Will We Stop Wasting Energy?

A dynamic Technological Innovation Systems perspective on the diffusion of repurposed EV batteries in the Netherlands and Sweden

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Abstract

The rapid growth of electric vehicle adoption increases the urgency of developing circular solutions for end-of-life batteries. Repurposing EV batteries for stationary storage can reduce environmental impacts and human rights risks embedded in critical raw material supply chains, as well as Europe's dependence on critical raw materials. Yet, the development of repurposing markets remains uncertain and differs across countries. Current research provides limited insight into how national contexts shape the diffusion of EV battery repurposing over time, particularly in relation to the dynamic and complex nature of this market. This thesis addresses this gap by analysing how contextual differences for the Netherlands and Sweden influence the diffusion of EV battery repurposing technology by answering the following research question: *"How do the national contexts of the Netherlands and Sweden affect the diffusion of EV battery repurposing technology?"*

To answer this question, a merged system dynamics model was developed by integrating two system dynamics models. The Circubat model captures the long-term market dynamics of the second-use EV battery sector from a profit-oriented perspective, incorporating country-specific parameters for supply, demand, treatment capacity, and policy interventions tailored to the Netherlands and Sweden. In parallel, a hybrid Technological Innovation Systems model evaluates innovation performance at a more abstract level. By integrating these two approaches, the merged model provides insights not only into the diffusion volumes of repurposed EV batteries, but also into the overall strength and quality of the underlying innovation system.

Although projected end-of-life EV battery streams are similar in both countries, diffusion volumes are substantially higher in the Netherlands. This is primarily driven by stronger structural demand for decentralised flexibility, resulting from high solar PV penetration and increasing grid congestion. From a system-dynamics perspective, demand functions as the central catalyst: stronger demand activates reinforcing feedback loops between scale, cost reductions, learning, and capacity expansion, whereas weaker demand dampens these dynamics and constrains long-term scaling. However, higher diffusion volumes do not necessarily indicate a well-developed innovation system. The Technological Innovation System assessment shows that overall system performance in both countries remains below half of its potential, reflecting persistent structural weaknesses that continue to constrain large-scale diffusion. Policy experiments testing taxation of new batteries, consumer subsidies for repurposed batteries, and demonstration funds reveal that effectiveness depends on the dominant national bottleneck. In demand-constrained Sweden, demand-oriented measures, particularly taxation and subsidies, effectively stimulate both demand and capacity expansion, while in the Netherlands their impact on supply remains limited due to feedstock constraints. Demonstration funds show more context-dependent effects, as higher input costs can raise prices and dampen demand under certain conditions. These findings underscore that policy effectiveness is strongly conditioned by national structural factors and requires alignment with the specific bottlenecks within each innovation system.

Keywords: EV battery repurposing; technological innovation systems; system dynamics; circular economy; diffusion dynamics

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List of abbreviations

Abbreviation	**Definition**
EV	Electric Vehicle
TIS	Technological Innovation System
EoL	End-of-Life
SoH	State of Health
BMS	Battery Management System
EPR	Extended Producer Responsibility
OEM	Original Equipment Manufacturer
R&D	Research and Development
DMNL	Dimensionless
KPI	Key Performance Indicator
LFP	Lithium Iron Phosphate (battery chemistry)
NMC	Nickel Manganese Cobalt (battery chemistry)
VoD	Valley of Death

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Chapter 1: Introduction

1.1 Background and context

Following the adoption of the Paris Agreement, European countries have committed to ambitious climate targets aimed at reducing greenhouse gas emissions across all sectors, including transport (UNFCCC, 2015). Transport is one of the largest contributors to global greenhouse gas emissions, responsible for about 15% of total emissions, most of which come from road transport (IPCC, 2019). Electrification is widely adopted as the primary strategy for reducing transport emissions, yet progress differs significantly across Europe. Norway leads by a wide margin, with 96% of new passenger cars registered as fully electric in 2025 (Reuters, 2025). Sweden and the Netherlands follow at a considerable distance, each reaching approximately 35% fully electric new car sales (RVO, 2025; Statistikdatabasen, n.d.). By comparison, EV adoption remains low in parts of Eastern Europe, such as Bulgaria, where only 7% of new car registrations were battery-electric in 2024 (Eurostat, 2024).

While the growth of electric mobility contributes to emission reductions during the use phase, it also leads to a rapidly increasing number of electric vehicle batteries associated with environmental and social risks. The extraction of critical raw materials required for battery production, such as lithium (Li), nickel (Ni), graphite (Gr) and cobalt (Co), is linked to significant environmental impacts, including biodiversity loss, water depletion, soil contamination, and land degradation, as well as human rights concerns in mining regions (EU, 2023). Lithium extraction, in Chile, is responsible for around 65% of the water in the Salar de Atacama region, one of the world's driest areas and is used for lithium mining (UNCTAD, 2020). In addition, expanding nickel supply for battery production can accelerate land-use change in forest-rich regions: in Indonesia, a global biodiversity hotspot and major nickel-producing region, deforestation in nickel-mining villages was found to nearly double between 2011 and 2018 (Lo et al., 2024). Beyond environmental degradation, battery supply chains are also associated with serious human rights concerns. A prominent example is the Democratic Republic of the Congo, where cobalt mining has been linked to hazardous working conditions and documented cases of child labour (Amnesty International, 2016).

Beyond the upstream challenges, the end-of-life phase of electric vehicle batteries introduces additional environmental concerns. If EV batteries are not properly treated at the end of their service life, they can release hazardous substances that negatively affect ecosystems and human health. While most batteries currently on the market remain in active use, a significant increase in end-of-life volumes is expected in the near future. The expanding electric vehicle market is projected to generate approximately 185 GWh of end-of-life batteries by 2030 worldwide (Melin, 2018). A recent analysis suggests that, under current regulatory efforts and projected infrastructure expansions, recycling capacity in Europe is unlikely to be sufficient to accommodate the projected increase in end-of-life battery volumes (Gianvincenzi et al., 2025).

Apart from environmental and social impacts, the battery supply chain also presents significant geopolitical and strategic risks due to its high geographic concentration, revealed in Figure 1. China holds a dominant position within the global battery supply chain. According to the International Energy Agency (2022), China accounted for approximately 76–77% of global EV battery production capacity in 2022, compared to only 7% in the European Union (n.d.). In absolute terms, this corresponds to 655 GWh in China versus 60 GWh in Europe. This imbalance is even more pronounced in upstream battery components, where Asia accounted for 97% of global cathode production and 99% of anode production in 2022. Despite ongoing European investments, China is expected to maintain around 70% of global battery production capacity by 2030 (IEA, 2022).

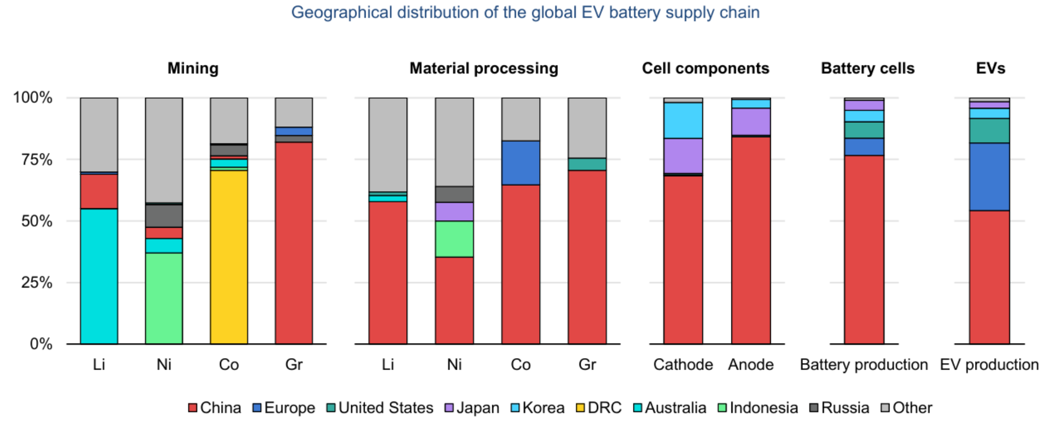


Figure 1: China dominates the entire downstream EV battery supply chain. Source: (IEA., 2022)

Europe faces supply chain vulnerabilities, critical raw material risks, growing volumes of end-of-life batteries, and significant environmental impacts from battery production. In response, the European Union adopted the EU Battery Regulation (2023/1542) to promote circular end-of-life management and reduce reliance on virgin resources. However, recent research by Seika & Kubli (2024) suggests that the regulation's strong emphasis on mandatory recycling targets may unintentionally limit the development of alternative circular strategies, such as battery repurposing. Battery repurposing refers to the redeployment of EV batteries that no longer meet automotive performance requirements into less demanding stationary applications, such as residential and commercial energy storage systems. While repurposing does not replace recycling, it delays material recovery, extends battery lifetimes, and reduces the need for new battery production, thereby lowering associated environmental and social pressures (Albertsen et al., 2021).

The relevance of repurposing is further reinforced by both technological and market developments. Lithium-ion batteries generally retain a substantial share of their original functionality at the end of their first automotive life, with studies estimating that 70–80% of initial capacity remains available (Bobba et al., 2018; Neubauer & Pesaran, 2011). At the same time, the energy storage sector is expanding rapidly, driven by the increasing penetration of renewable energy sources. Projections indicate that battery storage in Europe could reach approximately 32 TWh by 2030 and 115 TWh by 2050 (Philippot et al., 2022). In this context, repurposed batteries can provide storage solutions, supporting renewable energy integration (Lombardi & Schwabe, 2017).

Despite its potential, there is no scientific consensus on whether EV battery repurposing will become an economically viable technology (Iqbal et al., 2023). This uncertainty increases perceived investment risks, which may discourage both private and public actors from engaging in repurposing activities and thereby slow market development (He et al., 2022). As a result, the future development of EV battery repurposing remains uncertain. Recent system dynamics research indicates that the sector may encounter a "technology valley of death," defined as the critical stage between research and development and full commercialisation where innovations struggle to achieve market viability despite technical feasibility. For repurposed batteries, this risk emerges because they must compete with continuously declining costs and improving performance of new batteries, while consumer demand remains limited by safety concerns, durability expectations, and low willingness to adopt second-life products (Seika & Kubli, 2025). Analysing diffusion dynamics in this early formative phase is therefore crucial, as system structures and feedback mechanisms established at this stage can strongly influence long-term market trajectories and either enable or hinder sustained development (Bergek et al., 2008a).

1.2 Knowledge gaps

Despite increasing academic attention to EV battery repurposing, important gaps remain in both quantitative modelling and qualitative diffusion analysis.

From a quantitative perspective, existing forecasting studies primarily focus on techno-material parameters such as degradation, residual capacity, and cost developments (Abdelbaky et al., 2021; Al-Alawi et al., 2022). National regulatory and market conditions are often treated as static background variables. While Seika and Kubli (2025) provide a dynamic analysis for Switzerland, comparable system-dynamic diffusion studies for other European frontrunner EV markets are lacking. This limitation is significant, as countries differ in EV adoption rates, renewable energy integration, and recycling incentives (Skeete et al., 2020; Nurdiawati & Agrawal, 2022). These differences influence both the availability of end-of-life batteries and the economic attractiveness of repurposing versus recycling, potentially leading to divergent diffusion trajectories.

From a qualitative perspective, comparative case studies demonstrate that regulatory coordination, producer-responsibility regimes, and ecosystem alignment strongly influence the emergence of second-life battery markets (Jiao & Evans, 2016; Doi et al., 2024). For example, China's centrally coordinated traceability systems and enforced extended producer responsibility have enabled more rapid scaling of second-life applications, whereas more fragmented regulatory environments have slowed diffusion in other contexts (Doi et al., 2024). Even within the EU, differences in national safety governance, enforcement practices, and energy-market structures suggest that harmonised regulation does not automatically lead to uniform market outcomes (de Waal, 2025). However, existing qualitative studies do not systematically analyse how these national institutional differences interact dynamically with market formation, resource mobilisation, and legitimacy creation over time. As a result, the mechanisms through which national context shapes diffusion trajectories remain insufficiently understood.

These gaps are particularly relevant for the Netherlands and Sweden. Both countries are advanced EV markets, yet they differ in key structural dimensions that are likely to shape repurposing diffusion. The Netherlands is characterised by a highly decentralised energy system with strong congestion challenges and increasing pressure on grid flexibility, particularly in regions with high distributed renewable generation (IEAa, 2024). Such conditions create substantial potential for residential and decentralised storage applications, which may favour second-life battery deployment. In contrast, Sweden combines high renewable penetration with a comparatively centralised and coordinated energy system, where large-scale hydropower and industrial actors play a significant role (IEAb, 2024.; Nurdiawati & Agrawal, 2022). Moreover, Sweden has demonstrated strong industrial coordination in the battery value chain, supported by national initiatives aimed at developing domestic battery production and circular systems (Malik, 2023). Although both countries operate under the same EU Battery Regulation, these differences in energy-system configuration, market structure, and industrial strategy are likely to generate distinct diffusion pathways for EV battery repurposing. However, no study has yet comparatively analysed how such national characteristics influence the system-dynamic development of repurposed battery markets over time. Addressing this gap forms the central contribution of this thesis.

1.3 Research objective

The primary objective of this study is to advance understanding of how national contextual factors shape the diffusion of EV battery repurposing. Specifically, it examines how energy-system characteristics, regulatory frameworks, demand conditions, and industrial coordination interact dynamically over time to shape diffusion volumes and the quality of the innovation system in the Netherlands and Sweden.

By modelling these interactions using a system dynamics approach, the study is able to generate policy-relevant insights into how policy design can either accelerate or constrain diffusion trajectories. The focus is not on technological optimisation, but on understanding the systemic and feedback-driven dynamics that determine market formation in emerging circular battery systems.

Methodologically, the research contributes to the literature by integrating system-dynamic modelling with an innovation-system perspective, thereby offering a context-sensitive framework to explain how national structures and feedback mechanisms shape diffusion pathways in circular economy technologies.

1.4 Research questions

The research objectives are pursued through the following research question:

"*How do the national contexts of the Netherlands and Sweden affect the diffusion of EV battery repurposing technology?*"

To answer this question, the analysis is structured into three sequential sub-questions, each building on the previous step. First, the foundational conditions within each country are examined. This stage identifies and compares the key contextual variables that shape the innovation system for circular battery solutions. These variables not only describe the current system state but also provide the basis for analysing and projecting future diffusion.

Second, Sub-research Question 2 builds on this foundation by analysing the diffusion patterns of EV battery repurposing in both countries. It examines how differences in contextual conditions influence feedback mechanisms within the innovation system and, consequently, lead to different diffusion outcomes. This step links structural conditions to observable market developments.

Finally, Sub-research Question 3 focuses on the role of policies and their impact on diffusion volumes. Through scenario-based modelling, this stage addresses uncertainties in future diffusion and assesses how regulation can accelerate or constrain the deployment of battery repurposing and evaluates the robustness and effectiveness of these policies.

The research question is decomposed into the following three sub-questions.

- Sub-question 1: What is the state of key contextual variables/conditions that influence the innovation system of circular battery solutions in the Netherlands and Sweden?
- Sub-question 2: How do the diffusion patterns of EV battery repurposing differ between the Netherlands and Sweden, and what explains this diffusion behaviour?
- Sub-question 3: How do regulatory policies impact EV battery repurposing for the Netherlands and Sweden?

1.5 Research scope

This research investigates the early-stage development of EV battery repurposing at the national level, with a specific focus on the formative phase of the technology's diffusion through a system dynamics model covering the period from 2010 to 2050. The empirical scope is limited to two country cases: the Netherlands and Sweden. These countries provide a relevant basis for comparison, as both rank among Europe's leading EV adopters and exhibit similar levels of market penetration, while differing in their regulatory frameworks, market structures, and energy system characteristics.

In line with Seika & Kubli (2024), the technological scope of this study is restricted to currently dominant lithium-ion battery chemistries, particularly NMC and LFP batteries, which account for the majority of batteries deployed in today's EV market. Emerging technologies such as solid-state batteries are excluded due to their limited commercial scalability and uncertain market penetration within the timeframe considered

Focusing on the formative phase allows the study to capture critical system dynamics that influence longer-term diffusion pathways. At this stage, institutional arrangements, market formation processes, and coordination mechanisms are still emerging, making it possible to identify early barriers, enabling conditions, and potential path dependencies. The analysis is therefore confined to system-level diffusion dynamics and national contextual factors.

With regard to recycling, the Circubat model considers recycling at the stage where end-of-life batteries are processed into black mass. The analysis does not explicitly model subsequent metallurgical refining or material recovery processes. This modelling choice reflects the current structure of the European battery value chain, where advanced refining and cell material production are often located outside Europe. Consequently, recycling is represented at the level most relevant to national system dynamics within the studied timeframe, consistent with the modelling boundary applied by Seika & Kubli (2024).

1.6 Structure of the thesis

This thesis is structured into six chapters to systematically answer the research question. Chapter 1 introduced the research background, identifies the knowledge gaps, formulates the research question and sub-questions, and defines the scope. Chapter 2 reviews the literature on EV battery repurposing. It examined national and system-level factors influencing diffusion and introduces the theoretical and modelling frameworks used in this study. Chapter 3 presents the research methodology. It describes the merged system dynamics model, the data collection and contextualisation process, model validation, and the scenario and policy experiments. Chapter 4 presents the simulation results. It compares national contextual conditions, analyses diffusion patterns in the Netherlands and Sweden, and evaluates policy impacts on diffusion volumes. Chapter 5 interprets the findings and discusses their theoretical and managerial implications. It also reflects on methodological and conceptual limitations. Finally, Chapter 6 summarises the main conclusions, answers the research question, and provides policy and strategic recommendations to support EV battery repurposing and circular battery systems.

Chapter 2: Literature review EV battery repurposing

This section reviews the core concepts and existing literature relevant to this study in order to position the research and identify the remaining knowledge gap. It examines prior work on EV battery repurposing, focusing on what has been studied, which analytical approaches have been applied, and how national context has been incorporated. First, the EV battery lifecycle is outlined to explain how batteries move from first use to repurposing and recycling and to highlight the time delays inherent in circular battery systems. Second, EV battery repurposing is examined from a system perspective by reviewing the techno-economic and legal-regulatory preconditions that shape its feasibility and scalability. Third, national-level studies are reviewed to assess how demand, supply, and capacity factors have been addressed in different case studies. Finally, this chapter reviews existing approaches for analysing technology diffusion, with particular attention to system dynamics and Technological Innovation Systems frameworks, to motivate the analytical approach adopted in this thesis.

2.1 Background EV battery repurposing

EV batteries move through a sequence of interconnected life-cycle phases that determine their technical performance, economic value, and contribution to circularity. In line with circular economy principles embedded in the EU Battery Regulation (2023), linear end-of-life options such as landfilling and incineration are prohibited, making circular strategies mandatory. The regulation aligns with the broader circular economy objective of retaining value by keeping products and materials in use for as long as possible and reducing reliance on virgin resources (Kirchherr et al., 2017).

This study distinguishes four sequential phases in the EV battery life cycle: first use, assessment, repurposing, and recycling, presented in Figure 2, based on the research of Seika & Kubli (2024). Together, these phases describe how batteries move through the system over time and how slowing and closing loops interact.

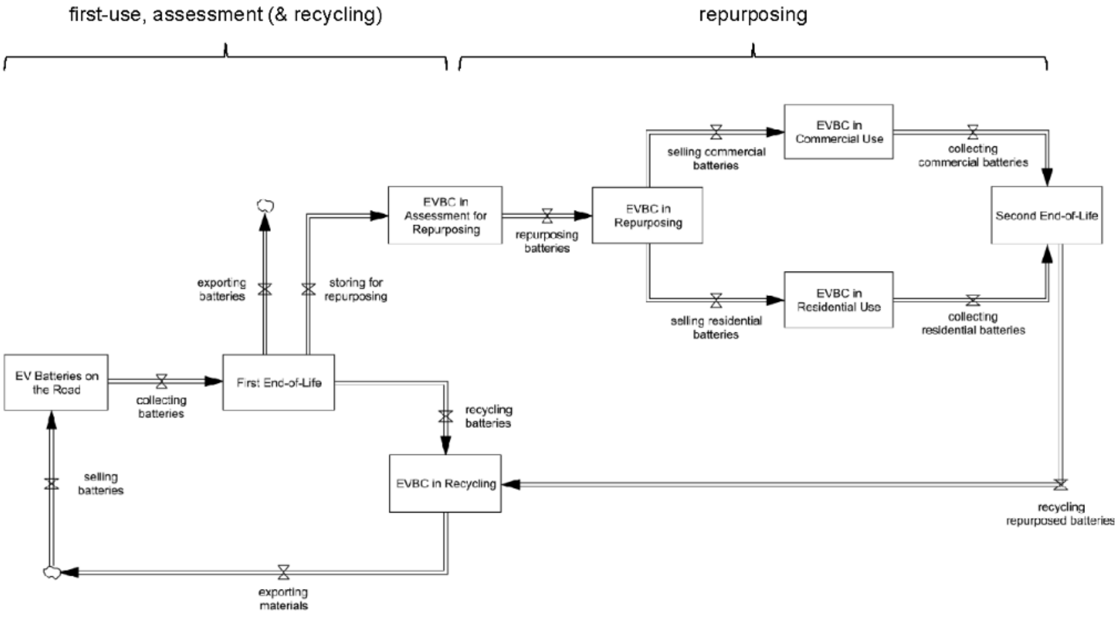


Figure 2: Lifecycle stages EV battery. Source: (Seika & Kubli, 2024)

The first use phase refers to the application of batteries in electric vehicles. The performance of the EV battery is mainly determined by the battery chemistry and is realised at the battery cell level through the choice of electrode materials, electrolyte, and cell design, which together influence electrochemical performance and ageing behaviour (Schmuch et al., 2018). During the use phase, battery degradation occurs gradually as a result of cycling, temperature exposure, charging behaviour, and calendar ageing (Han et al., 2019). An EV battery is generally considered to have reached end-of-life (EoL) for automotive use once its remaining capacity declines to approximately 70–80% of its initial level, a point typically reached after around 14 years of operation (Bobba et al., 2018; Etxandi-Santolaya et al., 2024). Battery capacity is commonly defined as the remaining usable capacity relative to its original capacity (Casals et al., 2019). This phase therefore determines when and in what volumes batteries exit the vehicle fleet, creating a time lag between EV adoption and the availability of EoL batteries for repurposing and recycling.

After first use, batteries undergo assessment to determine whether they are repurposed or sent directly to recycling. This decision is largely based on the State-of-Health (SoH), capturing remaining capacity, internal resistance, and expected degradation. Batteries below ~50% SoH are typically recycled, while higher-SoH batteries may be repurposed depending on economic and policy-driven market conditions (Al-Alawi et al., 2022).

In the repurposing phase, EV batteries that no longer meet automotive performance requirements are deployed in less demanding stationary applications, such as residential and commercial energy storage. Repurposing functions as a slowing-loop strategy within the circular economy by extending battery lifetime and delaying material recovery (Albertsen et al., 2021). During second-life use, batteries continue to degrade and are ultimately withdrawn once their SoH falls below an application-specific threshold, which is commonly assumed to be around 60% SoH (Wesselkämper et al., 2025). Empirical evidence indicates that below this threshold, a growing share of applications can no longer be reliably supported due to insufficient usable capacity, while batteries also experience sharply increasing internal resistance and a heightened risk of entering a phase of accelerated degradation, leading to greater performance uncertainty (Casals et al., 2019).

Recycling represents the final phase of the battery life cycle and a closing-loop strategy in which valuable materials are recovered and ideally, from a circular point of view, reintroduced into battery production. Batteries enter recycling either after completing a second life or directly following assessment when repurposing is not viable. The recycling process typically begins with battery pack disassembly and mechanical pre-treatment, during which battery cells are shredded and separated into material fractions, resulting in a powder known as black mass that consists valuable recycled metals (Harper et al., 2019).

Several recycling pathways are used to recover valuable materials from black mass, each differing in complexity, efficiency, and industrial maturity. Pyrometallurgical recycling relies on high-temperature smelting to recover metals such as cobalt and nickel and is valued for its robustness and flexibility with mixed battery chemistries, but it is energy-intensive and typically results in limited lithium recovery. Hydrometallurgical recycling uses aqueous chemical leaching and separation steps to recover a wider range of materials, including lithium, with higher recovery efficiencies, though at the cost of increased chemical use and process complexity. Direct recycling aims to retain the original crystal structure of cathode materials through careful separation and reconditioning, offering potential benefits in energy efficiency and material value preservation, but it remains at an early stage of industrial deployment. In Europe, current industrial practice predominantly combines pyrometallurgical and hydrometallurgical processes (Baum et al., 2022).

Until recently, black mass was frequently exported for further treatment outside Europe due to limited domestic refining capacity (Seika & Kubli, 2024). To strengthen environmental protection and enhance control over material flows, the European Commission has reclassified black mass as hazardous waste. This reclassification introduces stricter shipment controls and prohibits its export to non-OECD countries, thereby encouraging treatment and material recovery within Europe (European Commission, 2025).

2.2 General preconditions for EV battery repurposing.

The diffusion of EV battery repurposing is not determined by technological potential alone, but by a set of preconditions that shape whether second-life applications can move beyond pilot projects and scale in practice. The literature consistently highlights that both techno-economic factors and legal-regulatory frameworks play a decisive role in enabling or constraining repurposing activities. Importantly, while many of these preconditions are addressed at EU level, their interpretation, implementation, and enforcement vary across national contexts, influencing the pace and form of diffusion. This section reviews the key preconditions for EV battery repurposing identified in the literature, distinguishing between techno-economic and legal-regulatory aspects, and examines how these are addressed at EU level and within the national contexts of the Netherlands and Sweden.

2.2.1 Techno-economic preconditions

Before an EoL EV battery can function as a repurposed battery, several technical preconditions must be met. Because EV batteries are designed for traction applications rather than stationary energy storage, their reuse in second-life systems requires technical adaptation to account for differences in power, energy, and control requirements (Martínez-Laserna et al., 2018). Evidence from pilot projects confirms that the technical adaptation of end-of-life EV batteries for stationary second-life applications is feasible (Rallo et al., 2020).

Another key technical precondition for effective EV battery repurposing is the ability to manage heterogeneity in SoH when assembling second-life battery modules. Retired EV batteries exhibit significant variation in capacity, internal resistance, and remaining useful life due to different usage and ageing histories. If these differences are not considered when grouping cells, they can lead to accelerated degradation and reduced system performance. This challenge can be addressed through systematic cell matching based on data-driven clustering methods that group batteries with comparable health characteristics (Akram et al., 2025).

In addition, reliable and verifiable battery health assessment is a critical technical precondition for determining whether end-of-life EV batteries retain sufficient residual capacity and acceptable safety margins for second-life applications. Although advanced SoH estimation techniques are well established in research environments, this review indicates that their practical implementation in commercial repurposing remains challenging. Limited access to first-life battery management system (BMS) data and the lack of standardisation across EV battery designs increase the complexity, time, and cost of screening procedures (Kampker et al., 2023).

Closely related, the BMS originally integrated into EV batteries is optimised for first-life automotive operation and is generally unsuitable for second-life use. Effective repurposing therefore requires an adapted or redesigned BMS. This system must reliably monitor and control key parameters such as voltage, current, and temperature to ensure safe and stable operation in stationary applications (Kampker et al., 2023).

Overall, the literature and pilot projects demonstrate that EV battery repurposing is technically feasible when appropriate assessment, integration, and battery management adaptations are implemented (Rallo et al., 2020; Kampker et al., 2023). However, these technical requirements introduce additional costs, which directly affect the economic viability of repurposing. At the same time, the cost of new batteries continues to decline rapidly in terms of price per kWh, as shown in Figure 3 (IEA, 2024). This intensifies competition and reduces the cost advantage of second-life batteries. Consequently, the viability of EV battery repurposing depends not only on technical feasibility but also on maintaining total system costs that are competitive with new battery alternatives.

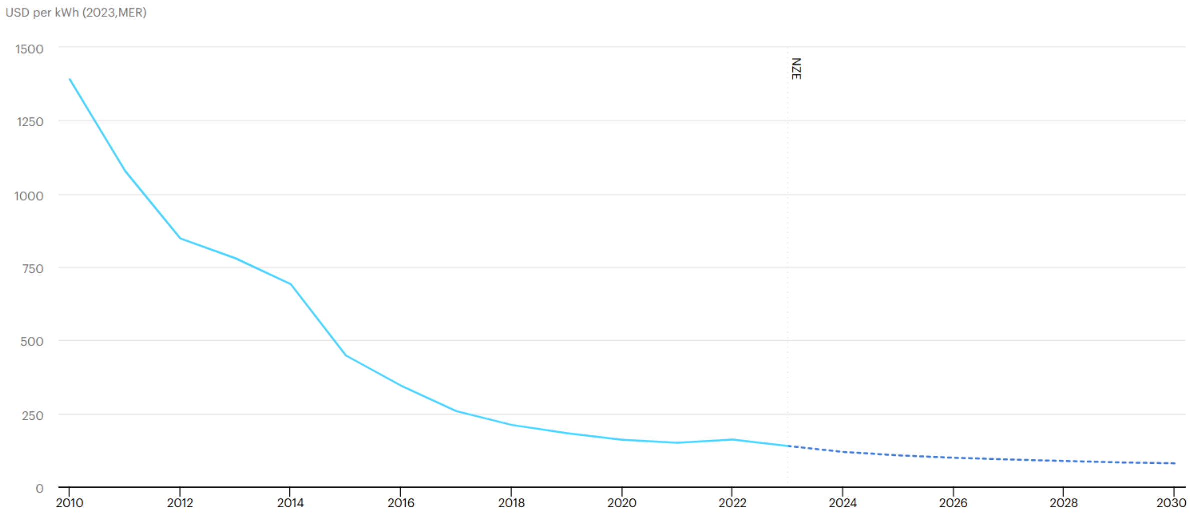


Figure 3: Rapidly declining LFP battery prices. Source: (IEA, 2024).

2.2.2 Legal and regulatory preconditions

A key legal and regulatory precondition for EV battery repurposing is the clear recognition of second-life batteries as products rather than waste. Under the former Batteries Directive, the frequent classification of used EV batteries as waste subjected repurposing activities to stringent waste transport, permitting, and handling requirements. These obligations substantially increased administrative burdens and costs, thereby discouraging higher-tier waste hierarchy strategies such as reuse and repurposing (European Commission, 2019; Dawson et al., 2021; Hill et al., 2019). The EU Batteries Regulation (EU) 2023/1542 addresses this barrier by explicitly defining repurposing and preparation for repurposing and by clarifying the transfer of responsibility when repurposed batteries are placed back on the market (Regulation (EU) 2023/1542, Arts. 3, 56; Kampker et al., 2023).

A second regulatory precondition concerns access to battery data and information rights. Safe and efficient repurposing relies on access to information such as state of health, expected lifetime, and battery composition. Historically, however, OEM-controlled data and proprietary battery management systems have limited transparency and hindered diagnostics (Hill et al., 2019; Kampker et al., 2023). The introduction of battery passports under the Batteries Regulation aims to reduce this information asymmetry and support second-life decision-making, although their implementation entails considerable administrative and compliance efforts (Regulation (EU) 2023/1542, Art. 77; Berger et al., 2023).

Safety standards and certification frameworks represent another critical regulatory precondition. Existing standards have largely been developed for new batteries and automotive applications and are therefore poorly suited to heterogeneous, aged batteries used in stationary second-life systems (Faessler, 2021; Eleftheriadis et al., 2023). While the Batteries Regulation introduces safety requirements for stationary energy storage systems, certification and enforcement remain partly dependent on national implementation (Regulation (EU) 2023/1542, Art. 12). In the Netherlands, an official risk assessment by the Netherlands Food and Consumer Product Safety Authority (NVWA) concludes that the safety of revised lithium-ion batteries is not yet adequately regulated. The assessment identifies regulatory gaps and safety uncertainties. It has an advisory rather than binding character, indicating that national policy responses are still under development rather than formally established (BuRO, 2025). Sweden, by contrast, does not appear to have adopted dedicated national safety guidelines specifically for repurposed EV batteries. Instead, relevant safety expectations are addressed through general electrical safety guidance for battery storage systems and through national emergency-response guidance for lithium-ion battery incidents covering EVs and stationary energy storage (Grönland et al., 2023; Swedish Civil Contingencies Agency, 2024; Elsäkerhetsverket, 2025).

Finally, extended producer responsibility (EPR) frameworks strongly influence the feasibility of EV battery repurposing by shaping battery availability, liability allocation, and economic incentives. Although EPR schemes have improved collection and recycling performance, they have also been criticised for prioritising recycling targets over reuse and repurposing and for creating uncertainty regarding responsibility transfer in second-life applications (Dawson et al., 2021; Olsson, 2018). The Batteries Regulation reduces this uncertainty by extending EPR obligations to actors that place repurposed batteries on the market. Nevertheless, concerns remain regarding incentive alignment, risk allocation, and coordination across the battery value chain (Regulation (EU) 2023/1542, Art. 56; Kampker et al., 2023).

Overall, while the regulatory framework for EV battery repurposing is increasingly harmonised at EU level through the Batteries Regulation, its practical effectiveness continues to depend on national implementation, enforcement capacity, and the resolution of remaining legal, administrative, and policy trade-offs (de Waal, 2025). While the technical feasibility of EV battery repurposing and the EU regulatory framework are increasingly established, diffusion outcomes differ across countries (Doi et al., 2024). This motivates a closer examination of national context in shaping repurposing diffusion, which is the focus of the following section.

2.3 National factors influencing EV battery repurposing

This section of the literature review synthesises national case studies that forecast or analyse the repurposing of EV batteries, with a focus on how national context is incorporated into modelling and forecasting analysis. Five key studies are reviewed, each examining a different country or region and employing distinct methodological approaches. Skeete et al. (2020) combine quantitative statistical forecasting of EoL LFP batteries with qualitative document analysis of automotive and policy sources to estimate future second-life availability in the UK. Seika & Kubli (2025) apply a system dynamics model to test policy and market strategies for overcoming the "valley of death" in the diffusion of second-life EV batteries for Switzerland. A Sweden-focused case study by Nurdiawati and Agrawal (2022) applies scenario-based material flow analysis combined with a multi-level perspective transition framework. The study examines how alternative end-of-life strategies, battery chemistries, and policy pathways influence future battery waste streams and circular value-chain development, without assessing economic viability. In the Netherlands, the DNV (2021) report primarily adopts a qualitative, expert-based and document review approach to assess the technical, regulatory, and market conditions shaping second-life EV battery applications. Although it includes quantitative forecasting projections, these are largely based on net present value calculations that assume static battery costs and a fixed process efficiency of 1%. As a result, the analysis remains techno-economic and static in nature, without modelling dynamic market interactions or feedback-driven diffusion processes. Finally, a comparative analysis by Doi et al. (2024) employs qualitative policy and institutional comparison across the EU, Japan, China, and the United States to examine how regulatory frameworks, traceability systems, and producer responsibility arrangements influence EV battery reuse and recycling.

Although these studies differ in methods and analytical focus, they collectively identify a range of national factors influencing the diffusion of second-life EV batteries. These factors are synthesised in the following sections and organised into demand-side conditions, supply-side conditions, and national capacity factors, providing the empirical basis for understanding how national context shapes diffusion pathways.

2.3.1 Demand factors

The case studies show that diffusion of second-life EV batteries is partly shaped by national energy-system structure and policy priorities influencing demand. In the EU and Japan, Doi et al. (2024) find that diffusion emerges mainly in electricity systems with a growing share of variable renewable energy, where flexible assets such as stationary storage and grid balancing are increasingly needed. This indicates that the share of renewables and the role of flexibility in national power systems are core national determinants of diffusion. China demonstrates how diffusion becomes more predictable and scalable when second-life batteries are embedded in nationally coordinated infrastructures, such as telecommunications and digital networks, highlighting the importance of anchor demand created through state-linked sectors (Na, 2018; Greenpeace, 2020). Complementing these findings, Seika and Kubli (2025) demonstrate that within the Circubat model the existence of demand for flexibility does not automatically lead to adoption of second-life batteries. They integrate empirical survey insights on consumer preferences in the residential storage segment. The analysis shows that purchasing decisions are strongly influenced by perceived safety, expected lifetime, and overall reliability (Seika, Forthcoming). As a result, even where structural demand for storage exists, limited consumer acceptance can constrain diffusion. This underlines that national demand conditions are shaped not only by energy-system needs, but also by consumer expectations and trust in second-life technologies.

2.3.2 Supply factors

Across the cases, Doi et al., (2024) show that diffusion on the supply side is shaped less by technical battery availability and more by national arrangements governing ownership, responsibility, and collection. In the EU and Japan, manufacturer-centred take-back systems enhance control over the timing and condition of batteries entering second-life pathways, supporting diffusion through coordinated producer responsibility (Foster et al., 2014; Doi et al., 2024). Evidence from the UK and Sweden shows that national EV transition plans and fossil fuel phase-out timelines affect when end-of-life batteries become available, which in turn influences how quickly second-life markets can develop (Skeete et al., 2020; Nurdiawati & Agrawal, 2022). In contrast, the US case shows that a fragmented regulatory environment leads to inconsistent flows of end-of-life EV batteries, which limits the development and scaling of repurposing activities (Kelleher Environmental, 2019). China's experience demonstrates that extended producer responsibility can enable large-scale diffusion, but only where enforcement is effective and informal markets are controlled (State Council, 2018; ATCRR, 2020; Autohome, 2020). Supply is further shaped by OEM end-of-life strategies, which determine whether batteries become available for repurposing. Because OEMs hold extended producer responsibility, they play a central role in deciding whether batteries are repurposed, recycled, or retained within proprietary value chains. Based on interviews with Dutch industry stakeholders, DNV (2021) assumes that in a positive scenario at most 50% of OEMs will make their end-of-life EV batteries available for repurposing, either by releasing them to the open market or by repurposing them internally in collaboration with third-party partners. This highlights that OEM strategies and ownership arrangements are key national supply-side factors influencing the availability of batteries for second-life applications. Consistent with this, evidence from Switzerland shows that strong recycling incentives and material recovery targets can encourage OEMs to prioritise direct recycling, thereby reducing battery availability for repurposing and slowing diffusion despite high EV adoption (Seika & Kubli, 2025).

2.3.3 Capacity factors

As EoL EV battery volumes increase rapidly, the diffusion of repurposing activities increasingly depends on the ability of national systems to scale repurposing capacity. This includes not only physical infrastructure but also the availability of skilled labour, technical expertise, and specialised testing facilities (DNV, 2021). Without sufficient human capital and operational capabilities, rising battery volumes do not automatically translate into increased second-life deployment. System dynamics analyses further demonstrate that capacity expansion is highly sensitive to financial investment flows and strategic decision-making. Seika and Kubli (2025) show that repurposing firms may struggle to survive the so-called "valley of death" if expected revenues remain uncertain or if there are instable or low demand signals. In such cases, capacity may fail to expand due to insufficient investment and can even result in firm exit and the collapse of emerging repurposing activities. The strategies tested extend beyond firm-level business models and include regulatory strategies that shape long-term market expectations and investment security (Seika & Kubli, 2025). Comparative international evidence highlights that national capacity formation is strongly conditioned by regulatory, institutional, and system-level readiness. In the United States, limited standardisation of testing and safety procedures has increased compliance costs and safety uncertainties, thereby constraining the development of repurposing capacity (Hill et al., 2019; CalEPA, 2019). In contrast, Japan's coordinated performance and safety standards demonstrate how national standard-setting can reduce uncertainty, lower transaction costs, and facilitate diffusion (Doi et al., 2024). Similarly, China's implementation of battery traceability platforms and detailed facility guidelines illustrates how state-led capacity building can support large-scale diffusion. However, weak enforcement mechanisms may undermine investor confidence and slow the build-up of repurposing capacity (MIIT, 2018a; MIIT, 2018b; Lee, 2021).

This section reveals that no unified set of national factors shaping the EV battery repurposing market has yet been established. Moreover, existing national case studies vary widely in research focus and methodology, which motivates the following section to examine which analytical framework is best suited to study the diffusion of EV battery repurposing in the Netherlands and Sweden.

2.4 Analytical frameworks for modelling diffusion of repurposed EV batteries.

Most national case studies provide insights into regulatory intentions and potential market outcomes, but offer limited understanding of long-term market dynamics. A key exception is the work of Seika and Kubli (2024), who develop the Circubat system dynamics model to analyse the long-term evolution of the repurposed EV battery market in Switzerland. The model captures regulatory effects through multiple feedback mechanisms and is further used to assess business and policy strategies for overcoming the "valley of death", a phase in which early market interest often declines before broad adoption occurs (Moore, 1991).

The Circubat model contributes to the literature in three main ways. First, it provides a quantitative assessment of regulatory impacts, extending earlier qualitative studies (Richter, 2022; Albertsen et al., 2021). Second, it estimates long-term market outcomes and profitability for repurposed and recycled battery applications. Third, it identifies feedback mechanisms that shape the development of a circular EV battery value chain. While the model could in principle be adapted to the Dutch and Swedish contexts by adjusting input variables, it does not specify which national variables are most relevant for such adaptation. Moreover, the model primarily focuses on firm-level profitability and strategic behaviour and does not explicitly model technology innovation system dynamics.

Diffusion processes can be examined using the Technology Innovation System (TIS)framework, which conceptualises technological change as a system-based process shaped by interactions between actors, technologies, and institutions (Coenen & López, 2010). Originally developed to explain how new technologies contribute to economic growth (Carlsson & Stankiewicz, 1991). Within this framework, diffusion is analysed through TIS functions that capture key innovation and diffusion processes over time (see Table 1). These processes are enabled or constrained by TIS building blocks, which represent the structural conditions, such as technologies, actors, and institutions, that shape these processes (see Table 2). When these building blocks are missing, incomplete, or misaligned, system development is constrained and diffusion slows. Conversely, diffusion accelerates when the structural components become sufficiently developed and aligned (Ortt & kamp, 2022). While the TIS framework offers a strong conceptual basis for identifying drivers and barriers to diffusion, it has primarily been applied as a qualitative analytical tool rather than a quantitative modelling approach.

Table 1: TIS functions. Source: adapted from Ortt & Kamp (2022).

TIS function	Description	Indicator	Source
Entrepreneurial activities	Activities concerning the new technology	Started and planned EV battery repurposed projects	Edsand & Bångens (2024)
Knowledge development	Knowledge created regarding the new technology	Number of publications regarding Repurposed EV batteries at the national technical universities over de past 10 years	Bergek et al. (2008)
Knowledge diffusion	Distribution of knowledge regarding the new technology through an actor network	Number of conferences about EV battery repurposing	Edsand (2019); Hekkert et al. (2007)
Guidance of search	Activities that shape the needs, requirements and expectations of actors regarding support of the new technology	Expected continuation of development and diffusion of EV battery repurposing	Bergek et al. (2008a); Suurs (2009)
Market formation	Market entry assistance for the new technology to encourage supply	Financial market incentives; e.g. EV battery repurposing subsidies for households, tax exemptions etc.	Vasseur et al. (2013), Edsand & Bångens (2024); Edsand (2019)
Resource mobilisation	Resources allocated to the new technology	Availability, size, and type of resources allocated to EV battery repurposing	Edsand & Bångens (2024); Edsand (2019)
Creation of legitimacy	Support for the new technology	Support for or against the acceptance of the repurposed EV batteries.	Edsand & Bångens (2024); Edsand (2019)

Table 2: building blocks. Source: (Massop, 2024) which was adapted from Ortt & Kamp (2022).

Building Block	Description	Corresponding TIS structure
Product performance and quality	A new technology with a good potential performance and quality compared to competing technology.	Technology
Production system	A production system delivering a high quality product at a large scale	Technology
Complementary products and services	Products and services supporting the development, productions, distribution, adoption, use, repair, maintenance, and disposal of the new technology	Technology
Product price	The financial purchase price of the new technology	Technology
Network formation and coordination	The networks of actors in the supply chain	Actors and networks
Customers	Customers that are aware of the innovations, see its benefits, and have the knowledge and the means to acquire the new technology	Actors and networks
Innovation-specific institutions	Formal rules surrounding the new technology	Institutions

Several studies have attempted to quantify the TIS framework using system dynamics, but often with a narrow focus. Uriona and Grobbelaar (2019) show that most system dynamics applications address specific policy domains, such as R&D or diffusion, rather than the innovation system as a whole. Walrave and Raven (2016) addressed this limitation by translating TIS functions and the 'motors of innovation' into a system dynamics model based on the functions identified by Hekkert et al. (2007). The motors of innovation refer to recurring interaction patterns within the innovation system that together drive its development over time. Their approach introduces a quantitative assessment of TIS functions, extending earlier qualitative methods (Bergek et al., 2008a; Edsand & Bångens, 2024). However, interactions between TIS structures and functions remain largely implicit and are treated as a black box (Walrave & Raven, 2016), which limits insight into how specific system weaknesses affect diffusion over time.

Massop (2024) addressed this gap by developing a hybrid system dynamics model that explicitly linked TIS functions to structural building blocks, enabling the analysis of technology diffusion through reinforcing and balancing feedbacks. This integrated framework captures the cumulative development of an innovation system over time and is particularly suited to analysing early diffusion dynamics. However, Massop applies the model to landfill gas–to–energy projects in Africa and therefore tailors both the selected TIS functions and the structural building blocks to developing-country contexts and the specific case study. While the hybrid structure is transferable, the building blocks must be adapted to reflect the technological, market, and institutional characteristics of EV battery repurposing. The model further focuses on the formative phase of a Technological Innovation System, when key structures are still emerging, uncertainty is high, and markets are weakly developed (Bergek et al., 2008a; Edsand & Bångens, 2024). As a result, system development is modelled as a process of gradual build-up rather than decline, with reinforcing and balancing feedbacks capturing slow initial growth and delayed diffusion dynamics (Markard, 2020).

This literature review demonstrates that the technical feasibility of EV battery repurposing and the EU-level regulatory framework are largely established, yet diffusion outcomes may vary substantially across countries due to differences in national implementation, particularly regarding safety standards, certification practices, and enforcement (Doi et al., 2024; de Waal, 2025). While existing national case studies recognise the importance of national context, they differ widely in research focus and methodology and do not provide a unified explanation of how national factors shape diffusion over time (Skeete et al., 2020; Nurdiawati & Agrawal, 2022; DNV, 2021). The Circubat system dynamics model offers the most advanced quantitative analysis of second-life battery markets to date but focuses on firm-level viability rather than at the development of the TIS and is tailored to the Swiss context (Seika & Kubli, 2024; Seika & Kubli, 2025). At the same time, the TIS framework offers a well-established lens for analysing how an entire innovation ecosystem developes, but has not yet been operationalised for EV battery repurposing in a comparative, system-dynamic manner. Consequently, there is currently no integrated framework that explains how national factors interact over time to influence the innovation system of repurposed EV batteries across countries, which motivates the research approach adopted in this thesis.

Chapter 3: Research Methodology

3.1 Research design

This study analyses how the innovation system for EV battery repurposing may develop in the Netherlands and Sweden, and how national context shapes this process. To capture both system-level innovation dynamics and detailed market behaviour, a merged system dynamics model is developed.

To operationalise this system perspective dynamically, the research design combines two existing system dynamics models. First, the hybrid TIS-based model developed by Massop (2024) is used as the conceptual backbone because it explicitly represents interactions between TIS functions and key structural building blocks over time. Second, the Circubat model (Seika & Kubli, 2024/2025) is used to represent detailed circular battery market dynamics, including battery volumes and flows, cost learning, investment decisions, demand development, policy instruments, and characteristic decision delays. By integrating Circubat variables as dynamic indicators for the TIS building blocks, the merged model links detailed market behaviour to system-level innovation dynamics. This approach enables the analysis to explain diffusion outcomes not only as market effects, but as the result of co-evolving innovation system conditions.

System dynamics is selected as the core simulation method because it is well suited to analysing long-term diffusion behaviour in complex socio-technical systems. In such systems, outcomes emerge endogenously from interacting feedback processes rather than from linear cause–effect relations (Sterman, 2000). In EV battery repurposing, diffusion depends on a multi-stage supply chain (battery returns, testing, repurposing, market uptake), capacity constraints, delayed responses in investment and policy, and reinforcing mechanisms such as learning effects and legitimacy building. Capturing how national differences propagate through these mechanisms, requires a feedback-oriented modelling approach rather than a static comparative assessment. This aligns with work emphasising that dynamic models are better suited than static approaches for studying TIS evolution and diffusion mechanisms (Ortt & Kamp, 2022).

The modelling process follows the iterative system dynamics cycle described by Auping et al. (2024): problem articulation, conceptualisation, formulation, evaluation, and policy testing. The problem articulation phase, addressed in Chapters 1 and 2, defined the core problem as understanding how differences in national context influence the development of innovation systems and thereby influence the potential for large-scale diffusion. This informed key design choices: a comparative case-study design (Netherlands and Sweden), a long time horizon (2010–2050), and a focus on the passenger car segment. The chosen time horizon captures historical developments while allowing simulations to explore how diffusion may emerge and evolve under different national conditions.

The analysis focuses on the formative phase of the innovation system, in which structures are still emerging, coordination among actors is limited, and reinforcing feedbacks that drive rapid diffusion are not yet fully established. In this phase, diffusion is expected to develop slowly at first, but may accelerate as structures mature and interactions strengthen. The formative phase is therefore particularly relevant for understanding how national context shapes early pathways and whether enabling mechanisms become established (Bergek et al., 2008a; Edsand & Bångens, 2024).

Figure 4 presents the research flow diagram and illustrates the structure of the remainder of this chapter, indicating where each sub-research question is addressed and how specific data collection methods inform the respective sections. Section 3.2 describes the data collection process supporting model development, including the desk research and expert interviews used to inform indicator selection, parameterisation, and contextual interpretation. Section 3.3 explains how national context is incorporated through the systematic identification and calibration of context-sensitive Circubat variables for the Netherlands and Sweden. Section 3.4 presents the conceptualisation of the merged model, detailing the integration of the hybrid TIS structure with the Circubat market dynamics and clarifying system boundaries and abstraction levels. Section 3.5 outlines the operationalisation of TIS functions and building blocks, including the modelling equations and indicator formulations. Section 3.6 discusses model validation and robustness testing. Finally, Section 3.7 explains how the model is configured and used for simulation experiments. It presents the base settings, defines the scenarios representing uncertain future developments, and introduces the policy interventions tested to analyse their effects on diffusion.

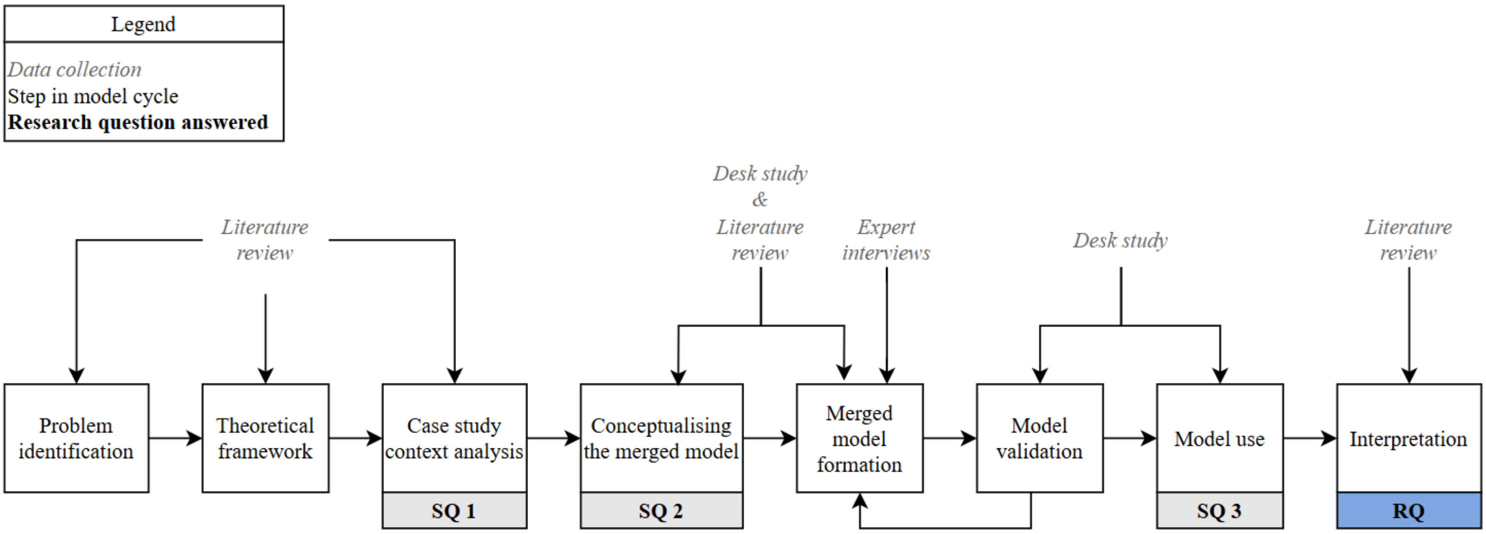


Figure 4: Research Design

3.2 Data collection for methodology

3.2.1 Literature review & Desk research

High-quality research depends on the use of reliable and relevant sources. This is particularly important in system dynamics modelling, where model behaviour depends on structural assumptions and parameter values, and where validation includes sensitivity and extreme-condition tests that explicitly assess the behavioural implications of parameter choices (Barlas, 1996; Senge & Forrester, 1980).

The literature review supported multiple stages of the modelling cycle.

The data collection process combined a structured literature review with complementary desk research. For problem articulation and theoretical framing, the study draws primarily on peer-reviewed academic literature on Technological Innovation Systems and circular EoL EV batterysolutions. Academic databases and search engines, including Google Scholar and Scopus, were used to identify relevant publications. Search strings combined keywords related to EV battery repurposing, second-life batteries, diffusion, and innovation systems. To enhance completeness, backward and forward snowballing were conducted by systematically screening reference lists of relevant articles and identifying studies citing key publications. This approach is recommended for complex research domains where important contributions may not be fully captured through keyword searches alone (Greenhalgh & Peacock, 2005). Priority was given to peer-reviewed journal articles and recent publications to ensure theoretical robustness and up-to-date insights.

For national contextualisation and model parameterisation, academic literature was complemented with targeted desk research. Several input variables, such as EV market shares, battery export rates, recycling capacities, and energy storage deployment, required country-specific quantitative data that were not sufficiently available in peer-reviewed sources. Therefore, grey literature and official data from transmission system operators, national statistical offices, ministries, regulatory agencies, and industry reports were consulted, including sources such as CBS, Rijksoverheid, TenneT, and Statistikdatabasen. These sources were selected based on institutional credibility, methodological transparency, and relevance to the specific variables required. Where necessary, supplementary information from consultancy reports, company publications, and reputable news sources was used cautiously to address remaining data gaps. To ensure transparency and reproducibility, all sources and their corresponding input parameters are documented in Appendix A.

Third, during the conceptualisation and model formulation phases, literature and desk research were used to verify identified causal relationships and modelling assumptions. Where empirical or theoretical evidence for a specific relationship was available, it was incorporated into the model design. Where direct evidence was lacking, assumptions were explicitly stated and, where possible, discussed with experts to ensure plausibility and consistency with existing knowledge.

Finally, in the discussion chapter, additional literature was consulted to interpret and contextualise the model results. This ensured that findings were critically reflected upon in light of existing research and contributed to positioning the study within the broader academic debate.

3.2.2 Expert interviews

To support the contextualisation of the TIS building blocks to the EV battery repurposing market and to strengthen the empirical basis of the study, four expert interviews were conducted.. The interviews complied with TU Delft's regulations on human research and ethics and were approved by the Human Research Ethics Committee (HREC number 4170). Their primary purpose was to deepen understanding of the current market status and the dynamics influencing the economic attractiveness of EV battery repurposing.

Although expert interviews are time-intensive and may yield subjective viewpoints, they offer substantial value in research on emerging technological systems because they allow for real-time clarification and exploration of complex themes (Alshenqeeti, 2014). Experts were contacted via publicly available contact details and LinkedIn. Two participants were based in the Netherlands and two in Sweden, ensuring exposure to different institutional and market contexts.

Interviews were semi-structured, lasting approximately 60 minutes each. This format provided a balance between comparability across interviews and the flexibility to follow up on expert-specific insights (Eppich et al., 2019). Two interviews were conducted online and the other two took place in person. Interviews were held in either Dutch or English, depending on participant preference. The interview guide is present in (Appendix D).

Prior to each session, informed consent was obtained for participation and audio recording. Recordings were transcribed using Microsoft Teams and subsequently reviewed and corrected manually to ensure accuracy. Because the purpose of the interviews was exploratory, the transcripts were not formally coded; instead, clear and accurate transcripts were essential for reliable interpretation. Participants were invited to review their transcripts for accuracy. To protect anonymity, transcripts are not included in this thesis, and quotations are cited as *personal communication*.

3.3 Contextualisation: Circubat National adaptation

Chapter 2 demonstrated that national context plays a decisive role in shaping the diffusion dynamics of EV battery repurposing. However, the literature does not provide a standardised or operationalised set of contextual variables for comparative system analysis. A synthesis of existing studies revealed three recurring dimensions; demand, supply, and capacity, as central determinants of innovation system development. These dimensions were therefore adopted as an analytical framework to systematically identify and structure context-sensitive variables within the Circubat model.

In consultation with Circubat developer M. Kubli, all input variables of the original model were reviewed to determine their sensitivity to national conditions. Variables influenced by country-specific conditions were selected, categorised under demand, supply, or capacity, and operationalised as contextual indicators (see Table 3).

Subsequently, desk research was conducted to assess the empirical state of these contextual variables in the Netherlands and Sweden and to calibrate corresponding model parameters. All sources, assumptions, and calibration choices are documented transparently in Appendix A to ensure replicability and methodological rigor. This contextualisation procedure directly addresses Sub-research Question 1: "*What is the state of key contextual variables/conditions that influence the innovation system of circular battery solutions in the Netherlands and Sweden?"*

The findings are presented in Chapter 4, structured according to the demand, supply, and capacity dimensions, thereby providing a systematic and comparable assessment of national conditions shaping the innovation systems in both countries.

Table 3: National factors reflected in the Circubat model

Variable [unit]	**Description**	**Category**
Passenger Car Market Volume [Vehicle]	Historical and projected size of the national vehicle stock	Supply
EV market share [Dmnl/year]	Historical and projected penetration of electric vehicles within the total vehicle stock	Supply
Battery export share [Dmnl]	Proportion EV batteries leaving the domestic system	Supply
Home storage battery sales [kWh/year]	Historical and projected demand for stationary battery storage	Demand
Share for home storage batteries [Dmnl]	Residential share of total stationary battery storage installations.	Demand
Level of subsidies [Dmnl]	Financial support mechanisms that lower the purchase price.	Demand
Recycling capacities of existing market actors [ton/year]	Scale of existing national recycling capacity.	Capacity

3.4 Conceptualising the merged model

This section addresses how the diffusion behaviour of repurposed EV batteries can be explained at a conceptual level. Accordingly, this section develops a feedback-based conceptual representation of the innovation system underlying EV battery repurposing. The conceptualisation provides the basis for explaining diffusion behaviour and interpreting the model results presented in later chapters.

3.4.1 Abstraction level of the merged model

This study does not develop a new conceptual structure from scratch, but integrates two existing and independently developed System Dynamics models: the Circubat model and a hybrid TIS model. Conceptualisation therefore focuses on preserving validated feedback structures while aligning the models across different levels of abstraction.

The Circubat model provides a detailed representation of circular battery flows and market dynamics, including battery volumes, prices, demand, learning effects, investor decisions, and policy instruments. These dynamics are modelled explicitly through stocks, flows, delays, and feedback loops and have been validated in earlier studies (Seika & Kubli, 2024). Market formation in the Circubat model emerges endogenously through mechanisms such as cost learning, and investment behaviour, rather than being imposed externally.

The hybrid TIS model is likewise a System Dynamics model, but it operates at a higher level of abstraction. Its stocks represent normalised, dimensionless system states. These states capture the development of innovation system functions and building blocks over time. Unlike the Circubat model, they do not represent physical quantities. such as energy volumes (e.g. kWh/year) or monetary prices. Instead, they reflect the development maturity of the innovation system (Massop, 2024).

3.4.2 Merged model system boundaries

The system boundary defines which processes are modelled endogenously and ensures the model is fit to analyse how national context shapes the diffusion of EV battery repurposing. As explained previously, the merged model uses variables from the Circubat model to operationalise the TIS building blocks in the hybrid model. The hybrid model is integrated on top of the Circubat structure. This integration follows a one-directional logic, whereby the hybrid model is tailored to the market context through Circubat variables. The Circubat model is retained as the structural core because it represents key market dynamics, including battery flows, demand, price formation, and investment behaviour (Seika & Kubli, 2025). All stocks, flows, delays, and feedback loops remain unchanged. The Circubat model tests different policy and business strategies, which are modelled exogenously to analyse their effects (Seika & Kubli, 2024). Section 3.7.1 described in more detail how these strategies are incorporated into the base-case model configuration. Retaining the original feedback architecture ensures structural consistency with earlier Circubat-based studies and allows meaningful comparison of model behaviour across different national contexts. Differences observed between cases, such as Sweden and the Netherlands, therefore arise from country-specific parameter values and exogenous assumptions, rather than from changes to the underlying feedback structure.

3.4.3 Merged conceptual model

Figure 5 presents the stock–flow diagram of the merged model. In line with the hybrid modelling approach developed by Massop (2024), the building blocks in the general stock–flow structure are represented at a high level of abstraction. They are conceptualised as cumulative constructs that develop over time, taking a value of 0 when absent and approaching 1 when fully developed. When the analysis zooms in on specific subsystems, this level of abstraction is reduced, allowing these components to be modelled using real-world variables and units.

The diagram builds on the relations identified in the hybrid TIS model, shown in black, and is extended with relationships derived from the Circubat model, shown in green. Relationships originating from the TIS framework of Walrave and Raven (2016) are depicted in red, while elements that are newly introduced or adapted in this study are highlighted in blue. The hybrid model thus serves as the conceptual foundation, which is subsequently adapted and expanded into the merged model presented in Figure 5.

To ensure that the merged model accurately captures the dynamics of the EV battery repurposing market, a systematic comparison was made between the hybrid model and the Circubat model. The conceptualisation focused on aligning the abstract innovation system logic of the hybrid model with the detailed market and capacity dynamics represented in Circubat. Where both models identified similar relationships but differed in interpretation or operationalisation, the Circubat formulation was adopted, as it constitutes the core behavioural logic underlying the EV battery repurposing system. The resulting adaptations are structured below by distinguishing which elements were changed, removed, or added relative to the original hybrid model.

3.4.3.1 Changed elements

Several relationships inherited from the hybrid model were reinterpreted to better reflect the characteristics of a second-life battery market. First, the inflow associated with the production system was redefined. While Massop (2024) models this inflow as new investments, the merged model specifies it as new production capacity. This change reflects the fact that, in a second-hand market, physical capacity to process end-of-life batteries is the primary constraint on supply, rather than investment attraction per se. The production system is therefore considered sufficient when repurposing capacity can accommodate both first-life and second-life battery flows.

Second, the relationship between the creation of legitimacy and customers was retained but reinterpreted. In the hybrid model, this link reflects increased public trust through lobbying and familiarity. In contrast, the Circubat model captures this relationship through consumer adoption utility driven by perceived value and price signals. The merged model follows the Circubat interpretation. A similar adjustment applies to the link between innovation-specific institutions and customers: while Massop (2024) frames this as general demand-enhancing policies, the merged model represents it more specifically through price-based instruments such as subsidies. Finally, changes in production capacity are linked to changes in product costs rather than prices, consistent with the Circubat logic.

3.4.3.2 Removed elements

Some elements of the hybrid model were excluded because they are not relevant to the national contexts analysed in this study. Specifically, market formation is not modelled as a separate TIS function. In Massop (2024), market formation consists primarily of pricing policies that stimulate supply, such as feed-in tariffs or tax exemptions. Given the strong conceptual overlap between these instruments and formal regulatory arrangements, this study incorporates market formation within the innovation-specific institutions building block rather than modelling it separately.

In addition, TIS functions that are specific to developing-country contexts were removed. Adaptive capacity, informal resource mobilisation, and the distinction between formal and informal legitimacy are not modelled, as the Netherlands and Sweden do not face the institutional constraints that motivated their inclusion in the hybrid model.

3.4.3.3 Added elements

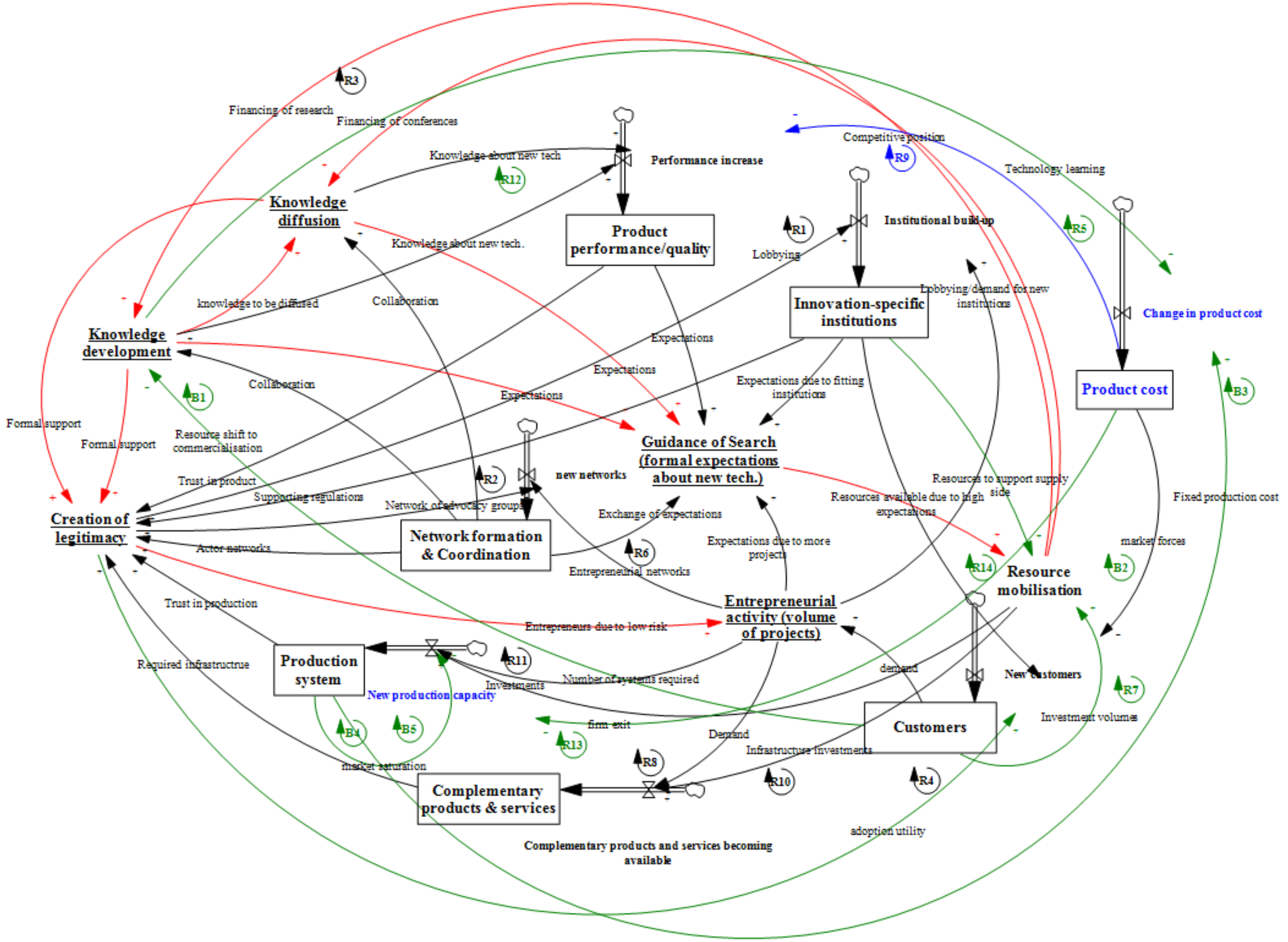
Several relationships were added to reflect key dynamics identified in the Circubat model that are essential for capturing EV battery repurposing. First, a direct link from product costs to the inflow performance increase was introduced, reflecting that lower costs improve the competitive position of repurposed batteries relative to new batteries.

Second, capacity-related balancing mechanisms were added. Following the Circubat model, larger production capacities increase fixed costs, counteracting further expansion. In addition, two saturation effects were included: existing production capacity and capacity under construction both constrain new capacity investments.

Third, demand-side dynamics were extended by linking customers to resource mobilisation. Higher demand for flexible assets increases expected sales volumes, which positively affects investment and R&D resources. Innovation-specific institutions were also linked to resource mobilisation, capturing the role of demonstration funding and other policy instruments that directly support supply-side development (Seika & Kubli., 2025).

Finally, a feedback loop from customers to knowledge development was added, representing a shift from research to commercialisation as adoption increases. This reflects the sales-dependent resource reallocation mechanism identified in the Circubat model, where growing market uptake reduces the need for exploratory research and redirects resources toward deployment and scaling.

In addition to presenting the structural composition of the merged model, Figure 5 also makes explicit the core reinforcing (R) and balancing (B) feedback loops that govern system behaviour. Reinforcing loops amplify change and drive growth or decline through self-reinforcing dynamics, whereas balancing loops counteract change and stabilise the system by moving it towards equilibrium. These feedback loops capture the dynamic interactions between demand, supply, capacity development, and institutional support that shape the diffusion of EV battery repurposing over time. The dominant feedback mechanisms identified in the merged model are summarised and described in Table 4, which links each loop to its functional role in explaining observed system behaviour.



Feedback loops:

R1: Creation of institutional legitimacy
R2: Legitimacy of TIS on network creation
R3: R&D finance for knowledge creation
R4: Legitimacy of TIS on customer utility
R5: Technology learning effects on production costs
R6: Entrepreneurial activity on lobbying power
R7: Volume dependent investments
R8: Demand for complementary infrastructure
R9: Improvement competitive position
R10: Complementary infrastructure building
R11: Production system building
R12: Technology learning on competitive position
R13: market exit
R14: New investments
B1: Sales dependent resource resources
B2: Price effect on battery demand
B3: Capacity dependent fixed costs
B4: Market saturation with built factories
B5: Market saturation under construction factories

Relations identified by Walrave & Raven (2016)
Relations identified by Massop (2024)
Relations identified by Seika & Kubli (Forthcoming)
Relations identified by this study

Figure 5: Conceptual merged model

Table 4: Central feedback loops merged model based on feedbacks identified by Massop (2024), Seika & Kubli (2025)

Feedback loops:	**Description**
R1: Creation of institutional legitimacy	Knowledge development and diffusion increase legitimacy, reduce perceived risk, and stimulate further entrepreneurial activity.
R2: Legitimacy of TIS on network creation	Entrepreneurial activity fosters advocacy groups that strengthen legitimacy and further support the innovation system.
R3: R&D finance for knowledge creation	Resource mobilisation enables knowledge development, which improves expectations and attracts additional resources.
R4: Legitimacy of TIS on customer utility	Growing legitimacy and knowledge diffusion increase customer acceptance and adoption through reduced perceived risk.
R5: Technology learning effects on production costs	Higher cumulative production lowers operational costs through learning effects.
R6: Entrepreneurial activity on lobbying power	Entrepreneurial activity increases lobbying for supportive policies, improving conditions for further entrepreneurship.
R7: Volume dependent investments	Higher investment volumes reduce unit investment costs through scale effects
R8: Demand for complementary infrastructure	entrepreneurial activity and market formation create a need for infrastructure
R9: Improvement competitive position	lower production cost, improves competitive position compared to new batteries.
R10: Complementary infrastructure building	Mobilised resources and investment decisions enable the development of supporting infrastructure
R11: Production system building	Improved expectations and legitimacy attract investments in production capacity, strengthening system development.
R12: Technology learning on competitive position	Increased demand for repurposed batteries crowds out new battery sales, reducing their prices.
R13: Market exit	Low profit margins reduce cost coverage and increase firm exit, reducing capacity.
R14: New investments	Higher investment volumes reduce unit investment costs through scale effects
B1: Sales dependent resource resources	Increasing adoption reduces the need for research resources, shifting focus toward commercialisation.
B2: Price effect on battery demand	Higher selling prices reduce consumer demand, stabilising prices.
B3: Capacity dependent fixed costs	Larger factory capacities increase fixed costs, counteracting expansion.
B4: Market saturation with built factories	Existing factory capacity saturates the market and constrains further expansion.
B5: Market saturation under construction factories	Capacity already under construction limits additional investments.

Building on the conceptual model developed, the analysis now moves from conceptualisation to formalisation. The following section translates the identified constructs and causal relations into a merged model structure by integrating the relevant model components and specifying their interactions.

3.5 Merged model formalisation

This section describes the equation logic used to operationalise the TIS functions, followed by the TIS building blocks. The structure of the merged modeland associated equations were implemented and tested in Vensim Pro 10.4.0. A complete overview of all variables, parameter values, and equations, specific of the merged model is provided in Appendix E. The structure and equations of the Circubat model remain unchanged and are documented in the supplementary materials of Seika & Kubli (2025).

3.5.1 Modelling core of TIS functions

The core TIS functions are modelled as stock variables whose development over time is governed by inflow equations adapted from the model developed by Walrave & Raven (2016) and further operationalised in the hybrid modelling approach by Massop (2024). Each TIS function is represented as a bounded stock with values ranging from 0 (no development) to 1 (full development). As the analysis focuses on the formative phase of the innovation system, functions are assumed to accumulate over time and no outflow is specified.

To represent the evolution of each TIS function over time, the model specifies a net change inflow that governs whether the function increases or stagnates:

$$\text{Change in } F_j = \frac{(1 - F_j) \cdot D_j}{\tau_j}$$

where $F_j$denotes the current level of TIS function j. The term $(1{-}F_j)$ represents the remaining potential for development, ensuring that growth slows as the function approaches maturity. The parameter $\tau_j$is a function-specific adjustment time that determines how quickly the function responds to changes in enabling conditions.

The term D_j captures the combined effect of the conditions driving the development of TIS function j. These conditions enter multiplicatively, reflecting the assumption, central to TIS theory, that weak performance in any one dimension can constrain overall functional development (Hekkert et al. 2007; Suurs & Hekkert, 2012; Walrave & Raven, 2016). For technological knowledge development, technological knowledge diffusion, perceived legitimacy, and guidance of search, $D_j$is constructed by multiplying the relevant indicators, adding the innovation-specific institutions building block, and normalising the result by division by two:

$$D_j = \frac{\text{Multiplicative enabling conditions}_j + \text{Innovation-specific institutions}}{2}$$

This normalisation moderates the combined influence of multiple enabling conditions and reflects the modelling choice to treat innovation-specific institutions as a comparatively strong system-level enabler for these functions, consistent with the hybrid modelling approach proposed by Massop (2024).

3.5.2 Modelling core of TIS building blocks

The equations for the building blocks used in this study follow the hybrid modelling logic developed by Massop (2024). Building blocks are interpreted following Ortt & Kamp (2022), who argue that diffusion depends on the joint development of multiple system components. In this view, full-scale diffusion becomes feasible only once all relevant building blocks reach a sufficient level of maturity. Consequently, each building block is represented as a stock variable bounded between 0 (non-existent) and 1 (fully developed). This bounded representation allows heterogeneous building blocks to be compared on a common scale, prevents unrealistic unbounded growth, and enables aggregation and interaction between system components. This modelling choice follows established practice in system dynamics models of technological innovation systems, where stocks represent levels of development ranging from absence to full maturity (Walrave & Raven, 2016).

To capture the gradual development of building blocks over time and to represent their status throughout the simulated period, a uniform stock–flow logic is applied to all building blocks. In this formulation, the rate of change of each building block depends on the remaining distance to its maximum level (normalised to 1), reflecting the extent to which underlying indicators act as drivers or barriers at that moment in time.

To represent the evolution of each building block over time, the model specifies a net change inflow that governs whether the building block grows or declines:

$$\text{Change in } BB_i = \frac{\text{Indicator}_{BB_i} - BB_i}{\tau_i}$$

where BB_idenotes the current level of building block i, Indicator_{BB_i}represents the difference in the relevant indicators affecting that building block, and $\tau_i$is the adjustment time parameter determining how quickly the building block responds to changes in these conditions.

3.5.2.1 Product system

The product system is defined as the operational capacity to deliver repurposed EV battery products at scale (Ortt & Kamp, 2022). A value of 1 represents a fully developed product system in which repurposing capacity is sufficient to process all batteries suitable for repurposing and SoH assessments are completed within acceptable time limits, allowing batteries to move smoothly through testing and repurposing without structural delays. The product system building block is constructed as the average of capacity saturation and process efficiency, reflecting the assumption that sufficient physical infrastructure and timely diagnostics are jointly necessary conditions for large-scale repurposing (Gu et al., 2024; Börner et al., 2022).

In the merged model, the product system is composed of two equally weighted indicators capturing both capacity sufficiency and operational feasibility.

The first indicator, *saturation of EoL EV battery repurposing factories*, shows whether there is enough repurposing capacity to handle the available batteries. It compares the annual repurposing capacity (in kWh per year) with the volume of batteries that are suitable for repurposing. The indicator is calculated as a ratio between capacity and available battery volume. The value is capped at 1. This means the system is considered fully functional once capacity is equal to or higher than the number of suitable batteries. If capacity is lower than demand, the product system forms a barriers in full-scale diffusion. The indicator is defined as:

$$\text{Factory saturation} = \min\left(1, \frac{\text{Repurposing capacity}}{\max\left(\text{Batteries suitable for repurposing}, 10^{-6}\right)}\right)$$

The small lower bound in the denominator ensures numerical stability without affecting the conceptual interpretation.

The second indicator, *efficiency of repurposing processes*, captures the operational feasibility of SoH assessment. Repurposing relies on timely testing to identify suitable batteries, making diagnostic throughput a critical bottleneck. This indicator is modelled as a delay-based efficiency factor that declines with increasing testing delays and reaches zero once a maximum acceptable delay of two months is exceeded. The two-month threshold is introduced as a modelling assumption. It is defined as:

$$\text{Process efficiency} = \min\left(1,\ \max\left(0,\ 1 - \frac{\text{Testing delay}}{\text{Maximum acceptable delay}}\right)\right)$$

Both indicators are dynamically linked. When factory saturation is low, indicating that incoming volumes exceed available repurposing capacity, testing queues increase, which in turn raises diagnostic delays and reduces process efficiency.

3.5.2.2 Building block: Complementary products and services.

Complementary products and services are defined as the supporting technologies, services, and organisational arrangements that enable EV battery repurposing to function at scale (Ortt & Kamp, 2022). In this model, the building block captures whether three enabling conditions are fulfilled: (1) a sufficiently large EV market share to ensure structural battery availability, (2) the presence of service-based organisational arrangements that provide complementary services such as installation, monitoring, and ownership-based control, and (3) sufficient recycling capacity to process batteries after their first and second life. A value of 1 represents a fully developed enabling environment in which EV market share has reached 100%, battery owners operate as service providers offering complementary services, and recycling capacity is sufficient to process all end-of-life batteries. Under these conditions, complementary infrastructure and organisational support structures no longer constrain repurposing. The relevance of service-based arrangements is confirmed by the interviews. As one expert explains: "*Hopefully then if our plans are true and delivered upon, some of these products will eventually also come with second life batteries inside. So then we would repurpose and create some sort of new product that we would sell or offer as a service. The question of which parties to target for sales remains a question with many options … Very many companies are exploring this … I think no one has found the perfect business model yet. Compared to other battery energy storage systems, which are more standardised products made in high volumes and come with pretty standard terms and warranties, second-life systems are a bit more complex to take to the market… Regarding extended producer responsibility, we are relatively confident about the perceived safety risks of second life batteries. I do not see safety as the main concern, particularly if we retain ownership and monitor the batteries within our own systems."* (personal communication, 2025).

The building block is composed of three equally weighted indicators. These capture EV market development, service provision structures, and EoL recycling capacity.

The first indicator, *EV market share*, represents the penetration of electric vehicles in the total vehicle fleet. It is directly taken from the Circubat model and reflects the long-term potential supply of EV batteries. Due to long vehicle and battery lifetimes, current and future EV adoption strongly determine the timing and magnitude of end-of-life battery flows (Seika & Kubli., 2024).

The indicator *share of service providers in repurposing* represents the extent to which organisational collaboration between OEMs and repurposing firms functions as a complementary service structure. Within the Circubat model, service-based arrangements influence battery access, revenue sharing, and coordination along the value chain (Seika & Kubli., 2025). A higher share indicates a more developed organisational support system that enables repurposing to operate at scale.

The third indicator, *saturation of EoL EV battery recycling factories*, represents whether available recycling capacity is sufficient to process all batteries reaching the end of their first and second life. It is modelled as the ratio between recycling capacity and the total volume of batteries sent to recycling, capped at unity to reflect a capacity-constrained system. A small positive constant is included in the denominator to prevent division by zero and ensure numerical stability, without affecting the conceptual interpretation of the indicator:

$$\text{Recycling saturation} = \min\left(1, \frac{\text{Recycling capacity}}{\max\left(V_{\text{recycling, first life}} + V_{\text{recycling, second life}}, 10^{-6}\right)}\right)$$

The volume of batteries sent to recycling after second-life use is calculated by converting second-life battery stocks into energy units using the average EV battery energy density and the remaining capacity at the second end-of-life stage:

$$V_{\text{recycling, second life}} = \frac{\text{Second-life batteries sent to recycling}}{\text{Average energy density}_{\text{EV}} \times \text{Capacity fraction at second EoL}}$$

Similarly, the volume of batteries reaching recycling directly after first life is defined as:

$$V_{\text{recycling, first life}} = \frac{\text{Batteries ready for recycling}}{\text{Average energy density}_{\text{EV}} \times \text{Capacity fraction at EoL}}$$

The average EV battery energy density is modelled as a weighted average of lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) batteries, accounting for time-dependent substitution between chemistries:

$$\text{Average energy density}_{\text{EV}} = (\rho_{\text{LFP}} \cdot (1 - s_{\text{NMC}})) + (\rho_{\text{NMC}} \cdot s_{\text{NMC}})$$

where s_{NMC}represents the time-corrected substitution intensity between NMC and LFP batteries. When recycling saturation equals 1, all end-of-life batteries can be processed within existing recycling capacity. If incoming volumes exceed capacity, the indicator immediately declines, reflecting a modelling assumption that recycling infrastructure becomes a binding constraint once capacity is exceeded.

3.5.2.3 Building block: innovation-specific institutions

innovation-specific institutions are defined as the formal and informal rules that explicitly govern the development and diffusion of a specific technology (Ortt & Kamp, 2022). In the context of EV battery repurposing, this building block represents the extent to which policy instruments provide regulatory certainty and economic incentives that enable repurposing to develop and scale. A value of 1 indicates a fully developed institutional environment in which three policy instruments are implemented simultaneously: ambitious battery collection targets, maximum consumer-side subsidies for repurposing, and active repurposing mandates. The expert interviews further provided insights into potential future regulatory developments, particularly the introduction of repurposing mandates for batteries above a minimum state-of-health threshold. Although such mandates are not currently in place, industry experts identified them as a plausible instrument within the broader context of EU climate governance. As one expert explained: *"Another way could be that more regulation comes in that sort of demands circular solutions. So, for example, if every customer of a battery energy storage system were kind of forced or encouraged to pick the battery energy storage system that comes with* *the lowest embedded carbon footprint, second life would come out really well. Or it could be mandated by the EU, for example, saying that if you have a vehicle battery that returns for some reason and it meets certain quality standards, you have to reuse it before it's recycled. I mean, you could force it as well. If circular merit is really important to you, it could be enforced. And then of course you would do this anyway because you have to. But on pure economic metrics, it's starting to look difficult."* (personal communication, 2025).

In the model, innovation-specific institutions are therefore operationalised as a composite of three equally weighted policy indicators, reflecting both current instruments and the potential strengthening of circularity-oriented regulation.

The first policy; *subsidy for repurposing* indicator captures the level of consumer-side financial support for repurposed batteries. It is modelled as:

$$\text{Subsidy indicator} = \frac{\text{Subsidy active} \times \text{Level of subsidies for consumers}}{\text{Maximum subsidy level}}$$

Subsidies for EV battery repurposing are capped at 60% of total costs. This reflects realistic policy practice, as full subsidisation is rarely implemented due to risks of market distortion and long-term dependency (Wu et al., 2024).). his formulation reflects the assumption that subsidies support market formation by lowering adoption costs and improving the competitiveness of repurposed batteries relative to new batteries.

The second policy; *battery collection targets* indicator represents the ambition of mandatory battery collection requirements introduced under the EU Battery Regulation. It is defined as:

$$\text{Collection target indicator} = \frac{\text{Mandatory collection targets}}{\text{Maximum collection rate}}$$

Mandatory collection targets follow an exogenous time-dependent lookup function reflecting the phased tightening of EU requirements under Regulation (EU) 2023/1542. While the Regulation aims to ensure that batteries are handled in a circular manner, the maximum binding collection target reaches 73% for portable batteries. This implies that a substantial share of batteries may remain outside formal collection streams. Because Member States are allowed to implement more ambitious national targets, the model includes the possibility of increasing collection rates up to a theoretical maximum of 100%. This allows assessment of how stronger national ambition could enhance feedstock availability for repurposing and strengthen innovation-system development.

3.5.2.4 Policy 3: Repurposing mandates

The *repurposing mandates* indicator captures whether regulatory rules explicitly require batteries above a minimum state-of-health threshold to be repurposed rather than directly recycled. It is modelled as a binary variable that is endogenously activated based on political pressure. Following the approach of Massop (2024), the mandate becomes active once average lobby power exceeds the pressure threshold required for policy implementation and remains inactive otherwise. Formally, this is represented as:

$$\text{Repurposing mandate} = Delay\ fixed \begin{cases} 1, & \text{if Average lobby power} \geq \text{Pressure needed to implement mandates} \\ 0, & \text{otherwise} \end{cases}$$

This logic is implemented using an IF THEN ELSE structure and includes a time delay to represent legislative and implementation processes (Massop, 2024).

The *Average lobby power* represents the political pressure exerted by the innovation system and is defined as:

$$\text{Average lobby power} = \frac{\text{Perceived legitimacy of the TIS} + \text{Repurposing entrepreneurial activity index}}{2}$$

This formulation assumes that both social legitimacy and observable economic activity are jointly required to trigger institutional change, following Massop (2024).

The *repurposing entrepreneurial activity index* is proxied by the relative scale of repurposing activity and is calculated as, and chosen on volumes instead of saturation. This is different from Massop (2024) approach. In the context of EV battery repurposing, saturation primarily reflects the short-term balance between available processing capacity and incoming battery volumes. However, this balance is not a reliable proxy for entrepreneurial activity in this system. The supply of end-of-life batteries is largely exogenous to repurposing demand and is driven by historical EV adoption patterns and battery lifetimes rather than by current market uptake of repurposed batteries. This results in pronounced and predictable waves of battery retirements that can temporarily exceed processing capacity, irrespective of the underlying level of entrepreneurial engagement. At the same time, capacity cannot be reduced quickly in response to periods of lower inflows. As a result, saturation largely reflects structural timing mismatches between supply and capacity rather than the intensity of entrepreneurial activity, making it unsuitable for representing entrepreneurial dynamics in EV battery repurposing systems. This following approach was used :

$$\text{Entrepreneurial activity index} = \frac{\text{Supply of repurposed batteries}}{\text{Maximum volume of batteries suitable for repurposing}}$$

This ratio captures how close actual repurposing activity, measured in terms of supplied battery volumes, is to its technical potential, defined as the maximum volume of batteries suitable for repurposing, taking into account that only a share of end-of-life batteries meets the state-of-health requirements for second-life use. The maximum supply of entrepreneurial activity is set equal to the projected volume of end-of-life batteries in 2050 (kWh/year). This is considered a reasonable upper bound, as vehicle markets in the Netherlands and Sweden are already mature and exhibit relatively stable annual sales patterns (Statistikdatabasen, n.d.; RVO., 2025). Assuming that policy targets are achieved and all new vehicles sold from 2030 onwards are electric (Rijksoverheid, n.d.; Morfeldt et al., 2021), the annual volume of end-of-life EV batteries stabilises by mid-century. Consequently, the battery outflow in 2050 can be used as a proxy for the long-term maximum technical potential for repurposing.

The *maximum potential supply of batteries suitable for repurposing* is calculated as:

$$\begin{aligned}
&\text{Max repurposing supply}\\
&\qquad = \text{Battery capacity per EV (time-corrected)}\\
&\qquad \times \text{Percentage battery capacity at end-of-life}\\
&\qquad \times \text{Share of batteries with high state-of-health}\\
&\qquad \times \begin{cases}\text{Swedish max repurposing supply}, & \text{if Swedish case}\\ \text{Dutch max repurposing supply}, & \text{if Dutch case}\end{cases}
\end{aligned}$$

This IF THEN ELSE formulation allows the model to represent country-specific constraints on repurposing potential.

3.5.2.5 Building block: product performance and quality

Product performance and quality refer to the extent to which repurposed EV batteries can deliver a competitive alternative to incumbent battery solutions, particularly new batteries (Ortt & Kamp, 2022). In this model, a product performance value of 1 represents a fully developed state in which repurposed batteries are competitive in terms of both cost per kWh and usable lifetime, and in which accumulated technological knowledge ensures consistent and reliable performance. Expert interviews, emphasised that competitiveness is currently assessed primarily in terms of battery lifetime duration and cost metrics. As one respondent explained: "*So the problem is that when a customer buys a fully optimised new system, they receive a very long warranty, something like 10 or 15 years. I don't see anyone willing to take the risk of offering that type of warranty on a second-life system. So the commercial competitiveness today is challenging, mainly because the price of new systems, the competing technology, so to say, has fallen so much. Technically, it is straightforward to implement second life. I would say we can demonstrate environmental benefits, but in terms of actual cost per cycle, or however a customer prefers to measure productivity, it is still difficult to compete with new, purpose-built technologies."* (personal communication, 2025)

The product performance / quality building block is operationalised as a composite of 3 indicators that capture competitive performance reflected in cost and lifespan and knowledge-driven quality improvements.

The first indicator, *effect of knowledge on product performance*, represents how technological learning improves the consistency and reliability of repurposed battery products. It is modelled as a lookup function based on the interaction between technological knowledge development and diffusion, based on Massop (2024):

$$\begin{aligned}&\text{Effect of knowledge on product performance}\\&\qquad\qquad = f(\text{Technological knowledge developed} \times \text{Technological knowledge diffused})\end{aligned}$$

This indicator captures the idea that knowledge only improves product performance when it is both generated and effectively diffused across firms and practitioners. The S-shaped formulation reflects early learning constraints and diminishing returns at higher knowledge levels (Walrave & Raven, 2016; Massop, 2024). Importantly, this effect improves quality consistency rather than directly reducing costs, thereby avoiding double counting with cost trajectories (Braco et al., 2022; Tang et al., 2025).

The second indicator, *cost competition*, captures the relative cost competitiveness of repurposed batteries compared to recycling on a cost-per-kWh basis, using cost variables derived from the Circubat model. It is modelled using an IF THEN ELSE formulation that assigns full competitiveness when repurposing costs are lower than or equal to recycling costs and otherwise declines linearly with the relative cost disadvantage:

$$\text{Cost competition} = \begin{cases} 1, & \text{if } C_{\text{repurpose}} \leq C_{\text{recycle}} \\ \max\ , \left(0,\ 1 - \dfrac{C_{\text{repurpose}} - C_{\text{recycle}}}{\max\left(10^{-6}, C_{\text{recycle}}\right)}\right), & \text{otherwise} \end{cases}$$

This formulation captures the idea that repurposing becomes fully competitive once it is no more expensive than recycling, while progressively losing competitiveness as the cost gap increases. A small constant in the denominator ensures numerical stability without affecting the conceptual meaning of the indicator.

The third indicator, *lifespan competition*, captures whether repurposed batteries can deliver a usable lifetime comparable to that of new batteries. It is defined as the ratio between the average lifespan of repurposed batteries, calculated as the mean lifespan across home storage and stationary applications, and the average lifetime of new batteries.

$$\text{Lifespan competition} = \frac{\text{Average lifespan of repurposed batteries}}{\text{Average lifetime of new batteries}}$$

3.5.2.6 Building block: network formation & coordination.

Network formation and coordination capture the extent to which relevant actors form stable linkages and coordinate activities across the EV battery repurposing value chain (Ortt & Kamp, 2022). For EV battery repurposing, coordination is crucial because batteries, ownership responsibilities, technical assessment, and market uptake are distributed across organisations. Interviews addressed that uncertainty in the market regarding policies and other market actor strategies influence their decisions. The interviews illustrate how strategic interdependence and external volatility complicate coordination. One respondent emphasised the role of political uncertainty:

"And then, of course, there is the political factor, which we have not yet discussed. At the moment, politics is moving towards protectionism, for example by imposing additional tariffs on batteries or cells imported from China. That again becomes a determining factor in the equation: is it cheaper to import LFP batteries from China, or is it more attractive to reuse a battery pack in Europe for a second life? One moment there might be a 25% tariff, and then perhaps 50% on LFP specifically. That makes it a fairly unpredictable factor that also plays a role here .. It is extremely difficult to make reliable predictions… the situation is simply too dynamic, and there are too many moving elements globally to make firm statements." (personal communication, 2025).

Another participant highlighted technological and supply-chain complexity:

"We expect a shift in battery chemistry, possibly towards solid-state cells, but given the massive investments across the entire supply chain … from mining to end-of-life … existing technologies will remain in use for a long time. This means multiple battery generations will coexist, and we will need to continue sourcing and supporting older battery packs for years to come. That complexity will only increase over time." (personal communication, 2025).

In this model, a value of 1 represents a fully developed state in which actor networks are well established, coordination routines are stabilised, and interactions across the chain no longer constitute a bottleneck for scaling repurposing activities.

Following the logic of TIS functions and the modelling approach of Massop (2024), network growth is driven by entrepreneurial activity and perceived legitimacy, while being delayed by the time required to build stable relationships.

The first indicator, the *repurposing entrepreneurial activity index*, represents the extent to which active repurposing initiatives create repeated interactions among actors. The formulation of this indicator is identical to that used in the innovation-specific institutions building block.

The second indicator, *perceived legitimacy of the TIS*, captures the extent to which EV battery repurposing is regarded as a credible, acceptable, and desirable activity by relevant stakeholders. Higher perceived legitimacy increases new networks by reducing uncertainty, increasing willingness to start entrepreneurship, and supporting shared interpretations of technical and market feasibility (Suurs, 2009; Walrave & Raven, 2016).

3.6 Model validation (Conclusion)

In line with Auping et al. (2024), the validation of the merged system dynamics model followed four complementary tests: (1) structure verification, (2) behaviour reproduction, (3) extreme-conditions testing, and (4) sensitivity analysis. In addition, technical verification was conducted in Vensim Pro 10.4.0, including a dimensional unit-consistency check to eliminate equation-level errors and a numerical robustness check using a fixed simulation time step of 0.01 years. This relatively small time step was selected to ensure numerical stability in the presence of nonlinear feedbacks and delay structures. Together, these tests assess whether the model is fit for its intended purpose: analysing formative-phase dynamics in national EV battery repurposing systems. Detailed results are provided in Appendix C.

3.6.1 Structure verification conclusion

The structure-verification test assessed whether the model's causal structure, feedback loops, and functional forms provide a plausible representation of EV battery repurposing system development. The overarching CircuBAT architecture and the links between TIS functions and building blocks were adopted from previously validated research (Seika & Kubli, 2026; Massop, 2024). The validation therefore focused primarily on the operationalisation of the TIS building blocks and their interactions.

All causal relationships, nonlinearities, and growth formulations were systematically evaluated against theoretical and empirical literature, as well as insights from expert interviews. The use of S-shaped growth dynamics for selected interactions is consistent with established innovation system theory and technological diffusion literature. The assumption of a shared causal structure for the Netherlands and Sweden strengthens internal validity and cross-case comparability, although it abstracts from structural national differences such as spatial or labour constraints.

Overall, the model structure does not contradict established theoretical knowledge and is considered structurally valid for analysing formative-phase innovation dynamics.

3.6.2 Behaviour reproduction

A behaviour-reproduction test examined whether the model plausibly reproduces observed system behaviour, particularly early-stage repurposing volumes. For the Netherlands, simulated 2023 repurposing volumes (13.06 MWh/year) were compared to an empirical estimate of approximately 11 MWh/year derived from national reuse data. Given uncertainties in chemistry composition, conversion efficiencies, and reporting boundaries, the simulated value is of the same order of magnitude as observed data. This suggests that early-stage system behaviour is reproduced plausibly.

For Sweden, confidentiality restrictions prevented quantitative validation (Statistikdatabasen, n.d.-c). As Bala et al. (2017) argue, behaviour-reproduction tests in system dynamics should prioritise the replication of realistic dynamic patterns rather than exact numerical correspondence. However, the absence of longitudinal and country-specific data on EV battery repurposing constrains the robustness of empirical validation, as key behavioural patterns cannot be systematically tested against observed developments.

3.6.3 Extreme-Conditions Test conclusion

A behavioural extreme-conditions test was conducted to assess logical robustness under boundary parameter values. Each parameter was varied independently to isolate its effect. Because both national cases share identical feedback architecture, testing was performed using the Dutch parameter set; structural inconsistencies would emerge irrespective of calibration.

Under all tested extreme conditions, the model produced bounded and logically consistent behaviour. No unintended oscillations, sign reversals, or structural breakdowns occurred. This indicates internal coherence of the feedback structure under boundary scenarios.

3.6.4 Sensitivity Analysis conclusion

A sensitivity analysis assessed robustness to small but plausible parameter variations (±10%). For most parameters, behavioural patterns and structural conclusions remained unchanged, indicating stable feedback dynamics. The aggregated TIS building blocks indicator served as the primary KPI for assessing system development.

Sensitivity was primarily observed for parameters directly related to battery performance and lifespan assumptions. Changes in the average lifetime of repurposed home storage batteries affect the *product performance and quality* building block and indirectly influence the *product system* building block through altered demand expectations and capacity expansion decisions. This propagates through entrepreneurial activity and network formation via feedback loops.

Similarly, variations in end-of-life battery capacity affect the technically suitable supply volume, directly influencing entrepreneurial activity and indirectly affecting network coordination. While these parameters influence the magnitude and timing of outcomes, they do not alter the fundamental feedback structure or behavioural modes.

In line with Auping's distinction, these results indicate behavioural robustness of the model structure under plausible parameter variation. The feedback architecture remains intact, while performance and lifespan assumptions emerge as influential parameters in shaping the magnitude and timing of diffusion outcomes.

3.6.5 Overall model validation conclusion

Overall, the validation tests indicate that the model is fit for its intended purpose of analysing formative-phase diffusion dynamics in national EV battery repurposing systems. The model structure is theoretically grounded and internally consistent, and behaviour remains stable under extreme-condition and sensitivity testing. However, empirical validation of simulated repurposed battery supply is limited by the lack of longitudinal and country-specific data, particularly for Sweden. The findings should therefore be interpreted as structurally informed diffusion trajectories rather than precise quantitative forecasts. The next section first outlines the model use and experimental setup, after which the simulation results for the Netherlands and Sweden are presented in chapter 4.

3.7 Model use and experimental setup

The model was used to address sub-research question 2, which examined how the innovation system development of repurposed EV batteries differ between the Netherlands and Sweden, and sub-research question 3, which analysed how regulatory policies influence the diffused volumes of repurposed EV batteries.

First, the base settings of the model are described. Section 3.7.1 explains the selected baseline configurations to ensure transparency and comparability between the two countries. The Circubat model, which is connected to the merged system dynamics model, was originally developed to test circular battery strategies (Seika & Kubli, 2025). To enable a consistent comparison between the Netherlands and Sweden, all base assumptions and parameter settings are explicitly documented.

Section 3.7.2 presents the experimental design. It first introduces the scenarios that capture uncertainty in the future development of the repurposed EV battery market. Subsequently, the policy interventions aimed at addressing problematic system behaviour are described. The rationale behind the scenario logic, model settings, and experimental setup is explained in this section, while the simulation results are presented in Chapter 4.

3.7.1 Base settings Circubat model

As mentioned earlier, the Circubat model evaluates alternative business and policy strategies, which are structured into four key strategic pillars: Collaboration, Demand, Price, and Regulation. The model results show that business viability in the EV battery repurposing market is strongly influenced by strategic choices across these pillars, as they shape profit margins, demand development, and investment behaviour (Seika & Kubli, 2025). Based on these findings, one strategy was selected for each pillar to define the base case configuration the justification for the strategy choices are described below, listed in Table 5. The justification for each selected strategy is described below. It is important to note that these strategic choices directly influence the model outcomes.

Within the collaboration pillar, independent battery ownership was selected. Seika & Kubli (2025) show that acting solely as a service provider to OEMs results in lower profitability, as firms capture less value and depend on OEM-controlled battery flows. Independent ownership enables firms to capture revenues across the repurposing chain and improves long-term profitability.

Within the demand pillar, offering second-use batteries with warranties to consumers was selected, as the results of Seika & Kubli (2025) revealed that this is a strategy that does well over the long term.

Within the pricing pillar, cost-oriented pricing is applied. Although this strategy results in lower profit margins compared to demand-oriented pricing, it increases demand by maintaining lower selling prices (Seika & Kubli, 2025). Given that this report primarily analyses diffusion volumes, this approach was adopted.

Finally, within the regulation pillar, lobbying for price subsidies to consumers was included. The results showed that subsidies increase demand and profitability by lowering adoption barriers. The subsidy level can be varied within the model, allowing alignment with country-specific policy conditions.

For Sub-question 2, the model is simulated under a base-case scenario that reflects the continuation of current trends, without introducing additional policy interventions beyond those already implemented. This base case enables a direct comparison of diffusion trajectories between the Netherlands and Sweden and allows analysis of how feedback loops respond to national contextual differences. Differences in diffusion patterns are assessed through the evolution of the technological innovation system.

Table 5: Base strategy settings from the Circubat model.

Pillar	Selected strategy
Collaboration	Acting independently as battery owners
Demand	Offering second-use batteries with warranties to consumers
Pricing	Applying cost-oriented pricing
Regulation	Lobbying for price subsidies to consumers

3.7.2 Scenario development

Scenario development was applied for sub-question 3 to explicitly address uncertainty in the future diffusion of repurposed EV batteries in the Netherlands and Sweden. In line with Auping (Section 8.4), the scenarios serve two purposes: 1) to explore how system behaviour may plausibly evolve under uncertainty, and 2) to test the robustness of policy interventions across different possible futures. Given the long time horizon and strong dependence on technological, market, and policy developments, a single deterministic projection would not adequately reflect the range of plausible system outcomes.

National contextual factors in Table 3 were assessed to identify key uncertainties for scenario development. As a result, subsidies were excluded because they were modelled as policy interventions. Moreover, recycling capacity was treated as certain, as current capacities are well documented. All remaining parameters; passenger car vehicle adoption, EV market share home storage battery sales and export shares were incorporated as uncertainties in the scenario design. Historical data shows that passenger car markets are sensitive to external shocks. For example, vehicle adoption declined during the COVID-19 pandemic, demonstrating that future adoption pathways may deviate from baseline expectations (Yan et al., 2022). Export levels of used EVs are also uncertain. Export patterns may differ from those of conventional vehicles and depend on infrastructure readiness, regulatory enforcement, warranty conditions and recycling capacity in importing countries (Olguín et al., 2025). In addition, national policy ambitions strongly influence EV market share. However, it remains uncertain whether the EV adoption targets will be fully achieved (Paradies et al., 2023). Furthermore, the need for stationary battery storage depends on grid development, the extent of congestion, and the degree of European electricity market integration (Sultana, 2018; Gomez et al., 2019). Increased cross-border electricity trade may reduce the need for local battery-based flexibility, while delayed grid expansion and rising congestion may increase demand for decentralized storage solutions. These developments are driven by policy decisions, infrastructure investments, and electricity market design, and are therefore inherently uncertain.

These four uncertain parameters were grouped into two key scenario axes: a supply axis (high versus low EoL EV battery supply) and a demand axis (high versus low demand for batteries), shown in Figure 6. These axes form a scenario logic that captures different but plausible future developments. In addition, a base case reflecting current expectations was included.

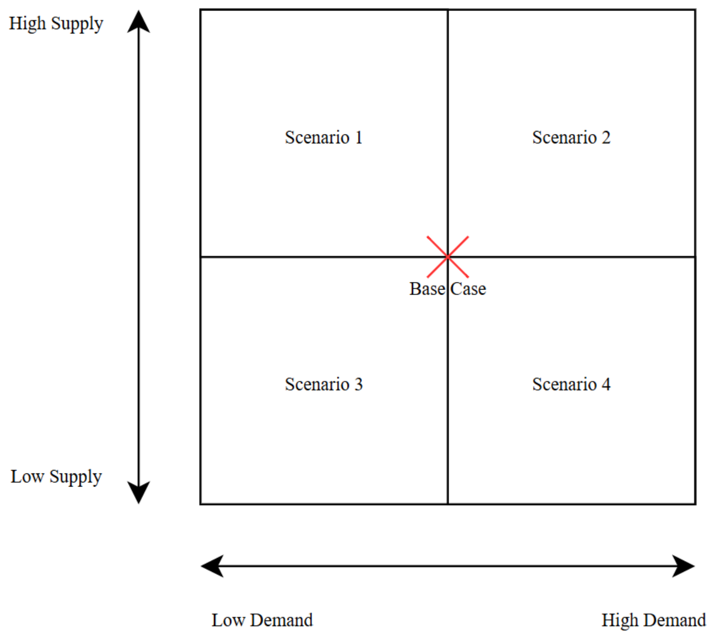


Figure 6: Scenario overview

Rather than testing each supply-side uncertainty individually, parameters were varied in internally consistent bundles, which is reflected in Table 6. Instead of performing univariate parameter tests for each supply parameter, this bundled approach captures the widest range of developments.

Table 6: Scenario design

Scenario	Supply settings	Demand settings
Base Case	Baseline assumptions for EV adoption, EV market share development, and EV export remain unchanged.	Baseline assumptions for home storage battery sales remain unchanged.
1	**EV supply increases** due to 20% higher car adoption, EV market share reaching saturation two years earlier, and 20% lower EV exports	**Home storage battery sales decrease** by 20% reflecting lower demand for stationary storage applications.
2	**EV supply increases** due to 20% higher car adoption, EV market share reaching saturation two years earlier, and 20% lower EV exports	**Home storage battery sales increase** by 20% reflecting higher demand for stationary storage applications.
3	**EV supply decreases** due to 20% lower car adoption, EV market share reaching saturation two years later, and 20% higher EV exports.	**Home storage battery sales decrease** by 20% reflecting lower demand for stationary storage applications.
4	**EV supply decreases** due to 20% lower car adoption, EV market share reaching saturation two years later, and 20% higher EV exports.	**Home storage battery sales increase** by 20% reflecting higher demand for stationary storage applications.

Furthermore, Table 6 presents the scenario design, where all percentages changes represent relative deviations from the respective country-specific base case. The experimental design consisted of five scenarios, including one base case and four alternative scenarios. Note that the 20% changes are applied only from 2026 onwards, reflecting that historical patterns remain unchanged. As the scenarios support answering sub-research question 3 on diffusion volumes, the key performance indicators are total demand and supplied repurposed batteries. The values for the adjusted parameters for each scenario are listed in Appendix B.

For the scenario analysis, the model was run five times over a simulation time horizon of 40 years (2010–2050). All simulations were performed using Vensim Pro version 10.4.0 on a Windows computer. The time step is 0.01 years and the integration type is Euler. Euler integration was selected as the numerical integration method. This method assumes that flow rates remain constant within each time step, allowing stock variables to be updated directly based on net inflows and outflows. Although this assumption introduces some approximation error, Euler integration is widely used in system dynamics due to its transparency, stability, and consistency with discrete-time simulation. As the objective of this study is to analyse structural system behaviour, compare scenarios, and assess policy robustness rather than to achieve precise short-term numerical accuracy, Euler integration provides an appropriate and sufficient level of precision.

Figures 7 to 10 present the scenario results for both case studies, showing the development of demand and supply under the base case and four alternative scenarios. The scales differ between the Netherlands and Sweden to improve readability. Across both countries, Scenario 3 consistently results in the lowest diffusion volumes, while Scenario 2 produces the highest. The demand figures follow the same ranking in both countries: Scenario 2, Scenario 4, the base case, Scenario 1, and Scenario 3. This ordering reflects the underlying scenario assumptions, which combine higher and lower supply and demand conditions. However, the supply results reveal a structural difference between the two countries. In the Netherlands, supply in Scenario 4 remains close to the low levels observed in Scenario 3 despite higher demand, indicating that the system is already operating near the upper limit of available end-of-life battery supply. This suggests that diffusion is constrained by physical availability rather than demand conditions. In contrast, Sweden shows a different pattern. Even when end-of-life battery availability is reduced, supply volumes can still increase when demand rises, as observed in Scenario 4. This indicates that the Swedish system has greater unused capacity and remains primarily demand-constrained rather than supply-constrained. Therefore it would be interesting to look at different type of policies increasing demand, supply through different mechanisms. To address these constraints and assess how policy can influence diffusion trajectories, section 3.7.3 introduces the policy interventions and the experimental setup.

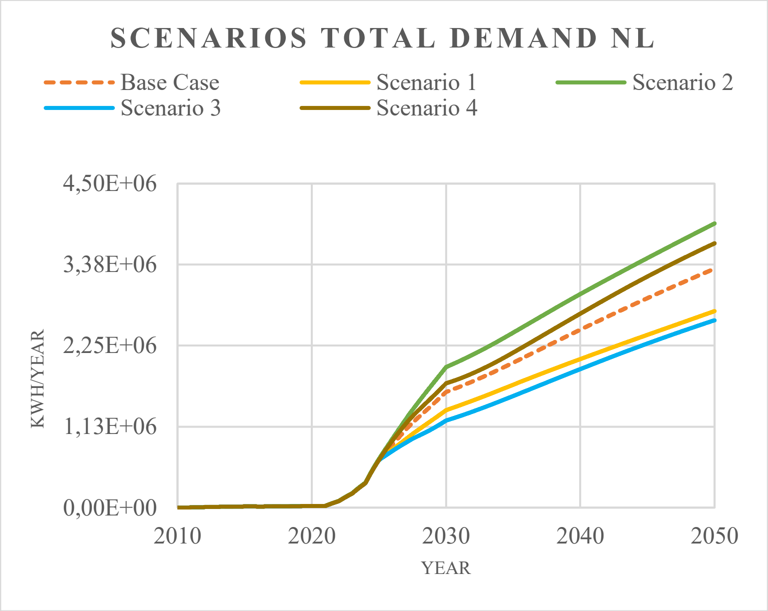


Figure 77: Scenarios total demand NL

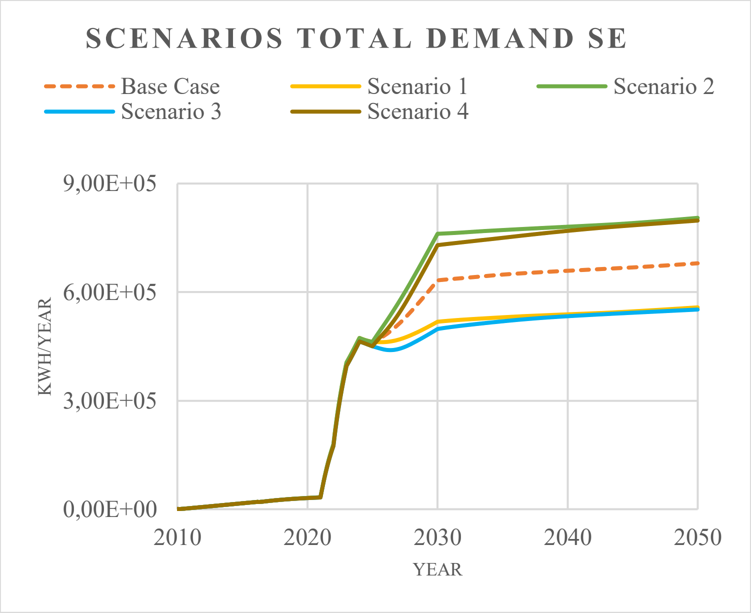


Figure 8: Scenarios total demand SE

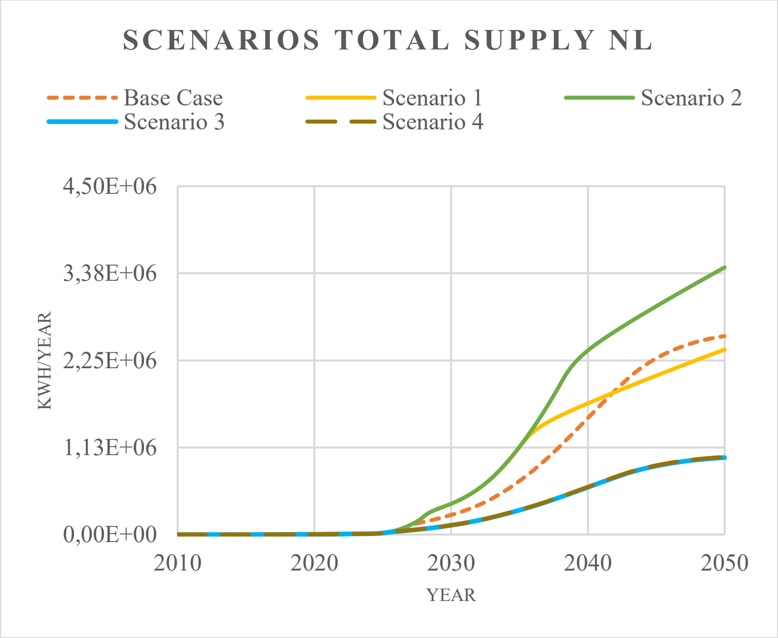


Figure 9: Scenario total supply EoL batteries NL

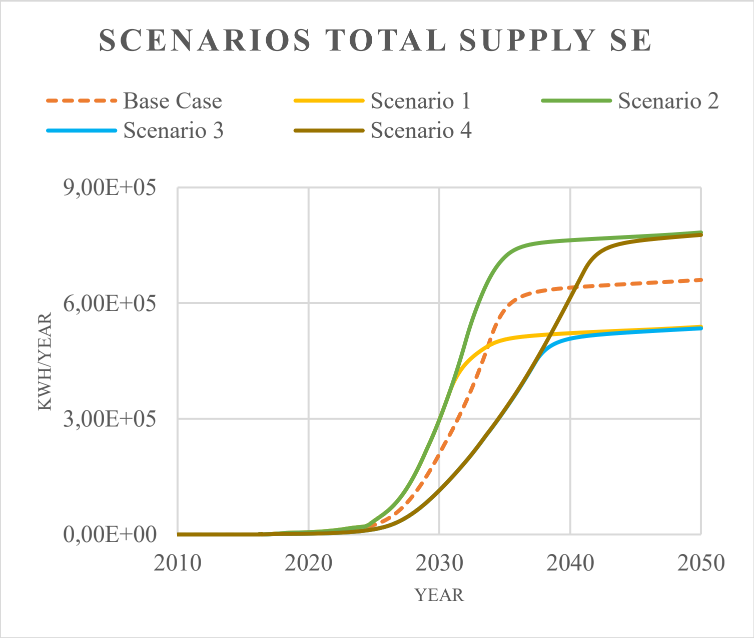


Figure 10: Scenarios total supply EoL batteries SE

3.7.3. Policy interventions

The scenario analysis revealed structural differences in how diffusion is constrained in the Netherlands and Sweden. In the Netherlands, diffusion appeared increasingly limited by the availability of end-of-life batteries, indicating supply-side constraints. In contrast, Sweden remained primarily demand-constrained, as higher demand translated into increased supply despite lower battery availability. These findings highlight that diffusion can be restricted by different mechanisms depending on national system conditions. Therefore, policy interventions were designed to target both demand-side and supply-side dynamics, as well as broader competitive conditions within the battery market.

The policy interventions tested are listed in Table 7. To design the experimental setup, the variables in the Circubat model were reviewed to identify parameters that can be influenced by the government, acting as the problem owner. Based on this assessment, three policy interventions were selected: providing consumer subsidies, offering demonstration funds to repurposing firms, and taxing new battery prices. Each intervention targets a different part of the system and influences distinct feedback mechanisms.

Consumer subsidies reduce the selling price of repurposed EV batteries, thereby lowering adoption barriers and increasing consumer demand (Gur et al., 2018). This intervention directly affects the balancing feedback loop in which lower selling prices stimulate customer demand (B2). Demonstration funds increase the financial resources available to repurposing firms, which can improve product performance (Iqbal et al., 2023). This intervention strengthens reinforcing feedback loops related to resource mobilisation and technology learning, where increased resources support knowledge development and improve market expectations (R3), and higher cumulative production reduces operational costs through learning effects (R5). Finally, taxing imported new battery prices increases the selling price of new stationary batteries, improving the relative price competitiveness of repurposed EV batteries. This intervention strengthens the reinforcing feedback loop (R12), in which increased adoption of repurposed batteries reduces the attractiveness and market share of new batteries, further reinforcing the diffusion of repurposed battery solutions.

Each policy intervention was tested separately across all scenarios, in addition to the no-policy baseline, to evaluate policy robustness. Policy robustness refers to the ability of a policy to remain effective under different plausible future conditions (Lempert et al., 2006). Following established robustness assessment approaches (Kwakkel et al., 2016), policies were evaluated based on whether the KPIs remain within acceptable ranges or improve under different scenarios. This resulted in 20 simulation experiments per country (5 scenarios × 4 policy configurations, including the baseline), and 40 experiments in total for the Netherlands and Sweden combined. Policy impacts were measured using the KPIs: the annual supply and demand of repurposed EV batteries (kWh/year), which indicate the diffusion of repurposed battery applications over time.

Policy interventions were implemented as relative changes to country-specific baseline conditions. This approach does not compare absolute policy costs or identical policy intensities between countries, but instead assesses the relative effectiveness of each intervention within its national context. This allows for analysing how differences in system structure influence the response to policy measures in the Netherlands and Sweden.

Table 7: Overview of policy interventions

Policy Interventions	Parameter description	Policy intervention
Consumer subsidies	Purchase price of low-quality batteries and initial selling price of new home storage batteries	Increase of 20% relative to the base case
Offering demonstration funds	Availability of public funding for demonstration projects supporting battery repurposing	ON (demonstration funds enabled)
Taxing new battery prices	Purchase price of low-quality batteries and initial selling price of new home storage batteries increases	Increase of 20% relative to the base case

Chapter 4: Result

This chapter presents the results of the analysis and addresses the three sub-research questions derived from the central research question: *How do the national contexts of the Netherlands and Sweden affect the diffusion of EV battery repurposing technology?* The results are structured in three parts. First, the key contextual conditions shaping the innovation system for circular battery solutions in both countries are examined. Second, the comparative diffusion patterns of repurposed EV batteries are analysed, linking observed developments in the TIS building blocks. Third, the impact of selected policies on diffusion volumes is evaluated through scenario analysis. Together, these results provide insight into how contextual factors and policy interventions influence the development and diffusion of EV battery repurposing in both national settings.

4.1 The innovation landscape for circular battery solutions in the Netherlands and Sweden

This section analyses the key contextual conditions that shape the development of the circular EV battery innovation system in the Netherlands and Sweden. To structure the comparison, the analysis distinguishes between supply conditions, demand conditions, and end-of-life treatment capacity. At the end of each subsection, a figure visualises the current state and projected future trends for both the Netherlands and Sweden, followed by a concluding paragraph.

4.1.1 Supply conditions

The current supply of EoL EV batteries suitable for repurposing is primarily shaped by historical EV adoption rather than current vehicle sales, reflecting the long time lag between vehicle deployment and battery end-of-life. The share of EV adoption is similar in the Netherlands and Sweden, with battery-electric vehicles accounting for approximately 34% of new registrations in the Netherlands and 35% in Sweden in 2024 (RVO, 2025; Statistikdatabasen, n.d.). However, absolute adoption volumes are higher in the Netherlands due to its larger passenger car market, resulting in a greater number of EVs entering the system (RVO, 2025; Statistikdatabasen, n.d.). Between 2010 and 2024, annual passenger vehicle sales remained relatively stable, although a slight declining trend is visible for both countries. It is assumed that this stabilisation continues until 2050, reflecting a saturated passenger car market (RVO, 2025; Statistikdatabasen, n.d.). Furthermore, both governments have committed to phasing out new petrol and diesel passenger cars by 2030 and to reach full electrification of new vehicle sales by 2030. While the EU-wide phase-out target is set for 2035, both countries have adopted more ambitious national targets of 2030 (Rijksoverheid, n.d.; Government of Sweden, 2019). Overall, this suggests that despite comparable electrification trends, the larger size of the Dutch vehicle market will result in structurally greater future availability of end-of-life EV batteries.

Figure 11 illustrates the projected availability of end-of-life EV batteries in both countries over time. The projections are based on historical passenger vehicle sales, EV adoption rates, and the time lag between vehicle deployment and battery end-of-life. The increasing trend until 2044 reflects the growing EV fleet, after this peak, volumes stabilise as vehicle sales remain constant and full electrification has been reached.

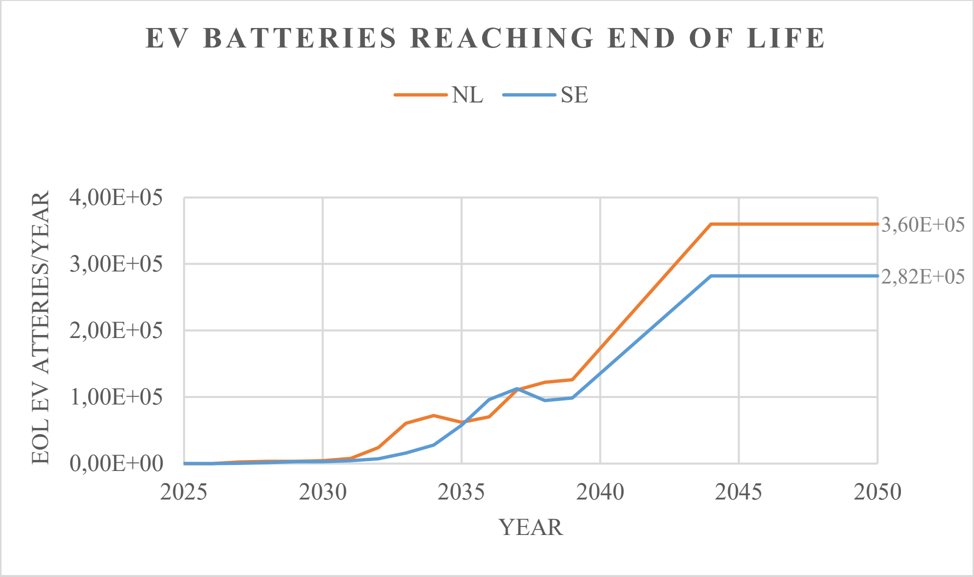


Figure 8: EV batteries reaching EoL for NL & SE

However, structural outflows further reduce domestic supply. Export shares of EoL vehicles and batteries are substantial in both countries but are higher in the Netherlands (approximately 0.62 percent) than in Sweden (around 0.56 percent) (CBS, n.d.; Trafikanalys, 2024). This indicates that for both countries more than halve of potentially repurposable EV batteries leave system, reducing domestic feedstock.

In conclusion, although the Netherlands is expected to generate higher absolute volumes of end-of-life EV batteries due to its larger vehicle market, higher export shares reduce the number of batteries available for domestic repurposing. In contrast, Sweden generates lower absolute volumes, but a larger share remains within the country. As a result, the effective domestic supply of batteries available for repurposing becomes more similar between the two countries.

4.1.2 Demand conditions

Demand-side conditions differ more clearly between the Netherlands and Sweden. In the Netherlands, demand for stationary battery storage has increased rapidly since 2021, particularly in the residential segment. This growth is driven by high solar PV penetration, increasing grid congestion, and rising needs for decentralised flexibility at the distribution level (Rijksoverheid, 2023; TenneT, 2025). In addition, the planned phase-out of the net metering scheme (salderingsregeling) in 2027 is expected to further stimulate residential battery adoption, as households with rooftop solar panels will face stronger incentives to increase self-consumption rather than feed excess electricity back into the grid (CE Delft & Witteveen + Bos, 2023). Residential battery sales reached approximately 834,000 kWh/year in 2025. Moreover, the Dutch electricity system is characterised by a rapidly growing share of renewable generation, with approximately 47–54% of electricity produced from wind and solar sources (IEAa, 2024). The variable nature of these generation technologies creates short-term balancing challenges, thereby increasing the need for flexible assets to help balance the grid. Approximately one-third of total installed battery capacity is allocated to the residential segment (Rijksoverheid, 2023). The total demand for batteries in kWh/year is calculated based on the home battery storage sales and the share of commercial batteries and is calculated to be 2.527.272 kWh/year for the Netherlands in 2025.

In contrast, Sweden's demand for residential battery storage remains lower and develops more gradually. The Swedish electricity system relies predominantly on stable baseload generation, with hydropower accounting for about 38% and nuclear power roughly 29% of overall electricity generation (IEAb, 2024). This reduces the need for decentralised flexibility. Furthermore, lower solar PV penetration and limited grid congestion further constrain household and commercial incentives to adopt battery systems. As a result, residential batteries represent a relatively small share of total installed flexibility capacity, at approximately 23% (Statistikdatabasen, n.d.-a; Svensk Solenergi, 2024). Residential battery demand reached around 290,000 kWh/year (Statistikdatabasen, n.d-a; Svensk Solenergi, 2024). Based on residential battery sales and the estimated share of commercial batteries, total battery demand in Sweden is projected to reach approximately 1,260,869 kWh/year in 2025.

Sweden partially compensates for weaker structural demand through stronger policy support, as subsidy levels for battery-related technologies are substantially higher (up to 48,5%) than in the Netherlands, where no direct residential battery subsidies are currently in place (Hammarstedt et al., 2025; Essent, 2025).

To assess how many repurposed batteries would be required to meet total stationary storage demand in both countries, Figure 12 compares the number of batteries needed with the projected domestic volumes of end-of-life EV batteries. Total battery demand (in kWh/year) is converted into the equivalent number of repurposed EV batteries required to meet this demand. This calculation accounts for technological improvements over time and adjusts for expected end-of-life battery capacities between 62 and 75 kWh, assuming a 72% remaining capacity in line with the Circubat model (Seika & Kubli, 2025). This translation represents a stylised calculation rather than a market forecast. The calculation does not account for consumer preferences, meaning that not all consumers will opt for a repurposed battery over a new one, nor does it consider that not all end-of-life EV batteries will be technically suitable for repurposing.

For the Netherlands, Figure 12 shows that projected domestic EoL EV battery volumes remain below the number of repurposed batteries required to meet stationary storage demand until approximately 2043. Due to the time lag between EV deployment and batteries reaching end of life, domestic EoL supply only reaches the level of total demand in the period 2043–2050. Showing that domestic end-of-life volumes are of a similar order of magnitude as total demand during this period, indicating that repurposing could constitute a substantial part of the solution. In Sweden, projected end-of-life EV battery volumes reach levels comparable to total demand already around 2034. Thereafter, EoL volumes increase substantially, further highlighting the demand-constrained nature of the innovation system.

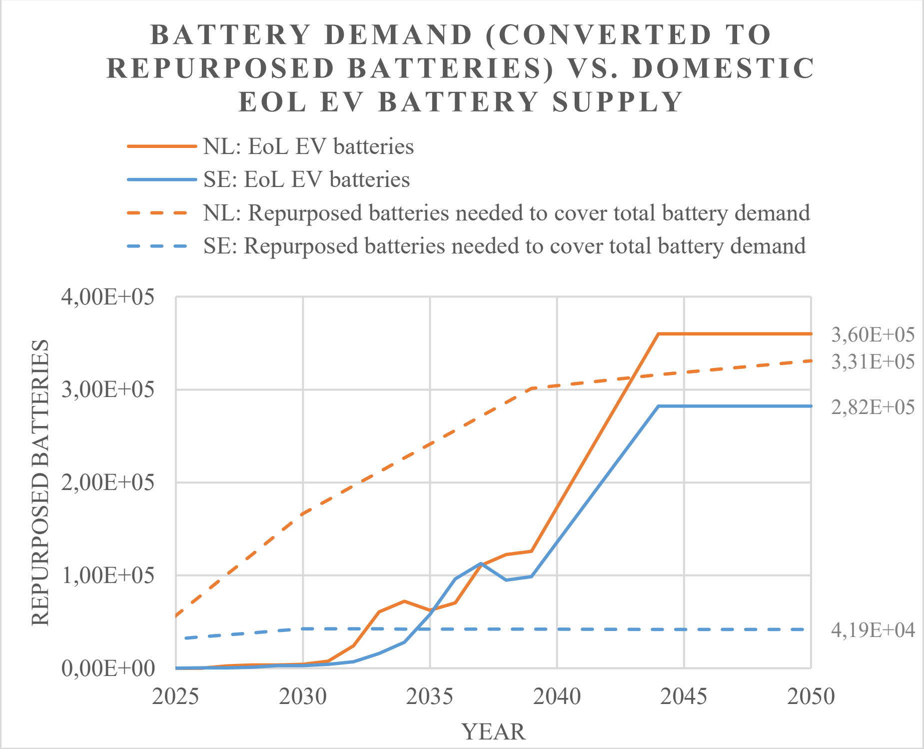


Figure 9: Repurposed batteries needed to meet battery demand vs. national EoL EV battery volumes excl. export

In conclusion, demand for stationary battery storage is significantly higher in the Netherlands than in Sweden. This difference is primarily driven by higher solar PV penetration, greater grid congestion, and stronger system needs for decentralised flexibility in the Dutch electricity system. In contrast, Sweden's stable baseload generation reduces the urgency for battery deployment, despite stronger financial support through subsidies.

4.1.3 Capacity conditions

End-of-life treatment capacity in both countries is currently dominated by recycling rather than repurposing. Dedicated repurposing capacity remains limited and has not progressed beyond pilot-scale initiatives (Stena Recycling, 2025; BuRO, 2025). This pattern aligns with Figure 11, which shows that end-of-life EV battery volumes remain low in the early years and only increase substantially between 2030 and 2035. At present, most EV batteries are still in use, and the majority of material entering the waste stream consists of production scrap rather than vehicle-derived batteries. While repurposing activities have limited use for production scrap, recycling processes can readily handle these flows, allowing the recycling market to establish viable business cases at an earlier stage (Gaines et al., 2023).

In the Netherlands, installed recycling capacity is currently estimated at approximately 10,000 tonnes per year, provided primarily by the SK Tes facility. Announced expansion plans indicate that total capacity could increase to around 20,000 tonnes per year (Dietert, 2025). Although the exact timeline for this expansion has not been formally confirmed, it is assumed in this analysis that additional capacity becomes operational around 2030.

In Sweden, recycling capacity is characterised by larger announced volumes. Prior to bankruptcy proceedings, the recycling capacity plans associated with Northvolt alone amounted to approximately 125,000 tonnes per year. These assets have since been acquired by Lyten (Lyten, 2025). However, the realisation of the originally announced expansion volumes has not yet been confirmed. In addition, Sweden hosts another recycling firm, Stena Recycling, with an estimated processing capacity of approximately 10,000 tonnes per year. This capacity is comparable to the current installed capacity of SK tes in the Netherlands (Dietert, 2025).

Figure 13 shows the gap between current and planned recycling capacity and the projected end-of-life EV battery volumes presented in Section 4.1.1. To express projected EoL battery volumes in tonnes per year, a conversion factor of 0.253 tonnes per battery was applied, based on battery weight data reported by Ellingsen et al. (2014).

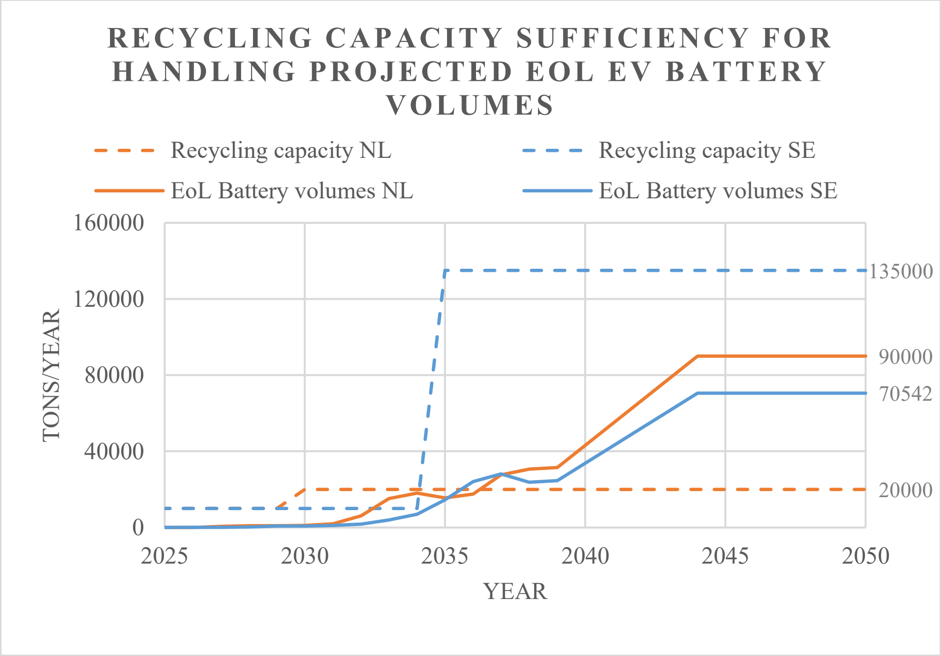


Figure 13: Capacity sufficiency for handling projected EoL battery volumes

In conclusion, recycling capacity developments differ substantially between the two countries. In Sweden, the announced recycling capacity associated with Northvolt, now acquired by Lyten, could reach approximately 125,000 tonnes per year. If realised, this capacity would significantly exceed the projected domestic end-of-life EV battery volumes, even when excluding exports. In contrast, the Netherlands currently has a recycling capacity of 10,000 tonnes per year, with planned expansion to 20,000 tonnes per year. Even with this expansion, projected end-of-life battery volumes are expected to exceed domestic recycling capacity over time. Even with this expansion, projected end-of-life battery volumes are expected to exceed domestic recycling capacity over time. This suggests that treatment capacity may become a structural bottleneck in the Netherlands if repurposing doesn't take off or when the recycling market is not stimulated, while Sweden is not expected to encounter structural constraints in circularly handling end-of-life EV batteries, assuming Lyten continues the planned expansion of Northvolt's facilities.

4.2 Comparative Diffusion Patterns of EV Battery Repurposing in the Netherlands and Sweden and Their Underlying Drivers

This subsection addresses Sub-research Question 2: *How do the diffusion patterns of EV battery repurposing differ between the Netherlands and Sweden, and what explains this diffusion behaviour?* The results presented here refer to the base case scenario, meaning that no additional policy interventions were included. The aim was to compare how the innovation system develops in both countries. To do so, the behaviour of each TIS building block was analysed and linked to the development of key indicators that support or constrain system development. The explanation is presented first, followed by figures 15-19 that illustrate the observed diffusion behaviour.

Three building blocks; network formation and coordination, product performance and quality, and complementary products and services, converge to similar end states in the Netherlands and Sweden by 2050.

For network formation and coordination, both countries reach the maximum score around 2030. Sweden reaches this level slightly earlier due to a steeper increase in perceived TIS legitimacy, but this early advantage does not affect the final outcome.

In product performance and quality, cost and lifespan competition are modelled as binary indicators that equal one when repurposed batteries match or outperform new batteries. This threshold is not met in either country throughout 2010–2050, resulting in a zero value for cost competition despite small cost differences. Lifespan competition is identical in both countries, as lifespan parameters are constant and independent of contextual factors. The contribution of knowledge development follows an S-shaped trajectory in both cases, reaching its maximum slightly earlier for Sweden.

The development of supporting products and services differs slightly between the Netherlands and Sweden in earlier years, but both countries reach similar levels by 2050. EV market shares evolve similarly, reflecting comparable historical trends and the shared policy objective of exclusively selling electric vehicles by 2030. The share of repurposing service providers remains zero in both countries, indicating insufficient institutional or market incentives. Recycling capacity is sufficient from 2022 onward, when the first EoL EV batteries become available, meaning both countries can process the combined volumes of first- and second-life batteries from that point forward.

Sweden performs better in innovation-specific institutions, driven primarily by policy differences. Battery collection targets develop similarly in both countries; however, Sweden introduces a substantial consumer subsidy in 2016, while the Netherlands does not. This policy intervention leads to a clear divergence in outcomes from that year onward. Neither country implements repurposing mandates, as low repurposing entrepreneurial activity limits lobbying power.

For the product system, both countries experience a decline after 2030, when scores are initially similar. The decline is steeper and occurs earlier in Sweden due to faster saturation of EoL EV battery repurposing. Sweden shows a pronounced decline after 2031, whereas the Netherlands declines later (around 2037) and more gradually. The efficiency factor exceeds two months in both countries, but this occurs one year earlier in the Netherlands (2028), indicating earlier system pressure alongside higher activity levels.

The repurposing entrepreneurial activity index diverges after 2032. While early developments are comparable, the index stagnates in Sweden but continues to grow in the Netherlands. This difference is mainly explained by capacity constraints, which limit the supply of repurposed batteries more strongly in Sweden.

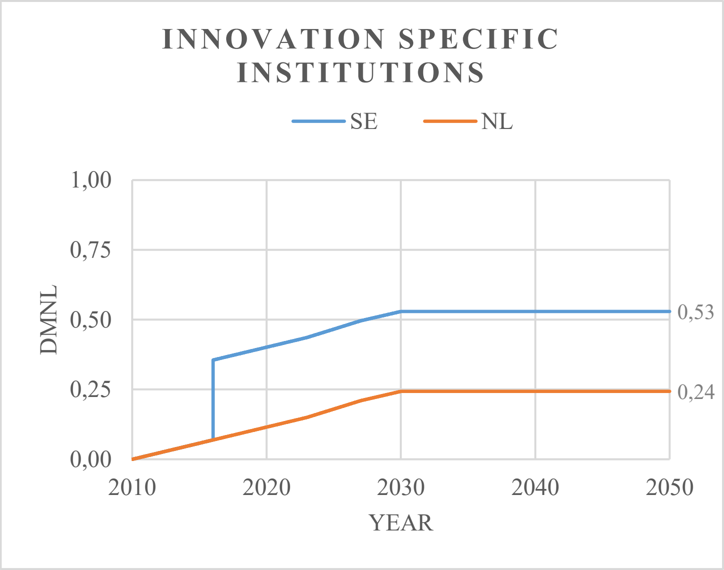


Figure 14: Results building block: innovation specific institutions

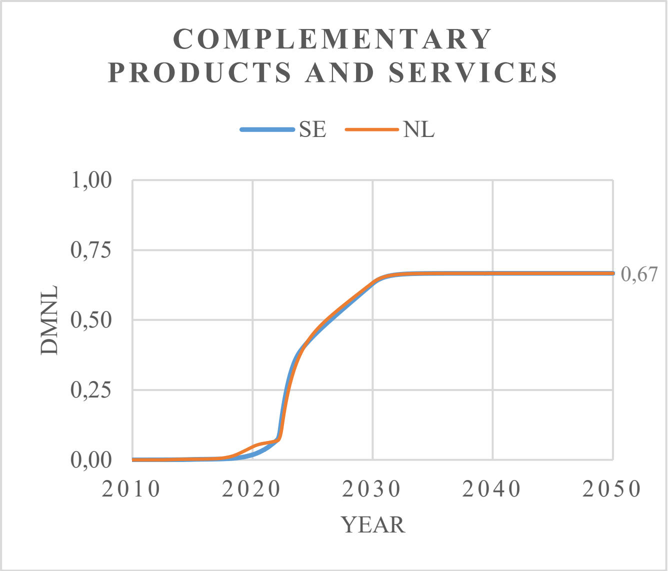


Figure 15: Results building block: complementary products and services

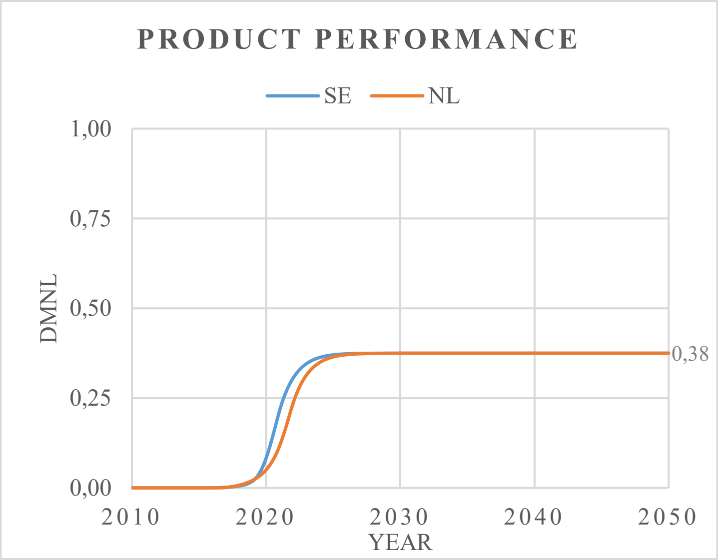


Figure 16: Results building block: product performance

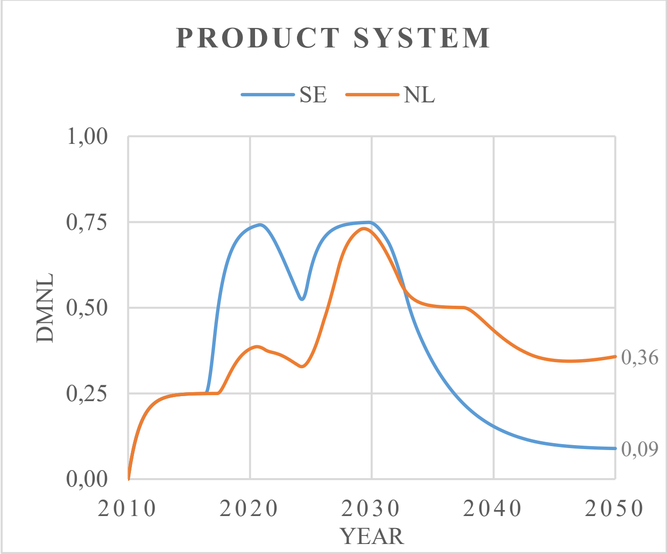


Figure 17: Results building block: product system

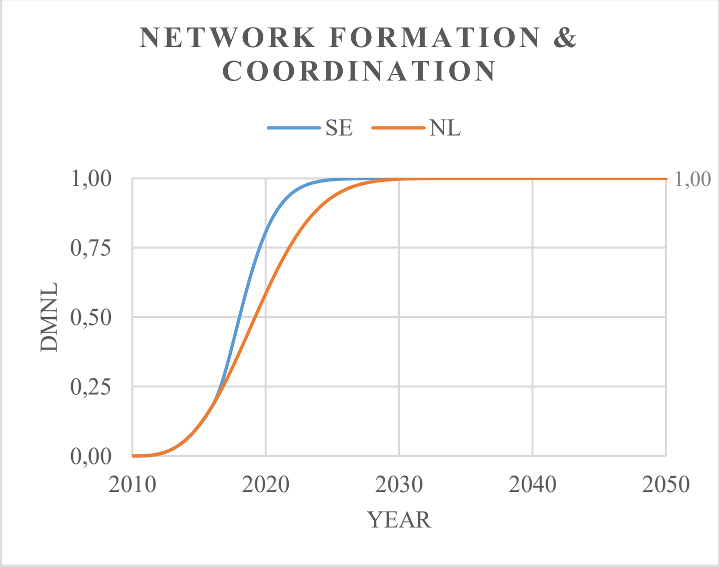


Figure 18: Results building block: network formation & coordination

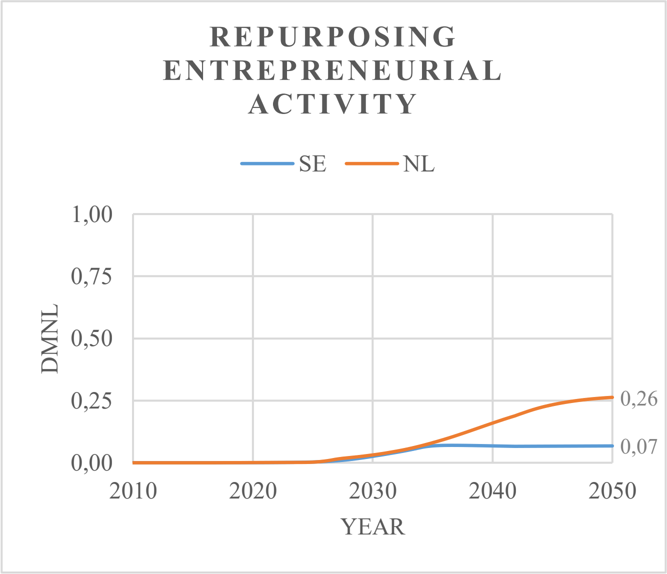


Figure 19: Results building block: repurposing entrepreneurial activity

To conclude, the results show that the innovation systems in both countries remain only partially developed under base case conditions. Network formation and coordination is the only fully developed building block in both countries, reaching the maximum level. Complementary products and services also show identical outcomes, reaching 0.68 in both the Netherlands and Sweden, indicating a similarly supportive ecosystem. Product performance and quality is also comparable, with both countries reaching values of 0.38, reflecting similar technological maturity. Clear differences emerge in innovation-specific institutions, where Sweden performs better with 0.53, compared to 0.24 in the Netherlands, reflecting stronger institutional support. In contrast, the Netherlands performs better in repurposing entrepreneurial activity (0.26 vs. below 0.1) and the product system (0.36 vs. below 0.1), although both remain weak. These results show that innovation-specific institutions, repurposing entrepreneurial activity, and the product system are most sensitive to contextual differences.

4.3. Impact of Regulatory Policies on the Diffusion Volumes of EV Battery Repurposing in the Netherlands and Sweden

This section addresses Sub-research Question 3: *How do regulatory policies impact EV battery repurposing in the Netherlands and Sweden?* Building on the scenario analysis, additional experiments were conducted to evaluate whether regulatory interventions can reduce system constraints and stimulate diffusion. Three policy measures were tested: consumer subsidies, demonstration funds for repurposing firms, and a tax on new battery prices. Each policy was implemented relative to country-specific baseline conditions, allowing for comparison within the national context. The results show how different regulatory approaches influence supply and demand dynamics and reveal which structural factors enable or constrain the scaling of EV battery repurposing in both countries.

In total, 40 experiments were conducted, generating results for two key performance indicators: total battery demand and the supply of repurposed batteries. To provide a clear overview and assess policy effectiveness and robustness, the results are first presented in Table 8. This table shows the relative changes in both indicators for each policy intervention compared to the base case. It also highlights the magnitude of policy effects under baseline conditions. Subsequently, Figures 20 and 24 present the median results of each policy intervention and the no-policy baseline across all scenarios, including the base case. These figures are shown separately for each country and include both key performance indicators. The median provides insight into policy robustness by showing how each intervention performs across a range of possible futures rather than under a single scenario.

Examining the relative changes under the tax on new batteries scenario in Table 8, both countries show an increase in demand, while the supply response differs. In the Netherlands, the supply of repurposed batteries increases by 0.18%, while total battery demand increases by 16.8%. For Sweden, supply increases by 18.12%, accompanied by a 17.64% increase in total demand. These outcomes are driven by the improved price competitiveness of repurposed batteries relative to new batteries. The tax increases the price of new batteries, making repurposed batteries more economically attractive and increasing demand in both countries. Higher demand strengthens the business case for repurposing and increases incentives to process more batteries. In Sweden, repurposing capacity has been a limiting factor due to limited investment, but the stronger demand signal encourages greater utilisation of existing capacity, resulting in a significant increase in supply. In contrast, supply in the Netherlands is constrained by the availability of end-of-life EV batteries suitable for repurposing. As a result, even though demand increases substantially, the limited availability of suitable batteries restricts further supply growth.

A similar dynamic is observed under the subsidy scenario (Table 8), although the magnitude of effects differs. In both the Netherlands and Sweden, subsidies increase demand and, to varying degrees, supply of repurposed batteries. In the Netherlands, supply rises by 0.19%, while total battery demand increases by 11.74%. In Sweden, supply expands more substantially by 13.88%, accompanied by a 10.58% increase in demand. As with the tax scenario, these effects are driven by improved price competitiveness of repurposed batteries, this time through a reduction in their selling price. The strengthened demand signal enhances investment incentives and capacity utilisation. However, the structural constraints remain unchanged: in Sweden, additional demand activates capacity expansion and results in a notable supply response, whereas in the Netherlands, feedstock availability continues to limit supply growth despite rising demand.

Looking at the relative changes under demonstration funding, clear differences emerge between the Netherlands and Sweden especially on the supply side. In the Netherlands, Table 8 shows that the supply of repurposed batteries increases by 7.33%, while in Sweden it decreases by 2.38%. At the same time, total battery demand declines in both countries, with a decrease of 5.11% in the Netherlands and 2.25% in Sweden. These outcomes are driven by how demonstration funding affects technological performance and system constraints. Demonstration funding increases the share of batteries with economic value for repurposing in both countries. In the Netherlands, this results in more batteries being classified as having high repurposing value, allowing repurposing supply to increase. In Sweden, however, repurposing capacity remains constrained, preventing additional suitable batteries from being processed. As a result the system is accumulating inventory rather than processing the EoL EV batteries more rapidly. Repurposing capacity does not expand in Sweden because investment decisions are driven by expected demand, which declines under the demonstration funding scenario. This decline in demand, which is observed for both countries, is caused by an increase in the purchase price of high-quality end-of-life batteries. Since the system applies a cost-oriented pricing strategy, higher input costs lead to higher selling prices for repurposed batteries. As selling prices increase, demand decreases, which in turn reduces incentives for capacity expansion and limits further growth in repurposing supply.

Table 8: Policy effectiveness base case results for Sweden and The Netherlands

Indicator	***Netherlands supply repurposed batteries in 2050[kWh/year]***	***Sweden supply repurposed batteries in 2050 [kWh/year]***	***Netherlands Total demand batteries in 2050 [kWh/year]***	***Sweden Total demand batteries in 2050 [kWh/year]***
Base case	*2.564.250*	*660.182*	*3.318.870*	*679.895*
Tax new batteries (+20%)	*2.568.860 (0.18%)*	*779.778 (18.12%)*	*3.852.560 (16.8%)*	*799.820 (17.64%)*
Subsidies (+20%)	*2.569.130 (0.19%)*	*751.803 (13.88%)*	*3.708.550 (11.74%)*	*751.803 (10.58%)*
Demonstration funds On	*2.752.100 (7.33%)*	*644.492 (-2.38%)*	*3.149.380 (-5.11%)*	*664.592 (-2.25%)*

The comparison across all experiments provides insight into the relative robustness of the policy interventions. Figures 20 to 23 present the median outcomes for each policy and key performance indicator, calculated across all four scenarios and the base case, showing how consistently each policy performs relative to the others under different future conditions. Taxing new batteries ranks first for demand in both countries and first or second for supply across all scenarios, indicating that it is the most consistently high-performing policy relative to the alternatives. Subsidies rank consistently second for demand in both countries and for supply in Sweden, and second or third for supply in the Netherlands. Although subsidies do not rank first, they still outperform the no-policy baseline in every scenario, demonstrating a stable positive effect across all experiments. In contrast, demonstration funds show lower robustness relative to the other interventions. In Sweden, they consistently rank third for both supply and demand. In the Netherlands, demonstration funds only rank highest for supply under supply-constrained scenarios (Scenarios 3 and 4), but rank lower in the other scenarios. This indicates that their performance depends more strongly on specific system conditions.

Overall, the results show that regulatory policies influence EV battery repurposing diffused volumes, but their impact depends on national system constraints. Taxing new batteries emerges as the most robust intervention, as it consistently improves demand and performs strongest relative to other policies across scenarios in both countries. Subsidies provide stable and consistently positive effects, outperforming the no-policy baseline in all experiments. Demonstration funds show more context-dependent effects. They are effective in the Netherlands under supply-constrained conditions, but less effective in Sweden where capacity limitations and declining demand restrict their impact.

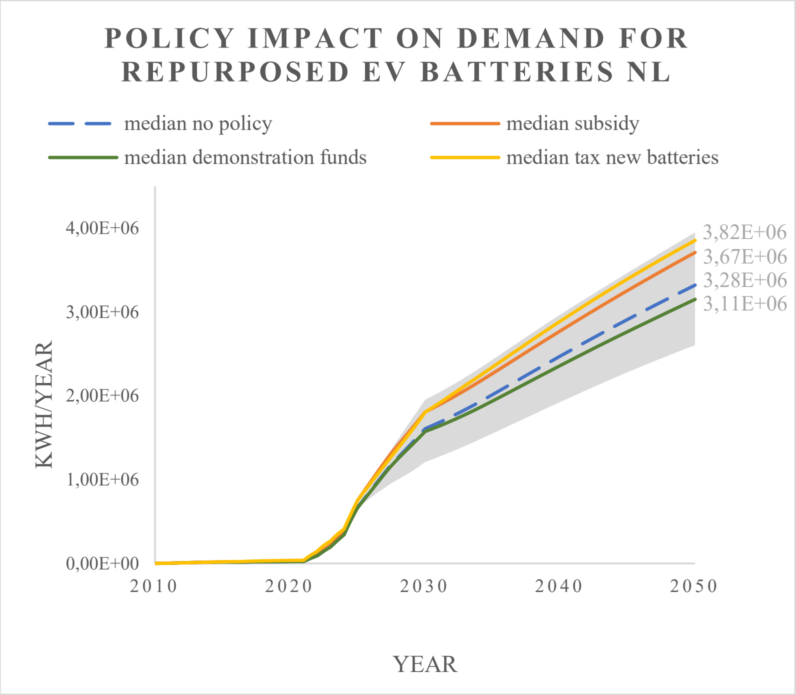


Figure 20: Policy impact on demand for repurposed EV batteries NL

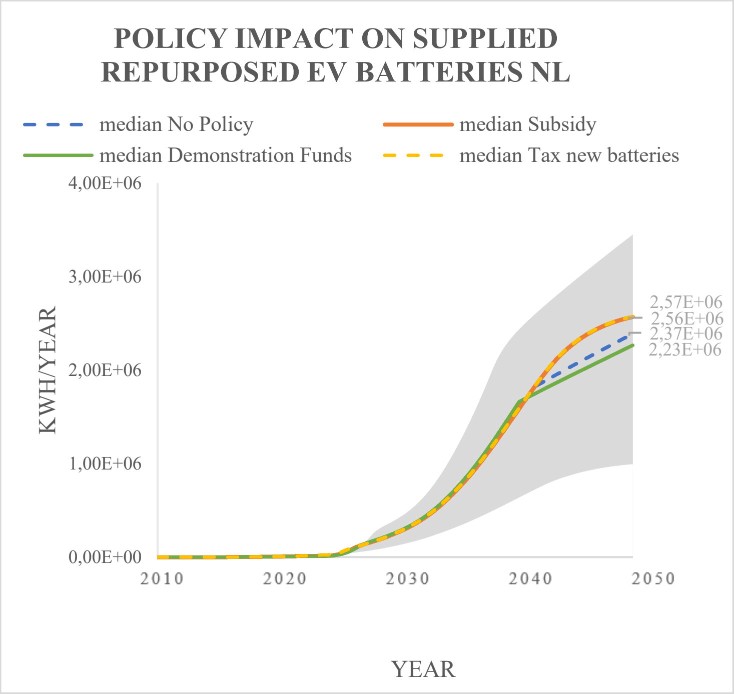


Figure 21: Policy impact on supplied repurposed EV batteries NL

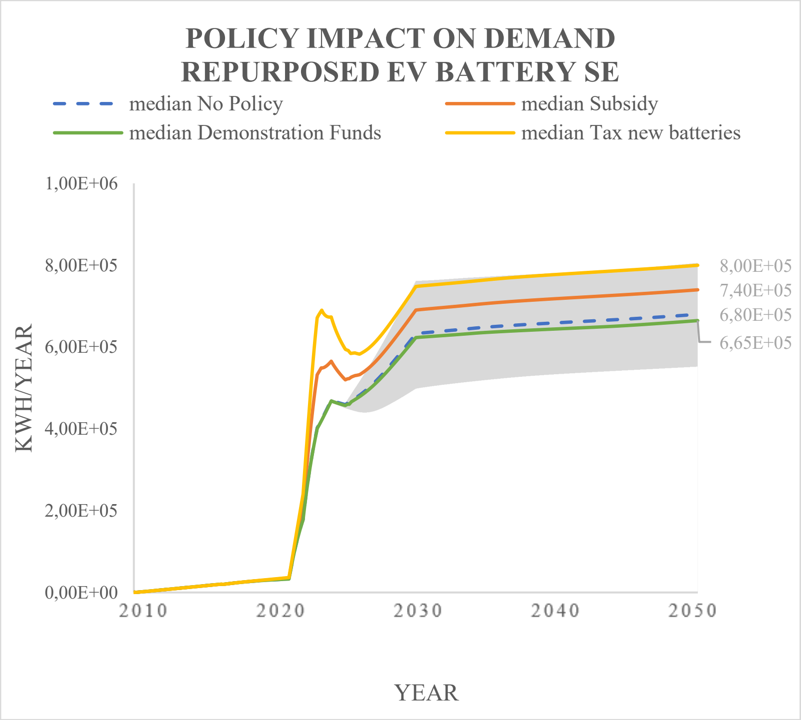


Figure 22: Policy impact on demand repurposed EV battery SE

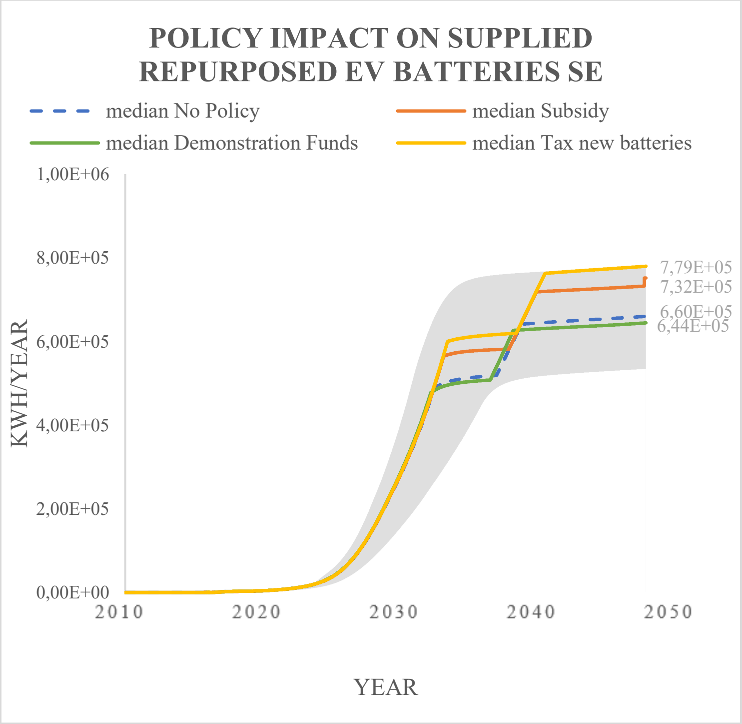


Figure 23: Policy impact on supplied repurposed EV batteries SE

Chapter 5: Discussion & Limitations

This chapter reflects on the broader meaning and robustness of the findings by discussing their theoretical and managerial implications, as well as the methodological and framework limitations of the study. By critically evaluating both contributions and constraints, the chapter positions the results within the wider academic debate and clarifies how they should be interpreted in future research and practice.

5.1 Theoretical implications;

This study contributes to the EV battery repurposing literature in four main ways.

First, it identifies which contextual factors are most relevant when assessing the market potential for EV battery repurposing. By examining which variables within the one-loop and two-loop structures of the Circubat model developed by Seika & Kubli (2025) require adaptation to reflect national conditions, the study provides a framework that can be applied to other European countries to project diffusion patterns. Importantly, it shows how these national factors influence diffusion through feedback mechanisms rather than linear cause–effect relationships, thereby improving understanding of system behaviour and supporting the identification of more effective policy interventions. This directly responds to the literature review's conclusion that national case studies recognise context but differ widely in focus and method, limiting comparability and theory building (Skeete et al., 2020; Nurdiawati & Agrawal, 2022; DNV, 2021; Doi et al., 2024).

Second, by translating the Circubat system dynamics model into an innovation system context, this research offers a novel approach to analysing the development of EV battery repurposing over time. While existing studies have identified drivers and barriers of second-life EV battery applications and modelled future projections (e.g., Albertsen et al., 2021; Kampker et al., 2023; DNV, 2021; Nurdiawati & Agrawal, 2022; Seika & Kubli, 2025), these analyses either focus on techno-economic feasibility, scenario-based material flows, or firm-level viability. They do not explicitly model innovation system dynamics through feedback mechanisms. By operationalising TIS building blocks from the hybrid model of Massop (2024), this study enables a quantitative assessment of how changes in national contexts affect the innovation system trajectories over time. Moreover, because the building blocks are interpreted in a consistent and transferable manner, the approach allows for comparative analysis across countries, thereby strengthening its relevance for future cross-national research. In doing so, the thesis builds on emerging quantitative TIS work that uses system dynamics, while addressing prior limitations where innovation system functional and structural interactions remain implicit (Walrave & Raven, 2016; Uriona & Grobbelaar, 2019) and extending the structural-function linkage proposed by Massop (2024) to the specific technological, market, and institutional characteristics of EV battery repurposing.

Third, the results provide long-term diffusion simulations for repurposed EV batteries in both the Netherlands and Sweden, thereby advancing the currently fragmented national literature. In the Dutch context, prior research such as DNV (2021) primarily assessed feasibility through qualitative expert analysis and static net present value calculations based on fixed cost assumptions, without modelling dynamic market formation. In Sweden, Nurdiawati and Agrawal (2022) combined material flow analysis with a socio-technical transition perspective, offering valuable insights into future waste streams and circular pathways, yet without testing economic viability or modelling feedback-driven diffusion. By contrast, this thesis integrates system dynamics with an innovation diffusion lens to explicitly simulate how demand conditions, governance structures, and capacity constraints interact over time.

Fourth, this study advances theoretical understanding of how national context shapes innovation system dynamics in emerging circular technologies. By distinguishing between demand conditions, feedstock availability, and handling capacity, the findings show that structural differences do not merely influence diffusion outcomes directly, but condition how reinforcing feedback mechanisms within the innovation system are activated. Even where EoL EV battery volumes are similar, variation in demand intensity can lead to fundamentally different scaling trajectories. Demand emerges as a central system-level driver, influencing investment incentives, capacity expansion, and long-term resilience. The results further demonstrate that policy effectiveness is not universal, but contingent upon the dominant structural constraint within a national system.

5.2 Managerial implications

Apart from its theoretical contributions, this study provides several managerial implications for policymakers, industry actors, and investors engaged in EV battery repurposing.

First, the simulations provide strategic insight for market actors in the Netherlands and Sweden. By modelling long-term diffusion trajectories, the study offers entrepreneurs and investors a clearer view of expected market volumes, timing of supply peaks, and demand development. This reduces strategic uncertainty and supports more robust business case calculations. For early-stage firms, understanding when and under which conditions diffusion accelerates is critical for investment timing, capacity planning, and partnership formation.

Second, the findings clarify long-term market dynamics for policymakers and public investors. The results demonstrate that repurposing markets are shaped by feedback effects. Government intervention therefore does not operate in isolation but influences systemic dynamics over time. National governments can actively steer the circular battery system by shaping price signals, coordinating actors, and aligning recycling and repurposing objectives.

Third, this study confirms, in line with Seika & Kubli (2024), that the EU Battery Directive is effective in stimulating the development of sufficient recycling capacity, but does not necessarily support repurposing to the same extent. The strong regulatory emphasis on material recovery ensures that all end-of-life EV batteries that are not repurposed are ultimately absorbed into recycling streams in both the Netherlands and Sweden. However, this prioritisation of recycling can increase competition for high-quality batteries and raise feedstock prices, thereby reducing the relative attractiveness of second-life applications. In Sweden, where domestic storage demand is relatively limited, a larger share of available batteries flows directly into recycling. In the Netherlands, stronger storage demand supports repurposing to a greater extent, but competition between recycling and repurposing remains present. These findings suggest that current policy frameworks structurally secure recycling outcomes, while providing fewer dedicated incentives for repurposing. Policymakers should therefore assess whether recycling and repurposing objectives are sufficiently differentiated to avoid unintended disadvantages for higher-value circular strategies.

Finally, European coordination is essential to improve overall system efficiency. This study reveals that national markets exhibit structural asymmetries between supply and demand. Cross-border coordination could allow countries with stronger demand conditions to absorb surplus end-of-life batteries from regions with higher availability. A hub-and-spoke model for repurposing and recycling infrastructure could reduce saturation effects and mitigate structural imbalances (Cattani et al., 2025). Such coordination aligns with broader EU ambitions to strengthen strategic autonomy in battery value chains while advancing circular economy objectives (European Commission, 2023).

5.3 Methodology limitations

As no model can fully capture the complexity of real-world systems, the model developed in this research is subject to several limitations. These limitations indicate where the study cannot provide complete certainty and where caution is required when interpreting the results.

A key limitation of this study concerns the translation of a qualitative TIS framework into a quantitative system dynamics model. Operationalising the TIS building blocks through a limited set of quantitative indicators necessarily simplifies complex and context-dependent processes, potentially overlooking important qualitative dynamics. To enable cross-country comparison of TIS building block development between the Netherlands and Sweden, selected indicators from the Circubat model were aggregated, which may further reduce the robustness and nuance of the resulting building block assessments. At the same time, this aggregation represents a deliberate trade-off, as it allows for consistent and systematic comparison across national contexts. Moreover, system dynamics modelling focuses on behavioural patterns, feedback loops, and non-linear interactions rather than precise point predictions (Bala et al., 2017), meaning that results should be interpreted as directional insights rather than exact forecasts.

An additional methodological limitation arises from the use of heterogeneous indicator scales within the TIS building blocks. Some indicators are represented as binary variables, while others are defined on a continuous scale between 0 and 1. This inconsistency in measurement resolution limits the comparability of indicators within and across building blocks, as binary indicators may overstate the presence or absence of a function while continuous indicators capture more nuanced developments. As a result, aggregation of these indicators may distort the relative importance of certain system components and influence the interpretation of building block maturity. Although the assumptions and modelling choices are explicitly stated, they introduce simplifications that reduce the precision of the building block assessment and should be addressed in future research through the development of more consistent and empirically grounded indicator scales.

Despite these uncertainties and simplifications, the model provides valuable insight into the magnitude and direction of potential system responses under different policy interventions. Rather than offering deterministic forecasts, the simulations serve as exploratory tools that clarify structural mechanisms, reveal leverage points, and support more informed strategic and policy discussions.

5.4 Framework limitations

Ortt and Kamp (2022) argue that all TIS building blocks must be fully developed for large-scale diffusion to occur. However, the findings of this study question whether this interpretation of full-scale diffusion is suitable for second-hand technologies. In conventional TIS analyses, product quality and performance are assessed relative to competing alternatives. In second-hand markets, second-life products are structurally compared to new ones and inherently face performance disadvantages due to degradation and ongoing technological progress. In EV battery repurposing, this is amplified by an approximate 14-year gap between initial production and second-life deployment, during which significant performance improvements occur (Bobba et al., 2018; Etxandi-Santolaya et al., 2024). Under this interpretation, repurposed batteries are unlikely to achieve performance parity with new batteries, making “full-scale diffusion”, understood as outcompeting the dominant technology, structurally improbable. Yet, in circular markets, second-life products are not intended to replace first-life technologies but to complement them. Applying the traditional TIS lens may therefore underestimate the diffusion potential of second-hand innovations. Future research could explore more integrated approaches that analyse first- and second-life applications as interdependent within a broader innovation system, offering a more appropriate framework for circular economy contexts.

A further limitation relates to the spatial scope of the analysis. This study adopts a national perspective, whereas technological innovation system theory often emphasises that diffusion processes can extend beyond national borders (Cattani et al., 2025). International flows of end-of-life EV batteries or repurposed battery products are not captured in the current model. Including cross-border supply and demand could alter diffusion outcomes, particularly for Sweden, where domestic demand is relatively low but could be complemented by export-oriented repurposing strategies. Future research could therefore extend the Merged model by explicitly incorporating international market interactions to assess how European-level dynamics influence national diffusion patterns.

Chapter 6: Conclusion & Recommendations

This final chapter synthesises the main findings of the study and translates them into an overarching conclusion and policy recommendations.

6.1. Conclusion

This thesis set out to answer the central research question: *How do the national contexts of the Netherlands and Sweden affect the diffusion of EV battery repurposing technology?*

The assessment of national contexts reveals both similarities and structural differences between the Netherlands and Sweden. Both countries show comparable projected end-of-life EV battery streams, reflecting similar EV uptake trajectories. However, they differ markedly in total battery demand and handling capacity. Demand is substantially higher in the Netherlands. Differences are also visible in treatment capacity. If Lyten continues Northvolt's expansion plans, Sweden would be able to process its domestic EoL EV battery volumes. The Netherlands, in contrast, faces a projected gap between recycling capacity and future EoL flows.

These structural differences do not remain static; they shape how the repurposing market develops over time. From a system-dynamics perspective, demand acts as the central catalyst. Higher demand increases scale, scale reduces costs, and lower costs stimulate further demand. This reinforcing feedback strengthens learning, attracts investment, and expands repurposing capacity. The comparison in Figure 24 illustrates this clearly. Although projected EoL supply is similar, lower structural demand in Sweden weakens investment incentives and slows capacity expansion, limiting repurposed volumes. The current recycling capacity appears to be less critical, as the EU Battery Directive already provides sufficient incentives to stimulate the expansion of recycling infrastructure. It is therefore projected that, in the Netherlands, the existing capacity gap will gradually close, enabling end-of-life EV battery streams to be managed in a circular manner. In this context, recycling capacity plays a supportive role: the Directive effectively drives the development of the recycling market, although its primary focus remains on recycling activities rather than on battery repurposing.

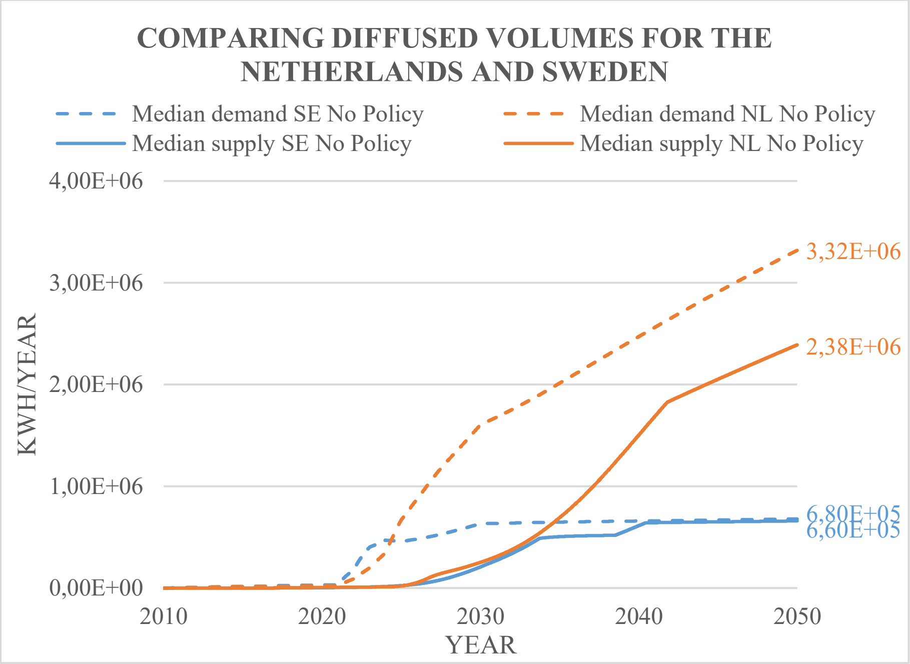


Figure 24: Comparing diffused volumes for the Netherlands and Sweden

The policy analysis further demonstrates that intervention effectiveness is strongly shaped by national context and depends on the dominant structural constraint. In Sweden, where demand constitutes the primary bottleneck, demand-oriented policies effectively increase both demand and supply by activating investment in repurposing capacity. Taxing new batteries emerges as the most robust intervention across scenarios, as it improves the relative price competitiveness of repurposed batteries, consistently strengthening demand and incentivising capacity expansion. In Sweden, this enhanced demand signal translates into substantial supply growth. In the Netherlands, however, similar demand-oriented policies increase total demand but generate only limited supply responses, as the availability of suitable end-of-life EV batteries forms the binding constraint. Consumer subsidies follow the same pattern, stimulating demand in both countries but producing marginal supply effects in the Netherlands due to feedstock limitations. Demonstration funds yield more context-dependent outcomes: while they increase the economic value of repurposing, higher input costs can raise selling prices and dampen demand, particularly in Sweden, thereby reducing diffusion volumes under certain conditions. These findings underscore that effective policy design must align with the underlying national bottleneck rather than applying uniform instruments across structurally different systems.

Beyond realised diffusion volumes, this thesis analysed the structural development of the Technological Innovation System, as full-scale diffusion is only possible when the system reaches a sufficient level of maturity. Examining the TIS provides insight into the systemic strengths and weaknesses that shape long-term scaling dynamics. Figure 25 presents the aggregated innovation system performance, calculated as the average of all building blocks. In both the Netherlands (0.47) and Sweden (0.45), the overall score remains below 0.5 and at relatively similar levels. This indicates that higher diffusion volumes do not automatically translate into a well-developed innovation system. Although each country demonstrates strengths in specific building blocks, persistent weaknesses in others constrain overall system performance and continue to hinder the transition toward full-scale diffusion.

The results show that contextual differences between the Netherlands and Sweden become most visible in the product system, innovation-specific institutions, and repurposing entrepreneurial activity. These building blocks are shaped by differences in supply and demand and by policy support. Sweden performs stronger in innovation-specific institutions due to earlier and more substantial subsidy support, including battery-related subsidies of up to 48.5%, compared to the Netherlands, which currently does not provide a dedicated battery subsidy. On the other hand, the Netherlands performs stronger in the product system and repurposing entrepreneurial activity.

Projected system developments indicate emerging barriers during periods of rapid growth. After 2030, both countries face a sharp increase in end-of-life EV batteries, exposing limitations in testing and processing capacity. If repurposing capacity does not expand in line with incoming volumes, factory saturation rises and system performance declines. The Netherlands is expected to manage this transition more effectively, as stronger demand for stationary storage reinforces capacity investment and delays saturation. In Sweden, weaker structural demand slows capacity expansion, leading to earlier saturation and a more pronounced decline in performance. These dynamics also shape entrepreneurial activity. In the Netherlands, stronger demand expectations stimulate continued investment, resulting in a larger share of domestically available EoL EV batteries being repurposed. In Sweden, weaker demand reduces investment incentives, constraining capacity utilisation and limiting growth in repurposing activity.

Another structural barrier in both countries is the competitive position of repurposed batteries. For repurposed batteries to diffuse at full scale, they must compete directly with new batteries in terms of cost, reliability, and lifetime. However, this competitive benchmark is not static. New battery technologies continue to improve in energy density, durability, and cost. Repurposed batteries, by contrast, begin their second life with inherent ageing, heterogeneous degradation profiles, and uncertainty regarding remaining lifetime. Even as repurposing techniques improve, they do so in the shadow of a continuously advancing frontier in new battery technology. This creates a structural performance gap that is unlikely to disappear.

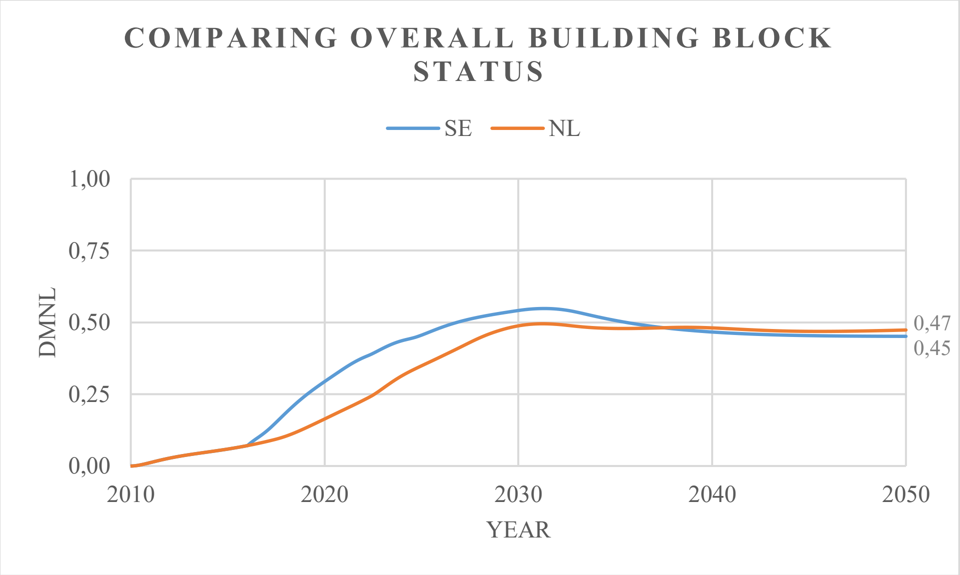


Figure 25: Comparing overall building block status

Overall, this thesis shows that the diffusion of EV battery repurposing technology is fundamentally shaped by national context. While feedstock availability and regulatory frameworks provide important boundary conditions structural demand differences largely determine whether reinforcing feedback mechanisms are activated and scaling becomes self-sustaining. Despite similar projected end-of-life EV battery streams in the Netherlands and Sweden, divergent demand conditions result in substantially different diffusion trajectories and policy effectiveness. At the same time, the aggregated innovation system performance in both countries remains below half of its full development, indicating that the system is not yet sufficiently mature to sustain large-scale diffusion without targeted support.

6.2 Recommendations

The results suggest four policy recommendations which are described below.

First, EV battery repurposing must be firmly placed on the political agenda. Without clear prioritisation, timely and targeted policy interventions are unlikely to emerge. This study shows that in both the Netherlands and Sweden, domestic end-of-life EV battery streams could technically meet total battery demand. Directly recycling these batteries without assessing their repurposing potential results in the loss of valuable functional capacity. Repurposing delivers clear energy, environmental, and social benefits by extending battery lifetimes, reducing resource extraction, and lowering embedded emissions. To reflect these advantages, policy discussions should move beyond narrow market prices and adopt a true pricing perspective that accounts for externalities such as carbon emissions, resource depletion, ecological damage, health impacts, and geopolitical supply risks. Because these societal costs are largely excluded from current market prices, competition between repurposing, recycling, and new battery production is distorted. Internalising externalities would enable decisions based on overall societal value, strengthen the case for targeted policy support, and provide clearer long-term investment signals ahead of the expected surge in battery volumes.

Second, timing is critical. The competitive position of repurposed EV batteries is not static. Recycling capacity is now scaling up in both countries, while new battery technologies continue to improve and decline in price. This narrows the window of opportunity for repurposing. If repurposing does not scale during this period, its relative position will weaken further, making future entry more difficult. Early investment and capacity expansion are therefore essential. Governments should actively attract repurposing firms, reduce regulatory uncertainty, and build on the momentum created by the EU Battery Directive. Acting now helps avoid long-term lock-in to pathways that may prove less sustainable in the long run.

Third, the findings show that policy effectiveness depends on the underlying national constraint. In demand-constrained contexts such as Sweden, instruments that strengthen demand expectations are most effective, as they activate the feedback mechanism between demand and capacity investment. Taxing new batteries emerges as the most robust intervention, consistently improving the relative price competitiveness of repurposed batteries and stimulating both demand and repurposing capacity expansion. In supply-constrained contexts such as the Netherlands, however, demand-oriented policies such as taxes and subsidies increase demand but have only marginal effects on supply when the availability of suitable end-of-life EV batteries forms the binding constraint. In such cases, policy should focus on improving access to domestic feedstock and aligning collection, export, and repurposing objectives. Overall, policy design should account for national structural conditions and system feedback mechanisms.

Fourth, coordination at the European level is essential, while remaining sensitive to national structural differences. This study demonstrates that Sweden may face periods with excess domestic end-of-life EV battery volumes relative to repurposing demand, whereas the Netherlands is constrained by feedstock availability. These asymmetries create opportunities for cross-border collaboration. A European network approach could facilitate the strategic allocation of EoL battery flows, connecting surplus supply regions with demand-driven markets where repurposing capacity can be effectively utilised. At the same time, diffusion remains strongly shaped by country-specific factors such as grid congestion, renewable penetration, electricity prices, and domestic flexibility needs. European coordination should therefore explicitly incorporate national contextual differences when designing policy frameworks and allocating volumes

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Appendix A: Settings for the Dutch and Swedish EV battery repurposing markets.

This section summarises the current state and projected development of the key contextual variables shaping the innovation system for EV battery repurposing in the Netherlands and Sweden. The corresponding parameter values are presented in Table 9 for the Netherlands and Table 10 for Sweden. The underlying data sources, modelling assumptions, and associated limitations are described below the respective tables.

Table 9: Dutch specific inputs for Circubat model

Variable [unit]	Value	Source	Assumption
LOOKUP Passenger Car Market Volume [Vehicle]	(2010, 413500), (2011, 413500), (2012, 413500), (2013, 413500), (2014, 386750), (2015, 444550), (2016, 377150), (2017, 409850), (2018, 442000), (2019, 442250), (2020, 351850), (2021, 314600), (2022, 303800), (2023, 361650), (2024, 375600), (2025, 360000), (2030, 360000), (2035, 360000), (2040, 360000), (2045, 360000), (2050, 360000)	(RVO, 2025)	From 2025 onward, passenger car sales are assumed to remain constant each year.
LOOKUP EV market share [Dmnl/year]	(2010,0.0), (2011,0.0), (2012,0.0), (2013,0.006), (2014,0.009), (2015,0.008), (2016,0.011), (2017,0.019), (2018,0.055), (2019,0.137), (2020,0.205), (2021,0.198), (2022,0.232), (2023,0.307), (2030,1), (2050,1)	(RVO, 2025), (Rijksoverheid, n.d.)	
SHARE OF BATTERIES EXPORTED FROM THE NETHERLANDS [Dmnl]	0.617	(CBS, n.d.)	
LOOKUP Home storage battery sales [kWh/year] (BAU)	(2010, 0), (2021, 19500), (2022, 84000), (2023, 202500), (2024, 387500), (2025, 834000), (2030, 2531632), (2050, 5897551)	(Rijksoverheid, 2023), (CE Delft & Witteveen + Bos, 2023), (Tennet, 2025)	Each residential (home) battery has an average installed capacity of 5 kWh
Share for home storage batteries [Dmnl]	0.33	(DNE Research, 2024).	
Level of subsidies [Dmnl]	0	(Essent, 2025)	
Recycling capacities of existing market actors [ton/year]	(2010, 0), (2019, 0), (2020, 0), (2021, 0), (2022, 0), (2023, 0), (2024, 10000), (2050, 20000)	(Dietert, 2025)	

Table 10: Swedish specific inputs for Circubat model

Variable [unit]	Value	Source	Assumption
LOOKUP Passenger Car Market Volume [Vehicle]	(2010, 308734), (2011, 326649), (2012, 301335), (2013, 292178), (2014, 323974), (2015, 361932), (2016, 388014), (2017, 392728), (2018, 365535), (2019, 366961), (2020, 303196), (2021, 314313), (2022, 299220), (2023, 298107), (2024, 277338), (2025, 282169), (2030, 282169), (2050, 282169)	(Statistikdatabasen, n.d.)	From 2025 onward, passenger car sales are assumed to remain constant each year.
LOOKUP EV market share [Dmnl/year]	(2010,0.0000358), (2011,0.000566), (2012,0.00088), (2013,0.001547), (2014,0.0039077), (2015,0.00806), (2016,0.00771), (2017,0.0111), (2018,0.01955), (2019,0.0430), (2020,0.09267), (2021,0.1842), (2022,0.3214), (2023,0.3783), (2024, 0.34196), (2030,1), (2050,1)	(Morfeldt et al., 2021), (Statistikdatabasen, n.d.)	
Battery export share [Dmnl]	0.56	(Trafikanalys, 2024)	
LOOKUP Home storage battery sales [kWh/year] (BAU)	(2010, 0), (2021, 10815), (2022, 71220), (2023, 213010), (2024, 277010), (2025, 290000), (2030, 450000), (2050, 520000)	(Statistikdatabasen, n.d.-b)	Each residential (home) battery has an average installed capacity of 5 kWh
Share for home storage batteries [Dmnl]	0.23	(Statistikdatabasen, n.d.-a), (Svensk Solenergi, 2024),	
Level of subsidies [Dmnl]	0.485	(Hammarstedt et al., 2025)	
Recycling capacities of existing market actors [ton/year]	(2010, 0), (2019, 0), (2020, 0), (2021, 0), (2022, 0), (2023, 10000), (2035, 135000), (2050, 135000)	(Dietert, 2025)	

Supply-Side Conditions

Passenger car market volumes for both countries are based on official national statistics. Between 2010 and 2024, annual sales remained relatively stable, although a slight declining trend is visible. It is assumed that this stabilisation continues and that the most recent data point remains constant until 2050, reflecting a saturated passenger car market (RVO, 2025; Statistikdatabasen, n.d.).

EV market adoption has progressed rapidly in both countries. In 2024, battery-electric vehicles (BEVs) accounted for 34% of newly registered passenger cars in the Netherlands (RVO, 2025) and

35% in Sweden (Statistikdatabasen, n.d.). Both governments have committed to phasing out new petrol and diesel passenger cars by 2030 (Rijksoverheid, n.d.; Government of Sweden, 2019). In the model, this is operationalised by assuming that EV market share reaches 100% of new vehicle sales by 2030. Although the EU-wide phase-out applies from 2035, national targets are more ambitious. This assumption implies full policy effectiveness and does not account for potential delays, behavioural resistance, macroeconomic shocks, or infrastructure constraints.

The availability of EoL EV batteries is subject to a significant time lag between vehicle deployment and battery retirement. Current supply is therefore primarily shaped by historical EV adoption patterns rather than present sales levels. Long-term EU climate commitments, including the objective of reducing transport-related greenhouse gas emissions by around 90% by 2050 under the European Green Deal (European Commission, 2019), reinforce expectations of sustained electrification and increasing long-term battery supply.

National supply is further affected by export shares of used vehicles and batteries. Export shares are relatively high in both countries, though slightly higher in the Netherlands (0.62) than in Sweden (0.56) (CBS, n.d.; Trafikanalys, 2024). This reduces the volume of batteries reaching domestic end-of-life and therefore limits feedstock availability for repurposing.

Recycling and processing capacity also influence supply conditions. Current EoL treatment capacity is concentrated among recycling actors, while repurposing capacity remains limited. Mandatory recycling targets under the EU Battery Regulation increase demand for retired EV batteries, raise end-of-life battery prices, and reduce the profitability of repurposing (Seika & Kubli, 2024). In the Netherlands, two recyclers provide an installed capacity of approximately 10,000 tons per year, with planned expansion to 20,000 tons (Dietert, 2025). In Sweden, Northvolt previously announced capacities of up to 125,000 tons per year before bankruptcy, and these assets were later acquired by Lyten (Dietert, 2025). The realisation of these plans remains uncertain, introducing additional supply-side uncertainty.

Demand-Side Conditions

Demand for repurposed EV batteries is influenced by consumer utility perceptions, sustainable awareness, flexibility needs in decentralised energy systems, and political support mechanisms such as subsidies or tax benefits. Historical sales of home and commercial stationary storage systems provide an important indication of future demand and societal acceptance of battery technologies (Klingler & Luthander, 2018).

Residential battery markets differ substantially between the two countries. In the Netherlands, residential battery deployment has grown rapidly since 2021, driven by high solar PV penetration, increasing grid congestion, and rising flexibility needs (Rijksoverheid, 2023; CE Delft & Witteveen + Bos, 2023; TenneT, 2025). This development is closely linked to the structure of the Dutch electricity system, where wind and solar account for approximately 47–54% of electricity generation (IEAa, 2024). The planned phase-out of net metering further increases incentives for residential storage. Approximately one-third of total installed battery capacity is allocated to the residential segment (Rijksoverheid, 2023).

In Sweden, the residential battery market remains smaller. The electricity system is dominated by hydropower (around 38%) and nuclear power (approximately 29%), providing stable and dispatchable generation (IEAb, n.d.). Lower solar PV penetration and limited grid congestion reduce household incentives to invest in storage, resulting in more gradual growth.

For modelling residential battery capacity between 2021 and 2025, annual capacity is estimated by multiplying the number of home batteries sold by an assumed average installed capacity of 5 kWh per unit (Rijksoverheid, 2023; CE Delft & Witteveen+Bos, 2023). The 5 kWh value is held constant over time, simplifying technological variation. For 2030 and 2050, total yearly installed battery capacity follows TenneT's System Outlook projections (TenneT, 2023), with the residential share observed in 2025 assumed to remain constant. For Sweden, power-based statistics are converted into energy capacity assuming a three-hour storage duration; 610 MW of grid-connected capacity in 2024 corresponds to approximately 1,830 MWh (Statistikdatabasen, n.d.-b).

Subsidy levels further shape demand conditions. The Netherlands currently provides no direct residential battery subsidy (Essent, 2025). Sweden, in contrast, offers tax deductions corresponding to an effective subsidy level of approximately 49% (Hammarstedt et al., 2025). Subsidy levels directly affect the purchase price of repurposed batteries and their competitiveness relative to new batteries (Zhang et al., 2024).

Capacity development

Charging infrastructure plays an important enabling role for EV adoption (Fier, 2025). In 2024, the Netherlands had approximately 0.33 public charging points per BEV, compared with 0.14 in Sweden (Fier, 2025). Although EV adoption rates are similar, infrastructure maturity differs. However, charging infrastructure is not modelled endogenously; it is implicitly reflected in EV market share assumptions.

Subsidies and export shares are assumed to remain constant over time in both countries. While this improves comparability across scenarios, it does not capture potential policy adjustments in response to changing market conditions.

Appendix B: Scenario values

Table 11: Scenario 1 Parameter values for the Netherlands and Sweden

Category	Variable [unit]	Value Netherlands	Value Sweden	Scenario classification
Supply	LOOKUP Passenger Car Market Volume [Vehicle]	(2010, 413500), (2011, 413500), (2012, 413500), (2013, 413500), (2014, 386750), (2015, 444550), (2016, 377150), (2017, 409850), (2018, 442000), (2019, 442250), (2020, 351850), (2021, 314600), (2022, 303800), (2023, 361650), (2024, 375600), (2025, 360000), (2030, 432000), (2035, 432000), (2040, 432000), (2045, 432000), (2050, 432000)	(2010, 308734), (2011, 326649), (2012, 301335), (2013, 292178), (2014, 323974), (2015, 361932), (2016, 388014), (2017, 392728), (2018, 365535), (2019, 366961), (2020, 303196), (2021, 314313), (2022, 299220), (2023, 298107), (2024, 277338), (2025, 282169), (2030, 338602.8), (2050, 338602.8)	After 2026 20% increase in passenger car market volume.
Supply	LOOKUP EV market share [Dmnl/year]	(2010,0.0), (2011,0.0), (2012,0.0), (2013,0.006), (2014,0.009), (2015,0.008), (2016,0.011), (2017,0.019), (2018,0.055), (2019,0.137), (2020,0.205), (2021,0.198), (2022,0.232), (2023,0.307), (2028,1), (2050,1)	(2010,0.0000358), (2011,0.000566), (2012,0.00088), (2013,0.001547), (2014,0.0039077), (2015,0.00806), (2016,0.00771), (2017,0.0111), (2018,0.01955), (2019,0.0430), (2020,0.09267), (2021,0.1842), (2022,0.3214), (2023,0.3783), (2024, 0.34196), (2028,1), (2050,1)	EV market share reaching saturation two years earlier
Supply	SHARE OF BATTERIES EXPORTED FROM THE NETHERLANDS [Dmnl]	0.417	0.36	20% lower EV exports
Demand	LOOKUP Home storage battery sales [kWh/year] (BAU)	(2010, 0), (2021, 19500), (2022, 84000), (2023, 202500), (2024, 387500), (2025, 834000), (2030, 2025305.6), (2050, 4718040.8)	(2010, 0), (2021, 10815), (2022, 71220), (2023, 213010), (2024, 277010), (2025, 290000), (2030, 360000), (2050, 416000)	20% lower demand for batteries

Table 12: Scenario 2 parameter values for the Netherlands and Sweden

Category	Variable [unit]	Value Netherlands	Value Sweden	Scenario classification
Supply	LOOKUP Passenger Car Market Volume [Vehicle]	(2010, 413500), (2011, 413500), (2012, 413500), (2013, 413500), (2014, 386750), (2015, 444550), (2016, 377150), (2017, 409850), (2018, 442000), (2019, 442250), (2020, 351850), (2021, 314600), (2022, 303800), (2023, 361650), (2024, 375600), (2025, 360000), (2030, 432000), (2035, 432000), (2040, 432000), (2045, 432000), (2050, 432000)	(2010, 308734), (2011, 326649), (2012, 301335), (2013, 292178), (2014, 323974), (2015, 361932), (2016, 388014), (2017, 392728), (2018, 365535), (2019, 366961), (2020, 303196), (2021, 314313), (2022, 299220), (2023, 298107), (2024, 277338), (2025, 282169), (2030, 338602.8), (2050, 338602.8)	After 2026 20% increase in passenger car market volume.
Supply	LOOKUP EV market share [Dmnl/year]	(2010,0.0), (2011,0.0), (2012,0.0), (2013,0.006), (2014,0.009), (2015,0.008), (2016,0.011), (2017,0.019), (2018,0.055), (2019,0.137), (2020,0.205), (2021,0.198), (2022,0.232), (2023,0.307), (2028,1), (2050,1)	(2010,0.0000358), (2011,0.000566), (2012,0.00088), (2013,0.001547), (2014,0.0039077), (2015,0.00806), (2016,0.00771), (2017,0.0111), (2018,0.01955), (2019,0.0430), (2020,0.09267), (2021,0.1842), (2022,0.3214), (2023,0.3783), (2024, 0.34196), (2028,1), (2050,1)	EV market share reaching saturation two years earlier
Supply	SHARE OF BATTERIES EXPORTED FROM THE NETHERLANDS [Dmnl]	0.417	0.36	20% lower EV exports
Demand	LOOKUP Home storage battery sales [kWh/year] (BAU)	(2010, 0), (2021, 19500), (2022, 84000), (2023, 202500), (2024, 387500), (2025, 834000), (2030, 3037958.4), (2050, 7077061.2)	(2010, 0), (2021, 10815), (2022, 71220), (2023, 213010), (2024, 277010), (2025, 290000), (2030, 540000), (2050, 624000)	20% higher demand for batteries

Table 13: Scenario 3 parameter values for the Netherlands and Sweden

Category	Variable [unit]	Value Netherlands	Value Sweden	Scenario classification
Supply	LOOKUP Passenger Car Market Volume [Vehicle]	(2010, 413500), (2011, 413500), (2012, 413500), (2013, 413500), (2014, 386750), (2015, 444550), (2016, 377150), (2017, 409850), (2018, 442000), (2019, 442250), (2020, 351850), (2021, 314600), (2022, 303800), (2023, 361650), (2024, 375600), (2025, 360000), (2030, 288000), (2035, 288000), (2040, 288000), (2045, 288000), (2050, 288000)	(2010, 308734), (2011, 326649), (2012, 301335), (2013, 292178), (2014, 323974), (2015, 361932), (2016, 388014), (2017, 392728), (2018, 365535), (2019, 366961), (2020, 303196), (2021, 314313), (2022, 299220), (2023, 298107), (2024, 277338), (2025, 282169), (2030, 225735.2), (2050, 225735.2)	After 2026 20% decrease in passenger car market volume.
Supply	LOOKUP EV market share [Dmnl/year]	(2010,0.0), (2011,0.0), (2012,0.0), (2013,0.006), (2014,0.009), (2015,0.008), (2016,0.011), (2017,0.019), (2018,0.055), (2019,0.137), (2020,0.205), (2021,0.198), (2022,0.232), (2023,0.307), (2032,1), (2050,1)	(2010,0.0000358), (2011,0.000566), (2012,0.00088), (2013,0.001547), (2014,0.0039077), (2015,0.00806), (2016,0.00771), (2017,0.0111), (2018,0.01955), (2019,0.0430), (2020,0.09267), (2021,0.1842), (2022,0.3214), (2023,0.3783), (2024, 0.34196), (2032,1), (2050,1)	EV market share reaching saturation two years later
Supply	SHARE OF BATTERIES EXPORTED FROM THE NETHERLANDS [Dmnl]	0.817	0.76	20% higher EV exports
Demand	LOOKUP Home storage battery sales [kWh/year] (BAU)	(2010, 0), (2021, 19500), (2022, 84000), (2023, 202500), (2024, 387500), (2025, 834000), (2030, 2025305.6), (2050, 4718040.8)	(2010, 0), (2021, 10815), (2022, 71220), (2023, 213010), (2024, 277010), (2025, 290000), (2030, 360000), (2050, 416000)	20% lower demand for batteries

Table 14: Scenario 4 parameter values for the Netherlands and Sweden

Category	Variable [unit]	Value Netherlands	Value Sweden	Scenario classification
Supply	LOOKUP Passenger Car Market Volume [Vehicle]	(2010, 413500), (2011, 413500), (2012, 413500), (2013, 413500), (2014, 386750), (2015, 444550), (2016, 377150), (2017, 409850), (2018, 442000), (2019, 442250), (2020, 351850), (2021, 314600), (2022, 303800), (2023, 361650), (2024, 375600), (2025, 360000), (2030, 288000), (2035, 288000), (2040, 288000), (2045, 288000), (2050, 288000)	(2010, 308734), (2011, 326649), (2012, 301335), (2013, 292178), (2014, 323974), (2015, 361932), (2016, 388014), (2017, 392728), (2018, 365535), (2019, 366961), (2020, 303196), (2021, 314313), (2022, 299220), (2023, 298107), (2024, 277338), (2025, 282169), (2030, 225735.2), (2050, 225735.2)	After 2026 20% decrease in passenger car market volume.
Supply	LOOKUP EV market share [Dmnl/year]	(2010,0.0), (2011,0.0), (2012,0.0), (2013,0.006), (2014,0.009), (2015,0.008), (2016,0.011), (2017,0.019), (2018,0.055), (2019,0.137), (2020,0.205), (2021,0.198), (2022,0.232), (2023,0.307), (2032,1), (2050,1)	(2010,0.0000358), (2011,0.000566), (2012,0.00088), (2013,0.001547), (2014,0.0039077), (2015,0.00806), (2016,0.00771), (2017,0.0111), (2018,0.01955), (2019,0.0430), (2020,0.09267), (2021,0.1842), (2022,0.3214), (2023,0.3783), (2024, 0.34196), (2032,1), (2050,1)	EV market share reaching saturation two years later
Supply	SHARE OF BATTERIES EXPORTED FROM THE NETHERLANDS [Dmnl]	0.817	0.76	20% Higher EV exports
Demand	LOOKUP Home storage battery sales [kWh/year] (BAU)	(2010, 0), (2021, 19500), (2022, 84000), (2023, 202500), (2024, 387500), (2025, 834000), (2030, 3037958.4), (2050, 7077061.2)	(2010, 0), (2021, 10815), (2022, 71220), (2023, 213010), (2024, 277010), (2025, 290000), (2030, 540000), (2050, 624000)	After 2026 a 20% higher demand for batteries

Appendix C: Model Evaluation tests

Model credibility was ensured by systematically evaluating both structural integrity and behavioural performance. Tests were applied in sequence, and any failed test prompted model revision followed by re-testing before continuation.

Structure verification test

Structure verification was conducted to assess whether the model provides a plausible representation of the real-world development of EV battery repurposing, in accordance with the structure-verification test described by Auping et al. (2024). The verification focused primarily on the TIS building blocks, as the overarching CircuBAT structure and the causal links between TIS functions and building blocks were adopted from prior validated studies and therefore not structurally modified in this research. The building blocks represented in the merged model were developed within the conceptual boundaries of the TIS framework and informed by literature review and expert interviews. During model development, the assumed causal relationships and feedback mechanisms were systematically evaluated for consistency with empirical evidence and theoretical insights. A limitation of this process is that experts were consulted to inform relevant mechanisms and building block interpretation, but the full model structure was not subjected to formal external validation by these interviewees. Where inconsistencies or conceptual gaps were identified during development, the structure was revised to better reflect the underlying system logic. The remaining assumptions and structural limitations are outlined below.

The model adopts S-shaped (logistic) growth formulations for selected interactions between building blocks and TIS functions, following Massop (2024) and Walrave & Raven (2016), specifically for (i) the effect of entrepreneurial activity on guidance of the search, (ii) the influence of networks on the time required for knowledge development and diffusion, and (iii) the impact of repurposing activities on the formation of new networks. These relations assume slow initial development, accelerated growth once reinforcing dynamics dominate, and deceleration as saturation or structural limits are approached. Such non-linear trajectories are consistent with established insights on technological and innovation system development, where performance improvements and diffusion processes typically follow S-shaped patterns rather than sustained exponential growth (Schilling & Esmudo, 2009). By preventing unbounded dynamics while capturing essential growth characteristics at an aggregated level, the adopted formulation is considered structurally valid for the model’s purpose.

The assumption of a shared causal structure across the Netherlands and Sweden strengthens the internal validity of the comparison. By holding the feedback architecture constant, observed differences in system behaviour can be attributed to parameter variations (e.g., capacity of existing market actors, historical demand patterns, policy settings) rather than structural reconfiguration, thereby preserving analytical clarity. Introducing country-specific feedback loops would complicate attribution and reduce comparability. However, this assumption may overlook structural differences that become relevant at a more detailed national level. For example, spatial constraints in the Netherlands could introduce an additional balancing feedback loop in which a physical space stock represents a barrier and accelerates saturation of repurposing or recycling capacity, potentially leading to earlier system constraints compared to Sweden, where spatial abundance may delay such effects. This illustrates a limitation of the aggregated structure. Moreover, in comparisons involving countries with substantially different cultural or developmental contexts, the current structural formulation may be insufficient; additional stocks or feedbacks, such as explicit talent pools or human capital constraints, might be required, particularly where shortages of highly educated labour form structural barriers to system development (Domah et al., 2002).

Measuring saturation levels of recycling and repurposing facilities is consistent with the national scope of the model. Although European policy aims to improve end-of-life battery management at the EU level, and decentralized hub-and-spoke structures have been proposed to reduce transport costs and increase scalability (Cattani et al., 2025), the present model adopts a national system boundary. This choice shapes the structure of the building blocks related to the product system and complementary products and services: when domestic supply of end-of-life batteries exceeds installed processing capacity, a saturation feedback reduces system performance. A limitation of this assumption is that international trade is not modelled; cross-border flows could alleviate domestic saturation effects. However, excluding trade is a deliberate choice to focus on national supply–demand dynamics and capacity development, which is consistent with the model's purpose.

The merged model, consistent with the hybrid model of Massop (2024), is explicitly structured around the formative phase of innovation system development. This scope assumption shapes the causal architecture: full-scale diffusion is assumed to occur only once all building blocks are sufficiently developed. Accordingly, three policy instruments, subsidies, collection targets, and repurposing mandates, are modelled as formative-phase interventions that stimulate niche development. In practice, such policy support often decreases or is phased out as technologies mature and enter large-scale diffusion (Markard, 2020). In the model, this decline is represented by a reduction of the corresponding building block, which may appear as a setback in system development. However, this reflects the structural focus on formative dynamics rather than diffusion maturity. Given that the model's purpose is to analyse early-stage system formation and barrier dynamics, this structural simplification is considered appropriate, while acknowledging that a diffusion-phase model would require a different structural representation of policy evolution.

Behaviour reproduction test

The behavioural reproduction test focuses on whether the model plausibly reproduces the observed supply of repurposed EV batteries in the Netherlands and Sweden. Building on the adopted CircuBAT structure, this test evaluates whether the model captures the early-stage dynamics of EV battery repurposing. In line with Auping et al. (2024)'s behaviour-reproduction logic, simulated outputs are compared with empirical data to assess whether the model generates a realistic order of magnitude for second-life EV battery volumes. Given the limited availability of national datasets, reported reused battery mass is converted into an equivalent annual energy volume (kWh/year), enabling direct comparison with the simulated annual supply of end-of-life batteries entering repurposing.For the Netherlands, the simulated annual volume of repurposed EV batteries in 2023 was compared with reported data from Auto Recycling Nederland (ARN), which states that 70,071 kg/year of lithium-ion automotive batteries were reused. Converting this mass to tonnes gives:
70,071 kg/year ÷ 1,000 kg/ton = 70.071 ton/year.

To estimate the corresponding second-life energy capacity, the energy density of NMC batteries was applied. NMC chemistry has historically dominated the European EV market and was widely used in early-generation electric vehicles, particularly in passenger cars, which aligns with the time delays embedded in the model (Schmuch et al., 2018).

Assuming an energy density of 200 kWh/ton (Ghosh, 2022) and 80% (Shah et al., 2022) remaining usable capacity at end of life, the calculation is:
70.071 ton/year × 200 kWh/ton × 0.80 = 11,211.4 kWh/year (≈ 11.2 MWh/year).

This results in an empirical estimate of approximately 11 MWh/year for 2023. The model simulates a repurposed EV battery supply of 13.06 MWh/year for the Netherlands in 2023. Given uncertainties regarding battery chemistry composition, second-life conversion efficiencies, and reporting boundaries, the simulated value is considered to be of the same order of magnitude as the empirical estimate. The model therefore plausibly reproduces the observed early-stage behaviour of EV battery repurposing in the Netherlands.

For Sweden, although the national statistical database includes a “reused” category for automotive batteries, the reported values are marked as confidential (“..”), meaning that the data are either unavailable or suppressed for confidentiality reasons (Statistikdatabasen, n.d.-c). Consequently, a quantitative behavioural reproduction test could not be conducted for Sweden for to verify the supply of repurposed EV batteries. Bala et al. (2017) states that validation should ideally focus on reproducing overall behavioural patterns and underlying system logic rather than exact numerical correspondence. However, due to the limited availability of empirical data on EV battery repurposing, the assessment had to rely on a single observed data point in time for the Netherlands, and none for Sweden. This restricts the ability to evaluate dynamic trends or growth patterns and therefore constitutes a limitation of the behavioural validation.

Extreme conditions test

Following Auping et al.(2024) ’s validation framework, a behavioural extreme-conditions test was conducted to assess model robustness under extreme but plausible parameter settings. The test was implemented behaviourally by simulating extreme values and analysing their impact on system dynamics. Each condition (Table 15) was varied independently to isolate its effect on model behaviour. The objective was to examine whether the model produced realistic and logically consistent responses without unbounded growth, structural breakdowns, or implausible dynamics. As the Dutch and Swedish cases share the same causal structure, the extreme-conditions test was performed using the Dutch parameter set. The objective of this test is to assess structural robustness rather than country-specific calibration. Since the feedback architecture is identical in both cases, any structural inconsistencies would emerge independently of national parameter differences. Therefore, adjusting Swedish input values was not necessary for this validation step. The model responded plausibly under all tested conditions, supporting its behavioural robustness within the defined scope. The conditions were aimed to target the behaviour related to the building blocks. Results are shown in Figure 26-29

Table 15: Extreme conditions test and expected impact

Condition	Expected behaviour	
Pressure needed to implement repurposing mandates	When the pressure needed to implement repurposing mandates is extremely low, the threshold for policy activation is easily met. As a result, Policy 1 is activated earlier in time, even at relatively low levels of average lobbying power.	Deze nu nog niet 0.1 ipv 0.85
Low second life lifetime for repurposed batteries.	A lower average lifespan for repurposed home batteries reduces the average lifespan of repurposed applications, worsening the lifespan competition indicator and weakening the competitive position of repurposed batteries relative to new batteries.	1 year instead of 9 years
Extreme low NMC battery energy density	It is expected that lowering the energy density of NMC batteries increases the volumes of both	20 ipv 200

	second-life batteries and end-of-first-life batteries sent to recycling. This lowers pressure on EoL EV battery recycling facilities, resulting in greater remaining (unused) recycling capacity.	
No export option.	Extremely low battery exports cause most end-of-life batteries to remain within the national system, increasing the inflow of non-OEM batteries to SoH testing facilities. Once testing demand exceeds disassembly capacity, congestion occurs and the delay time for battery testing increases proportionally, which reduces the **efficiency factor for repurposing processes**.	0 export ipv 0.616
Extreme low EV share	When there is low EVs there will be low saturation of entrepreneurial activity, As the demand cannot be met sufficiently via repurposed battery supply.	0.02 for each year ipv; (2010,0), (2011,0), (2012,0), (2013,0.006), (2014,0.009), (2015,0.008), (2016,0.011), (2017,0.019), (2018,0.055), (2019,0.137), (2020,0.205), (2021,0.198), (2022,0.232), (2023,0.307), (2030,1), (2050,1)

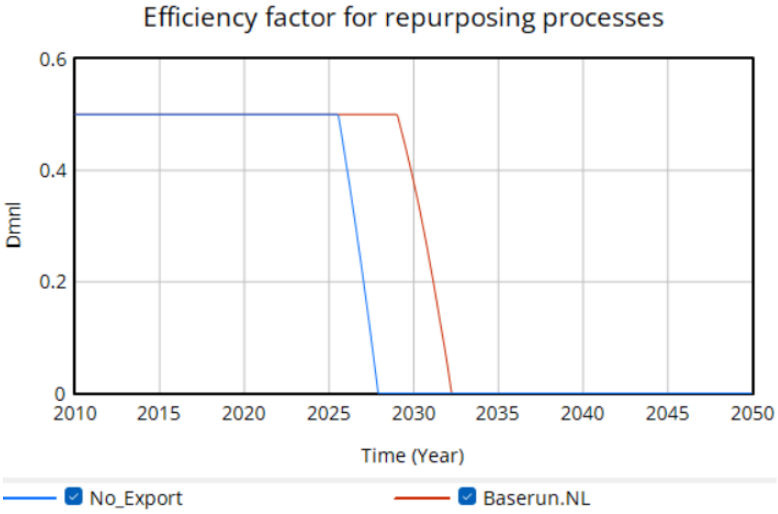

Figure 26: Extreme conditions test of no export on Efficiency factor for repurposing processes

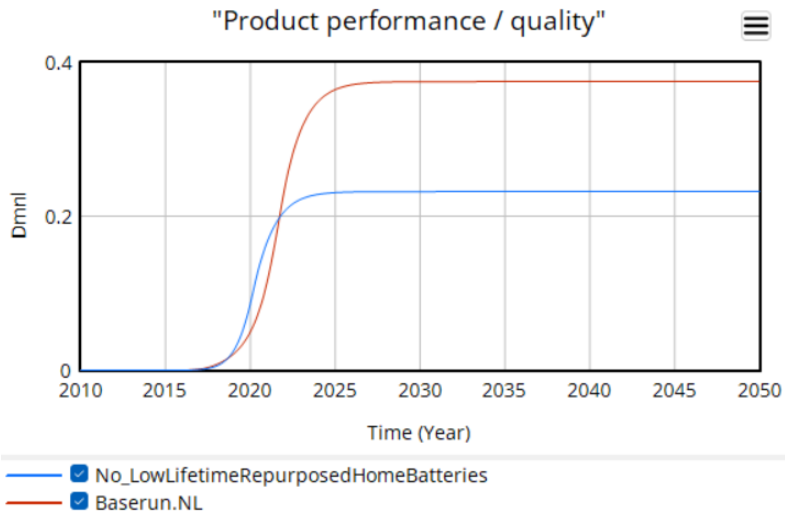

Figure 27: Extreme condition test of Low Lifetime Repurposed Home batteries on Product performance / quality

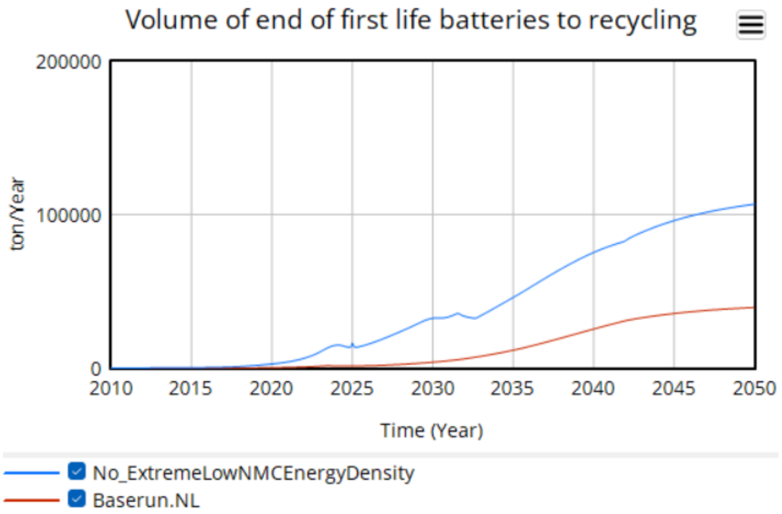

Figure 28: Extreme conditions test Extreme low NMC energy density on Volume of end of first life batteries to recycling.

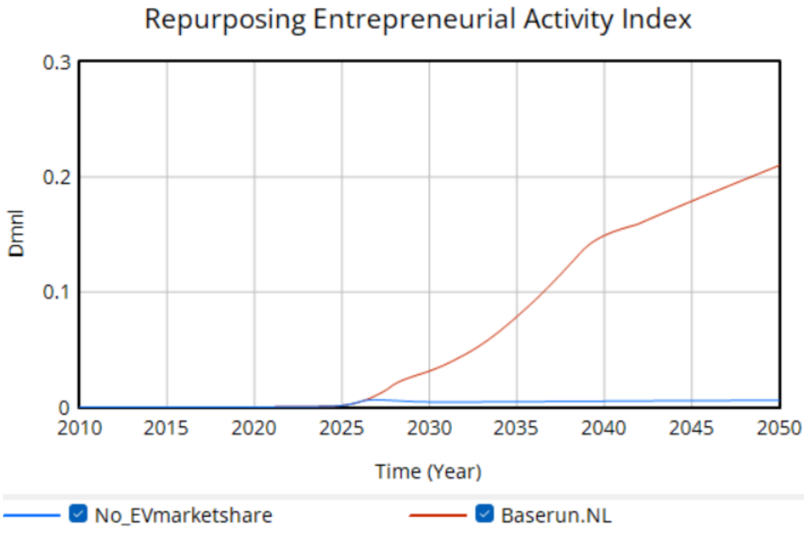

Figure 29: Extreme conditions test on Entrepreneurial activity

Sensitivity test

A behavioural sensitivity test was conducted to assess how sensitive the model is to plausible variations in key parameter values. In line with Senge & Forrester (1980), this test evaluates the robustness of model behaviour to small changes in assumptions and identifies parameters that exert strong influence on system dynamics. Selected parameters were varied systematically within a ±10% range. Univariate sensitivity analysis was first performed to examine the individual effect of each parameter on model behaviour. Following Bala et al. (2017), the test also assessed whether small parameter changes would alter behavioural patterns or undermine conclusions drawn from earlier validation steps. As full-scale diffusion occurs only when all TIS building blocks are sufficiently developed (Ortt & Kamp, 2022), the aggregated building block development indicator was used as the primary KPI. Subsequently, multivariate sensitivity tests were conducted by varying closely related parameters simultaneously to investigate their combined effects. The parameters tested and their respective ranges are presented in Table 12, and the resulting sensitivity graphs are shown in Figures 30–39.

Table 16: behavioural sensitivity test input values

Parameter	Lower value	Base case value	Upper value
Pressure needed to implement repurposing mandates [dmnl]	0.765	0.85	0.935
Max subsidy level [dmnl]	0.54	0.6	0.66
Share of batteries with high state of health [dmnl]	0.72	0.8	0.88
Dutch max repurposing supply [EV/year]	259,200	288,000	316,800

Percentage battery capacity at second-end-of-life [dmnl]	0.54	0.6	0.66
Percentage battery capacity at end of life stage [dmnl]	0.72	0.8	0.88
Average energy density of NMC batteries [kWh/ton]	180	200	220
Average energy density of LFP batteries [kWh/ton]	144	160	176
Average battery lifetime for repurposed home storage batteries [years]	8.1	9	9.9
Average lifespan for repurposed stationary batteries [years]	10.8	12	13.2
Max acceptable delay time [year]	0.15	0.1667	0.1833

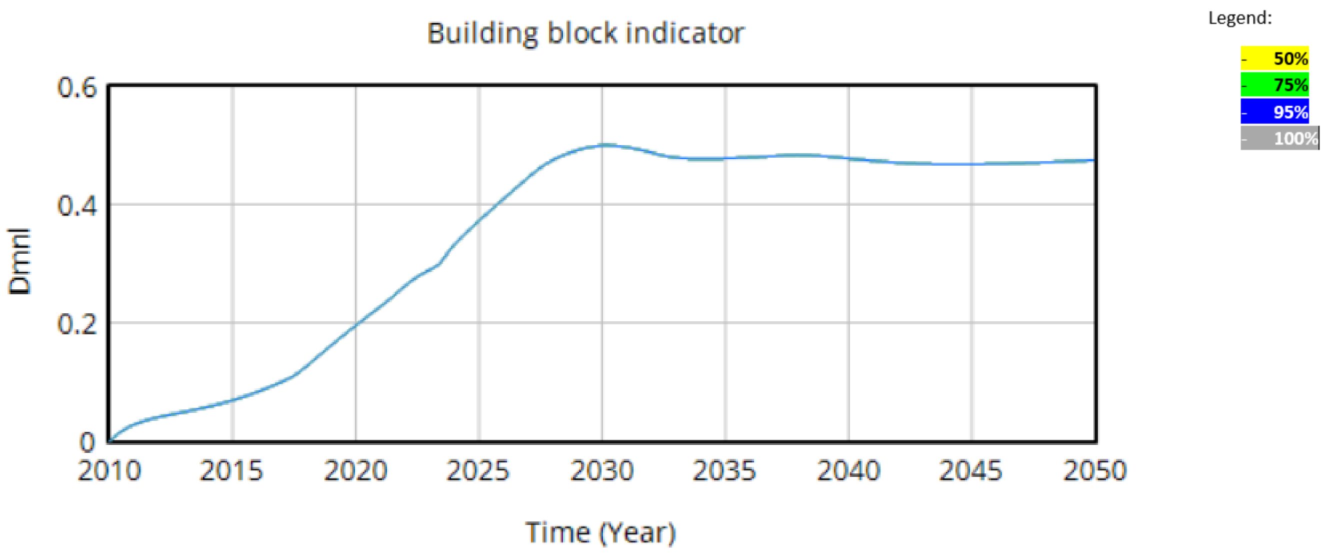

Figure 30: Sensitivity analysis Pressure Needed to Implement Repurposing Mandates NL

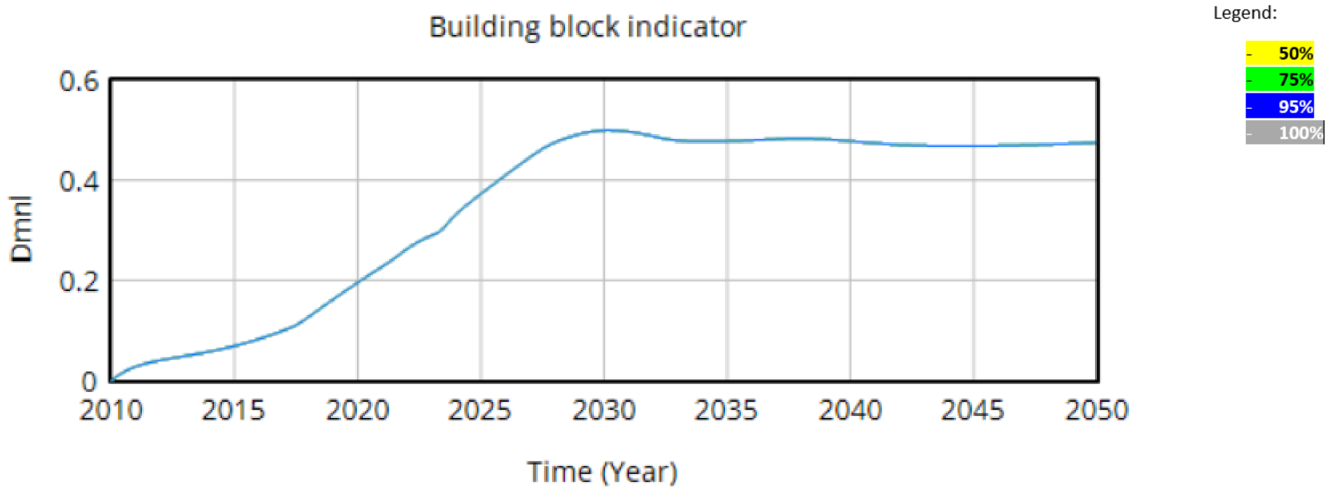

Figure 31: Sensitivity analysis Max subsidy level NL

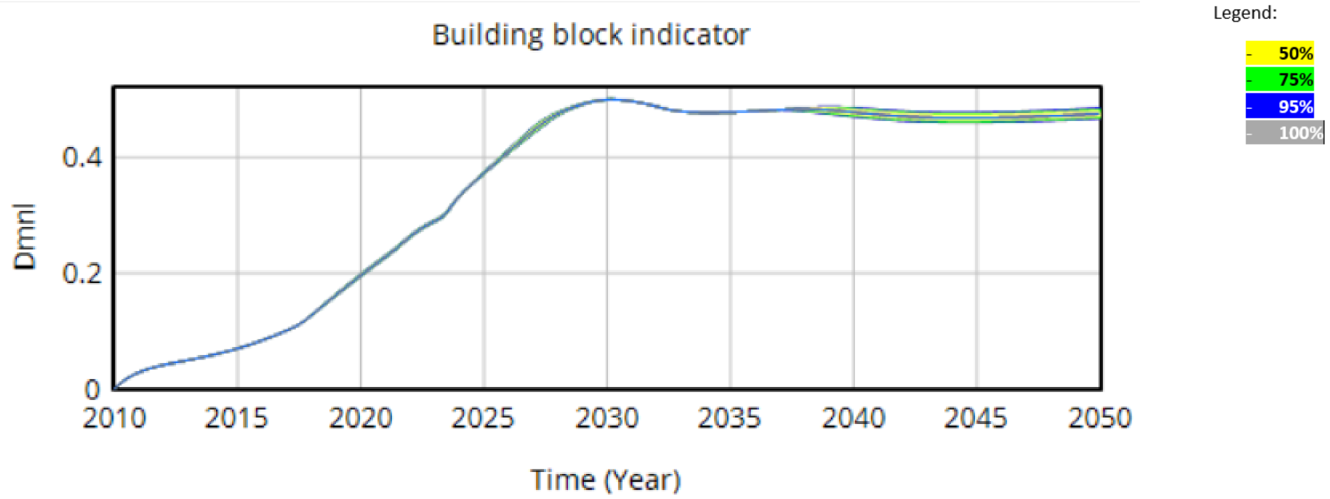

Figure 32: Sensitivity analysis on share of batteries with high state of health NL

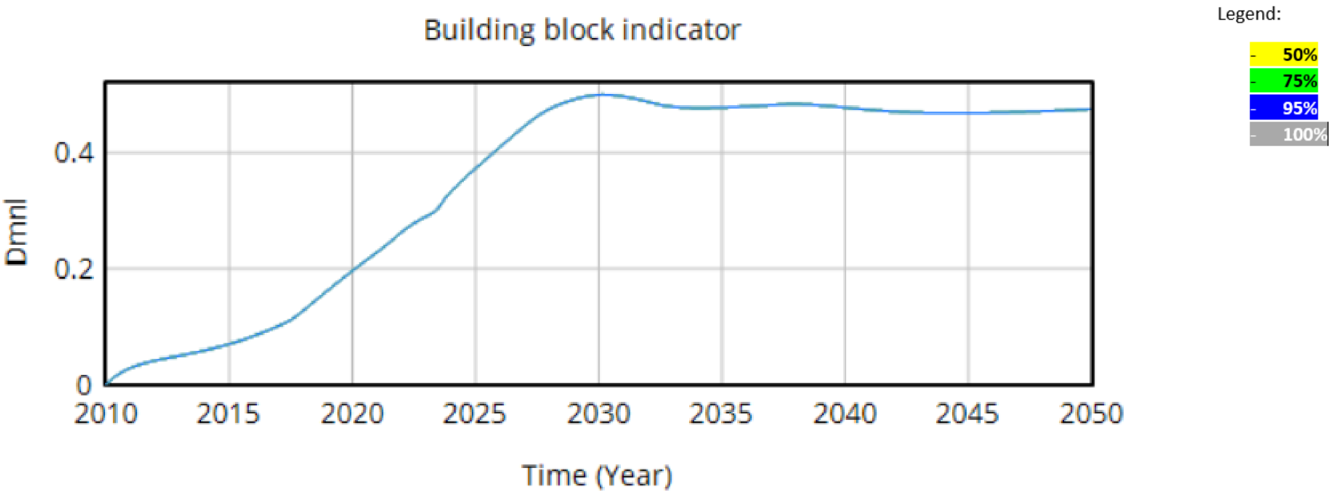

Figure 3310: Sensitivity Analysis on Dutch max repurposing supply NL

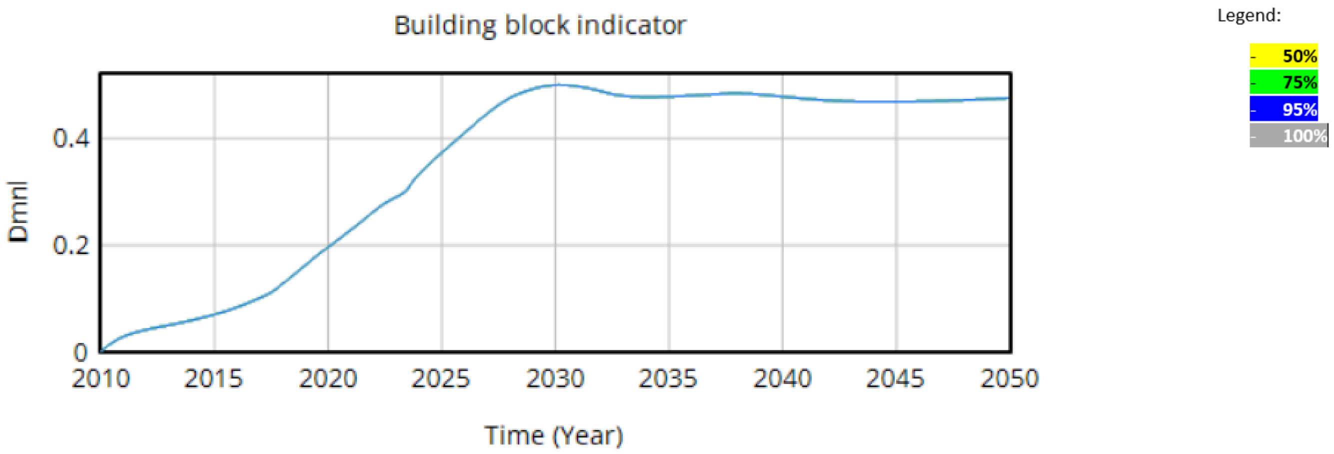

Figure 34: Sensitivity Analysis on Percentage battery Capacity second end of life NL

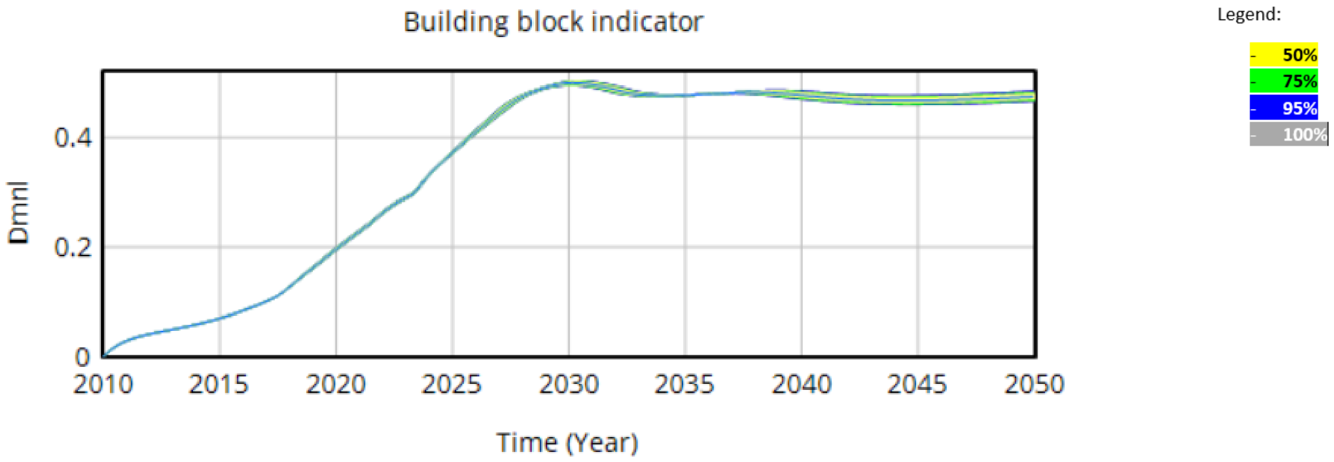

Figure 3511: Sensitivity Analysis on Percentage Battery Capacity at end of life stage NL

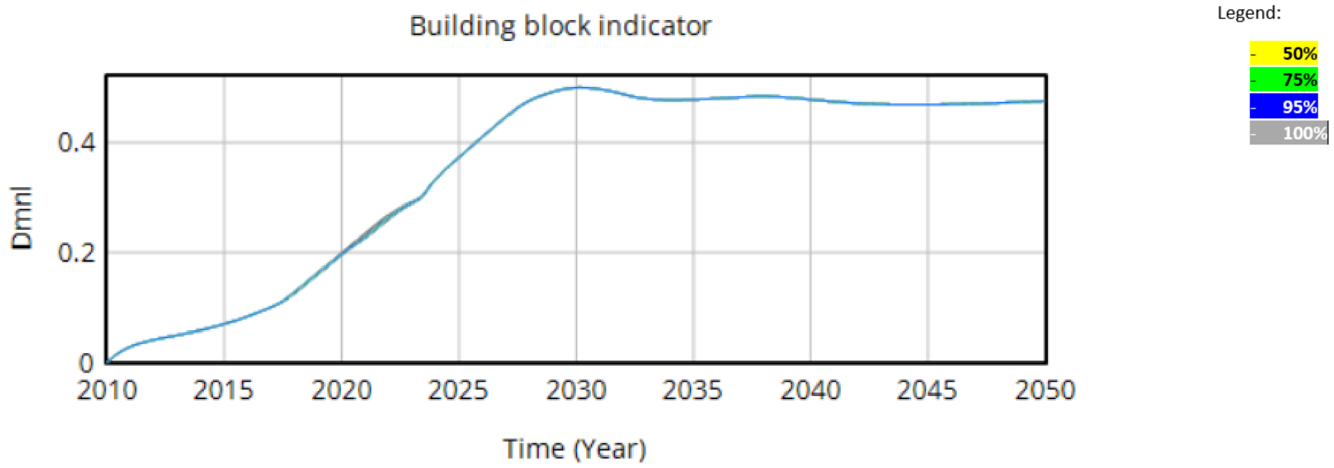

Figure 36: Sensitivity Analysis on Average Energy Density of NMC Batteries NL

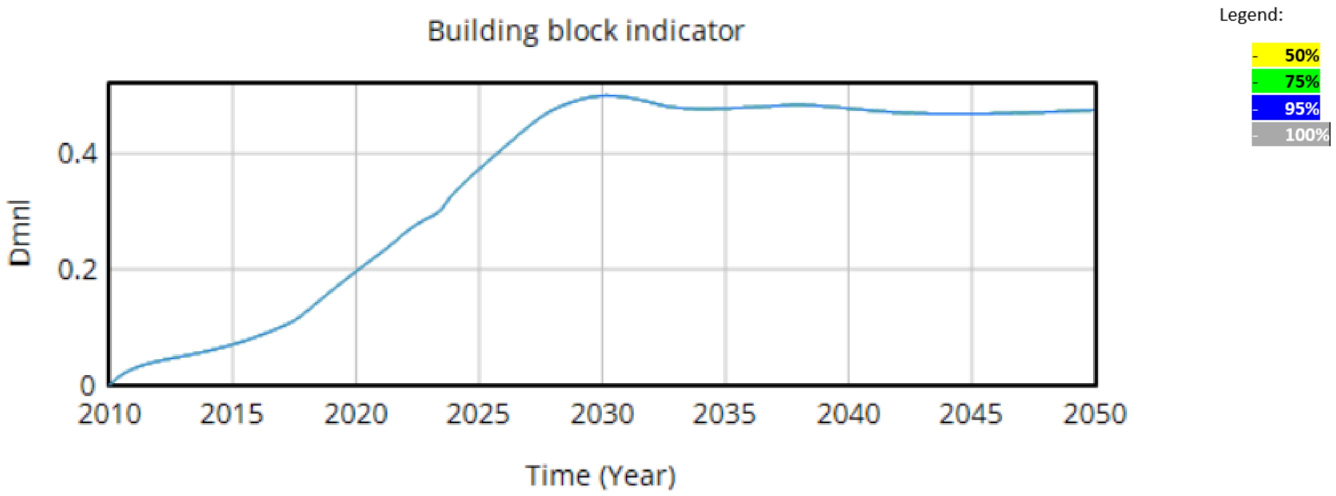

Figure 37: Sensitivity Analysis on Average Energy Density of LFP batteries NL

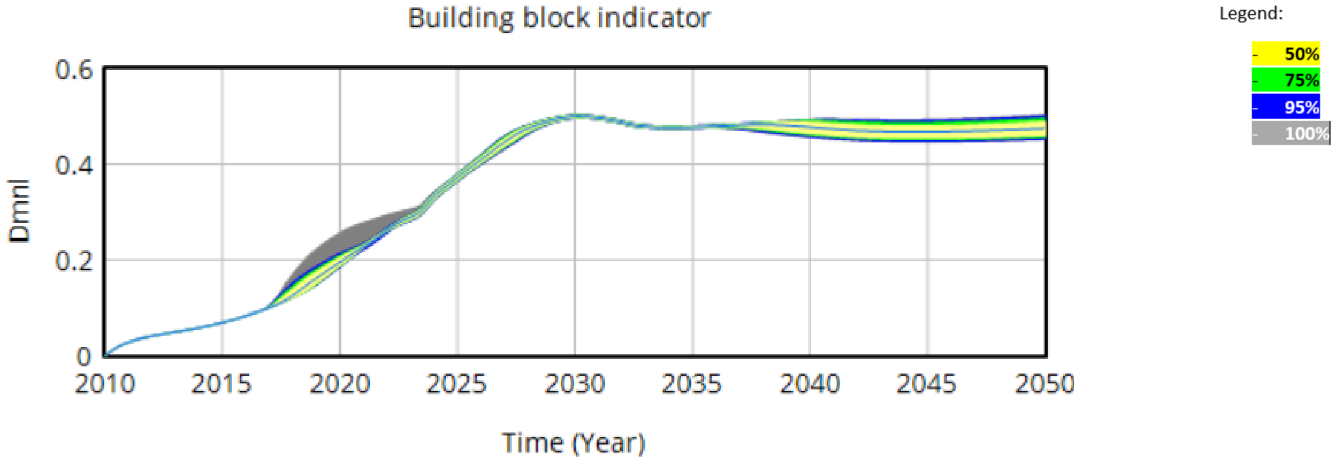

Figure 38: Sensitivity analysis Average lifetime for repurposed home storage batteries NL

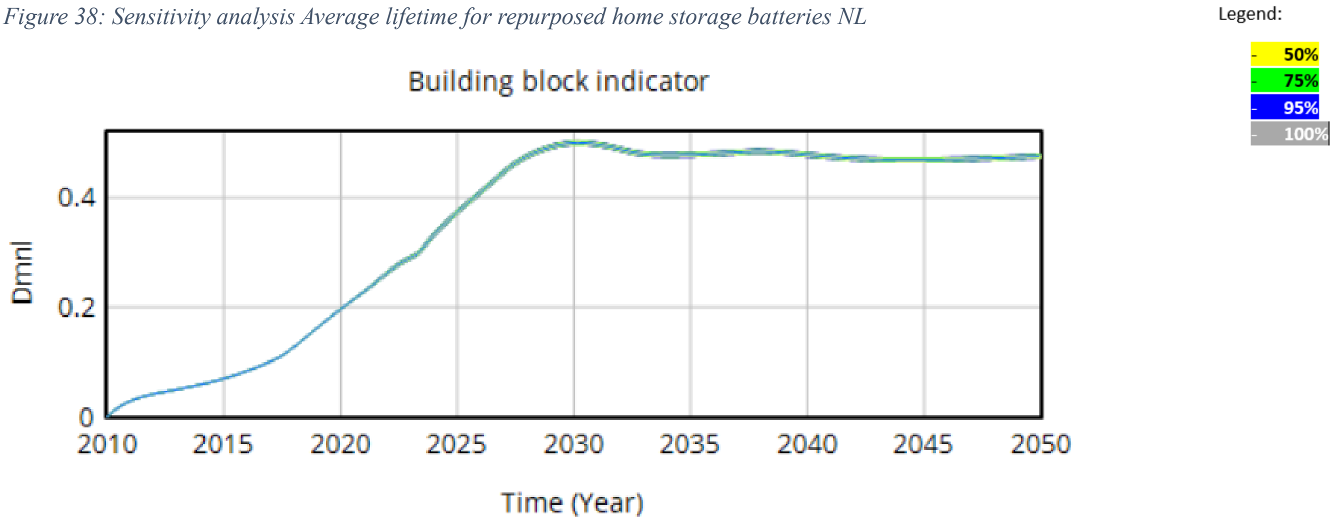

Figure 3912: Sensitivity Analysis on Average lifespan for repurposed stationary batteries NL

Appendix D: interview guide

The interviews were conducted in a semi-structured format. This format allowed for comparability across interviews while leaving room to explore specific issues in greater depth when relevant. As the interviewees held different roles within the EV battery repurposing ecosystem (e.g., OEMs, recyclers, policymakers, energy sector actors), the wording and emphasis of certain questions were adapted prior to each interview to align with the participant's expertise and institutional background.

The guide was structured around three main themes: (1) experience and role in the ecosystem, (2) systemic barriers based on the TIS framework, and (3) assessment of innovation system performance. Where necessary, short explanations of the TIS functions and structural elements were provided during the interview to ensure a shared understanding of terminology.

1. Experience with EV Battery Repurposing

This section aimed to contextualise the participant's background and involvement in the field.

- What is your experience with EV battery repurposing in the Netherlands or Sweden?
- How is your organisation involved in end-of-life EV battery management (e.g., recycling, repurposing, policy, infrastructure, vehicle manufacturing)?

2. Systemic Problem Identification (TIS Framework)

This section explored perceived barriers to the diffusion of EV battery repurposing.

- From your perspective, which system function most strongly hinders the diffusion of EV battery repurposing, and why?
  (Entrepreneurial activities, knowledge development, knowledge diffusion, guidance of the search, market formation, resource mobilisation, creation of legitimacy.)
- Regarding the function identified as the main barrier, which structural elements contribute most to its weak performance?
  (Actors, interactions, institutions, infrastructure.)
- Would you describe this weakness primarily as a lack of presence (missing actors or institutions) or a lack of capability (existing elements not functioning effectively)?
- Which policy instrument could improve the performance of the identified structural element, and how?

3. Assessment of Innovation System Performance

This section focused on expectations regarding future development and system legitimacy.

- What percentage of retired EV batteries do you expect to be repurposed by 2040?
- How large do you expect the repurposing market to become in your country?
- On a scale from 0 to 10, how would you rate the likelihood of widespread adoption of EV battery repurposing in the near future? Please explain your reasoning.
- On a scale from 0 to 10, how would you assess the current influence of advocacy groups on the diffusion of EV battery repurposing? Please explain your reasoning.
- On a scale from 0 to 10, how would you assess the current degree of public support and social acceptance for EV battery repurposing? Please explain your reasoning.

Appendix E: Merged model documentation

Table 17: Merged Model Documentation

Variable Name	Category	Mathematical Formulation	Unit	Initial Value
Adjustment time complementary products and services	Parameter	1	Year	1
Adjustment time institutional fit	Parameter	0.01	Year	0.01
AVERAGE BATTERY LIFETIME OF NEW BATTERY	Parameter	14	Year	14
AVERAGE ENERGY DENSITY OF LFP BATTERIES	Parameter	160	kWh/ton	160
AVERAGE ENERGY DENSITY of NMC BATTERIES	Parameter	200	kWh/ton	200
AVERAGE LIFESPAN FOR REPURPOSED HOME STORAGE BATTERIES	Parameter	9	Year	9
AVERAGE LIFESPAN FOR REPURPOSED STATIONARY BATTERIES	Parameter	12	Year	12
Dutch Max Repurposing Supply	Parameter	288000	EV/Year	288000

Swedish Max Repurposing Supply	Parameter	225735	EV/Year	225735
SHARE OF BATTERIES WITH HIGH STATE OF HEALTH	Parameter	0.8	Dmnl	0.8
PERCENTAGE BATTERY CAPACITY AT END OF LIFE STAGE	Parameter	0.72	Dmnl	0.72
PERCENTAGE BATTERY CAPACITY AT SECOND-END-OF-LIFE STAGE	Parameter	0.6	Dmnl	0.6
Max acceptable delay	Parameter	2/12	Year	2/12
Max collection rate	Parameter	1	Dmnl	1
Max subsidy level	Parameter	0.6	Dmnl	0.6
Pressure needed to implement repurposing mandates	Parameter	0.1	Dmnl	0.1
Repurposing mandate in initial year	Parameter	0	Dmnl	0
Switch Dutch or Swedish	Switch	0	Dmnl	0
LEVEL OF SUBSIDIES FOR CONSUMERS	Policy Variable	0	Dmnl	0
Complementary products and services	Stock	INTEG(Complementary products and services building, 0)	Dmnl	0
Guidance of Search	Stock	INTEG(Development of expectations, 0)	Dmnl	0

"Innovation-specific institutions"	Stock	INTEG(Institution building, 0)	Dmnl	0
"Network formation & coordination"	Stock	INTEG(New networks, 0)	Dmnl	0
Perceived legitimacy of the TIS	Stock	INTEG(Change in PLofTIS, 0)	Dmnl	0
"Product performance / quality"	Stock	INTEG(Performance quality difference, 0)	Dmnl	0
Product system	Stock	INTEG(Production system building, 0)	Dmnl	0
Recycling Factories	Stock	INTEG(acquisition rate + building planned factories - exit rate of recycling companies, 0)	ton/Year	0
Repurposing Factories	Stock	INTEG(acquisition rate for repurposing - exit rate of repurposing companies, 0)	kWh/Year	0
Resource mobilisation	Stock	INTEG(Resource mobilisation rate, 0)	Dmnl	0
Technological knowledge developed	Stock	INTEG(Knowledge development rate, 0)	Dmnl	0
Technological knowledge diffused	Stock	INTEG(Knowledge diffusion rate, 0)	Dmnl	0
Complementary products and services building	Flow	(Gap complementary products and services)/Adjustment time complementary products and services	1/Year	—
Change in PLofTIS	Flow	((1-Perceived legitimacy of the TIS)*(...))/Average time to create formal legitimacy	1/Year	—
Institution building	Flow	Institutional difference/Adjustment time institutional fit	Dmnl/Year	—

Knowledge development rate	Flow	(1-Technological knowledge developed)*Resource mobilisation*(Proportion resources to knowledge/2)/Time to develop knowledge	Dmnl/Year	—
Knowledge diffusion rate	Flow	(1-Technological knowledge diffused)*Resource mobilisation*Technological knowledge developed*(Proportion resources to knowledge/2)/Time to diffuse knowledge	1/Year	—
Performance quality difference	Flow	(Competition difference*Effect knowledge on product performance)/Time to increase performance	Dmnl/Year	—
Production system building	Flow	Production system difference/Time to build elements production system	Dmnl/Year	—
Resource mobilisation rate	Flow	(1-Resource mobilisation)*Guidance of Search/Time to translate GoS to resource mobilisation	1/Year	—
New networks	Flow	(1-'Network formation & coordination')*((Repurposing Entrepreneurial Activity Index+Perceived legitimacy of the TIS)/2)/Time to build networks	Dmnl/Year	—
Volume of end of first life batteries to recycling	Flow	batteries ready for recycling/(average energy density EV battery*PERCENTAGE BATTERY CAPACITY AT END OF LIFE STAGE)	ton/Year	—
Volume of end of second life batteries to recycling	Flow	sending SB batteries to recycling/(average energy density EV battery*'PERCENTAGE BATTERY CAPACITY AT SECOND-END-OF-LIFE STAGE')	ton/Year	—

INITIAL TIME	Simulation Control	2010	Year	2010
FINAL TIME	Simulation Control	2050	Year	2050
TIME STEP	Simulation Control	0.01	Year	0.01
SAVEPER	Simulation Control	TIME STEP	Year	—