomes. Moreover, the literature mentioning this effect is fewer than that for Demand Adjustment Initiated by Efficiency.

In the Re-Design mechanism, the variable design opportunity for additional features is relative and can be perceived differently by each firm. This variability means that while one firm may identify and capitalize on a design opportunity, another may see it as less viable or beneficial. This difference in perception can lead to diverse anticipations, adding complexity and unpredictability to the overall system. The literature mentioning this effect is also less than that for Demand Adjustment Initiated by Efficiency.

In Supply Adjustment, the CLD involves additional complexity due to the potential supply of EV batteries by other companies. The choice of other firms to increase supply in response to excess demand introduces an external factor that can be treated as uncertainty, significantly influencing the system. This variable also introduces conflicting interests among firms, whether to increase supply or not, further contributing to the uncertainty within the analysed system and beyond the scope of this research. The literature about this effect is also less.

In the CLD for Producer-Induced Demand Adjustment, the focus of this mechanism is on the production process, where the demand is analysed as the demand for the process, involving variables such as excess supply versus demand of the process. However, the goal of this research is to focus more on the demand and supply of the product. The literature about this effect is also less.

Based on these considerations, it can be concluded that the most significant mechanism for this class is the **Demand Adjustment Initiated by Efficiency**.

4.3.5. Combined Income-Output Mechanism with Delay

While the Combined Income-Output Mechanism provides valuable insights into the delayed and complex interactions between income and output mechanisms, including them in the analysis would be redundant. The primary elements and effects of these mechanisms are already captured in the individual analyses of the Consumption-Induced Mechanisms and Production-Driven Mechanisms. Including a combined category would duplicate these effects without adding new insights. Consumption-Induced Mechanisms and Production-Driven Mechanisms sufficiently cover the potential impacts of combined long-term responses. Analysing these combined effects separately does not provide additional differentiation or value in understanding the primary drivers of rebound effects in circular EV batteries.

4.4. Model Validation

Validation is an important step in ensuring the accuracy and applicability of the developed CLDs for the CE practices of EV batteries. This validation is conducted through expert interviews, ensuring that the assumptions, relationships, and feedback loops accurately represent real-world dynamics and stakeholder perspectives. These interviews were conducted online, with interview questions available in Appendix B, and the transcripts can be found in Appendix C. A total of 3 in-depth interviews were conducted using semi-structured interviews to allow for both guided discussions and the flexibility to explore additional relevant topics that arose during the conversation.

The validation of the CLD model for CE practices of EV batteries, based on insights from expert interviews, confirms the model's robustness and accuracy in capturing real-world dynamics. Expert A emphasized the necessity of reinforcing and balancing loops, regulatory influences, and categorization of mechanisms to effectively understand and mitigate rebound effects. Expert B reinforced the significance of incorporating recycling initiatives and regulatory impacts, while also highlighting the need for qualitative analysis of feedback loops. Expert C stressed the importance of addressing long-term unintended consequences, and the role of regulatory frameworks like Extended Producer Responsibility. Collectively, these expert insights ensure that the CLD model accurately represents the complex interplay of factors influencing the CE of EV batteries and provides a strong foundation for developing effective mitigation strategies. The detail of the conducted interviews is shown below.

4.4.1. Interview with Expert A

This interview was conducted with a Researcher at the Department of Civil and Mechanical Engineering Design for Sustainability, Technical University of Denmark. This expert has expertise related to UN Sustainable Development Goals and has published several papers about Circular Economy, Sustainability Transitions, Rebound Effects, and System Dynamics.

Mechanisms in CLD

The interview highlighted the importance of reinforcing and balancing loops in understanding the rebound effects. The CLD should include reinforcing loops, such as efficiency improvements (e.g., better battery design, enhanced recycling) that lower costs and increase disposable income for consumers. This leads to increased demand for EVs, further driving efficiency improvements. For instance, variables like efficiency improvements leading to cost reduction, which increases disposable income and higher EV demand, ultimately resulting in more investments in efficiency improvements, should be clearly illustrated.

Conversely, balancing loops such as the increased supply of EVs leading to market saturation should also be included. As the supply of EVs increases, market saturation can occur. Increased supply can lower prices, but beyond a certain point, it could also lead to reduced profitability for manufacturers, balancing the initial surge in demand. For example, increased EV supply leading to price reduction, market saturation, reduced profitability, and slowed investments in efficiency improvements, is a critical balancing dynamic that needs to be mapped.

The interview discussed specific mechanisms such as income effects, motivational consumption, and re-spending. These should be explicitly modelled. For the income mechanism, efficiency actions like improved battery design for end-of-life, reverse logistics, and recycling processes should be linked to cost savings, increased disposable income, higher EV demand, and increased resource consumption, further influenced by external pressures for efficiency.

Incorporate Regulatory Influences

Regulatory bodies, like the EU Battery Directive, play a crucial role in influencing market dynamics. Their regulatory requirements, increased recycling targets, higher compliance costs, and their influence on market prices and consumer demand, should be incorporated into the model to ensure it accurately represents the external pressures.

Regulations significantly impact the CLD, and incorporating these influences is crucial for accuracy. The EU Battery Directive imposes requirements for recycling and material recovery, influencing both supply and demand dynamics. For example, regulatory requirements leading to increased recycling targets, higher compliance costs, and their subsequent impact on market prices and consumer demand should be highlighted in the CLD.

Categorization and Prioritization

Expert A discussed the need to identify the most significant mechanisms contributing to rebound effects. This involves analysing the number of triggers or drivers each mechanism has and their impact on the system. Expert A suggested focusing on mechanisms with the most significant triggers or drivers for effective mitigation.

Expert A suggested using the approach to categorizing mechanisms into different groups based on their structure and actors (e.g., consumer, firm) can help prioritize which mechanisms to address first. This categorization can aid in systematically analysing each mechanism's impact and developing targeted mitigation strategies. Expert A also recommended combining mechanisms where possible, especially those with shared triggers or drivers. This holistic view can help understand the overall system behaviour and identify key leverage points for intervention. For example, combining the income mechanism with the output mechanism can provide insights into how increased disposable income from efficiency actions drives higher demand and production, leading to potential rebound effects.

4.4.2. Interview with Expert B

This interview was conducted with a PhD Candidate at the Institute for Economy and the Environment at the University of St-Gallen. Expert B is currently especially focused on repurposing and recycling pathways for EV batteries and aims to simulate future scenarios using a System Dynamics Model.

Rebound Effect in Circular Economy

Expert B highlighted that rebound effects include both positive and negative secondary effects, which align with the broader understanding of rebound effects discussed in the research. This supports the foundation of the CLD model focusing on unintended consequences of efficiency improvements. The discussion on mechanisms such as increased demand due to efficiency actions (e.g., better battery design, reverse logistics, and recycling processes) mirrors the mechanisms identified in the CLD model. Expert B's insights into how improved efficiency leads to increased consumption and potential backfire effects validate the model's focus on these dynamics.

Expert B emphasized the importance of focusing on recycling initiatives within the circular economy for EV batteries. This aligns with the research's decision to prioritize recycling as a key intervention, highlighting the environmental and economic benefits, such as reducing the need for virgin material extraction and managing waste. The interview mentioned the impact of regulations like the EU Battery Directive and the role of market dynamics in shaping the adoption of CE practices. This supports the CLD model's inclusion of external pressures and regulatory influences as significant factors in the system.

Mechanisms in CLD

Based on the interview, the research should ensure the CLD includes both reinforcing and balancing feedback loops to represent the dynamic interplay between efficiency actions and rebound effects. The interview's insights into increased demand due to efficiency savings (reinforcing loop) and potential balancing factors (e.g., market saturation, regulatory constraints) should be explicitly modelled. Expert B suggested using qualitative analysis to critically evaluate each mechanism's significance and potential impact. This involves creating detailed causal loop diagrams for each mechanism, explaining their interactions and potential rebound effects. This qualitative approach ensures that the CLD is grounded in real-world dynamics and expert insights.

According to Expert B, the CLD should integrate discussed mitigation strategies to break reinforcing loops. For instance, designing for longevity should be mapped to show how improved battery design extends lifespan, reduces the frequency of replacements, and lowers overall demand for new batteries. Similarly, improving reverse logistics should be illustrated to show how enhanced logistics reduce costs for returning and recycling batteries, lowering overall production costs. Focusing on recycling should highlight how increased recycling efficiency boosts the supply of recycled materials, reducing the need for virgin materials and lowering environmental impact.

4.4.3. Interview with Expert C

This interview was conducted with the Assistant Professor of Circular Economy, Operations, and System Dynamics in the Department of Industrial Engineering and Innovation Sciences. Expert C has published several articles in well-known journals, such as Technovation, Journal of Cleaner Production, Sustainable Production and Consumption, International Journal of Contemporary Hospitality Management, Science of the Total Environment, Renewable and Sustainable Energy Reviews, and Resources, Conservation and Recycling.

Rebound Effects in Circular Economy for EV

Expert C's insights emphasized the long-term unintended consequences of promoting EVs. While short-term effects seemed favourable, long-term promotion could lead to higher vehicle numbers, increased traffic, and congestion, demonstrating the rebound effect. Continued promotion without addressing broader systemic issues could lead to significant long-term rebound effects. For instance, promoting EVs as a sustainable transportation mode could result in an increased total number of vehicles on the road, leading to higher traffic congestion and greater environmental impact over time. This underscored the need to include balancing loops in the CLD to address these long-term consequences.

Expert C pointed out that promoting EVs could inadvertently increase the total number of vehicles. While EVs were intended to replace internal combustion engine vehicles, the ease of acquiring and operating EVs could lead to more people owning multiple vehicles or not disposing of their old ones. This resulted in more vehicles on the road, increased traffic congestion, and additional demand for infrastructure and energy. Another critical aspect Expert C discussed was the source of electricity used to power EVs. If the electricity was generated from fossil fuels, the overall environmental benefit of EVs diminished significantly. This highlighted the importance of considering the entire lifecycle and energy source of EVs in the CLD, ensuring a comprehensive view of their environmental impact.

Expert C explained that promoting EVs as environmentally friendly could lead to increased usage, as consumers might feel less guilty about driving more frequently. This behavioural change could offset the environmental benefits of EVs, as increased usage led to higher overall energy consumption and potential strain on energy resources. The interview highlighted that producers might not fully engage in sustainable practices unless incentivized or mandated by regulations. This challenge stemmed from a conflict of interest, where financial incentives often outweighed environmental considerations. Hence, strong regulatory enforcement was essential to ensure compliance and drive the adoption of circular economy practices.

In the interview, the discussion on EPR highlighted the importance of regulatory frameworks in managing the lifecycle of EV batteries. Expert C pointed out that producers might not fully account for EoL impacts unless regulated, emphasizing the need for strong regulatory influences in the CLD. This aligned with the model's inclusion of external pressures and regulatory impacts on market behaviour. The importance of collaboration between manufacturers and end-of-life process handlers was also discussed. Improved communication and collaboration could lead to innovations and better solutions for recycling batteries.

5 Mitigation of Rebound Effects

5.1. Overview of Circular Business Model for EV Battery

According to Font Vivanco et al. (2016), the mitigation strategies for rebound effect can be described as:

1. Consuming more efficiently by increasing efficiency across consumption sectors
2. Consuming more differently by shifting to greener consumption patterns
3. Consuming less by downsizing consumption

Published studies on reducing rebound effects have been limited, with most focusing on market-based tools like carbon and energy pricing (Saunders, 2011). However, some authors have proposed several policy approaches, including non-market tools. Maxwell et al. (2011) identify six pathways for addressing rebound effects: (1) designing, evaluating, and implementing policy instruments, (2) promoting sustainable lifestyles and consumer behaviour, (3) raising awareness and education in business, (4) fostering technology and innovation, (5) using economic instruments, and (6) developing new business models. This framework is considered the most comprehensive to date for mapping and discussing policy alternatives for mitigating rebound effects (Font Vivanco, 2016). For choosing which pathway to choose, the book Strategic Management for Technological Innovation by Melissa Schilling (2020) will be used as a guide. For selecting the appropriate pathway, the book "Strategic Management of Technological Innovation" by Melissa Schilling (2020) will be used as guidance since this research focuses on the company level. The book's emphasis on aligning innovation strategies with core competencies and leveraging technological advancements will be crucial in developing solutions that address the potential rebound effects in the EV market.

Policy approaches will not be included in the mitigation strategy. Government policies are external factors over which companies have limited control. Instead, firms can leverage their internal capabilities, such as innovation and competitive strategies, to more effectively achieve their objectives. Schilling (2020) emphasizes the importance of leveraging a firm's core competencies and resources to foster innovation and competitive advantage.

Promoting sustainable behaviour and raising awareness are broad initiatives typically managed by societal and governmental efforts. Companies often have limited control over these initiatives, making it challenging to integrate them effectively into company-specific strategies. Efforts to promote sustainable behaviour and raise awareness may not align with a company's specific strengths and capabilities, especially if they fall outside its primary business functions. Schilling (2020) underscores the necessity of aligning innovation strategies with a firm’s resources and core competencies, reinforcing why these initiatives will not be considered for the mitigation strategy.

Fostering technological innovation will be included but will focus on process improvement rather than product innovation. Process innovation aims to improve production methods and operational procedures, leading to cost reductions and increased efficiency. By streamlining processes, companies can lower production costs, reduce waste, and improve overall operational efficiency. Schilling (2020) also highlights the significance of process innovation in achieving cost leadership and operational excellence.

Economic instruments will not be considered as they involve broader economic activities beyond the firm's scope, such as subsidies, tax incentives, or carbon pricing, which depend heavily on government policies and regulatory frameworks. These external factors are beyond the control of individual firms, making it challenging for companies to rely on them as a consistent and predictable component of their innovation strategy.

Thus, this research will focus more on business models. Business model patterns are purely business-oriented, not involving government policy or technological/product improvements. Instead, the emphasis will be on process improvement.

5.2. Circular Business Model as Mitigation Strategies

Takacs et al. (2020) highlight several circular ecosystem patterns that provide a blueprint for designing a circular ecosystem within an industry. These patterns are based on extensive literature reviews and successful case studies of companies that have implemented sustainable and circular solutions in their respective sectors. The patterns can be chosen based on their relevance to the three strategies outlined by Font Vivanco et al. (2016) and their applicability to the context of circular EV batteries. This selection process is detailed in Figure 11, where nine potential business models are presented.

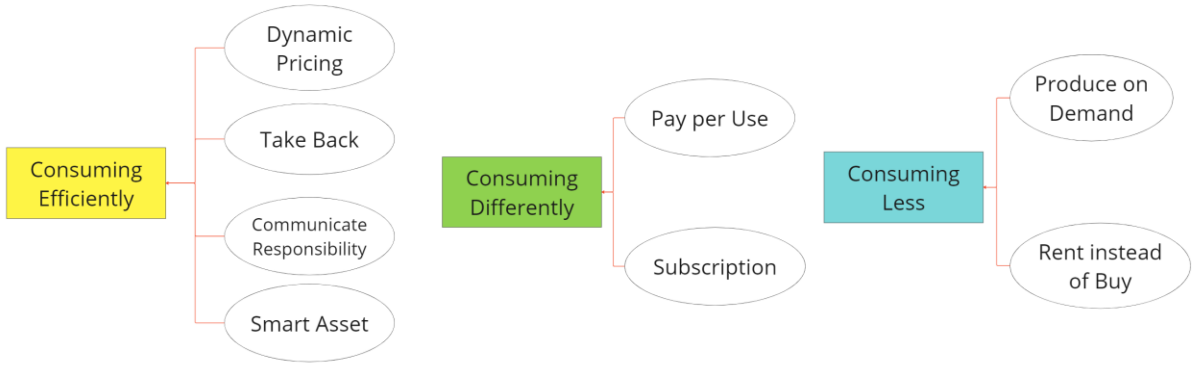

Figure 11 Potential Business Models

The use of CLD can provide a strategic framework for identifying leverage points to mitigate unintended consequences in the context of circular economy models, particularly concerning EVs. The focus on leveraging points is crucial as it allows for targeted interventions that can significantly alter system dynamics (Guzzo et al., 2023). This approach will be applied to four significant mechanisms identified: the Income mechanism, Output mechanism, Substitution mechanism, and Demand Adjustment by Efficiency. Each of these mechanisms involves specific feedback loops that, if left unchecked, could lead to increased consumption and production, undermining sustainability goals.

In relation to the Income mechanism, the leverage point highlights the need to mitigate the potential for increased demand resulting from consumers having more disposable income due to the decreased total cost of EVs. It is crucial to ensure that this additional budget does not lead to an unintended rise in overall consumption, which could offset the environmental benefits of adopting EVs.

For the Output mechanism, the leverage point indicates the necessity of addressing how reduced battery production costs, which lead to increased company profits, might result in heightened battery production. Mitigation strategies should focus on preventing an excessive scale-up in production that could contribute to resource depletion and environmental harm.

The leverage point in the Substitution mechanism points to the need to manage the potential increase in demand for EVs resulting from their lower total cost. While the shift to EVs is generally beneficial, it is essential to control this demand surge to prevent strain on resources and infrastructure.

Lastly, for the Demand Adjustment by Efficiency mechanism, the leverage point underscores the importance of mitigating the potential for increased demand due to price drops from an excess supply of EVs compared to demand. Lower prices, while beneficial for accessibility, could lead to unsustainable consumption patterns if not properly managed.

Overall, these leverage points indicate the importance of implementing targeted mitigation strategies to manage the impacts of reduced costs and increased accessibility on demand and production within the EV market. Table 12 illustrates how different CE patterns adapted from Takacs et al. (2020) can mitigate significant mechanisms identified from the CLD to address and mitigate rebound effects that arise from increased resource efficiency. The yellow-shaded cells in the table indicate that the selected strategy can be used to mitigate the corresponding rebound mechanisms.

Table 12 Mitigation Strategies

		Rebound Mechanisms				
		Income	Output	Substitution	Demand Adj. by Efficiency	Increased Resource Consumption
Mitigation Strategies	Dynamic Pricing	■	■	■	■	
	Take Back					■
	Communicate Responsibility					■
	Smart Asset		■		■	
	Pay per Use	■	■	■		
	Subscription	■	■	■		
	Reverse Logistics					■
	Produce on Demand		■		■	
	Rent instead of Buy			■	■	

Pay per Use

The "Pay per Use" model refers to a revenue system where customers do not purchase products outright; instead, they enter into a contractual agreement with providers to pay a fee based on the usage of the product (Takacs et al., 2020). The product or service use by the consumer is measured based on a specified metric, such as time or unit count. This metric serves as the basis for payment, increasing the consumer's incentive for more efficient and economical use (Takacs et al., 2020). The shift towards pay-per-use models has been observed in various sectors, with a strategic analysis highlighting the increasing prevalence of these models over the past decades (Ladas et al., 2022). Furthermore, the integration of pay-per-use models within a circular economy framework has been identified as a way for manufacturing companies to enhance sustainability efforts and adapt to changing business landscapes (Moorthy & Rapaccini, 2023).

Pay per use helps mitigate the income mechanism by charging customers based on their actual usage, which ensures that savings from not owning a vehicle are not excessively redirected to other high-consumption activities (Bocken et al., 2018). This model also mitigate substitution mechanism, allowing consumers to use EVs without committing to ownership, making EVs more attractive compared to other transportation alternatives without increasing the overall demand for new vehicles. The pay per use model mitigates the output mechanism by linking revenue to the actual usage of the product rather than the volume of production. This model encourages manufacturers to focus on the quality and longevity of their products rather than producing more units to drive sales.

Subscription

This model allows customers to acquire products or services by making regular payments of a predetermined fee (Takacs et al., 2020). Pauwels and Weiss (2008) discuss how transitioning from free to fee-based models enables companies to develop regular and predictable revenues while fostering long-term customer relationships. Customers benefit from the convenience of regular payments, which save time and often cost less than one-time purchases or multiple individual transactions. This model can also promote the purchase of sustainable products by lowering entry barriers for critical customers. Linder and Williander (2017) highlight that subscription models, by providing predictable revenue streams, support companies in managing the inherent uncertainties of circular business models, which depend on long-term customer relationships and sustainable practices. Danaher (2002) offers insights into the financial benefits of subscription pricing, which often results in cost savings compared to individual purchases, making this model appealing to cost-conscious consumers.

Subscription mitigates the income mechanism by spreading payments over time, making it easier for customers to budget and reducing the likelihood of spending additional savings on other consumptive behaviours (Iyengyar et al., 2022). This also mitigates substitution mechanism by providing access to an EV through a subscription, so this model makes EVs an attractive alternative to other transportation options, ensuring increased EV use without necessarily increasing the number of EVs produced. The subscription model also mitigates the output mechanism by generating consistent revenue streams through regular, predefined fees rather than through increased production and sales.

Dynamic Pricing

Dynamic pricing is a flexible strategy that adjusts prices based on real-time demand, competition, and market factors to help businesses swiftly respond to changes, manage inventory efficiently, and optimize resource use (Takacs et al., 2020). Haws and Bearden (2006) emphasize that dynamic pricing requires a thorough understanding of products and advanced data processing capabilities to ensure fairness and efficiency. Kannan and Kopalle (2001) discuss the impact of dynamic pricing on consumer behaviour online, noting that it can lead to better capacity utilization by aligning prices with consumer demand patterns. Faruqui and George (2005) quantify consumer responses to dynamic pricing, demonstrating how such strategies can optimize capacity utilization and prevent inefficiencies by adjusting prices according to consumption patterns and demand fluctuations.

Dynamic pricing can mitigate Output and Demand Adjustment by Efficiency mechanism by adjusting prices based on real-time demand, helping to balance supply and demand efficiently and prevent excessive consumption (Clastres and Khalfallah, 2021). Therefore, increased company profit will be used for other improvements rather than increasing production. Dynamic pricing also helps mitigate the income and substitution mechanism, because when the demand for EVs increases, the prices are adjusted upward, which can prevent consumers from having excessive budget left over for other consumptive behaviours. This ensures that the savings from not spending on other items are not redirected to high-consumption activities. This can also discourage excessive switching from other transportation alternatives to EVs as EVs are less attractive when demand spikes.

Take Back

The success of Circular Economy (CE) models relies significantly on effective product take-back mechanisms, which ensure that products are returned to manufacturers for recovery and recycling. These systems often involve contractual agreements or incentivized take-back arrangements (Takacs et al., 2020). Quariguasi Frota Neto and Van Wassenhove (2013) emphasize the importance of these initiatives, particularly noting the leadership role of large multinational manufacturers. They identify two common incentive systems: refundable deposit schemes, where a deposit is returned upon product return, and buy-back programs, where producers repurchase unwanted products from customers. Heese et al. (2005) explore the competitive advantages of taking back used products, highlighting that incentivized take-back systems not only contribute to waste reduction but also improve capacity utilization and operational efficiency for producers.

Take back mechanisms ensure that products are returned for recovery and recycling, preventing waste and reducing the need for new materials. This prevents increased resource consumption because of increased production or consumption.

Produce on Demand

The concept of producing on demand aims to manufacture products only when there is confirmed consumer demand, effectively reducing overproduction, unsold stock, and inefficient resource use (Takacs et al., 2020). Bocken et al. (2014) discuss how sustainable business models can leverage this approach to minimize waste and optimize resource utilization. Similarly, Lüdeke-Freund et al. (2018) emphasize the importance of understanding customer needs and integrating them into the product development process, highlighting how aligning production with actual demand can achieve greater sustainability and efficiency.

Produce on demand mitigates the output mechanism by manufacturing products only when there is confirmed demand, preventing overproduction and ensuring that company profits from reduced production costs do not lead to unnecessary increases in output (Lüdeke-Freund et al., 2018). By ensuring that products are manufactured only when there is a confirmed need, Produce on Demand helps maintain a balance between supply and demand, promotes resource efficiency, and minimizes the environmental impact of production.

Smart Asset

Smart Asset utilizes IoT and sensor technologies to enhance transparency, simplify product traceability, and enable data-driven decision-making, thus improving maintenance and repair processes while facilitating effective take-back systems (Takacs et al., 2020). The Ellen MacArthur Foundation's report, Intelligent Assets: Unlocking the Circular Economy Potential, emphasizes that the increasing connectivity of intelligent assets and IoT devices significantly aids in achieving transparency and traceability. This supports sustainable business practices by allowing producers to monitor the condition and location of their products throughout their lifecycle, enabling efficient resource use and waste reduction. The McKinsey Quarterly article by Bughin, Chui, and Manyika (2010) outlines how big data and smart assets drive business trends, leading to more informed and sustainable decision-making processes in line with CE principles. Additionally, Bradley, Barbier, and Handler (2013) from Cisco discuss the substantial economic benefits and improved operational efficiencies resulting from enhanced connectivity and data utilization.

Smart asset management using IoT and sensor technologies can mitigate demand adjustment by efficiency by optimizing the usage, maintenance, and lifecycle of EVs, reducing the need for frequent replacements. It also helps in optimizing production processes and reducing wastage, ensuring that increased profits do not translate into unnecessary increases in production.

Rent instead of Buy

The concept of renting rather than buying products offers several benefits, including lower upfront capital requirements for customers and higher profit margins for companies through rental fees (Takacs et al., 2020). Tukker (2015) discusses how product-service systems (PSS) contribute to a resource-efficient and circular economy by shifting the focus from product sales to service solutions. Cohen and Kietzmann (2014) explore mobility business models within the sharing economy, highlighting the advantages of rental systems. Additionally, Agrawal et al. (2012) analyse the environmental benefits of leasing over selling, demonstrating that leasing can be more sustainable by improving product lifecycle management and resource use. This model also enhances product utilization efficiency by reducing non-usage periods and simplifies product reuse or recycling due to retained ownership by the company.

Renting instead of buying mitigates the substitution mechanism by providing temporary access to EVs, encouraging shared use and higher utilization rates (Brendel et al., 2018). This reduces the need for individuals to own multiple vehicles, thus controlling the demand for new EVs. This model also mitigates demand adjustment by efficiency by ensuring high utilization rates and reducing idle times. By managing availability and usage efficiently, it prevents excessive production and keeps supply in check with actual demand.

Communicate Responsibility

The concept of a producer taking responsibility for the full lifecycle of their products includes certifying products, offering long guarantees, and committing to take-back systems through predefined channels (Takacs et al., 2020). Spicer and Johnson (2004) discuss the role of third-party de-manufacturing as a solution for extended producer responsibility, emphasizing its importance in efficiently managing the entire lifecycle of products. Wijethilake (2017) further explores the impact of proactive sustainability strategies and control systems on corporate sustainability performance. This research highlights the significance of sustainability control systems in driving sustainable practices and improving corporate performance. By implementing these systems, companies can better monitor and manage their sustainability goals, link rewards to sustainability performance, and thereby foster a culture of sustainability within the organization.

By taking responsibility for the full lifecycle of products, including offering long guarantees and take-back systems, companies can promote sustainable practices and ensure products are reused or recycled, reducing overall resource consumption.

6 Discussion

6.1. Interpretation of the Research

1. Actors Responsible for Rebound Mechanism

Both consumers and firms are central to creating rebound effects. Consumers drive these effects through increased usage and demand in response to efficiency improvements, while firms contribute by scaling up production and expanding markets. Together, these actors create a feedback loop that can lead to greater overall resource consumption, challenging the sustainability goals of efficiency initiatives.

The interactions between consumers and firms further amplify rebound effects. As firms reduce costs and improve product efficiency, they stimulate consumer demand. This increased demand prompts firms to scale up production, leading to more resource consumption. Conversely, heightened consumer demand signals firms to continue innovating and expanding, perpetuating the cycle of increased resource use.

2. All mechanisms lead to increased general resource consumption

All mechanisms lead to increased general resource consumption. When actions aimed at reducing resource consumption are implemented, they can trigger mechanisms that result in increased demand or supply, counteracting the initial efforts. This is observed when an action intended to decrease resource consumption in a local system inadvertently leads to increased demand or supply, thereby reinforcing resource consumption on a larger scale. Furthermore, efforts to reduce supply or demand in one area can lead to compensatory reactions in another, further undermining the initial goals. It is crucial to distinguish between increases in resource consumption that stem directly from rebound effects, where improvements in efficiency lead to increased use, and those that arise from technology diffusion, where new technologies replace older, less efficient ones. While technology diffusion aims to decrease resource use through better efficiency, rebound effects can counteract these savings. For example, as more efficient technologies become widely available and cheaper because of diffusion, they might be used more extensively than anticipated, leading to a rebound effect.

If the goal of sustainability actions is to reduce overall resource consumption, measures need to be in place to mitigate rebound effects while promoting the diffusion of efficient technologies. Without this, the full benefits of new technologies might not be realized due to increases in consumption driven by rebound effects.

3. Most of the rebound mechanisms occur during the use phase

Through CLD, it can be seen that most identified rebound mechanisms occur during the use phase of EV. Although the initial triggers may originate from other phases such as production, collection, or recycling, the primary drivers of rebound effects are rooted in consumer behaviour. In the use phase, consumer actions and decisions play a pivotal role in shaping the demand for EVs. As consumers experience the benefits of increased efficiency, lower operating costs, or improved vehicle performance—often the result of advancements in production or recycling technologies—they are more likely to increase their usage of EVs. This increased usage translates directly into a higher demand for EVs, which, in turn, drives a surge in the EV sales rate.

Additionally, there are rebound effects originating from the firm's side. In these cases, the actor creating the rebound effect is the firm itself. When firms increase the supply or production of EVs, this leads to a corresponding increase in general resource consumption. This heightened production not only boosts the availability of EVs but also stimulates consumer interest and demand, further driving up EV sales rates, which also happens in the use phase.

While consumer behaviour mostly drives the rebound effects by boosting EV demand and sales, firms also play a significant role by increasing EV production. This increased production enhances EV availability, which in turn escalates resource consumption and further amplifies the demand and sales cycle in the use phase. Both dynamics work together to reinforce the cycle of efficiency gains and increased consumption, highlighting the complex interplay between different actors and phases in the lifecycle of EV.

4. Role of Societal Pressure for Sustainability influencing consumer behaviour and company strategies

Societal pressures can significantly influence consumer behaviour and company strategies. These pressures often arise from heightened awareness of environmental issues, driven by factors such as media coverage, public campaigns, and educational programs. As a result, consumers increasingly demand more sustainable products and practices. This shift in consumer preferences pushes companies to adopt more environmentally friendly strategies, not only to meet consumer demand but also to align with regulatory requirements and avoid reputational risks.

Moreover, societal pressures can drive firms to adopt circular economy principles, aiming to reduce waste and promote recycling and reuse of materials. This can influence the entire lifecycle of products, from design and production to disposal and recycling, ultimately contributing to more sustainable resource consumption patterns.

5. Rebound Mechanisms can be classified into 5 classes based on structural and dynamics characteristics

Each class will represent a specific type of feedback mechanism that can lead to rebound effects and this results in 5 distinct classes. In Consumption-Induced Mechanism, the mechanisms highlight how efficiency improvements, such as cost savings from improved battery designs or recycling processes, can lead to increased disposable income for consumers. This additional income often results in higher consumption levels, which can negate the environmental benefits of the initial efficiency improvements. The reinforcing feedback loops identified in this study indicate that cost savings directly influence increased EV demand, leading to a paradox where the very actions aimed at reducing environmental impact end up increasing overall resource consumption.

Production-Driven mechanisms focus on how firms reinvest profits from efficiency improvements into expanding production capacities. For instance, improved production processes reduce costs, increase profits, and enable firms to scale up production. This cycle, characterized by reinforcing feedback loops, ultimately leads to higher overall production and consumption of EV batteries. The analysis shows that these mechanisms have a direct influence on the recycling rate and disassembly rate, thereby aligning closely with CE principles.

In Substitution Dynamics, Substitution effects occur when cheaper, more efficient EV batteries replace other products, maintaining a constant level of utility for consumers. This mechanism is critical in understanding how efficiency improvements can lead to shifts in consumption patterns, potentially offsetting the intended sustainability gains. The study found that substitution effects are a major driver of rebound effects, emphasizing the need for policies that account for these dynamics to ensure realistic projections and effective interventions.

Demand Response Mechanism describes how changes in supply or efficiency can lead to increased overall consumption. The interaction between consumers and firms often results in an escalation of resource use, where efficiency gains lead to lower costs and subsequently higher demand. This class of mechanisms underscores the complexity of achieving sustainability goals, as improvements in efficiency can paradoxically drive higher consumption levels.

6. There are 4 identified Most Significant Rebound Mechanisms based on the analysed CLDs and literature review

The study identified four key rebound mechanisms that significantly impact the effectiveness of recycling interventions within the CE practice for EV batteries. These mechanisms are Income, Output, Substitution, and Demand Adjustment Initiated by Efficiency. Mitigating these mechanisms is crucial for ensuring that sustainability goals are met and that the environmental benefits of CE practices are realized.

The Income mechanism describes how efficiency improvements, such as cost savings from enhanced battery designs or recycling processes, can lead to increased disposable income for consumers. This additional income often results in higher consumption levels, negating the environmental benefits of the initial efficiency improvements.

The Output mechanism focuses on how firms reinvest profits from efficiency improvements into expanding production capacities. Improved production processes reduce costs, increase profits, and enable firms to scale up production, leading to higher overall production and consumption of EV batteries.

The Substitution mechanism occurs when cheaper, more efficient EV batteries replace other products, maintaining a constant level of utility for consumers. This mechanism highlights how efficiency improvements can lead to shifts in consumption patterns, potentially offsetting the intended sustainability gains.

The Demand Adjustment Initiated by Efficiency mechanism describes how improvements in efficiency lead to lower costs, which then drive higher demand. This mechanism involves both consumers and producers, where efficiency gains lead to lower prices and subsequently higher consumption levels.

7. Implementing Circular Business Models can be strategies for mitigating Rebound Mechanisms

The mitigation strategies for rebound effects can be broadly categorized into three approaches as highlighted by Font Vivanco et al. (2016): consuming more efficiently, consuming differently, and consuming less. These strategies aim to reduce the environmental impact by altering consumption patterns. However, the challenge lies in effectively implementing these strategies within the context of a firm's operations.

Published studies on reducing rebound effects have predominantly focused on market-based tools like carbon and energy pricing (Saunders, 2011). While these tools are effective, they often require external policy interventions, which may be beyond the control of individual firms. Instead, firms can leverage their internal capabilities, such as innovation and competitive strategies, to achieve their objectives more effectively.

For this research, the emphasis is placed on developing new business models and fostering technological innovation, focusing on process improvement rather than product innovation. This choice is guided by the strategic management principles outlined by Schilling (2020), which emphasize leveraging a firm's core competencies and resources to foster innovation and competitive advantage. The rationale for focusing on business models and process improvement includes the following considerations:

1. **Internal Capabilities**: Companies have more control over their internal processes and business models compared to external policy instruments. By focusing on these areas, firms can directly influence their sustainability outcomes.
2. **Core Competencies**: Aligning innovation strategies with a firm's core competencies ensures that the efforts to mitigate rebound effects are both effective and sustainable in the long term. Schilling (2020) highlights the importance of leveraging a firm's strengths to achieve a competitive advantage.
3. **Predictable Outcomes**: Process improvements can lead to predictable and measurable outcomes, such as cost reductions and increased efficiency. This aligns with the goal of achieving operational excellence and cost leadership.
4. **Sustainability Integration**: Business models that promote sustainability, such as pay-per-use and subscription models, can be integrated into the company's existing operations, providing a seamless transition towards more sustainable practices.

8. Strategies Focus on Circular Business Models and Exclusion of Broader Economic Instruments and Policy Approaches

The exclusion of broader economic instruments, such as subsidies and carbon pricing, is due to their dependency on government policies and regulatory frameworks. These factors are often beyond the control of individual firms, making them less reliable as components of a firm's innovation strategy. Similarly, promoting sustainable behaviour and raising awareness, while important, are typically managed by societal and governmental efforts. Companies often have limited control over these initiatives, making it challenging to integrate them effectively into company-specific strategies.

The selection of circular business models as a mitigation strategy is based on their relevance to the three approaches outlined by Font Vivanco et al. (2016) and their applicability to the context of circular EV batteries. Takacs et al. (2020) highlight several circular ecosystem patterns that provide a blueprint for designing a circular ecosystem within an industry. These patterns are chosen for their potential to address significant rebound mechanisms identified in the research.

- **Income Mechanism**: Circular business models like subscription and pay-per-use help spread costs over time, making it easier for customers to manage budgets and reducing the likelihood of increased consumption due to additional disposable income.
- **Output Mechanism**: Models such as produce on demand and smart asset management ensure that production aligns with actual demand, preventing overproduction and unnecessary resource use.
- **Substitution Mechanism**: Renting instead of buying promotes shared use and higher utilization rates, reducing the need for individual ownership and controlling the demand for new EVs.
- **Demand Adjustment by Efficiency**: Dynamic pricing adjusts prices based on real-time demand, balancing supply and demand efficiently and preventing excessive consumption.

6.2. Limitations

1. Qualitative Analysis for Rebound Mechanisms

The research primarily relies on qualitative system dynamics modelling to identify and analyse rebound mechanisms. While this approach provides valuable insights, it lacks the quantitative precision necessary for detailed impact assessments. Qualitative modelling helps understand the complex interactions within the system, but it does not provide the measurable strength of each mechanism or the precise interactions between variables. To improve the accuracy and robustness of the findings, incorporating a quantitative approach would be beneficial. Quantitative models can offer more precise evaluations of the strength of each mechanism and the interactions among variables, thereby enhancing the reliability of the conclusions drawn.

Selecting the most significant mechanisms involves a degree of subjectivity inherent in qualitative analysis. The selection process is based on critical thinking and assumptions about the impact of various factors, which may not be universally agreed upon. Different researchers might prioritize mechanisms differently based on their interpretations and biases. This subjectivity can influence the prioritization of mechanisms and, consequently, the development of mitigation strategies. The weighing used for the selection is also still vague and subjective. To mitigate this issue, a more standardized approach, possibly incorporating quantitative metrics, could help ensure more objective and replicable results.

Additionally, the availability and quality of data on EV battery lifecycles and recycling processes significantly limit the robustness of the qualitative models. Inaccurate or incomplete data can lead to flawed analyses and conclusions. Improved data collection and reporting standards are crucial for enhancing the accuracy of future research. Comprehensive and high-quality data would enable more precise modelling and provide a solid foundation for both qualitative and quantitative analyses. By improving data standards, researchers can better capture the complexities of EV battery lifecycles and recycling processes, leading to more reliable and actionable insights.

2. Assumptions in CLDs

The creation of CLDs in this study relies heavily on assumptions regarding the relationships and interactions within the circular economy for EV batteries. These assumptions are grounded in existing literature and expert interviews, providing a basis for understanding system dynamics.

However, they may not fully capture the complexities and nuances of real-world dynamics. The inherent reliance on assumptions can introduce biases into the models, potentially limiting their accuracy and effectiveness. It is crucial to acknowledge that while assumptions are necessary for constructing initial models, they should be continuously validated and refined through empirical data and real-world observations to improve their reliability.

Additionally, the study acknowledges the presence of uncertainty within the model due to numerous external factors that influence the feedback loops. These factors, often not analysed within the scope of the model, can significantly impact the system's behaviour. External influences such as market fluctuations, regulatory changes, and technological advancements can alter the dynamics in ways that are not anticipated by the initial assumptions. This uncertainty underscores the need for robust sensitivity analysis and scenario planning to explore how different external conditions might affect the model's outcomes.

3. Biases in Expert Inputs

The validation and refinement of CLDs through expert interviews are influenced by the personal biases and perspectives of the interviewed experts. These biases can affect how feedback loops are interpreted, and which variables are considered important, potentially skewing the final models. Experts bring their own experiences and knowledge, which, while valuable, can inadvertently shape the outcomes in ways that may not fully align with objective reality. This reliance on expert opinion introduces an element of subjectivity that can affect the accuracy of the CLDs.

Additionally, the answers provided by the interviewees are based on their specific experiences and areas of expertise. While this specialized knowledge is crucial for understanding complex systems, it also means that their answers can be biased. Experts might emphasize certain aspects of the system over others based on their professional backgrounds, potentially overlooking other critical factors. This can lead to an incomplete or unbalanced representation of the system dynamics, affecting the overall reliability of the model.

4. Limited Scope of Intervention Focus

This study focuses only on Recycling as the main strategy within the circular economy framework for EV batteries. While recycling is very important, other strategies like repurposing, reusing, and refurbishing are also crucial. These strategies can help extend the lifespan of batteries and reduce the need for new materials. However, by focusing only on recycling, the study may not cover all the important aspects of the circular economy. This limited focus might miss out on the benefits and challenges of other strategies, giving an incomplete picture of how the circular economy can work for EV batteries.

Additionally, the study does not analyse several mechanisms that involve interactions between different sectors. These mechanisms are important for a full understanding of the circular economy. For example, repurposing used EV batteries for energy storage involves both the EV and energy sectors. By not considering these cross-sector interactions, the study may overlook important dynamics that affect the overall effectiveness of circular economy strategies.

5. Dynamic Capabilities and Market Variability

The dynamic nature of market conditions and technological advancements can significantly affect the applicability of the study's findings. Market demand, regulatory frameworks, and technological innovations are constantly evolving, and these changes can alter the dynamics of the circular economy. As a result, some of the study's conclusions may become less relevant over time.

Changes in market demand can greatly influence the effectiveness of circular economy strategies. For instance, a sudden increase in demand for EV batteries could lead to shortages of critical materials, impacting the feasibility of recycling and repurposing initiatives. Conversely, a drop in demand might reduce the economic viability of such interventions. Market fluctuations can also affect consumer behaviour, altering the effectiveness of strategies like pay-per-use or subscription models.

6. Limitations on Expert Validations

The study relies on inputs from selected experts, which may not fully represent the diversity of perspectives from all relevant stakeholders, including consumers, policymakers, and industry practitioners. Moreover, the tight timeline also become a constraint on exploring the potential experts for validations. This limited engagement can impact the generalizability and robustness of the findings. When the views of a broader range of stakeholders are not considered, the study may miss out on important insights and concerns that could influence the effectiveness of circular economy strategies. For instance, consumers might have different priorities and concerns compared to industry experts, and these differences need to be accounted for to create more comprehensive and applicable solutions. Including a wider array of voices could help ensure that the strategies developed are more inclusive and better aligned with the needs and expectations of all parties involved.

Moreover, the study does not analyse conflicting interests between stakeholders, which can significantly impact the implementation and success of circular economy initiatives. For example, some firms might prefer to reduce prices due to excess supply, while others might want to maintain original prices to protect their profit margins. These conflicting interests can create challenges in achieving consensus and coordinated action. Without addressing these conflicts, the study's recommendations may overlook practical barriers to implementation.

6.3. Future Research

1. Incorporate Quantitative Analysis

Future research should aim to incorporate quantitative system dynamics modelling to complement the qualitative approaches currently used. While qualitative modelling provides valuable insights into the complex interactions within the system, quantitative models can offer precise evaluations of the strength of each mechanism and the interactions among variables. This dual approach can enhance the robustness and accuracy of the findings, allowing for detailed impact assessments and more reliable conclusions. Developing standardized quantitative metrics will also help ensure that the results are objective and replicable.

2. Refining Assumptions Used in CLDs

Given the reliance on assumptions in creating CLDs, future studies should continuously validate and refine these assumptions through empirical data and real-world observations. Incorporating robust sensitivity analysis and scenario planning can help explore how different external conditions, such as market fluctuations, regulatory changes, and technological advancements, might affect the model's outcomes. This iterative approach will improve the reliability and accuracy of the CLDs, ensuring they reflect real-world dynamics more accurately.

3. Addressing Biases in Expert Validations

To mitigate biases in expert validations, future research should involve a more diverse range of stakeholders, including consumers, policymakers, and industry practitioners. This broader engagement will help balance individual biases and provide a more comprehensive view of the system. Employing structured elicitation techniques, such as the Delphi method, can minimize the impact of individual biases by converging toward more accurate and consensus-based models. Triangulating expert inputs with empirical data will further enhance the CLD validity.

4. Expanding Scope of Intervention Focus

Future studies should broaden the scope of interventions beyond recycling to include strategies such as repurposing, reusing, and refurbishing. Each of these strategies offers unique benefits and challenges that are crucial for developing a robust circular economy framework. By analysing mechanisms that involve multiple sectors, such as the interactions between the EV and energy sectors in repurposing used batteries, researchers can gain a more holistic understanding of the circular economy. This expanded focus will help capture important dynamics that affect the overall effectiveness of circular economy strategies.

5. Broader Expert Validation

To improve the generalizability and robustness of the findings, future studies should engage a wider array of experts for validation. Including diverse perspectives from consumers, policymakers, and industry practitioners will help ensure that the strategies developed are more inclusive and aligned with the needs and expectations of all parties involved. Addressing conflicting interests between stakeholders is also crucial. Future research should analyse these conflicts and develop strategies to achieve consensus and coordinated action, overcoming practical barriers to the implementation of circular economy initiatives.

6.4. Core Contributions

6.4.1. Academic Relevance

On a theoretical level, the research aims to deepen the understanding of rebound effects within the CE context for EV batteries. By comprehensively analysing the EV battery value chain and its alignment with CE principles, the study will identify key components and processes, highlighting the systemic challenges and opportunities in achieving circularity. Insights into system structure dynamics, including feedback loops and drivers of rebound effects, will contribute to theoretical advancements in sustainability transition research. Empirically, the research will provide empirical evidence of rebound effects observed in existing real-world CE initiatives, which can serve as valuable insights into the emerging field of CE for EV batteries. Expert validation will further strengthen the credibility of these findings, enhancing their applicability to CE practices for EV batteries.

6.4.2. Managerial Relevance

On industry level, industry stakeholders involved in EV battery production, distribution, and management will gain actionable insights into systemic challenges and opportunities associated with achieving circularity. By understanding the dynamics of rebound effects and their implications for CE initiatives, companies can develop informed strategies and policies to transition towards sustainable battery management practices. Additionally, the exploration of strategies for mitigating rebound effects and integrating them into CBMs will offer practical guidance to industry actors, enhancing the environmental, social, and economic sustainability of their operations.

This research has the potential to drive transformative change within the EV battery industry, fostering innovation, collaboration, and sustainability across the value chain. By bridging the gap between theory and practice, the study will contribute to the advancement of CE principles and facilitate the transition towards a more sustainable and circular economy for EV batteries.

6.5. Reflection

6.5.1. General Reflection

In this section, the reflection on the successes and challenges encountered during this research study will be conducted and the lessons learned for future research processes will be discussed. Conducting this research presented numerous challenges that required adjustments and adaptations to the research process.

One significant challenge was refining the scope and focus of the research. Initially, I aimed to examine all possible interventions within the circular economy framework for EV batteries, including reuse, repurposing, and refurbishing. However, due to time constraints, it became necessary to narrow the research scope to focus primarily on recycling. This decision was essential to ensure the research remained manageable and could be completed within the available timeframe. While this limitation restricted the comprehensiveness of the study, it allowed for a more in-depth analysis of the chosen intervention.

Another major challenge was the methodology employed in this research. The use of qualitative CLDs posed difficulties in analysing the most significant mechanisms. Having no prior experience with system dynamics or CLDs, I had to quickly learn and apply these methods within a short period. This learning curve was steep and required numerous revisions to the CLDs to improve their accuracy and relevance. Despite the ongoing need for further refinement, this process provided valuable insights into the complexity of system dynamics and highlighted the importance of flexibility and adaptability in research methodologies.

Selecting the appropriate strategies for mitigating rebound effects was also challenging. The absence of standardized methods for choosing these strategies meant that the selection process was iterative and continuously evolving. This iterative approach, although time-consuming, ultimately led to more robust and context-specific strategies. However, it underscored the need for developing standardized frameworks for strategy selection in future research to streamline the process and enhance consistency.

Additionally, conducting validation interviews posed difficulties due to the limited availability of companies willing to participate in the research. This constraint restricted the breadth of industry perspectives that could be incorporated into the study. Overcoming this challenge required persistence and resourcefulness in reaching out to potential interviewees and making the most of the available data.

6.5.2. Tools Used for This Research

VENSIM was utilized to create the CLDs, while Microsoft Teams facilitated interviews and generated transcripts. Language barriers posed challenges throughout the research, which were addressed by leveraging AI tools like ChatGPT to enhance the clarity and quality of the research documentation. Grammarly was also employed for grammar correction.

7 Conclusion

7.1. General Conclusion

The transition to EVs and the adoption of CE principles for LIBs are crucial for reducing CO2 emissions and promoting sustainability in transportation. However, rebound effects—where increased efficiency leads to higher overall resource use—pose a significant challenge. This study underscores the importance of considering the entire lifecycle of EV batteries, from production to disposal, to implement effective CE strategies. By identifying the points in the battery lifecycle where rebound effects are most likely, stakeholders can better design measures to minimize these unintended consequences.

Furthermore, incorporating an understanding of rebound effects into CBMs allows businesses to more accurately evaluate the environmental benefits of their initiatives. This helps avoid overstating the positive impacts and ensures that efforts towards sustainability are genuinely effective. The research provides a framework for companies and policymakers to recognize and address rebound effects, thereby improving the overall effectiveness of CE practices in the EV battery industry. The findings highlight a deeper understanding of the dynamics of CE practice for EV batteries. Three sub-questions were used to answer the main research question. By addressing these sub-questions, this study analyses various aspects of circular ecosystems and their potential implications for more sustainable packaging practices.

SQ1: What are the key components of the current EV battery value chain, and how do they relate to circular economy principles?

The key components of the current EV battery value chain include several stages that align with circular economy principles to promote sustainability and resource efficiency. The process begins with exploring and extracting lithium, a crucial raw material for batteries. This lithium is then mined and processed to produce materials suitable for battery production. These materials are used to manufacture battery cells, which are then assembled into EV battery packs. These packs are installed in electric vehicles and used by consumers until they reach the end of their life. At this point, the batteries are collected and assessed to determine their condition. The batteries are then disassembled, with parts either disposed of or sent for recycling. These key components are illustrated in Figure 5.

In this research, recycling is highlighted as a key intervention to create a closed-loop system. The recycling process recovers valuable materials from used batteries, which are then reused to produce new batteries. This reduces waste and the need for new raw materials. By reusing these materials, the value chain becomes more efficient and less harmful to the environment. This continuous reuse of materials supports a regenerative system, extending the life cycle of products and reducing the overall environmental impact. Circular economy practices in the EV battery value chain help stabilize supply chains, lower costs for raw materials, and reduce environmental harm, making the industry more sustainable and resilient. Recycling is crucial for achieving these goals, highlighting the importance of minimizing waste and maximizing resource use to create a sustainable future.

SQ2: What are the dynamics of system structure within the circular economy of EV batteries that contribute to the emergence of rebound effects?

The system structure within the circular economy of EV batteries is characterized by a series of interconnected stages and feedback loops, each contributing to the potential emergence of rebound effects. These dynamics include the entire lifecycle of EV batteries, from raw material extraction to manufacturing, usage, and end-of-life management, focusing on the recycling process. Key dynamics that contribute to rebound effects involve improvements in the efficiency of battery recycling, which can lower the costs of recycled materials. While beneficial, this can lead to increased production and consumption of batteries, as manufacturers take advantage of lower material costs to produce more batteries. This increase in production can negate the environmental benefits gained from recycling, leading to higher overall material consumption and waste generation.

Additionally, cost savings from using recycled materials can create economic incentives for higher production levels. As recycled materials become cheaper, the profitability of producing more batteries increases, encouraging manufacturers to expand their production capacities, which can lead to an overall increase in resource use, offsetting the gains made from recycling and other circular economy practices. Behavioural responses from consumers and industries also play a crucial role. Consumer behaviour changes, driven by the availability of cheaper and more efficient EV batteries, can lead to increased adoption of EVs. While this shift is positive for reducing reliance on fossil fuels, it can result in greater overall resource use if the demand for EVs and batteries rises significantly.

This phenomenon, where efficiency improvements lead to higher overall consumption, is a classic example of the rebound effect. Specific rebound mechanisms further illustrate these dynamics: **consumption-induced mechanisms**, where efficiency improvements lead to cost savings and higher consumption levels; **production-driven mechanisms**, where firms reinvest profits from efficiency improvements into expanding production capacities; **substitution dynamics mechanisms**, where cheaper, more efficient EV batteries replace other products, maintaining a constant level of utility for consumers; and **demand response mechanisms**, where changes in supply or efficiency lead to increased overall consumption. These dynamics demonstrate how interconnected stages and feedback loops within the circular economy framework can lead to the emergence of rebound effects. Addressing these effects requires a comprehensive understanding of systemic and behavioural responses and the implementation of strategies that align circular economy practices with broader sustainability goals, ensuring that the environmental benefits of circular economy initiatives are not undermined by increased overall consumption and production.

SQ3: What managerial strategies are most effective in mitigating rebound effects when integrated into the circular business model for EV batteries?

Effective managerial strategies to mitigate rebound effects within the circular business model for EV batteries include dynamic pricing, pay-per-use models, subscription models, take-back systems, produce on demand, smart asset management, and renting instead of buying. Dynamic pricing adjusts prices based on real-time demand to balance supply and prevent excessive consumption. Pay-per-use models charge customers based on usage, encouraging efficient use without the need for ownership. Subscription models spread costs over time, reducing consumptive behaviours and generating consistent revenue without increasing production. Take-back systems incentivize the return of used batteries for recycling, reducing waste and the need for new materials. Produce on demand aligns production with confirmed demand, preventing overproduction and minimizing environmental impact. Smart asset management utilizes IoT technologies to optimize usage and maintenance, reducing the need for frequent replacements. Renting instead of buying encourages shared use and higher utilization rates, controlling the demand for new EVs. These strategies collectively address key mechanisms driving rebound effects, ensuring that the environmental benefits of circular economy practices are realized and sustained.

RQ: Which stages in the circular economy for EV batteries are prone to lead to rebound effects, and what managerial strategies and circular business models can be effectively integrated to mitigate them?

From the identified significant mechanisms, it is clear that three mechanisms—Income, Substitution, and Demand Adjustment by Efficiency—are particularly prevalent in the EV usage phase. These mechanisms can lead to rebound effects that undermine the environmental benefits of electric vehicles if not properly managed. To address these rebound effects effectively, several strategic approaches can be employed.

The Income Mechanism arises when efficiency improvements and lower operational costs of EVs result in increased disposable income for consumers. With more money saved from reduced fuel and maintenance costs, consumers may spend their surplus income on other goods and services, potentially leading to increased overall resource consumption. To mitigate this, dynamic pricing can be an effective strategy. Dynamic pricing adjusts the cost of using EVs based on real-time demand and usage patterns. By increasing costs during peak usage times, dynamic pricing can reduce the disposable income effect by encouraging users to drive less during expensive periods, thereby preventing surplus income from being spent elsewhere.

The Substitution Dynamics mechanism occurs when efficient and cost-effective EVs replace other forms of transportation, such as public transit, cycling, or walking. While substituting EVs for more polluting vehicles is beneficial, it can lead to an overall increase in vehicle miles travelled, which negates the environmental benefits. To counteract this, implementing rent instead of buy and subscription models can be effective. Renting EVs encourages shared use and higher utilization rates, reducing the need for individual ownership and promoting the use of alternative transportation modes. Subscription models provide access to EVs through regular payments, encouraging efficient use of the vehicles and reducing the overall number of vehicles on the road.

The Demand Adjustment by Efficiency mechanism is prominent in the EV usage phase due to the lower operational costs and improved efficiency of EVs, which encourage users to drive more frequently and for longer distances. This increased usage can lead to higher overall energy consumption and greater demand for EVs, offsetting the gains from efficiency improvements. Pay-per-use models can help mitigate this by charging users based on their actual usage, making them more conscious of their driving habits, and reducing unnecessary trips. Additionally, dynamic pricing can vary prices according to demand, discouraging excessive use and maintaining a balance between supply and demand.

To further emphasize, dynamic pricing not only addresses the income mechanism by reducing disposable income through higher costs during peak times but also mitigates substitution dynamics by making alternative transportation more attractive during these periods. It also directly impacts the demand adjustment by efficiency by discouraging excessive use through variable pricing. Rent instead of buy and subscription models encourage shared and efficient use of EVs, reducing the likelihood of these vehicles being used excessively and promoting other forms of transport.

7.2. Recommendations

The recommendations will be targeted for firms to better mitigate the rebound effect associated with circular EV batteries.

1. Firms should identify and understand the mechanisms within their operations that lead to rebound effects, focusing on those most likely to undermine sustainability efforts. This study has pinpointed four key mechanisms—Income, Output, Substitution, and Demand Adjustment by Efficiency—that are particularly significant in this context. By concentrating on these mechanisms, companies can develop targeted strategies to mitigate the negative impacts. Addressing these specific areas will enable firms to more effectively balance efficiency improvements with sustainable practices, ensuring that their efforts to reduce environmental impact are not offset by unintended increases in consumption or production.
2. Based on the identified mechanisms likely to cause rebound effects, firms should select the most suitable strategies to mitigate these impacts. Dynamic Pricing is highly recommended as it effectively addresses all significant mechanisms—Income, Output, Substitution, and Demand Adjustment by Efficiency. By adjusting prices in real-time according to demand and usage patterns, Dynamic Pricing can reduce excessive consumption, balance supply and demand, and discourage inefficient use. This comprehensive approach ensures that efficiency gains do not lead to increased overall resource use, thereby supporting more sustainable business practices.
3. Pay-per-Use and Subscription models are also effective alternative strategies for firms to mitigate rebound effects. These approaches promote efficient resource use by tying costs directly to usage, which can discourage excessive consumption. Pay-per-Use charges customers based on their actual usage, encouraging mindful consumption and reducing unnecessary trips. Subscription models provide regular access to EVs through periodic payments, fostering shared use and higher utilization rates while preventing the accumulation of surplus disposable income that could lead to additional consumption. Both strategies help address the Income, Substitution, and Demand Adjustment by Efficiency mechanisms, supporting more sustainable and responsible usage patterns.
4. Many of the proposed strategies, such as subscription models and pay-per-use schemes, rely heavily on changes in consumer behaviour. The effectiveness of these models assumes that consumers will adopt and adhere to these new consumption patterns. However, consumer behaviour is often unpredictable and influenced by various external factors, making it challenging to ensure consistent adoption and usage patterns. There is also potential resistance from consumers accustomed to traditional ownership models. Transitioning to rental or subscription-based models may encounter resistance due to perceived loss of ownership and control over products. Therefore, firms should incorporate this aspect.
5. Implementing circular business models such as produce on demand and dynamic pricing requires sophisticated operational capabilities and advanced data analytics. Smaller firms or those lacking in technological infrastructure may find it challenging to adopt these models effectively. Moreover, the transition to new business models and process improvements can involve significant upfront costs. These include investments

in technology, training, and changes to existing business processes. For some firms, particularly SMEs, these costs may be prohibitive, so this also should be considered when implementing the strategy.

6. When implementing these strategies, firms should consider the interests and impacts of all stakeholders involved in the system. This includes consumers, policymakers, industry partners, and environmental groups. Engaging with a diverse range of stakeholders ensures that the strategies are well-rounded, widely accepted, and effectively address the broader social, economic, and environmental implications. Collaboration and open communication with stakeholders can help identify potential challenges, align goals, and foster a collective commitment to sustainable practices. By taking a holistic approach, firms can enhance the effectiveness of their strategies and contribute to a more sustainable and resilient circular economy.
7. Firms should also consider internal organizational aspects when transitioning to new business models. This includes evaluating the readiness of their infrastructure, workforce, and operational processes to support the new strategies. Adequate training and resources should be provided to employees to ensure they are equipped to implement and sustain these changes. Additionally, firms should align their organizational culture and incentives with the goals of the new business model to promote commitment and engagement across all levels of the company. By addressing these internal factors, firms can facilitate a smoother transition and enhance the long-term success of their new business models.

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Appendix A

CLDs for Rebound Mechanisms

1. Income Mechanism

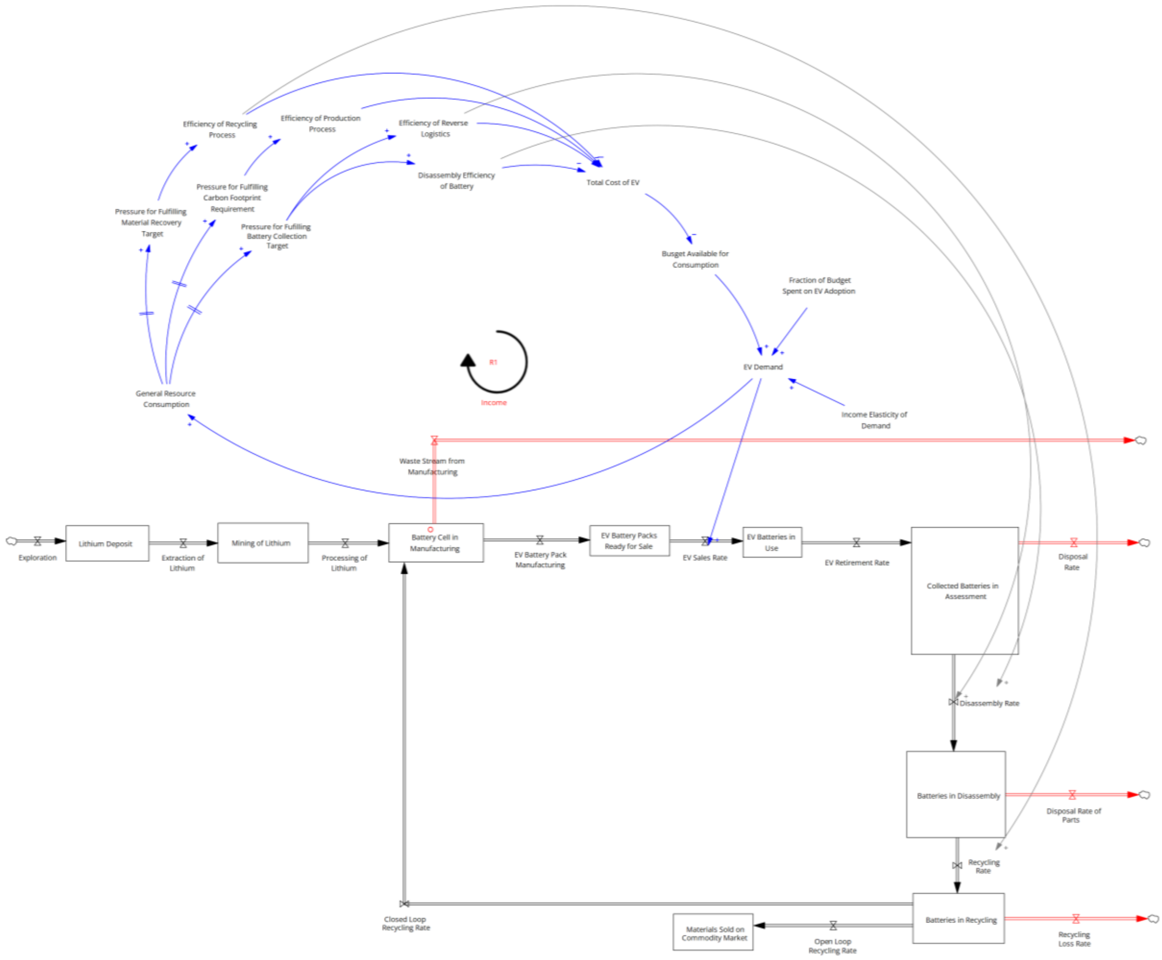

Figure 12 Income Mechanism

2. Consumption Time Mechanism

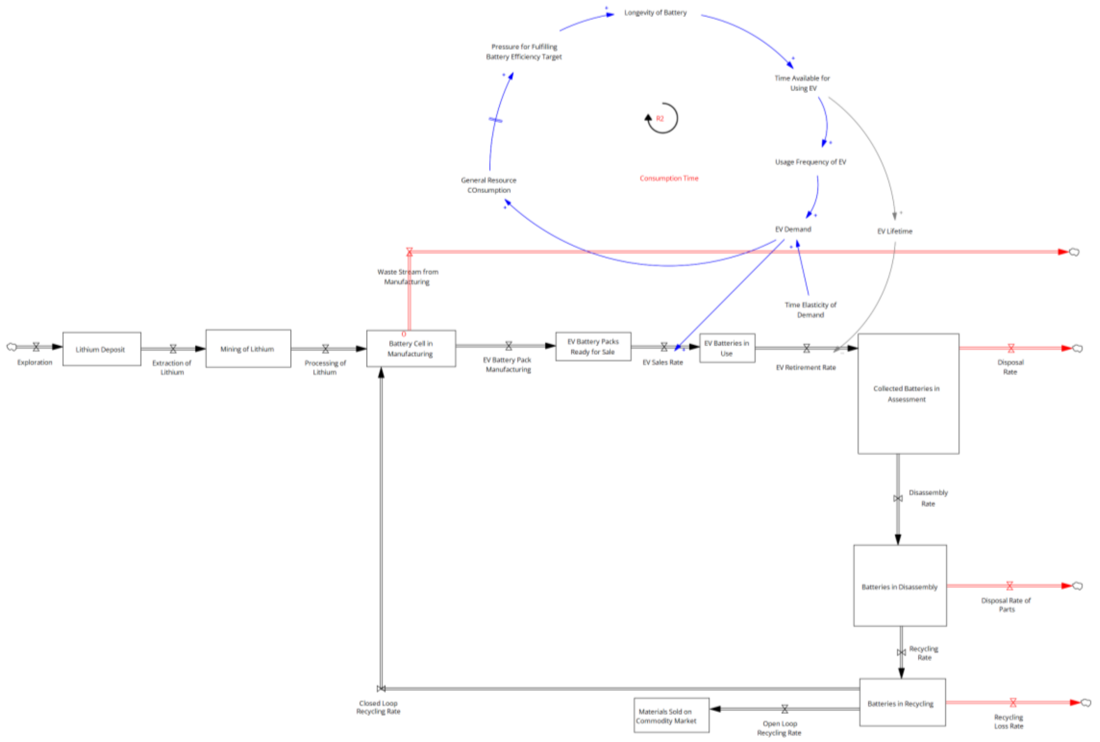

Figure 13 Consumption Time Mechanism

3. Motivational Consumption Mechanism

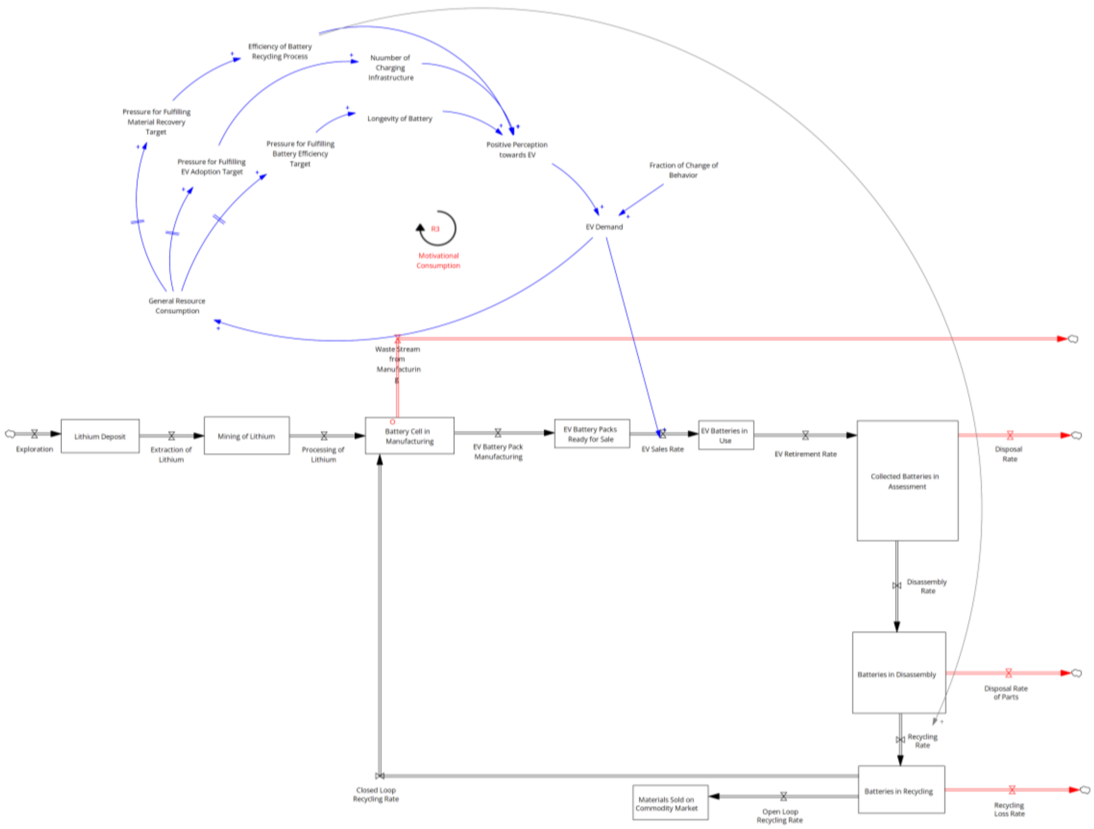

Figure 14 Motivational Consumption Mechanism

4. Re-Spending Mechanism

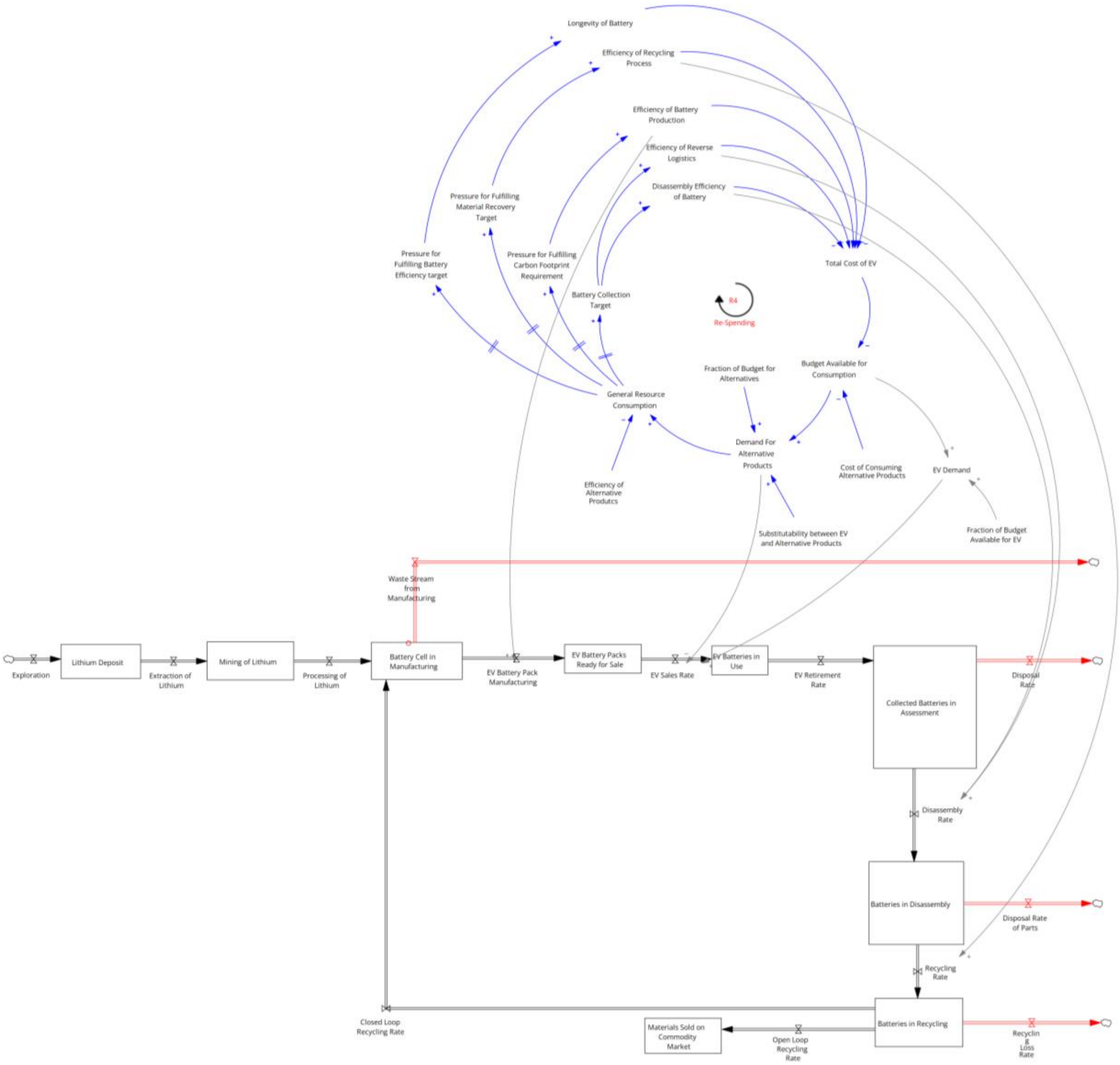

Figure 15 Re-Spending Mechanism

5. Re-Spending with Limited Income Mechanism

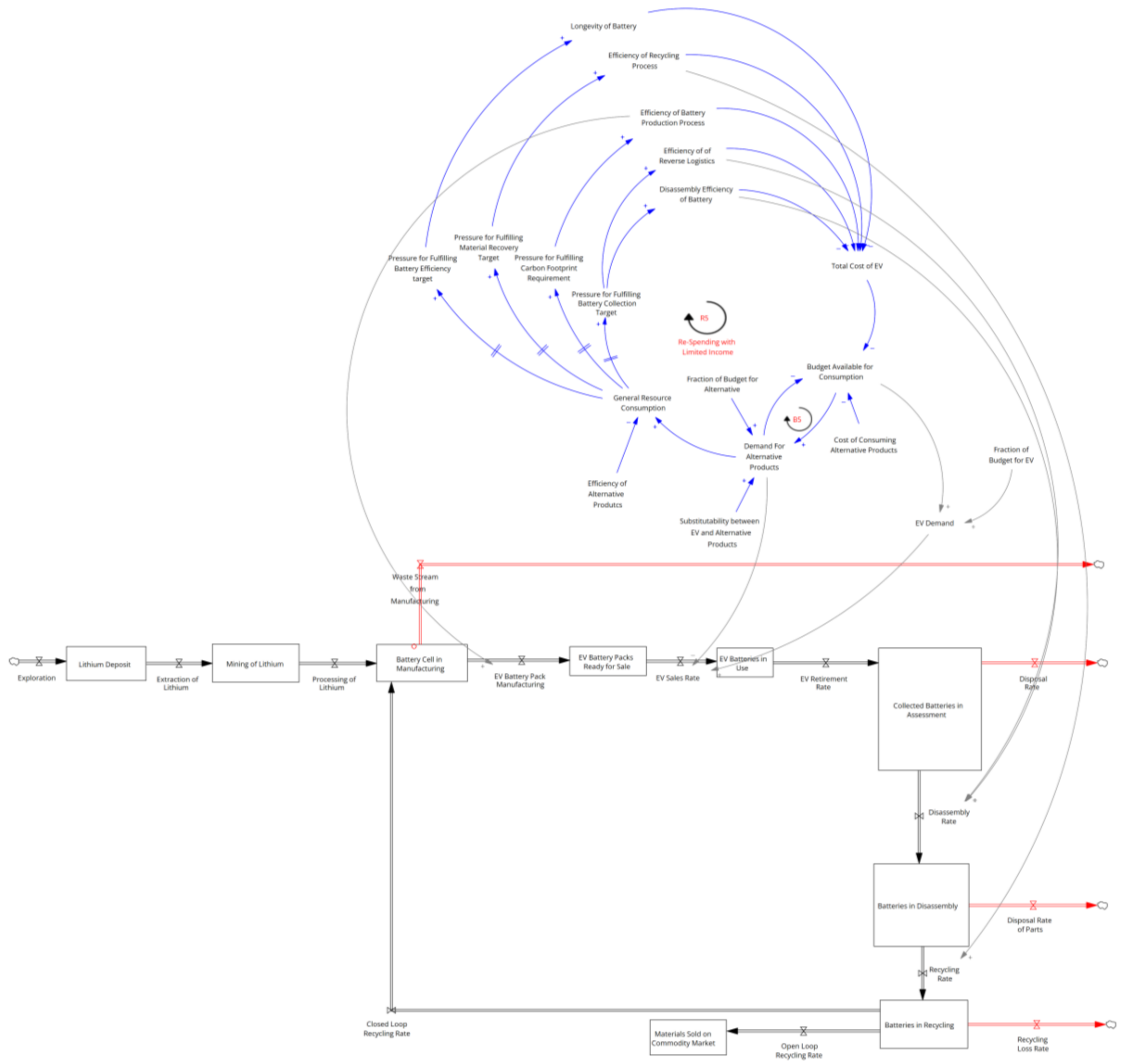

Figure 16 Re-Spending with Limited Income Mechanism

6. Output Mechanism

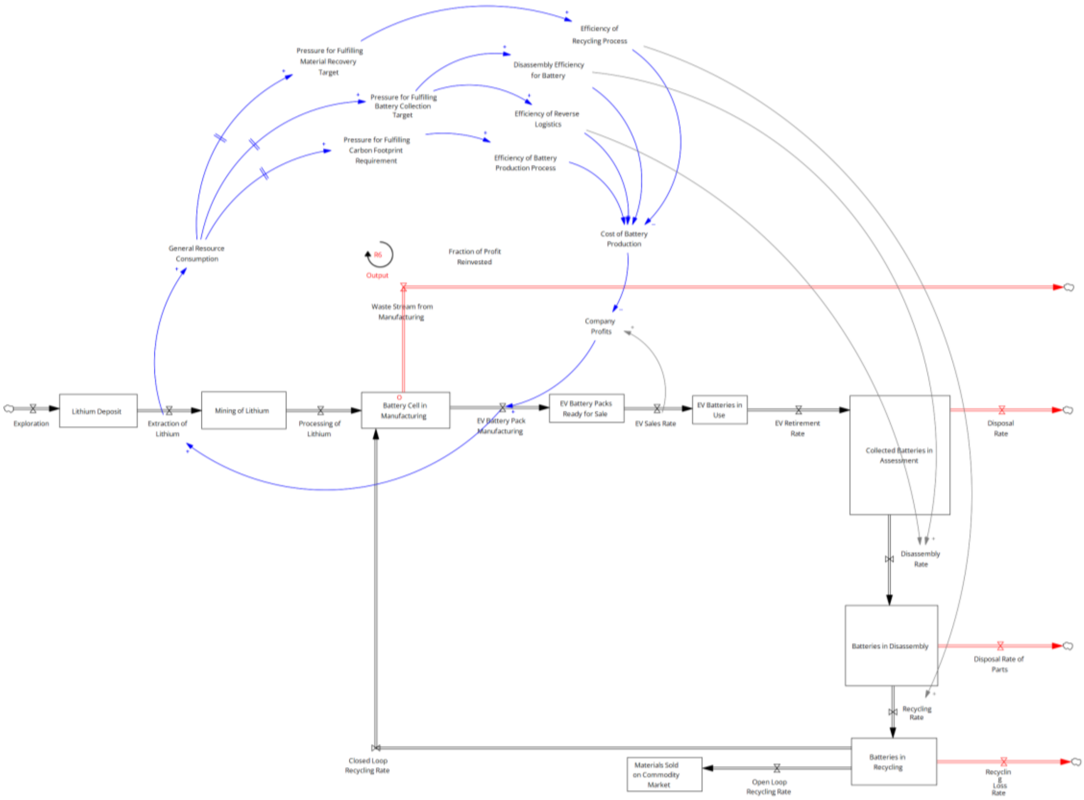

Figure 17 Output Mechanism

7. Production Time Mechanism

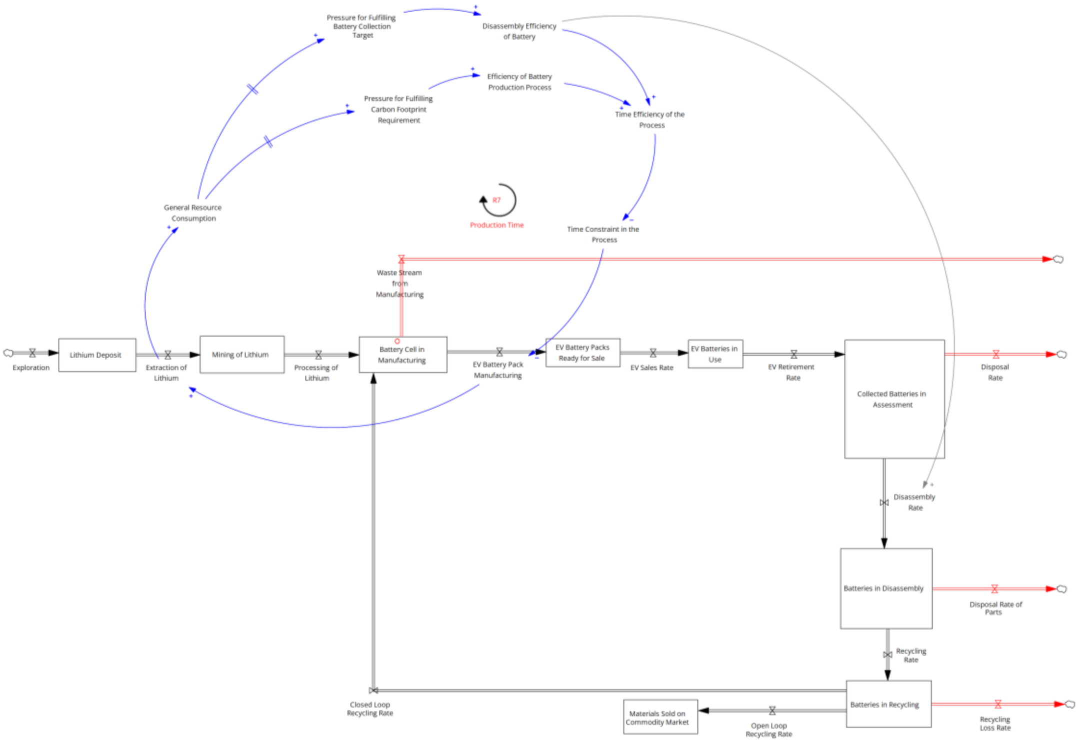

Figure 18 Production Time Mechanism

8. Re-Investment Mechanism

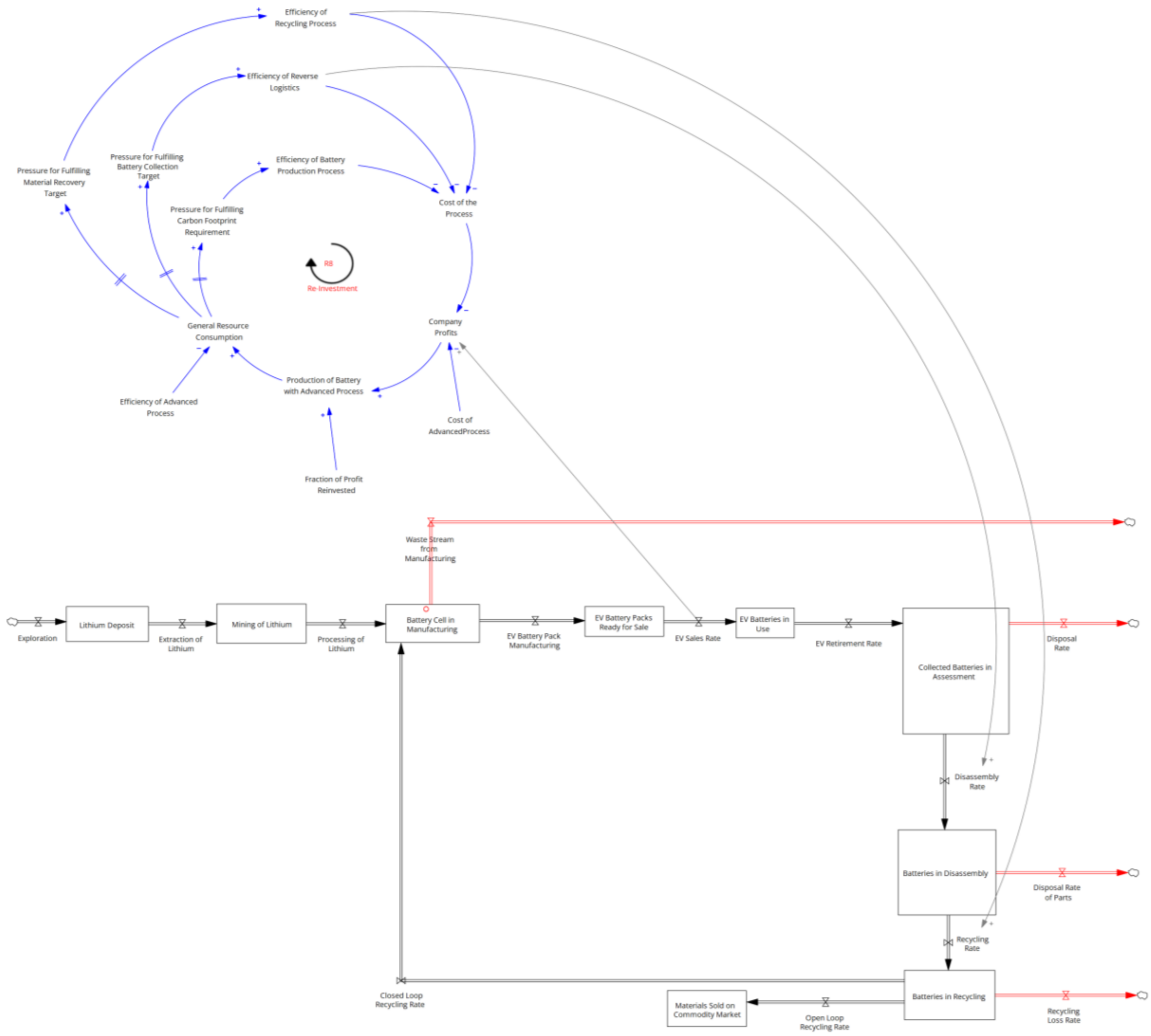

Figure 19 Re-Investment Mechanism

9. Cost-Dependent Output Mechanism

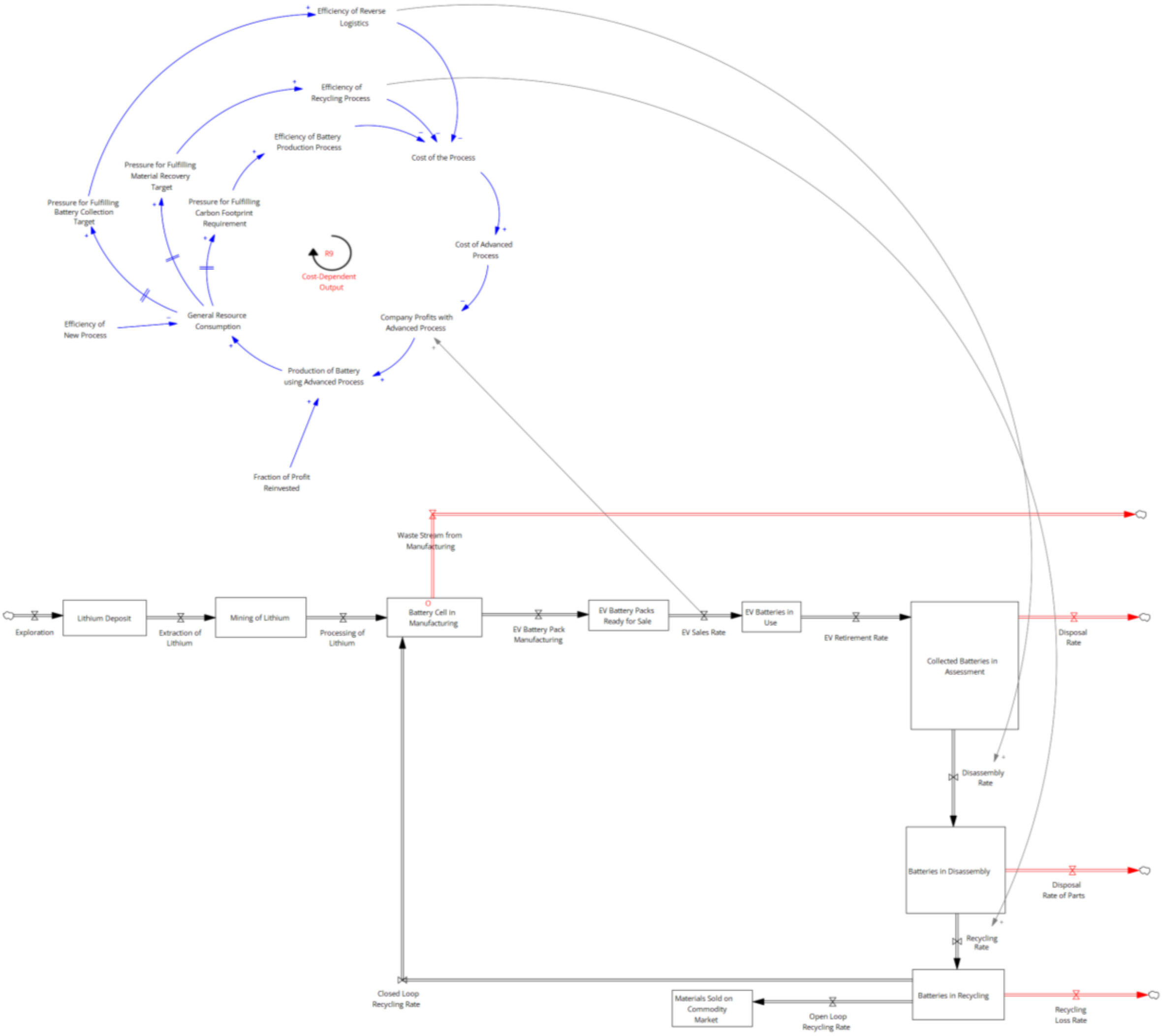

Figure 20 Cost-Dependent Output Mechanism

10. Substitution Mechanism

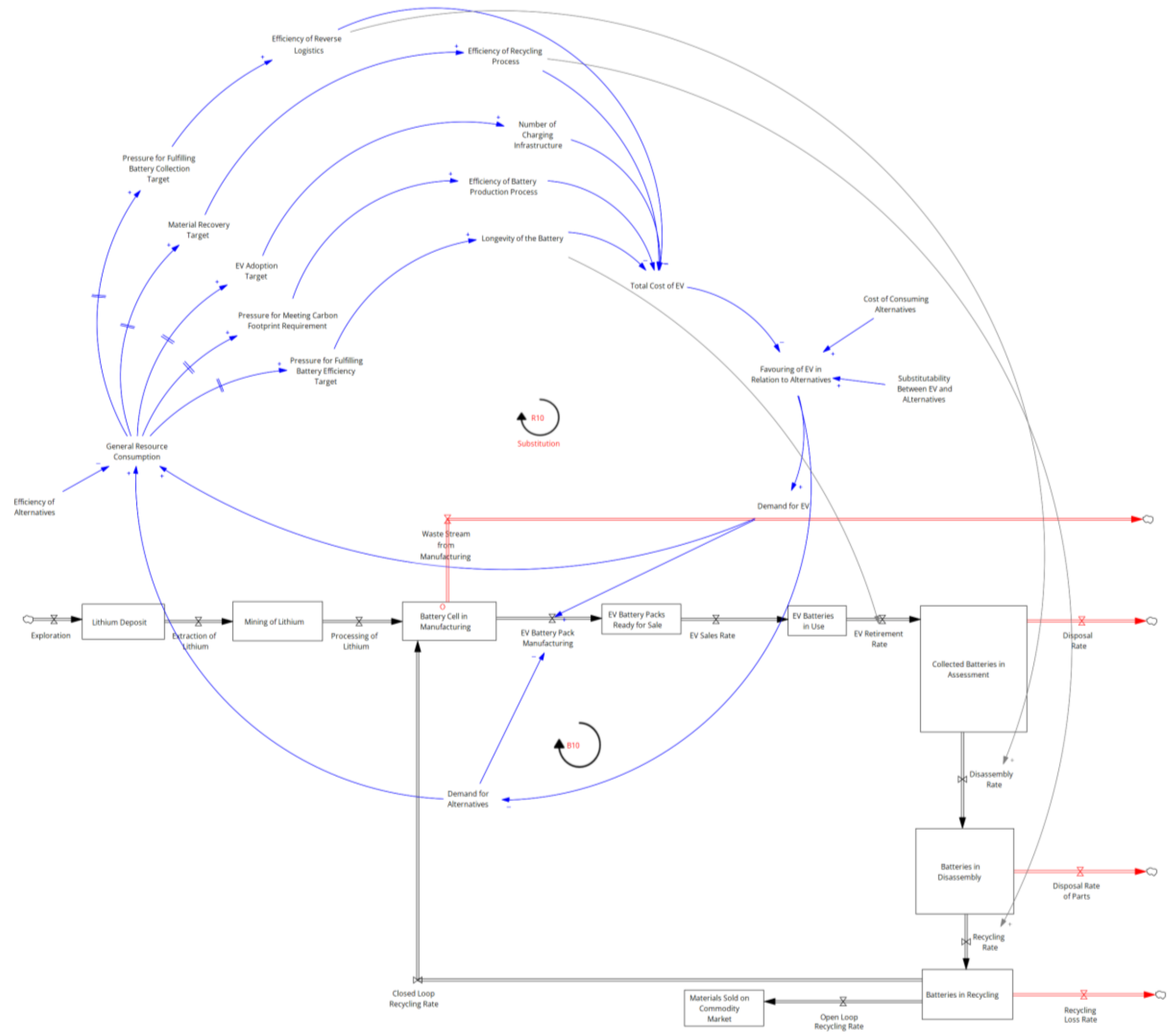

Figure 21 Substitution Mechanism

11. Motivational Substitution Mechanism

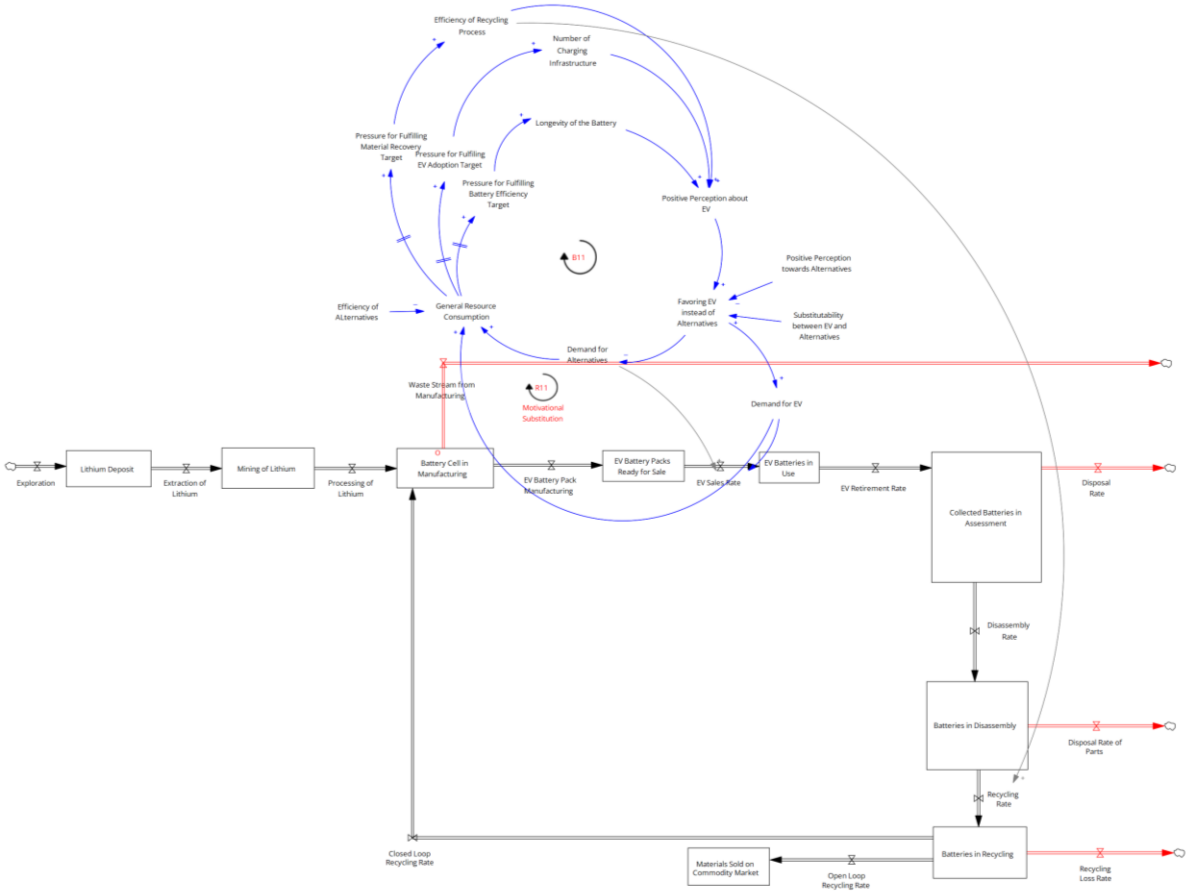

Figure 22 Motivational Substitution Mechanism

12. Factor Substitution Mechanism

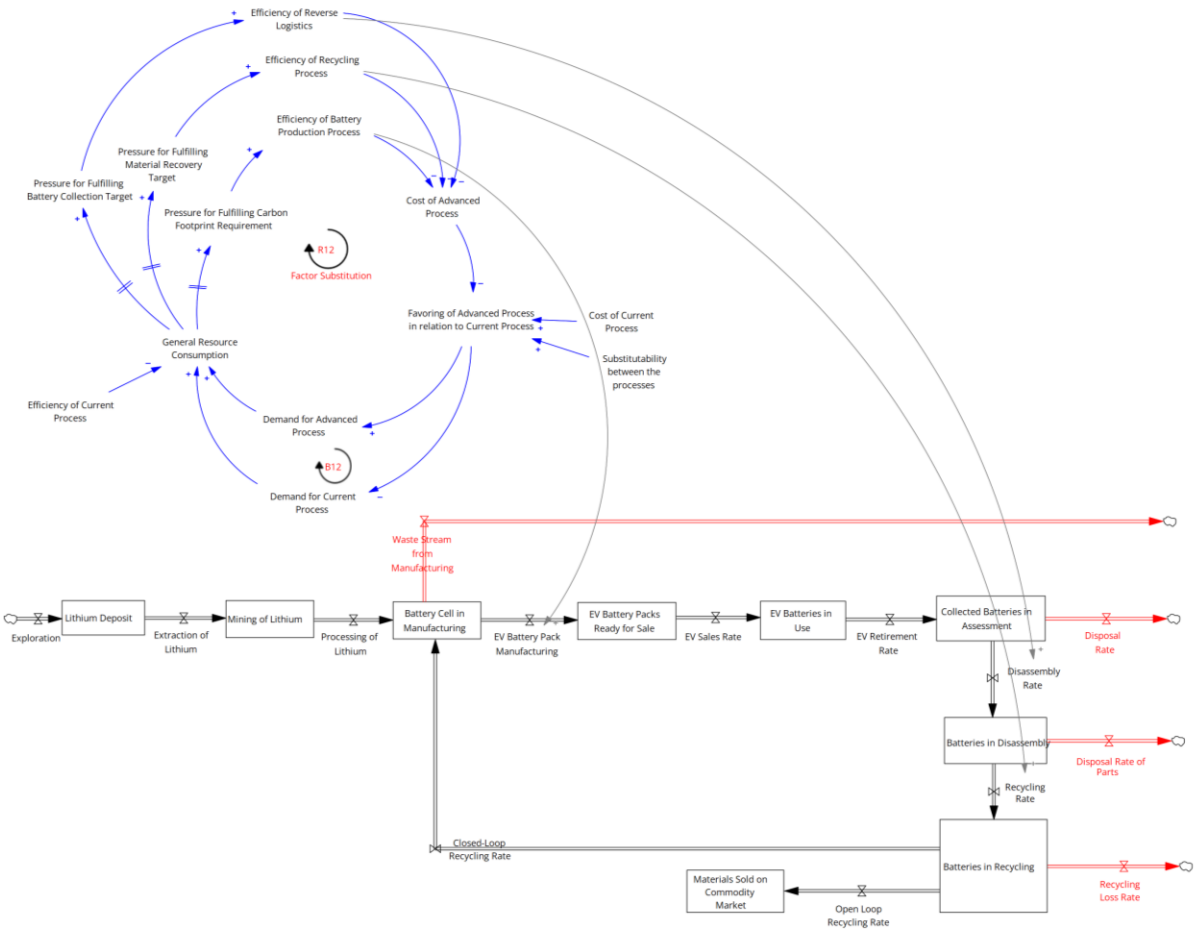

Figure 23 Factor Substitution Mechanism

13. Demand Adjustment by Sufficiency Mechanism

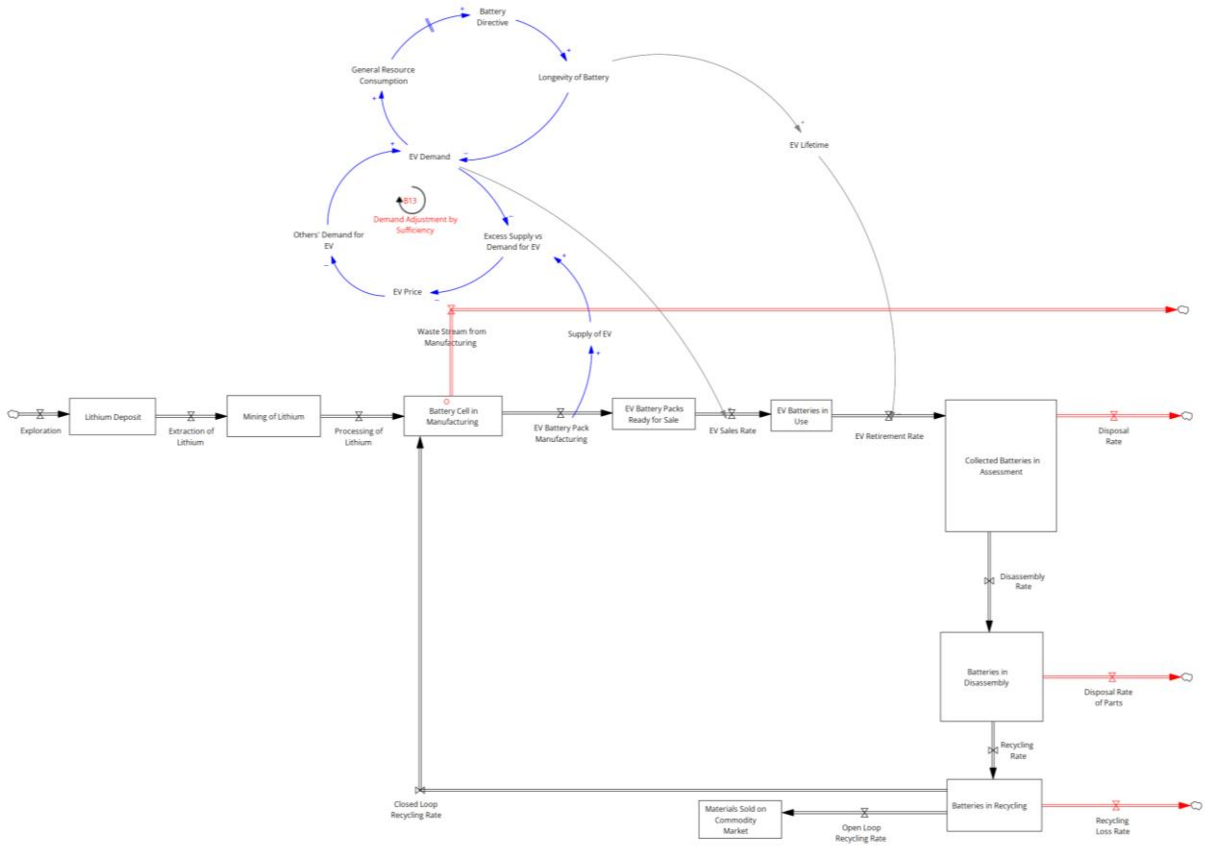

Figure 24 Demand Adjustment by Sufficiency Mechanism

14. Demand Adjustment by Efficiency Mechanism

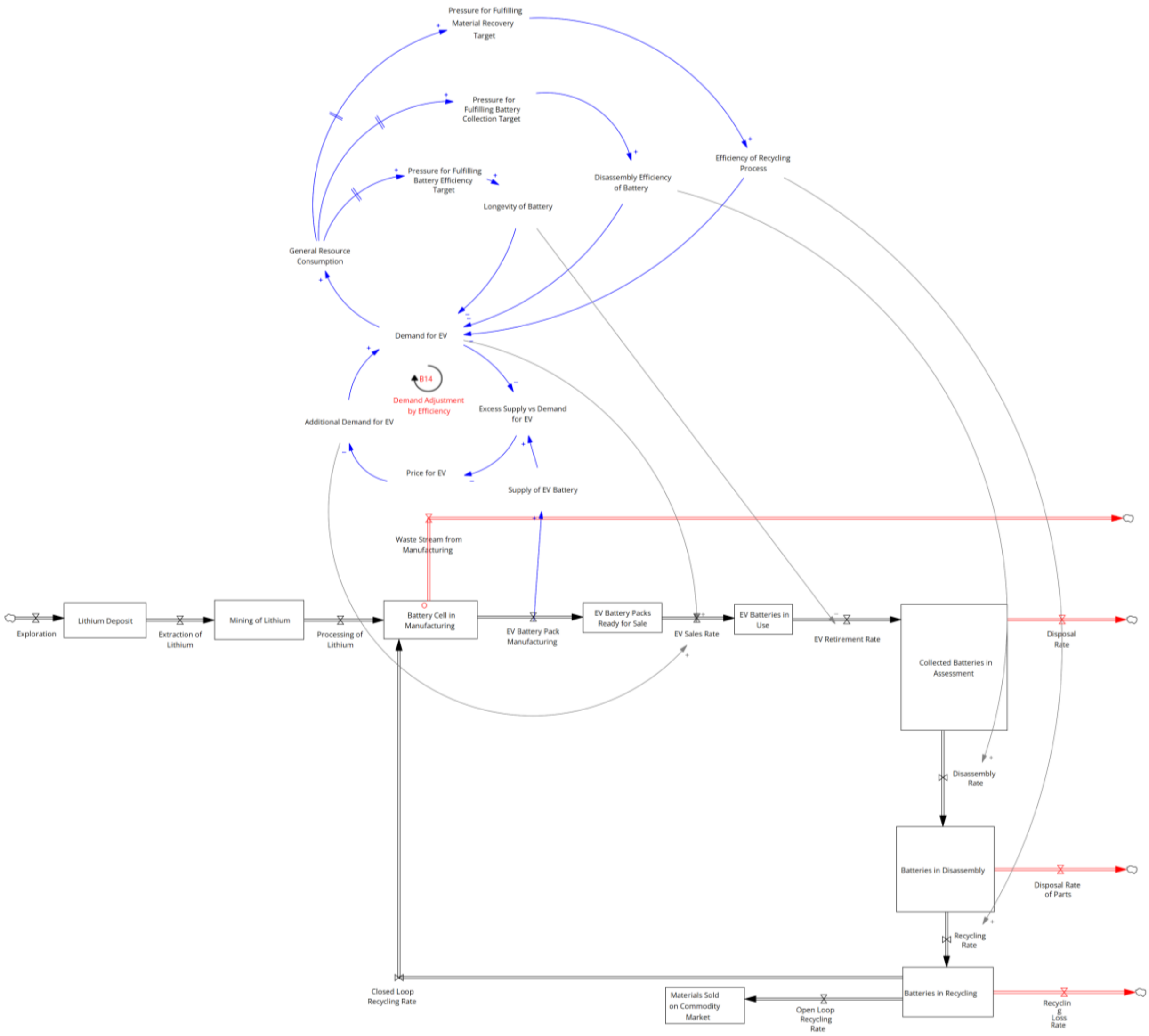

Figure 25 Demand Adjustment by Efficiency Mechanism

15. Demand Adjustment with Investment Adjustment Mechanism

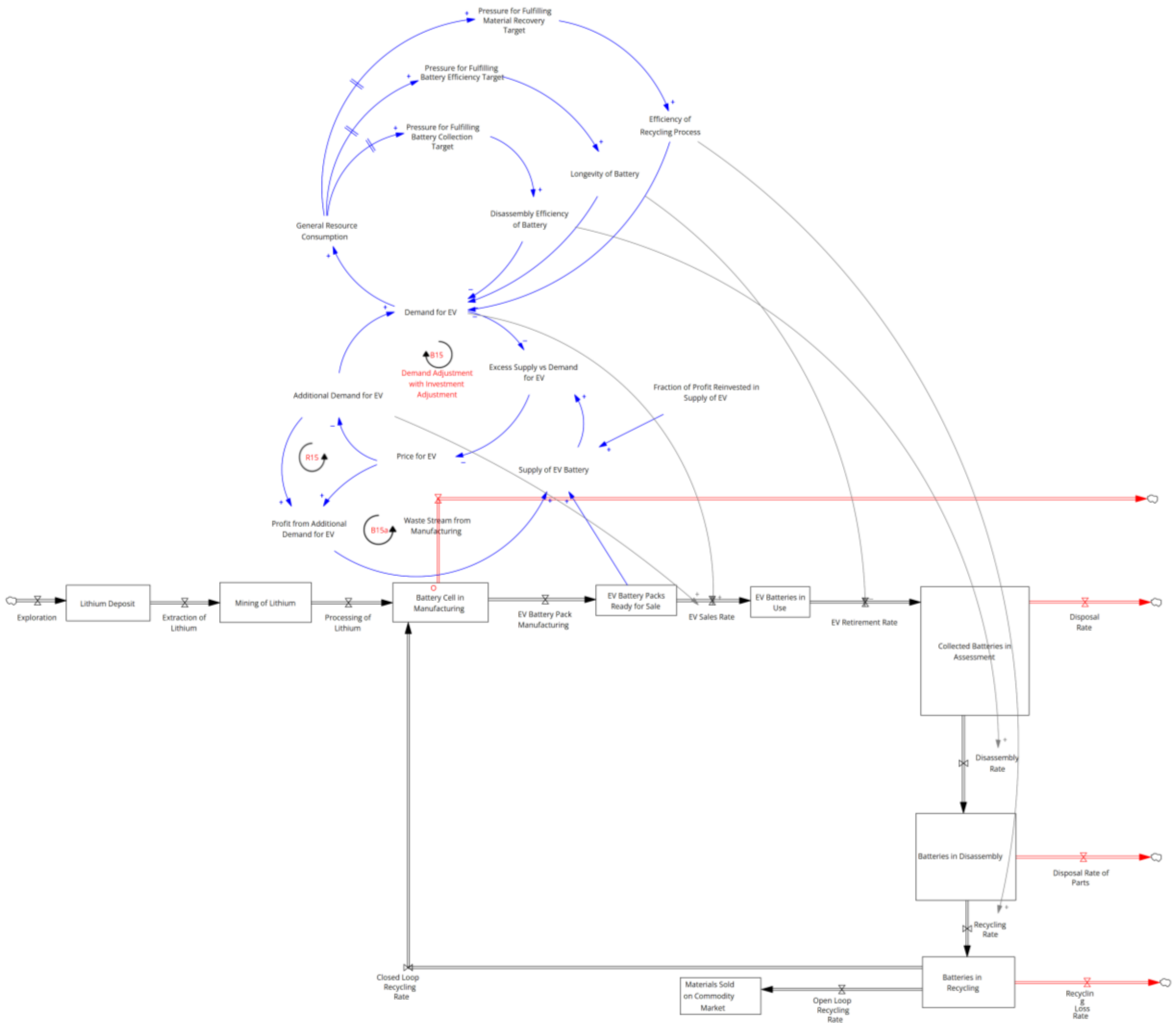

Figure 26 Demand Adjustment with Investment Adjustment Mechanism

16. Re-Design Mechanism

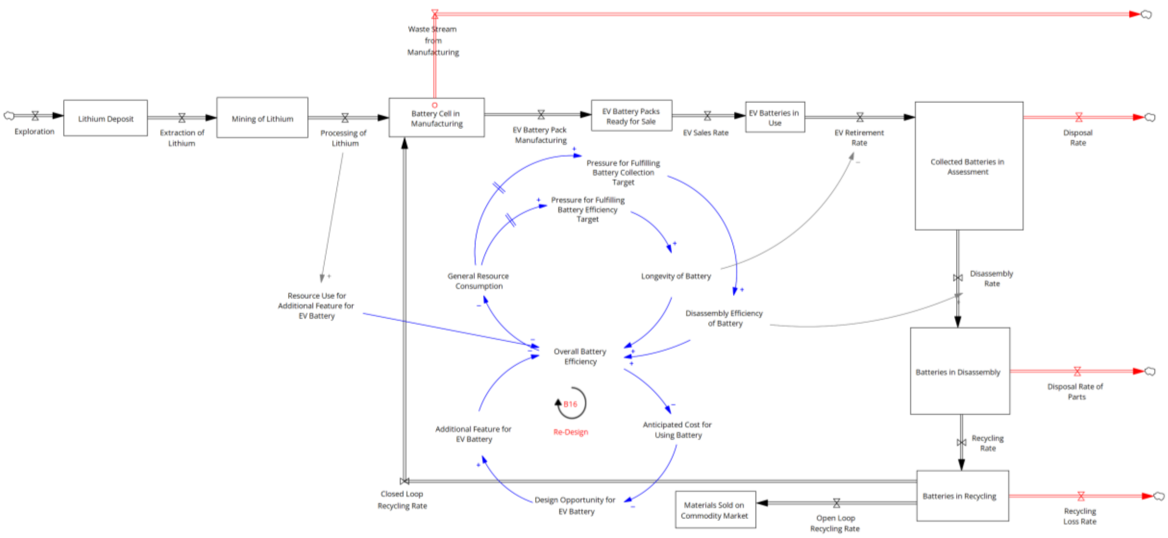

Figure 27 Re-Design Mechanism

17. Supply Adjustment Mechanism

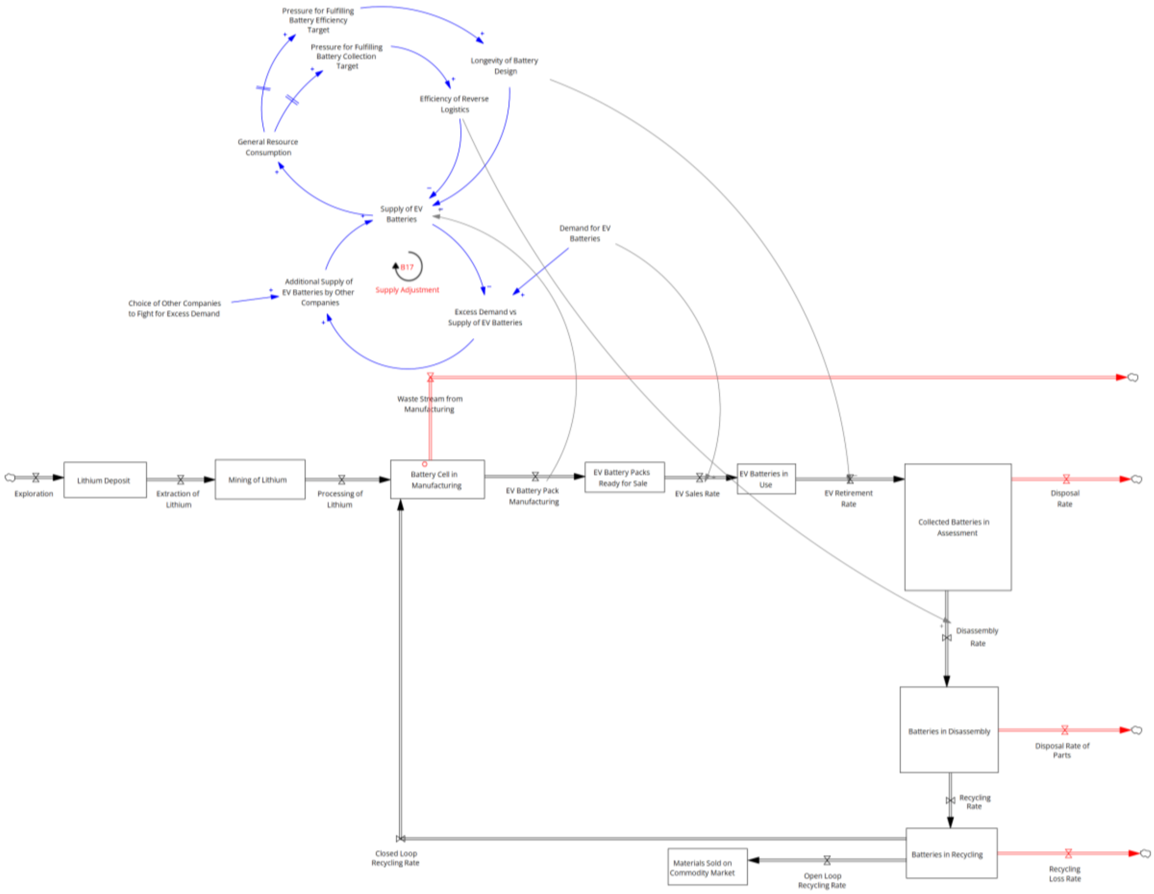

Figure 28 Supply Adjustment Mechanism

18. Producer-Induced Demand Adjustment Mechanism

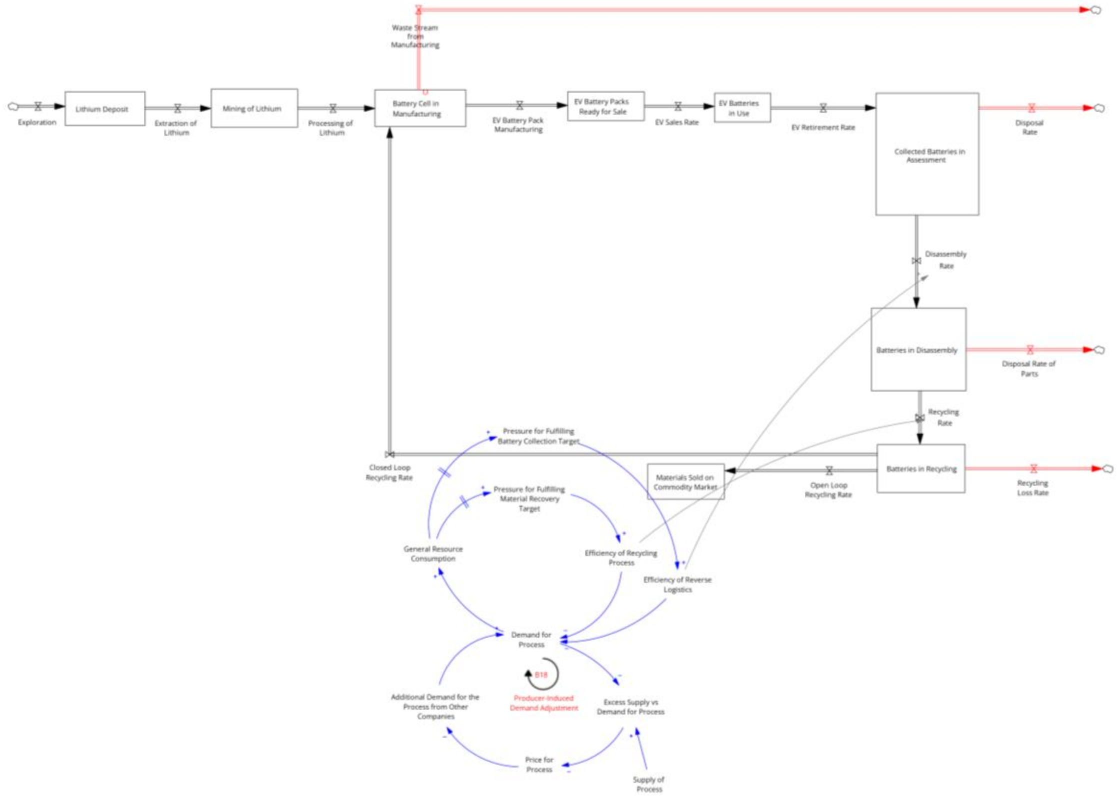

Figure 29 Producer-Induced Demand Adjustment Mechanism

19.Economies of Scale Mechanism

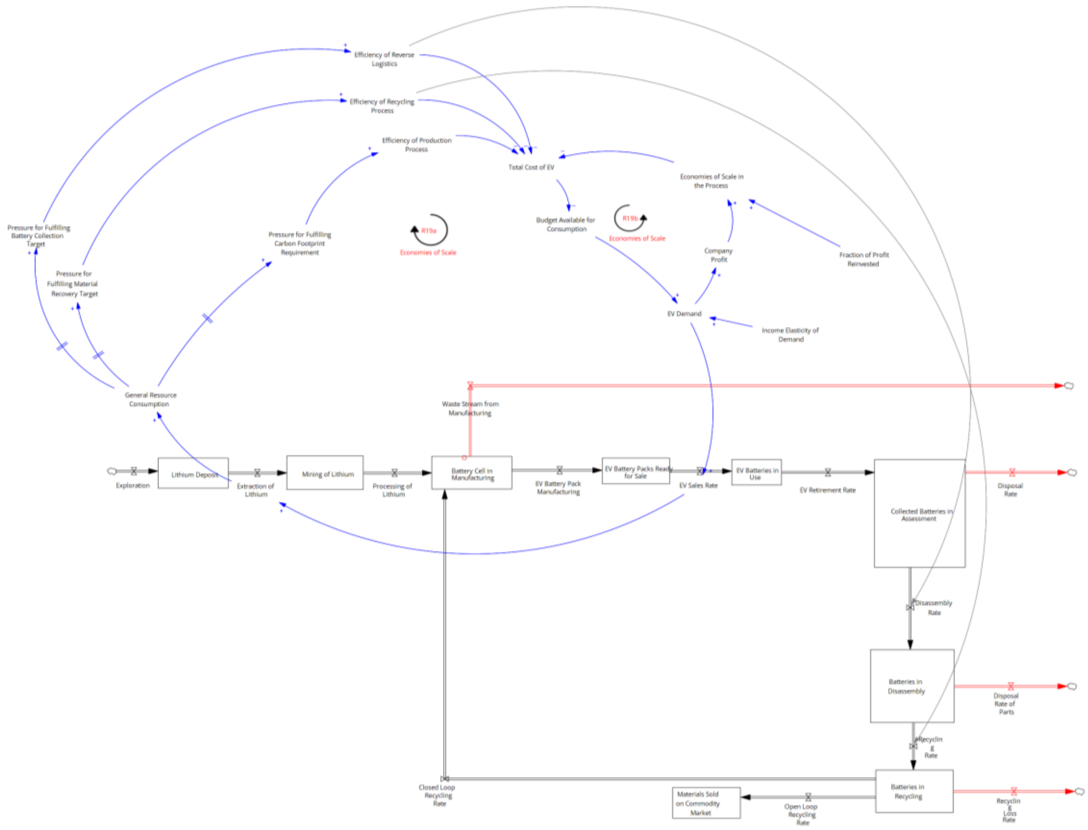

Figure 30 Economies of Scale Mechanism

20.Market Price Mechanism

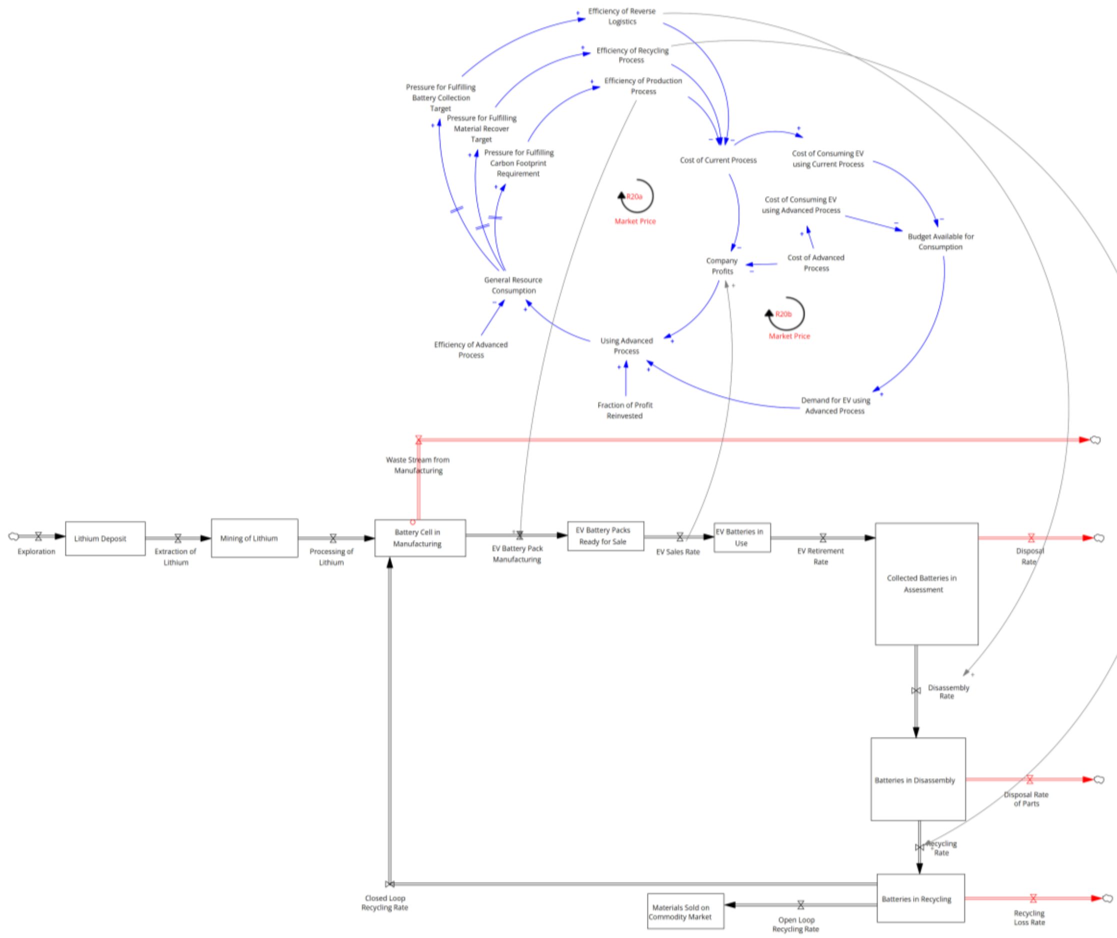

Figure 31 Market Price Mechanism

Appendix B

Interview Questions

Interviewee A – Experts in System Dynamics

- Considering your study primarily discusses rebound mechanisms in a general context, could you advise on how to adapt these mechanisms to the specificities of the EV battery circular economy? Are there particular considerations or modifications necessary to apply these models effectively? What specific adaptations would you recommend for this sector?
  Have you adjust this clds to case-specific?
- In your study, you identify several key variables that influence rebound effects through system dynamics. Which of these variables do you believe will have the most significant impact when studying rebound effects in the circular economy for EV batteries?
- Are there any limitations in transferring your findings to a more focused industrial sector?
- Could you provide insight on how to identify and interpret the most critical feedback loops for a study focused on EV batteries within a circular economy?
- Your paper outlines strategies to mitigate rebound effects. How can these strategies be specifically tailored to address rebound effects in the circular economy practices of EV batteries?

Interviewee B – Researcher in the field of EV

- Have you ever heard about the term rebound mechanism while you conduct your research in the field of circular ev battery?
- In my research, I'm going to focus in 1 intervention for circular EV batteries, which is recycling. Do you have any concerns or opinion that why I choose this?
- From your experience researching EV battery end-of-life scenarios, have you observed any indications of rebound effects, such as increased resource consumption due to efficiencies in battery recycling?
- In your research, which stages of the EV battery lifecycle did you find most susceptible to rebound effects within the circular economy framework?
- In your analysis, how do current EU regulations potentially influence manufacturers' or consumers' behaviors in ways that might lead to rebound effects in the circular economy for EV batteries?
- Based on your findings, could you speculate on how consumer preferences for EV batteries, influenced by increased recycling, might change consumption patterns or overall demand for EVs?
- From your research perspective, what strategies would you recommend to mitigate potential rebound effects when implementing more efficient recycling processes for EV batteries?
- Could you suggest any CBM that might help minimize the unintended consequences of improved recycling efficiencies in the EV battery sector?

Interviewee C – Professor in Circular Economy and System Dynamics

- Circular ev is emerging topic, and I want to analyze the rebound effect, which is a step further the current siuation. But do you think rebound effect is important?
- I want to identify which mechanisms is the most important to be considered and mitigated as it creates the most rebound effect. But since this research is qualitative, I don't know how
- What criteria should be considered when selecting strategies to mitigate rebound effects within circular business models for EV batteries?
- How do you prioritize these criteria based on different business or environmental objectives?
- Could you describe the process for assessing the potential impact of different mitigation strategies on rebound effects?
- Can you provide examples where a particular strategy was successfully implemented to mitigate rebound effects?

Appendix C

Interview Transcript with Expert A

Interviewer: Hello! How are you?

Expert A: I'm doing good, thanks. How about you?

Interviewer: I'm doing well, thank you. I see you're looking sideways; is your camera over there?

Expert A: Yeah, that's right. Sorry about that.

Interviewer: No worries at all. So, I sent you the CLD (Causal Loop Diagram) that I created. It’s not perfect, but it’s a start. I’m hoping we can discuss ways to improve it.

Expert A: Yes, I got it. I think I have an idea of what we can discuss today. Maybe you could share your screen, and we can go through some of it together?

Interviewer: Sure, what’s the goal? Ideally, I would like to validate all 20 mechanisms, though I’m not sure if that’s possible. Maybe we could focus on a few specific ones?

Expert A: That sounds like a good approach. You could show me some that were particularly challenging, whether due to wording or conceptual issues, or those that you had to remove. This way, we can review them systematically. You can report afterward that the expert reviewed a subset, and you learned specific things that might need iteration.

Interviewer: That makes sense. What I really want to see is how all these mechanisms interact with each other. For instance, can all these mechanisms be combined into one CLD? I’m particularly interested in how the economies of scale mechanism, which links income and output, interacts with the others.

Expert A: That’s a good question. The interactions often depend on the triggers or variables that these mechanisms share. If the trigger of one mechanism is the driver of another, they might interact. However, not all drivers or limiting factors are present in all mechanisms, which makes it complex. Some connections might be hidden or limited by factors like time or budget constraints.

Interviewer: Can we identify which mechanism contributes the most to the rebound effect within this system? For example, could we determine this based on the number of triggers, drivers, or actions? Particularly in the context of EVs (Electric Vehicles), can we see which mechanism has the most significant impact?

Expert A: Without quantifying them, it’s challenging. Generally, system dynamics and qualitative models apply here. Some mechanisms, like those related to economies of scale, might be more impactful due to reinforcing loops. However, analytically, it’s tough to pinpoint without flows. You might need heuristics to identify potentially impactful modes of consumption and limiting factors.

Interviewer: Have you tried implementing these 26 mechanisms into a real-life case? What findings have you had from doing so?

Expert A: I’ve done some initial work on that, but it’s more of a meta-case. For instance, I looked into sharing platforms. I systematically examined descriptions to find rebound mechanisms, which led to some interesting findings. For example, reinforcing loops often vanish because the dynamics of the system might limit the effects. It’s crucial to communicate these findings effectively through simplified diagrams.

Interviewer: In your CLD, do you consider interactions from the perspective of one actor, like the lender, or do you combine interactions from multiple actors? For instance, can mechanisms involving consumers and firms be combined?

Expert A: I think they can be combined. In the CLD I shared, you have interactions involving both renters and lenders. So, from a single representation, you can see the dynamics from multiple actors' perspectives. It’s possible to combine mechanisms where different actors are involved, like consumers in income mechanisms and firms in reinforcement mechanisms.

Interviewer: In your paper, you categorized the mechanisms into five big groups. Why did you categorize them this way? Would it be useful to combine categories that share similar structures?

Expert A: The categorization was based primarily on the structure and actors involved. However, I’m not entirely satisfied with that organization. It might be more useful to categorize based on actors and triggers rather than structure when trying to combine mechanisms. The current organization might not be the most helpful for combining them systematically.

Interviewer: Sometimes, I struggle to understand the differences between mechanisms. For example, in the "Demand Adjustment by Efficiency" mechanism, why does the demand decrease despite efficiency actions that should typically increase demand?

Expert A: That’s a good point. Sometimes, there’s an aggregate representation or delay that isn’t immediately clear. For instance, improving a product's efficiency might reduce the demand for specific inputs, leading companies to adjust prices or production. This broader dynamic can sometimes make the immediate effects seem counterintuitive.

Interviewer: I see. What about simpler mechanisms, like the income mechanism? How do these interact within the broader system?

Expert A: Simpler mechanisms like the income mechanism revolve around budget availability and demand elasticity. In this case, the trigger is the budget available for consumption, and the driver is income elasticity. It’s interesting that you’re connecting this with the broader value chain, which adds complexity but also offers deeper insights.

Interviewer: My ultimate goal is to identify and mitigate the most significant mechanisms that create a rebound effect, particularly within the context of EV batteries. I’m not quantifying them but rather trying to see how they interact qualitatively. What would you suggest as a strategy for identifying and mitigating the most impactful mechanisms?

Expert A: That’s a fair approach. Identifying leverage points through critical analysis and reasoning is essential. You might consider narrowing down to a few key mechanisms and exploring them in more detail to understand their impacts and how to mitigate them. The triggers are crucial here, as they often indicate which mechanisms are at play.

Interviewer: I've been advised to choose which mechanisms to focus on and to make a strong case for my selection. How did you determine the hazard or significance of mechanisms in your analysis?

Expert A: My analysis was based on critical reasoning, assessing the likelihood and impact of each mechanism. It's a bit like a balanced scorecard approach, where you evaluate each mechanism's potential risk and hazard. This method isn't perfect, but it helps to systematically prioritize mechanisms for further study.

Interviewer: That makes sense. I also wanted to ask if you have any documents or manuscripts that could help me with this?

Expert A: I can share some additional papers and resources that might be helpful. They cover similar reasoning and could provide further insights into the mechanisms and their interactions.

Interviewer: Thank you so much, Expert A. This has been incredibly helpful. I'm looking forward to applying these insights to my work.

Expert A: You're welcome. Good luck with your work! I'm curious to see where you end up. When's your deadline?

Interviewer: July 18th.

Expert A: You're on track. Best of luck, and feel free to reach out if you need further assistance.

Interviewer: Thank you! Goodbye!

Expert A: Goodbye!

Interview Transcript: Expert B

Interviewer: Thank you so much for your willingness to help me with this research.

Expert B: Of course.

Interviewer: I don't have much experience in the field of circular economy and EV batteries. There aren't many people I know who are doing research in this area. That's why I'm looking for insights from those working in system dynamics related to circular economy, especially focusing on EV batteries. Have you considered or encountered the rebound effect in your research?

Expert B: Yes, I've come across the concept of rebound effects in my work. I understand them as secondary effects, mostly negative, that aren't the primary focus but can arise from actions taken in pursuit of sustainability. For instance, within the circular economy for EVs, promoting the purchase of cars could increase the stock of batteries or vehicles on the road, which might have negative environmental impacts. This is an example of a potential rebound effect.

Interviewer: Yes, that's the type of rebound I'm focusing on. Specifically, how efficiency actions intended to reduce carbon emissions can paradoxically lead to an increase in EV demand. I want to explore the mechanisms behind this. I've identified around 26 mechanisms that could lead to such rebound effects and am working on creating Causal Loop Diagrams (CLDs) to visualize them. My focus is primarily on recycling within the circular economy because of the importance of recovering rare materials used in batteries. Do you think this focus is appropriate?

Expert B: I think focusing on recycling is very valid. Recycling is crucial, especially given the need to recover materials for new battery production. However, it's important to note that rebound effects can also occur in other areas like repurposing. For example, repurposing older batteries might be environmentally friendly, but using new, more efficient batteries could have better long-term benefits. Your decision to focus on recycling makes sense, but be aware of the broader context.

Interviewer: Thank you. In the EV sector, do you think regulations are more focused on reuse or repurposing, or is there a general emphasis on all initiatives?

Expert B: One key regulation to consider is the EU Battery Directive. It impacts both repurposing and recycling. Our research, which is not yet published, shows that without such regulations, there's a trend toward repurposing due to its economic advantages. Repurposing requires fewer production steps and is therefore more cost-effective. However, with regulations in place, we see a shift towards recycling, as policies might drive batteries that could be repurposed towards recycling instead.

Interviewer: In my research, I'm using a conceptual model that includes various stages, such as new production, manufacturing, and recycling. Where do you think rebound effects are most likely to occur within these stages?

Expert B: Rebound effects are most prominent in the use phase. The goal of circular economy initiatives isn't to reduce car consumption but to substitute new cars with recycled ones. This can sustain or even increase consumption. The use phase is where the most significant rebound effects occur, as it involves both new and repurposed batteries being used by consumers.

Interviewer: In terms of current EU regulations, how might they influence manufacturer and consumer behaviors in ways that lead to rebound effects?

Expert B: Regulations like the requirement to use a certain percentage of recycled materials could lead to rebound effects. For instance, instead of substituting virgin materials, producers might increase their overall production, including recycled materials, leading to a net increase in resource use. Additionally, the ICE (Internal Combustion Engine) ban might influence consumer behaviour, as people might rush to buy traditional cars before the ban, creating a temporary surge in ICE vehicle sales.

Interviewer: In the CLD I created, one trigger I identified is the income elasticity of demand. When EV prices decrease, demand is expected to increase. Does this actually happen in real-world cases?

Expert B: The connection is valid. Generally, lower prices lead to higher demand, which is a basic market mechanism. However, the current high costs of recycling mean that the price difference between a standard EV and one with recycled batteries might not be significant. Economies of scale play a role in both traditional and recycled battery markets, so the impact on demand may vary.

Interviewer: Who is typically responsible for recycling EV batteries? Is it the OEMs (Original Equipment Manufacturers) or third-party companies?

Expert B: It varies. OEMs may own the batteries, but they often don’t handle recycling themselves. Instead, third-party operators or service providers usually take on this role. The OEM might have a contract with these firms or sell the batteries to them directly. The Extended Producer Responsibility (EPR) mandates that OEMs take back batteries if they have no value, but if the batteries are still valuable, third parties might handle the recycling.

Interviewer: How might consumer preferences for EV batteries change with the availability of recycled materials? Could this lead to changes in consumption patterns?

Expert B: That’s a possible rebound effect, but it’s unlikely that consumers would start buying more EVs just because they know the batteries can be recycled. Consumer behavior is still largely constrained by income. However, overall adoption of EVs might increase as people become more aware of environmental benefits, especially with regulations like the ICE ban coming into effect.

Interviewer: My goal is to identify the most significant rebound mechanisms in the context of EV batteries and then mitigate them through circular business models. Do you have any knowledge or suggestions about circular business models that could be relevant here?

Expert B: Circular business models like leasing could be effective, especially in controlling the number of cars on the market. Leasing allows for better management of resources and can help mitigate rebound effects by regulating how and when products are used. It’s important to consider both primary and secondary effects when defining business strategies. While companies usually focus on primary effects, secondary effects, like rebound effects, should also be considered in strategy development.

Interviewer: What important aspects should be considered when choosing the right strategy for mitigating these effects?

Expert B: The key is to have a clear problem statement. If the problem is well-defined, it becomes easier to identify the right strategies. You might want to create a balanced scorecard or a ranking system based on criteria you find important. Start with your critical thinking, then refine it with additional research if needed. If you have a solid understanding of the problem, the strategies will naturally align with your goals.

Interviewer: Thank you for your insights. This has been very helpful. I'm new to this area, and your guidance has given me a clearer path forward.

Expert B: I'm glad I could help. It's a challenging area, but your approach is solid. Don't hesitate to reach out if you have more questions as you progress.

Interviewer: Thank you so much, Expert B. I really appreciate your time and support.

Expert B: You're welcome. Best of luck with your research!

Interviewer: Have a great day!

Expert B: You too. Goodbye!

Interview Transcript with Expert C

Interviewer: Thank you so much for taking the time to help me with this research.

Expert C: Of course, I'm happy to assist.

Interviewer: I'm relatively new to the field of circular economy and EV batteries, and there aren't many people I know who are conducting research in this area. I've been looking for insights on system dynamics, particularly focusing on EV batteries. Have you considered or encountered the rebound effect in your research?

Expert C: Yes, I'm familiar with the concept of rebound effects. These are secondary, often unintended consequences that can arise from efforts to promote sustainability. For example, while promoting electric vehicles (EVs) seems beneficial, if we continue promoting them without considering other factors, we might end up increasing the total number of vehicles on the road, which could lead to higher congestion and more pollution. This is a classic example of the rebound effect.

Interviewer: That's exactly what I'm focusing on. Specifically, I'm interested in how efficiency actions meant to reduce carbon emissions might actually increase the demand for EVs. I've identified around 20 mechanisms that could lead to such rebound effects and am working on creating Causal Loop Diagrams (CLDs) to visualize them. My primary focus is on recycling within the circular economy, particularly because of the importance of recovering rare materials used in batteries. Do you think this is a valid focus?

Expert C: Focusing on recycling is absolutely valid, especially given the need to recover materials for new battery production. However, it's also important to consider the potential rebound effects in other areas like repurposing. For instance, using older batteries in new applications might seem environmentally friendly, but it could lead to unforeseen consequences if not managed properly. Your decision to focus on recycling makes sense, but it's important to keep the broader context in mind.

Interviewer: Thank you. In the context of EV batteries, do you think there are specific regulations that focus more on reuse or repurposing, or is the emphasis more generalized across all initiatives?

Expert C: One key regulation to consider is the EU Battery Directive. It has implications for both repurposing and recycling. From what I've observed in my research, without strong regulations, there's a trend toward repurposing due to its cost-effectiveness. However, with regulations in place, there might be a stronger push toward recycling. This is because regulations can drive companies to focus on specific actions, like meeting material recovery targets.

Interviewer: I see. In my research, I'm using a conceptual model that includes various stages, such as production, use, and recycling. Where do you think rebound effects are most likely to occur?

Expert C: Rebound effects are most prominent in the use phase. The challenge with promoting EVs as a sustainable option is that it doesn't necessarily reduce overall car usage. Instead, it could increase the total number of vehicles on the road, which in turn increases demand for electricity and resources. This could lead to unintended consequences, like more congestion and higher pollution from the increased production and disposal of vehicles.

Interviewer: That makes sense. How might current EU regulations influence manufacturer and consumer behaviours in ways that could lead to rebound effects?

Expert C: Regulations like the EU Battery Directive, which mandates the use of a certain percentage of recycled materials, could have unintended consequences. For instance, instead of replacing virgin materials, companies might increase their overall production, leading to a net increase in resource use. Additionally, the phasing out of internal combustion engine (ICE) vehicles might lead to a temporary surge in ICE vehicle purchases as consumers try to buy them before they're banned, which could also create rebound effects.

Interviewer: Who is typically responsible for recycling EV batteries? Is it the OEMs (Original Equipment Manufacturers) or third-party companies?

Expert C: It varies. OEMs may own the batteries, but they often don't handle recycling themselves. Instead, third-party operators or service providers usually take on this role. The OEM might have a contract with these firms or sell the batteries to them directly. The Extended Producer Responsibility (EPR) mandates that OEMs take back batteries if they have no value, but if the batteries are still valuable, third parties might handle the recycling.

Interviewer: How might consumer preferences for EV batteries change with the availability of recycled materials? Could this lead to changes in consumption patterns?

Expert C: That's a possible rebound effect, but it's unlikely that consumers would start buying more EVs just because they know the batteries can be recycled. Consumer behavior is still largely constrained by income. However, overall adoption of EVs might increase as people become more aware of environmental benefits, especially with regulations like the ICE ban coming into effect.

Interviewer: My goal is to identify the most significant rebound mechanisms in the context of EV batteries and then mitigate them through circular business models. Do you have any knowledge or suggestions about circular business models that could be relevant here?

Expert C: Circular business models like leasing could be effective, especially in controlling the number of cars on the market. Leasing allows for better management of resources and can help mitigate rebound effects by regulating how and when products are used. It's important to consider both primary and secondary effects when defining business strategies. While companies usually focus on primary effects, secondary effects, like rebound effects, should also be considered in strategy development.

Interviewer: What important aspects should be considered when choosing the right strategy for mitigating these effects?

Expert C: The key is to have a clear problem statement. If the problem is well-defined, it becomes easier to identify the right strategies. You might want to create a balanced scorecard or a ranking system based on criteria you find important. Start with your critical thinking, then refine it with additional research if needed. If you have a solid understanding of the problem, the strategies will naturally align with your goals.

Interviewer: Thank you for your insights. This has been very helpful. I'm new to this area, and your guidance has given me a clearer path forward.

Expert C: I'm glad I could help. It's a challenging area, but your approach is solid. Don't hesitate to reach out if you have more questions as you progress.