The transition to a circular lithium system and the potential effectiveness of Europe's battery circularity policy: an exploratory modelling approach

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The transition to a circular lithium system and the potential effectiveness of Europe's battery circularity policy: an exploratory modelling approach

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Executive Summary

The energy transition makes us less dependent on fossil fuels, but it also brings a new dependence to the table: a dependence on critical metals for green technology. European demand for lithium, an essential material for rechargeable battery technology required for electric vehicles and energy storage, is expected to increase sixty-fold by 2050. One of Europe's strategies to become resilient regarding material availability is to promote the circularity of raw materials. The European Commission has proposed a renewal of the Battery Regulation, which aims to stimulate the transition to a circular battery supply chain, including the circularity of lithium.

This study used an Exploratory System Dynamics Modelling and Analysis approach to analyse the transition to a circular lithium system towards 2050 and the potential effectiveness of the Battery Regulation. First, a system dynamics model was formulated that covers the lithium system and various circularity strategies for lithium-ion batteries, being recycling (with or without lithium recovery), re-purposing of lithium-ion batteries and material reduction. Then, the model was used to perform experiments under a wide variety of uncertainties. With a system analysis, the interactions between the various circularity strategies and the lithium system have been explored. In the subsequent policy analysis, the model was used to examine the effect of the Battery Regulation on the transition to a circular lithium system.

The system analysis showed a form of competition between the various recycling types and re-purposing, in which the profit forecasts for the recycling types react more strongly to rising material prices than profit expectations for re-purposing. While the cost-reducing measures of the Battery Regulation are expected to be more favourable to re-purposing, the mandatory share of recycled content may be encouraging recycling instead. The reduction of cobalt and nickel in waste lithium-ion batteries resulted in an upward shift of the lithium recycling efficiency, meaning that a larger share of the recycling facilities would include lithium recovery in their recycling process. However, in some of the scenarios, it simultaneously led to a decrease of the total amount of recycled lithium. The Battery Regulation is expected to eliminate this risk, as diversion to incineration or landfill will no longer be possible once the minimum processing requirements are in place. Reducing the cobalt and nickel content in lithium-ion batteries is therefore not expected to have a major impact on recycling levels in Europe. At most, it may have a positive effect on the position of re-purposing versus recycling.

Furthermore, the results show that the contributions of lithium recycling to increase the supply capacity, and of lithium-ion battery re-purposing to reduce demand, are limited if demand continues to grow until 2050. This, because not enough lithium has yet been consumed to be subsequently exploited as a secondary raw material. Nevertheless, the Battery Regulation showed to reduce the number of scenarios in which there is a gap between lithium availability and demand, indicating the importance of the implementation of circularity strategies.

For the European context, the full policy as formulated in the announced Battery Regulation is expected to increase the end-of-life lithium recovery rate, even under adverse uncertain conditions. This is caused by the sum of extended producer responsibility, a ban on landfilling and incineration of waste batteries, a minimum percentage of lithium recovery in any recycling process and the mandatory share of recycled content required for fresh batteries. Lastly, if the Waste Shipment Regulation prevents batteries from being exported, no other options remain but to recycle or re-purpose end-of-life batteries within Europe.

The scientific contribution of this study lies in evaluating the transition to a circular lithium system, and in applying an exploratory modelling approach to link the material system to the product-dependent circularity strategies. Interconnecting these system elements added to the complexity of the model and resulted in a couple of challenges regarding the aggregation level. Moreover, European policies were evaluated with a global model, and therefore further research is recommended to test policies at the regional scale. Despite these limitations, the study provided insights regarding the interactions between circularity strategies for lithium-ion batteries and the lithium system and the potential effectiveness of the announced Battery Regulation on the transition to a circular lithium system.

Overall, this study showed that the Battery Regulation is likely to increase the end-of-life lithium recovery rate, also within the European context. However, it is yet unsure whether the set of policies is robust in preventing recycling from coming at the cost of lifetime-extending strategies. Therefore, the European Commission is recommended to better ensure the prioritisation of lifetime extending circularity strategies. Furthermore, even with a successful implementation of the Battery Regulation, the contribution of circularity strategies to increase supply and reduce demand is limited in the short-term. Therefore, it is recommended to give extra focus to the highest rungs of the circularity ladder, *Refuse*, *Rethink* and *Reduce*. In the end, decreasing the material intensity of our economy will at the same time decrease the European dependency on critical materials for the energy transition.

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List of Abbreviations

Abbreviation	Definition
Co	Cobalt
Cu	Copper
EMA	Exploratory Modelling & Analysis
EoL	End-Of-Life
ESDMA	Exploratory System Dynamics Modelling & Analysis
ETFS	Extra Trees Feature Scoring
EV	Electric Vehicle
EU	European Union
KDE	Kernel Density Estimation
L	Levers in XLRM framework
Li	Lithium
LIB	Lithium-Ion Battery
Li_2CO_3	Lithium carbonate
LiOH	Lithium hydroxide
M	Output metrics in XLRM framework
n	number of scenarios
Ni	Nickel
PRIM	Patient Rule Induction Method
R	Model relations in XLRM framework
SD	System Dynamics
SSPs	Shared socioeconomic pathways
X	External factors (uncertainties) in XLRM framework

1. Introduction

If humanity wants to avoid a temperature increase of 1.5 - 2 C°, we have to drastically lower worldwide CO2-emissions (IPCC, 2021). This makes it inevitable that a global shift from fossil fuels to renewable energy needs to take place. Although this shift makes our energy system less dependent on oil and gas, it becomes more dependent on critical raw materials used to produce clean energy technology, resulting in a rapidly increasing demand for materials in the coming decades (IEA, 2021d; The World Bank, 2017). Additionally, Europe is currently largely dependent on imports from non-European countries for the supply of critical raw materials (Bobba et al., 2020; Gregoir & van Acker, 2022).

In 2020, lithium was added to the European list of critical raw materials. According to the definition of the European Commission, a material is considered to be *critical* if it is crucial for the economy and if its delivery is under threat (European Commission, 2020b). Many studies have confirmed the importance of lithium for the energy transition (Calvo & Valero, 2021; Greim et al., 2020; Jones et al., 2020; Junne et al., 2020; Månberger & Stenqvist, 2018; Mohr et al., 2012; Sverdrup, 2016; Xu et al., 2020). It is one of the main materials used for Lithium-Ion Batteries (LIBs), which are currently dominating the market for rechargeable batteries because of their high energy density and long cycle life (Placke et al., 2017). Today, approximately 74% of lithium supply is allocated to the battery industry (USGS, 2022). The global demand for lithium is expected to be 42 times as large in 2040 as it was in 2020 due to the emergence of electric vehicles (EVs) and electrical energy storage applications (IEA, 2021d). The EU estimated that it requires 60 times more lithium in 2050 than is currently being imported for its economic activities (European Commission, 2020b).

Multiple studies foresee that current lithium reserves will be depleted in 2050 (Hache et al., 2019; Junne et al., 2020; Kushnir & Sandén, 2012; Valero et al., 2018) due to the excessive increase in demand. Although lithium is abundantly available from a geological perspective (Yaksic & Tilton, 2009), other aspects that determine the supply risk are the global concentration of supply, political (in)stability, regulations, and social attitudes (Graedel et al., 2012; Grosjean et al., 2012). Rather than the lack of physical availability, resources might become inaccessible due to environmental, social, political, or technical constraints (Mudd & Jowitt, 2018). Furthermore, the pace at which lithium resources become available and thus "flow" into society can form a strong constraint (Kushnir & Sandén, 2012; Vikström et al., 2013).

Europe does contain some reserves and resources in Portugal, Czechia, Finland, Germany, Serbia, and Spain, in which feasibility studies towards increased mining capacities have been or are being performed. However, only approximately 1% of lithium production originated from Europe (Portugal) in 2021. It illustrates Europe's current dependency on import for lithium supply (Kavanagh et al., 2018; USGS, 2022). Furthermore, the LIB supply chain consists of more than mining alone. China has taken a dominant position in the refining and manufacturing phase for lithium and other essential battery materials like cobalt, nickel, and manganese (X. Sun et al., 2019). Simon et al. (2015) showed for a hypothetical situation of a closed European market that Europe would run out of its lithium already by 2026, indicating that Europe is far from self-sufficient when it comes to the LIB supply chain (Lebedeva et al., 2014).

The lithium system's future depends on various uncertain factors on both the demand and the supply side and is thereby characterised by deep uncertainty. Characteristics of systems with deep uncertainty are that there is uncertainty or disagreement about (1) what the appropriate conceptual model is for describing the relationships between elements of the system, (2) the probability distributions that translate the uncertainties into the mathematical model, and (3) how the various outcomes should be ordered from most to least desirable (Lempert et al., 2003). For the lithium system, the uncertainties primarily belong to the first and second types of deep uncertainty. On the demand side, the degree of supply risk largely depends on the extent and speed at which the market for EVs and battery storage develops, both within and outside Europe. For example, the development of China's market significantly impacts the worldwide lithium demand (Jones et al., 2020). Furthermore, the mix of future battery technologies and their specific material content highly impacts the extent to which the lithium demand will increase (Junne et al., 2020). On the supply side, it is uncertain at what pace resources become economically viable to extract. For example, Hache et al. (2019) do not expect any supply problems, based on the assumption that sufficient resources will become available, but point out that China's strategy regarding lithium supply creates uncertainty in the market. Finally, sufficient recycling capacity is expected to avoid or at least reduce supply risk (Greim et al., 2020; Mohr et al., 2012; Olivetti et al., 2017; Sverdrup, 2016; Valero et al., 2018), but it is uncertain how fast recycling capacity will come available.

The European Commission has recognised the importance of ensuring critical material availability and published its resilience strategy (European Commission, 2020b). The strategy contains four general policy directions: to improve the resilience of supply chains, to improve the circular use of resources, to increase domestic mining and refining capacity, and to diversify the supply from third countries. Regarding lithium, the European Commission set the ambition to produce 80% of the lithium supply out of European sources by 2025 (European Commission, 2020b). Although Europe has several lithium reserves, mining them brings uncertainties, risks, and negative (environmental) consequences (Hernández-Morales & Diogo Mateus, 2021). That is why next to additional mining, the European Green Deal considers the recovery of valuable materials from end-of-life (EoL) LIBs as an essential contributor to the supply. Thereby simultaneously reducing the environmental impact of LIBs (Alessia et al., 2021; European Commission, 2020c). In 2019, 51% of all sold batteries and accumulators were collected for recycling (Eurostat, 2019). However, in 2020, 0% of lithium supply originated from secondary sources (European Commission, 2020b). Although it is technically possible to recover lithium, current recycling practices mainly focus on recovering cobalt and nickel because lithium recovery is economically more challenging (Chen et al., 2019; Gaines, 2019).

In 2020, the European Commission proposed a new Battery Regulation. The plan is currently being debated in Brussels and aims, among other things, to address the sub-optimal functioning of recycling markets (European Commission, 2020d). Examples of policies in the announced regulation are at least 70% of lithium recovery from LIBs and the mandatory use of recycled lithium in newly produced LIBs in 2030 (European Commission, 2020a). The dynamics arising from the announced Battery Regulation aimed at the circularity of the LIB supply chain and its effect on the lithium system is the central focus of this thesis project.

For this research, circularity strategies is the collective term used to point towards different strategies that can be applied to move towards a more circular economy. The EC defines a *circular economy* as an economy *"where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised"* (European Commission, 2015). Circularity strategies entail *material reduction* (refuse, rethink, reduce), which is preferred over *life-time extension* (reuse, re-manufacture and re-purpose), which is again preferred over *material recovering* (recycling) (Hanemaaijer et al., 2021). It is interesting to look into the interaction of these different strategies because they might compete. For example, reducing the amount of cobalt in LIBs might harm the business case for recycling since cobalt is nowadays the most valuable metal being recovered (Gaines, 2019). Furthermore, lifetime extension delays the moment these resources can be recovered from waste (Bobba et al., 2019). Although this can never be an argument to stop reusing and start recycling, it is relevant to investigate to which market dynamics and potentially counterproductive incentives circular policies may lead.

Various recent review articles have discussed the state-of-the-art technologies and technological challenges for LIB recycling (Chen et al., 2019; Duan et al., 2022; Harper et al., 2019; Mossali et al., 2020; Windisch-Kern et al., 2022). Other studies focus on the challenges arising from LIB recycling with regard to obtaining full circularity (Velázquez-Martínez et al., 2019), economic aspects (Lander et al., 2021a), environmental impacts (Alessia et al., 2021) or a combination of those (Gaines et al., 2018). Previous studies used a dynamic modelling approach to investigate the potential role of one or more circularity strategies to reduce the supply risk of lithium on either the global or European level. Most studies used Material Flow Analysis on global (Watari et al., 2019; Ziemann et al., 2018), European (Abdelbaky et al., 2021; Bobba et al., 2019) or national level (Busch et al., 2017; Kamran et al., 2021; Qiao et al., 2021). Although these studies yielded valuable insights regarding the potential of circularity strategies both on the global and EU level, market dynamics were not included, despite being highlighted as an important factor (Abdelbaky et al., 2021; Ziemann et al., 2018). Mo and Jeon (2018) investigated the influence of battery recycling on the price dynamics of lithium but did not include how prices affect the development of recycling capacity, while implementation of circularity strategies is largely influenced by its economic feasibility (Albertsen et al., 2021).

Studies that included the lithium price's effect on the development of recycling capacity are Sverdrup (2016), who used a system dynamics approach and foresaw a large role for recycling to make the transition to EVs possible. With a dynamic economic model of the global lithium market, Rosendahl and Rubiano (2019) investigated the potential impact of lithium recycling on the supply side. They discovered that prices would increase much faster when recycling is unavailable, and that market interventions like subsidies are preferred to stimulate recycling. However, these studies did not consider the potential interaction between multiple circularity strategies. Therefore, to the author's best knowledge, no previous research used a system dynamics approach to explore the interaction between the market dynamics in the lithium system and the implementation of circularity strategies. The model has been used to evaluate the effect of the upcoming Battery Regulation in Europe, which has so far only been evaluated using a material flow analysis approach, again excluding the influence of market dynamics (Hoarau & Lorang, 2022). The above-identified research gap results in the following research question:

How will the European battery circularity policy affect the implementation of interacting circularity strategies and the lithium market dynamics towards 2050?

The implementation of interacting circular strategies and the their impact on the lithium system, will be referred to as *the transition to a circular lithium system*. This thesis builds on the work of Auping et al. (2014), Van der Linden (2020), who both used an Exploratory System Dynamics Modelling and Analysis (ESDMA) approach to model the future availability of copper, cobalt, and nickel. As outlined above, this study will explore the lithium system, for which the ESDMA approach has never been used before, focusing on the market dynamics arising from the announced battery circularity policy. However, circularity strategies are not applied to lithium but to the products containing lithium. Since LIBs are the most significant potential source of lithium compared to other lithium-containing products, the focus of this study will be on the circularity of LIBs, stimulated by the Battery Regulation, and their impact on the lithium system as a whole. The time scope until 2050 was chosen because previous research showed that the circularity of lithium becomes important towards 2050, but has limited impact on the short term (Watari et al., 2019).

This thesis project has aimed to fulfil two main objectives. The first objective was to improve the existing system dynamics (SD) model by implementing circularity strategies and their interactions with the market dynamics of the lithium system. The second research objective was to evaluate the effectiveness of the announced European policy regarding the circularity of LIBs under uncertain circumstances. The following sub-questions were formulated to achieve these goals:

1. What are the relations between circularity strategies for lithium-ion batteries and the existing lithium market dynamics?
2. Which uncertainties, policies and outcome metrics need to be taken into account to explore the transition to a circular lithium system?
3. Given the uncertain factors, how does the transition to a circular lithium system develop towards 2050?
4. Given the uncertain factors, how does the European battery circularity policy affect the transition to a circular lithium system compared to a situation with no policy implementation?

The methodology will be discussed in chapter 2. The concepts used for this study and their implementation in the model are explained in chapter 3, leading to an answer to sub-question 1. It is followed by a discussion on the validity of the resulting model for this study. In chapter 4, the included uncertainties, policies, and output metrics are defined, answering sub-question 2. Chapter 5 shows the results of the exploratory analysis concerning the system development and the interaction between circularity strategies and the lithium market dynamics, answering sub-question 3. Chapter 6 shows the results of the policy implementation compared to a situation with no policy, resulting in an answer to sub-question 4. Then, in chapter 7, the used methods, the limitations of the model, and the results will be discussed. The latter section discusses to what extent the modelling results will hold in the real world and the potential effectiveness of the Battery Regulation in the European context. Finally, the conclusion and policy recommendations are presented in chapter 8.

2. Methods & Data

2.1. Approach

A modelling approach has been used to answer the research question of this study. Modelling a system provides the opportunity to simulate many experiments that are impossible to perform in the real-world (Bala et al., 2017). The model was the means to evaluate Europe's battery circularity policy, as well as a deliverable since new structures regarding the circularity strategies have been added.

This study built further on an SD model developed by Auping (2011) to explore the copper system, which has been expanded with the cobalt and nickel system by Van der Linden (2020). Both authors made use of an exploratory modelling approach, which has been defined by Bankes (1993) as *"the use of series of such computational experiments to explore the implications of varying assumptions and hypotheses"* (p. 435). It allows to experiment with different representations of the system and to explore interactions between the system elements under various circumstances, thereby allowing the exploration of systems that suffer from deep uncertainty (Auping, 2018; Pruyt, 2007). Combining exploratory modelling with SD results in the Exploratory System Dynamics Modelling and Analysis (ESDMA) approach (Kwakkel & Pruyt, 2015).

The ESDMA approach can be translated into five steps, eventually leading to an answer to the research question. First, the system and its interacting sub-systems have been mapped. Then, the system had to be translated into a model, also referred to as the modelling formulation phase. Third, the use phase consisted of designing and running experiments with the model, after which the results have been analysed. The last step to answer the main question was a discussion about the extent to which the results hold up in the real world. An overview of the research steps is shown in figure 2.1.

Figure 2.1.: Research flow diagram

2.2. System Dynamics

SD modelling with software tool Vensim was chosen to model the lithium system. SD is particularly suitable for modelling systems with complex and not easy-to-predict dynamics. Therefore it is used to model systems containing feedback loops, accumulation of stocks, and delay structures, since especially the combination of these three can result in very non-linear dynamics (Pruyt, 2013). The lithium system contains multiple feedback loops (e.g., in price dynamics), accumulation of stocks (e.g., mining or recycling capacity), and delays (e.g., when mining or recycling capacity expands), and therefore SD is considered as a very suitable method. SD has often been used before to model material systems (Kwakkel et al., 2014; Olafsdottir & Sverdrup, 2021; Pruyt, 2010; Sverdrup, 2016) and it has also proven to be helpful to study recycling supply chains (Fan et al., 2018; Georgiadis, 2013; Georgiadis & Besiou, 2010) and to study the impact of policy instruments to stimulate recycling (Joshi et al., 2021; Y. Wang et al., 2014).

2.2.1. Model formulation

For this study, building the model consisted of two main steps. First, the initial model, describing the cobalt (Co), nickel (Ni), and copper (Cu) system, was converted into a model describing the lithium (Li) system. Second, the model was expanded to include circularity strategies for lithium-ion batteries (LIBs). These steps are schematically shown in figure 2.2 and explained in detail in chapter 3.

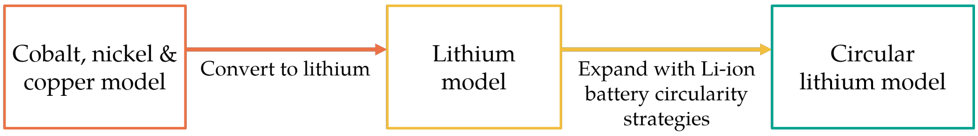

Figure 2.2.: Modelling steps to obtain a suitable SD model

2.3. Exploratory Modelling & Analysis

The experiments and results have been performed and analysed with the Exploratory Modelling & Analysis (EMA) workbench, an open-source python library developed by Kwakkel (2017). The purpose of the EMA workbench is to assist in decision-making under deep uncertainty. It entails tools that help investigate system factors' importance and policies' robustness in multiple ways.

2.3.1. Experimental set-up

One of the key frameworks the EMA-workbench builds upon is the XLRM-framework (Lempert et al., 2003). In this research, the policies evaluated were based on announced EU plans (European Commission, 2020d). These policies have been translated into levers (L) with a specific relationship to the system (R), allowing evaluation of the levers under a large variety of circumstances (X). The performance of the levers was then assessed according to predefined performance metrics (M). Figure 2.3 shows an overview of the experimental set-up. The experiments consist of two parts. First, the development of the lithium system was tested without policy implementation. This part will be referred to as the *system analysis*. In the second round of experiments, the policy comes into play, referred to as the *policy analysis*. Within the experiments, there was a distinction between two levels of the uncertainty space. The level 1 uncertainty space consists of 66 uncertain parameters, while the level 2 uncertainty space consists of a selection of 37 uncertainties. The uncertainty space for both level 1 and level 2, as well as the levers and output metrics, have been defined in chapter 4. During the policy analysis, six extra policy-related uncertainties were included, resulting in 72 uncertain factors in total.

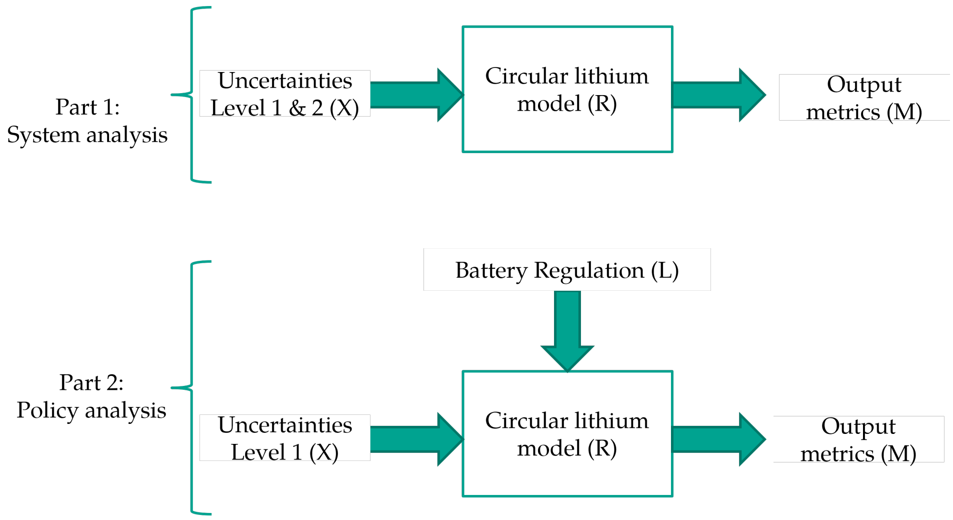

Figure 2.3.: XLRM frameworks for two sets of experiments with and without the implementation of the battery circularity policy

2.3.2. Analysis

EMA can be used for both open exploration, also referred to as vulnerability analysis, and for directed search. Open exploration focuses on how the various uncertainties and policy options, i.e., different states of the world, influence the outcomes of the system. Directed search uses optimisation techniques to find the most robust policy or the worst-case scenario (Kwakkel, 2017). Since the levers have been based on planned EU policy for this study, the goal was to evaluate this policy over the uncertainty space rather than searching for an optimal combination of levers. The analysis was therefore based on open exploration tools, including visual analysis, global sensitivity analysis, and scenario discovery (Kwakkel, 2017). An overview of the analysis methods, their goals, and the settings used for each method is provided in table 2.1 for the system analysis and 2.2 for the policy analysis.

Method	**Tool**	**Number of scenarios (n)**	**Uncertainty space**
Visual analysis	Line graphs with KDE	5000	Level 1 = 66
Sensitivity analysis	ETFS over time	20000	Level 2 = 37
Scenario discovery	Time series clustering & PRIM	20000	Level 2 = 37

Table 2.1.: Overview of methods and tools used for the system analysis

Method	Tool	Number of scenarios (n)	Uncertainty space
Visual analysis	Line graphs with KDE	3000 for each policy	Level 1 = 72

Table 2.2.: Overview of methods and tools used for the policy analysis

Visual analysis

The visual analysis consists of line graphs with Kernel Density Estimation (KDE). Plotting the values of an output metric for each input scenario over time provides insight into the dynamics over the entire uncertainty space. The KDE shows how the scenarios are distributed over the outcome range. Because not all scenarios have the same probability of becoming a reality, the peaks in the KDE do not necessarily equate to the probability that this value will become truth. However, grouping scenarios by input parameters or by whether or not policies are implemented can provide insight into the shifts that occur as a result of these input scenarios or policies.

Extra Trees Feature Scoring

Extra Trees Feature Scoring (ETFS) was used as a tool to perform the global sensitivity analysis to the results. The most accurate results would have been obtained by using SOBOL sampling and the Sensitivity Analysis library. However, SOBOL sampling requires the number of experiments to be at least 2^n, in which n is the number of uncertainties. For this model, the required number of experiments would become too large and computationally too expensive. Jaxa-Rozen and Kwakkel (2018) found that ETFS is an alternative, less computationally demanding option for sensitivity analysis, which can approximate results that would be obtained with SOBOL sensitivity analysis. Therefore, ETFS will be used to evaluate the relative importance of the different uncertainties over time. A couple of experiments were performed to gain confidence in the validity of the feature scores, of which the results are shown in appendix A. It shows that the scores are sufficiently constant to assume they provide a valid alternative to SOBOL sensitivity analysis.

Scenario discovery

Scenario discovery aims to identify combinations of parameters that lead to a specific outcome of interest. Since this study mainly focuses on the outcome parameters' dynamics over time, the method chosen to discover scenarios of interest combines time series clustering and the patient rule induction method (PRIM). Time series clustering can be used to cluster the experiments which show similar behaviour over time (Steinmann et al., 2020). Subsequently, the PRIM can be used as a guide to explore for each cluster which combinations of uncertainties result in the clusters' behaviour.

2.4. Data

Multiple data types were required for this study. Firstly, building the SD model required qualitative data on how the lithium system functions and how the various system elements are related. Quantitative data is required to parameterise the model. Both qualitative and quantitative input was mainly based on previous scientific research focused on the lithium system and circularity strategies for lithium-ion batteries. Data on lithium resources and reserves were retrieved from USGS (2022). The EverBatt model, which models the costs and environmental impacts of battery recycling to support battery recycling decisions, was used to estimate recycling costs for the different types of processes (Dai et al., 2019). Data on the battery transition was retrieved from Bloomberg NEF by Van der Linden (2020) in 2019. Because this source was inaccessible during this study, it was assumed that the trends anticipated in 2019 are still accurate today. Data from the International Energy Agency (IEA, 2021d) was used as a supplement. Data gaps have been filled by assumptions communicated in the relevant sub-sections. One of the key benefits of the ESDMA approach is that various values for uncertain parameters can be tested, resulting in a broad range of scenarios under which the system can be evaluated.

3. Model

This chapter describes how the conceptualised understanding of the system has been translated into the SD model, thereby providing an answer to sub-question 1.

> Sub-question central to this chapter:
>
> SQ1: What are the relations between circularity strategies for lithium-ion batteries and the existing lithium market dynamics?

First, in section 3.1 an overview is provided of the initial model, the extension with circularity strategies, the resulting feedback loops and interactions and its initialisation. Second, the restructuring of initial model of Van der Linden (2020) towards a model describing the lithium system is discussed (section 3.2). Thirdly, the implementation of circularity strategies is described in section 3.3. Finally, section 3.4 discusses the validity of the model to use it for its intended purpose. The full model can be found at https://github.com/liekevanessen/thesis.

3.1. Model overview

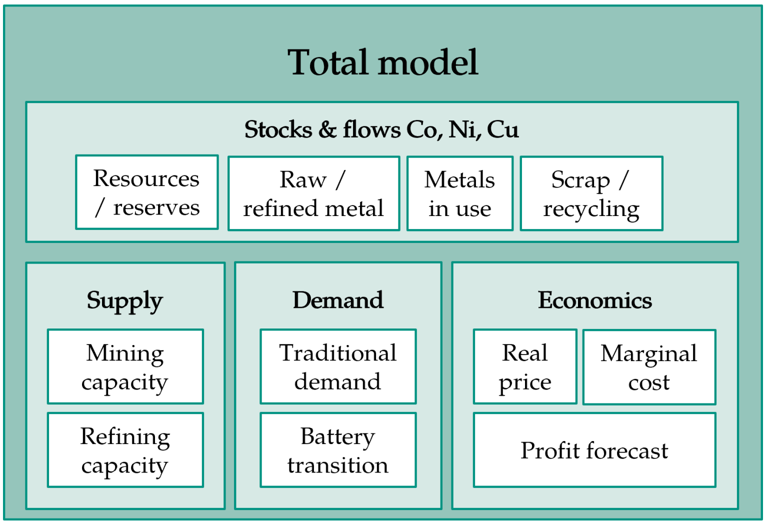

Figure 3.1.: Sub-system diagram of model as built by Van der Linden (2020)

3.1.1. Initial model for cobalt, nickel and copper

The model for this study builds on the initial model of Auping (2011), which describes the copper system. Van der Linden (2020) extended this model for the cobalt and nickel system. A stock-flow structure describes the main system. Three sub-systems determine how these metals flow through the system: the supply, the demand, and the economic sub-system. An overview of the sub-systems included in the initial model is shown in figure 3.1. The lithium model used for this study has been obtained by first restructuring the model to make it valid for lithium and then extending the model with the implementation of circularity strategies.

3.1.2. Model extension for circularity strategies

Circularity strategy	Level of modelling	Implementation in model
Reduce	Exogenous	Represented in uncertain factors: battery capacity for EV, change in technology mix
Reduce	Endogenous	Reduction of demand caused by high lithium price and substitution
Re-manufacture	Exogenous	Uncertain battery lifetime reflects potential lifetime extension due to re-manufacturing
Re-purpose	Endogenous	Re-purposing EV LIBs to stationary storage capacity, competing with recycling and LIB price
Recycle	Endogenous	Two recycling pathways included: pyrometallurgical (with or without lithium recovery) and hydrometallurgical recycling, where profit forecast is based on content and prices of lithium, cobalt and nickel

Table 3.1.: Overview of which circularity strategies are included in the model and how these have been implemented. Circularity strategies are given in order of most desirable (reduce) to least desirable (recycle) according to the R-ladder.

Scoping of circularity strategies

The Netherlands Environmental Assessment Agency adopted the R-ladder to order different circularity strategies with the most preferred strategies (refuse/rethink, reduce) on top and the least preferred strategies at the bottom of the ladder (recycle, recover) (Hanemaaijer et al., 2021). This study considered the strategies *reduce, re-use (re-manufacture and re-purpose), and recycle*. No distinction was made between *rethink, refuse and reduce*. The term *reduce* indicates a reduction in the demand for materials per LIB or a reduction in demand for LIBs themselves. *Reuse, repair, refurbish, re-manufacture, and re-purpose* are all strategies that result in an extended lifetime of the battery materials. In this study, there has been distinguished between *re-manufacture* and *re-purpose*. Re-manufacturing points to the lifetime extension in the same application, while re-purposing points to the lifetime extension in a different application. Recycling points towards the methods that recover materials from the used products that can be given a second life in newly produced products. Table 3.1 provides an overview of the included strategies and their implementation and scoping in the model. This study's main focus is handling EoL LIBs either by re-purposing or recycling, also referred to as *EoL processing options*.

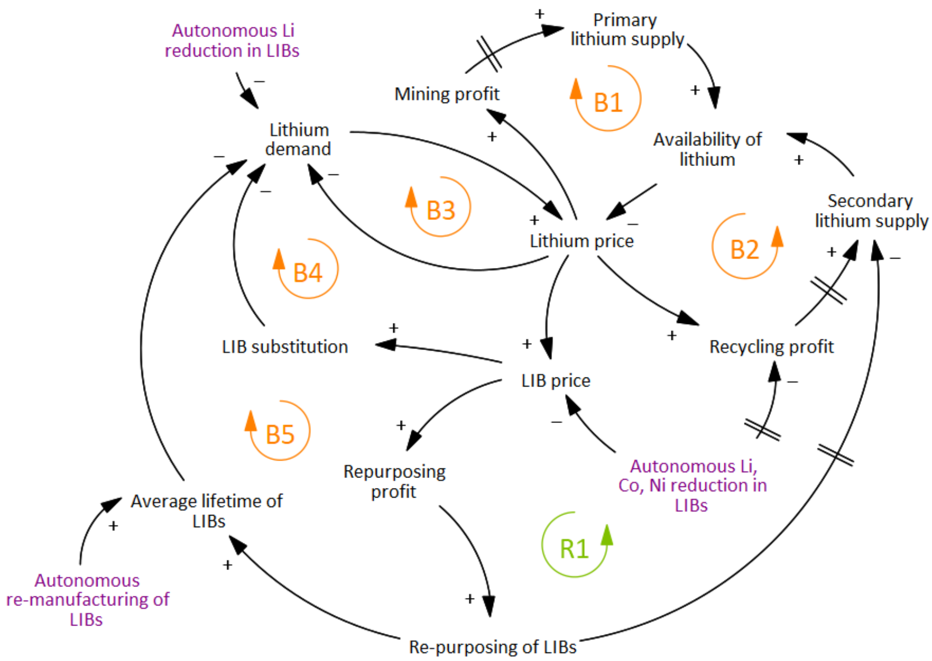

Figure 3.2.: Causal loop diagram of interactions between different sub-models, including the various circularity strategies: reduction, re-purposing and recycling.

Interaction between the sub-models

This study aimed to model the interaction between the total lithium system and the implementation of circularity strategies, including the interactions between the various considered strategies. In order to achieve this goal, multiple sub-models were added to the initial model. Figure 3.2 shows how the sub-models interact.

The balancing feedback loops B1 and B2 show how increasing lithium prices positively stimulate primary and secondary lithium supply, resulting in more available lithium, which causes lower prices in return. It also shows the interaction between the primary and secondary supply system since both primary and secondary are influencing these price and supply feedback loops. In general, the lithium price influences the profitability of lithium recycling, and indirectly the profitability of LIB re-purposing, via the price of new LIBs. Feedback loops B3, B4, and B5 show how demand might be reduced in three ways. Firstly, high prices will stimulate lithium-demanding parties to reduce their required demands. Demand reduction might also be caused by technological innovation, which has been included as an exogenous factor. Secondly, high prices will, at a certain point favour the choice of lithium substitutes. Thirdly, the re-purposing of LIBs, resulting in a higher average lifetime, will partly replace the demand for new LIBs, showing a form of interaction between the total lithium system and circularity strategies again. The only reinforcing feedback loop (R1) in the structure is caused by the fact that the re-purposing of LIBs delays the recovery of materials via recycling (Bobba et al., 2019), which is a typical example of an interaction between different circularity strategies. A second interaction included in the model is the reduction of cobalt and nickel in LIBs, potentially negatively impacting the business case for recycling (Gaines, 2019). The final interaction between re-purposing and recycling is that both methods depend on one and the same flow of waste LIBs and are thus ”competing” EoL processing options.

3.1.3. Model initialisation

The model describes the lithium system over 35 years. 2015 was chosen as a starting point since it was the last year with a relatively constant lithium production and price (Statista, 2022b). It was also the first year the EV fleet reached a size of more than one million cars, after which it started to drastically increase to more than ten million electric cars in 2020 (IEA, 2021b). The battery technology used from 2015-2020 will largely influence the recycling opportunities and requirements since these batteries will be the first large-scale batch available for recycling. Initialising the model in 2015 allows for endogenous determination of the technology mix released for recycling. The model was built in the software tool Vensim DSS version 9.2.1 (Ventana Systems, n.d.), and the model was run with the Euler integration technique and a time step of 0.0078125 years.

3.2. Implementation of primary lithium system

This section discusses the restructuring of the initial model into a model describing the primary lithium system, divided into three sub-models: supply, demand and economics. Structural relations which are not being discussed in this chapter have remained unchanged compared to the model of Van der Linden (2020) and are thus assumed to be valid for the lithium system as well. The reader is referred to the documentation of Auping (2011) and Van der Linden (2020) for a more elaborate discussion of the basic model structure.

3.2.1. Lithium supply

Resources and reserves

Whether shortages of raw materials, in general, caused by exhaustion, are likely to occur has been debated by scholars for many years. Tilton (1996) condenses this discussion into two paradigms: the fixed stock paradigm, which supposes a limited availability of reserves that can be depleted, and the opportunity cost paradigm, which supposes that depletion of current reserves results in higher resource prices, causing more resources to become economically interesting and technologically viable to mine. Reserves are thus defined as our currently exploitable stocks, while the concept of resources points to the total amount of physically present stocks on earth that are likely to become viable to extract in the future (McKelvey, 1972). The resource base is defined as the total amount of lithium that is physically available on earth. Lithium is one of the fourteen most abundant elements on earth, with concentrations ranging from 20 to 65 ppm in the earth’s crust and another 0.17 ppm in seawater (Yaksic & Tilton, 2009), resulting in a total resource base of more than 24 billion gigatonnes of lithium. In 2015, reserves and resources were estimated at 14 and 41 Mt respectively (USGS, 2016), which rapidly increased to 22 (reserves) and 86 Mt (resources) in 2020 (USGS, 2021). This development supports the opportunity cost paradigm, which is thus considered the most appropriate approach for this study.

The two main types of lithium deposits from which lithium is currently being produced are lithium-rich brines and pegmatites (Kesler et al., 2012). Lithium has also been found in clay deposits, and although it only represents less than 3% of global lithium resources, it is expected to become more important in the future (Tabelin et al., 2021). Other potential sources of lithium are geothermal brines, extraction from waste streams, or seawater. However, these deposits are generally more challenging and expensive to exploit because of the low lithium concentrations. For this study, it is not required to know from which sources lithium is produced; therefore, this distinction has not been made. What matters is the costs of lithium extraction and whether extraction is profitable. Section 3.2.3 explains how has been dealt with increasing costs of lithium production due to a decrease in lithium concentration in the different deposits.

Supply developments

The primary supply chains of lithium from different deposits differ significantly. Sourcing lithium from pegmatites follows the traditional mining and refining structure. First, the lithium-rich minerals are mined from the pegmatite deposits, after which several refining steps follow to obtain either lithium carbonate (Li_2CO_3) or lithium hydroxide (LiOH). In the case of brine deposits, after the brine is pumped from the aquifer, Li_2CO_3 is produced by concentrating the lithium solution by solar evaporation and purifying and precipitating the solution (Tabelin et al., 2021). Li_2CO_3 can eventually be processed into LiOH. The model does also not distinguish between the different lithium products. All lithium in stocks and flows is given in tonnes of lithium content as if it was in the form of pure metal (Li). The inherent assumption here is that there is always enough capacity to convert lithium from one form into another. In the case of pegmatites, the mining and refining step often occurs at two locations. In contrast, for brine deposits, the refining steps are often integrated with and take place at the same plant as the mining process (IEA, 2021d). Since no distinction is being made between the different deposits (see section 3.2.1), the model considers lithium production as one process at one location. In reality, there might be an extra delay or limit in capacity due to the lack of availability for one of the production steps, but this is not considered.

Suppose the profit forecast for primary lithium production is positive. In that case, the market will respond at an uncertain pace, indicated by the *Market response factor*, by increasing the *primary production capacity*. The higher the normalised profit forecast, the larger the relative increase of production capacity in preparation. It takes up to ten years to develop new lithium production capacity (Coppola, 2022), so after a delay of five to ten years, the capacity in preparation turns into operational capacity. However, this is only possible when there are enough reserves available. The physical availability of lithium is not the first concern, but whether it is socially and environmentally feasible to exploit these reserves (Mudd & Jowitt, 2018). Therefore, the maximum increase in capacity is limited by the physical availability of reserves, multiplied by an uncertain factor indicating the share of reserves that is politically feasible to exploit.

3.2.2. Lithium demand

Battery transition

Demand for lithium is split into the demand for LIBs and demand for remaining purposes, which are ceramics, glass, and lubricating greases (USGS, 2016). The share of lithium demand arising from batteries rose from 35% in 2015 to 74% 2021 (USGS, 2016, 2022) and is expecting to rise even more in the coming years (IEA, 2021d) as a result of the ongoing energy transition.

Lithium demand for remaining purposes is based on the relatively stable lithium consumption over the period 2010-2015 and moves along with the development of GDP (World Bank, 2021). Van der Linden (2020) used a bottom-up approach to model the demand for cobalt and nickel-based on the number of vehicles expected to be produced and the share of these vehicles that will be electric at a certain moment of production. The input data from Bloomberg NEF have not been adjusted. However, EV took 10% of the global sales market in 2021 (IEA, 2022), which indicates a faster transition than initially implemented in the model. Therefore, a scenario was included with faster uptake of EVs, reaching a share of 100% in 2050.

The model distinguishes three types of batteries: LIBs for EVs (buses, trucks, and cars), LIBs for portable electronics, and LIBs for stationary energy storage. The demand for lithium, cobalt, and nickel is determined by the number of batteries and the chemistry of the cathodes. The lithium content in different types of cathodes is relatively constant between 0.1 and 0.14 kg/kWh of lithium (Olivetti et al., 2017). The same lithium demand has therefore been assumed for the different cathode types, to which production losses and lithium requirements for the electrolyte have been added (Kushnir & Sandén, 2012). Due to technological innovation, reduction of the lithium requirements may be expected, which is why the lithium demand in kg/kWh slightly decreases over time, driven by an uncertain *Reduction factor*.

Battery replacement

The bottom-up approach considers the demand for batteries used in new vehicles. However, it does not account for the fact that the average lifetime of LIBs is generally lower than the lifetime of the vehicles (Abdelbaky et al., 2020). It is therefore expected that LIBs need to be replaced. Demand caused by the replacement of LIBs is based on the battery capacity reaching its EoL and the difference between the average lifetime of the vehicle and the average lifetime of the battery, indicating which share of the batteries needs replacement. If the lifetimes are equal, there will be no replacement demand. If the vehicle's lifetime is twice as large, all batteries are assumed to be replaced.

Future (lithium) batteries and substitution

Although LIBs are so far the winner regarding rechargeable battery technology, multiple next-generation rechargeable batteries are currently being developed, which might substitute LIBs in the future. Expected developments in the near term are the replacement of graphite anodes with silicon anodes and moving from cobalt-rich cathodes to nickel-rich and lithium- and manganese-rich cathodes (Choi & Aurbach, 2016). The shift from cobalt-rich to nickel-rich cathodes has been accounted for as explained in section 3.3.

For the longer term, battery types in development are metal oxide batteries, metal sulfide batteries, batteries in which other metal ions like sodium replace lithium, and all-solid-state batteries (Choi & Aurbach, 2016; Placke et al., 2017). According to Placke et al. (2017) it is very uncertain whether these technologies will be able to replace LIBs in the future. Lithium oxide and lithium sulfide batteries are the most developed for metal oxide and metal sulfide batteries. Since these technologies still require lithium and their performance is uncertain, they are not expected to reduce lithium demand and thus are not considered in this study.

Two forms of lithium demand-reducing substitutions were taken into account: LIBs might be replaced by lithium-free batteries and battery EVs by fuel cell EVs. It is hard to compare the prices of the alternative battery technologies directly to LIBs since both the price and the performance contribute to the choice of a particular battery type. The model assumes that lithium-free batteries are three times as unattractive to choose as LIBs, which decreases over time due to an innovation factor. Fuel cell EVs are typically compared to battery EVs in total transport costs per kilometer. In 2016, these costs were approximately twice as high for fuel-cell EVs compared to battery EVs (Ajanovic & Haas, 2019). The difference is expected to become smaller in the future (Morrison et al., 2018), which is implemented with an innovation factor, reducing the relative costs of fuel-cell EVs over time. The prices of both substitution options are compared to the price of new LIBs. How the LIB price has been modelled will be explained in section 3.3.2.

It is acknowledged that these two types of substitution do not cover all possible replacements of LIBs. Stationary storage capacity, for example, might be substituted by storage in the form of solar fuels, pumped storage hydropower, or concentrated solar power (IEA, 2021c). However, since the leading share of demand is expected to come from EVs, substitution options for EVs are included, and substitution options for stationary storage and consumer electronics have been left out of scope.

3.2.3. Primary lithium economics

The profit forecast for lithium production plays a central role in the model because it determines the relative growth of the *Primary production capacity*. It is based on the marginal cost of mining and refining on the one hand and the lithium price determining the revenues of mining on the other hand.

Marginal costs of production

Yaksic and Tilton (2009) analysed in accordance with the opportunity-cost paradigm how much lithium would become available for extraction in case producers are willing to pay higher costs for production due to higher lithium prices. They estimated that if producers are willing to pay 10$/lb of lithium, there would be a practically infinite stock of lithium since this would allow lithium to be produced from seawater. This cumulative availability curve was used to determine the marginal costs of lithium production based on the previously extracted amount of lithium. In this way, the cumulatively mined lithium determines which deposits are the next ones to be extracted and estimates the marginal costs. The curve was calibrated to the current cost of lithium production from brines (S&P Global, 2019) and is being used as a baseline [1]. The model takes into account three energy price scenarios (figure C.2), a cost-reducing innovation factor and potential CO2 costs, resulting in an estimation of the total *Marginal cost of lithium production*.

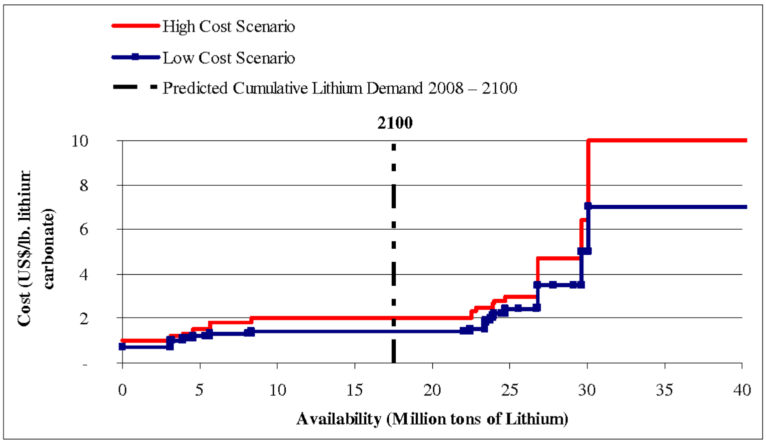

Figure 3.3.: Cumulative availability curve in relation to costs of lithium production provided by Yaksic and Tilton (2009). The high price scenario curve was, after calibration for current production costs, taken was a baseline to model the marginal costs of lithium production.

Lithium price

As shown in figure 3.2, the price plays a central role in the feedback mechanisms in the model. The study of Van der Linden (2020) compared two price mechanisms. The first mechanism is based on lithium availability and forecasted consumption, while the second is based on the days of demand in stock. For this study, it was chosen to continue with the first mechanism. Thereby, the price is directly influenced by the positive or negative difference between forecasted consumption and the supply of lithium.

3.3. Implementation of circularity strategies

The implementation of circularity strategies is limited to those applying to LIBs. How EoL LIBs are handled is influenced by various factors. The interview- and literature-based reviews from Albertsen et al. (2021), Kurdve et al. (2019), and Olsson et al. (2018) were used to determine the most important factors to be included for this study to validly model which EoL strategies will be pursued. It is crucial to understand what drives involved actors to recycle or to re-purpose LIBs. Both Albertsen et al. (2021) and Kurdve et al. (2019) distinguish four categories of drivers for circularity: (1) political and legal factors, (2) economic factors, (3) social and industrial norms and (4) technological factors. Although Olsson et al. (2018) found that collaboration between actors in the battery value chain is of utter importance, social and industrial norms will be left out of scope, because the circularity strategies are being

[1]Lithium production from brines was in 2019 slightly more expensive than from pegmatites (S&P Global, 2019). In general, the price of metals is determined by the costs of the most expensive deposit that can fulfil demand. Therefore the highest price scenario of Yaksic and Tilton (2009) was chosen as the baseline, and the costs of brine extraction were taken as the calibration point

assessed on a more aggregate level rather than on the level of individual company decisions. In line with the initial model (Van der Linden, 2020), economic factors have been modelled endogenously, while technological and political factors have been included as exogenous (uncertain) factors.

Recycling types

There are three main recycling processes for LIBs: pyrometallurgical, hydrometallurgical, and direct recycling (Chen et al., 2019). The main difference between these processes, which is relevant for the flow of lithium through the system, is the stage of lithium when it exits the recycling process and the number of process steps required to result in battery-grade lithium (Chen et al., 2019; Gaines, 2019). Of these three methods, pyro- and hydrometallurgical recycling are the most mature technologies. In the case of pyrometallurgical recycling, expensive materials like cobalt, nickel, and copper are recovered, but lithium normally ends up in the slag. Recovering lithium from the slag is possible but comes with extra processing steps (Klimko et al., 2020). When the lithium value increases, it becomes economically feasible to recover lithium from slag, which was illustrated by the fact that some companies announced lithium recovery after its pyrometallurgical processes (Umicore, 2022). Therefore, in the model, pyrometallurgical recycling is considered in two forms: with or without lithium recovery. First, lithium ends up in the stock *lithium in slag*. Depending on the capacity of slag recovery, lithium flows into the *Refined lithium inventory*, where it merges with the lithium produced out of primary sources. In hydrometallurgical recycling processes, chemical reagents are used to separate and extract the different cathode materials, including lithium, at a relatively high purity (Duan et al., 2022). The output product is comparable to refined lithium, explaining why the flow of hydrometallurgical recycling directly ends up in the *Refined lithium inventory* stock in figure 3.4. Note that losses of non-collected batteries, recycling efficiencies and land-filling and incineration of batteries are not shown in the figure, but are included in the model. A full stock-flow diagram can be found in figure C.1.

Direct recycling is currently in the experimental phase (Chen et al., 2019), and although it might become important in the future, it was decided to leave it out of scope for this study for the following reasons. Direct recycling is currently in the experimental phase (Chen et al., 2019), and although it might become important in the future, it was decided to leave it out of scope for this study for the following reasons. Firstly, since the profit forecast for recycling is based on the raw material prices, it is hard to compare these profits with the profit for direct recycling, which depends on the demand for a specific cathode type. Secondly, it is very uncertain whether direct recycling will contribute to a decrease in primary demand, since the cathodes are revived but not recycled back to the original materials that can be used again for all purposes and cathode types. Therefore, it can also be considered as a lifetime extension of the battery, which is taken already into account as an uncertain factor.

Re-purposing, re-manufacturing and reduction

For this study, only the re-purposing of EV LIBs into energy storage systems is considered, since it is expected to be the main re-purposing destination of EoL EV LIBs (Martinez-Laserna et al., 2018). Re-manufacturing is not included, except that average battery life is an uncertain factor in the analysis. Two types of material reduction are exogenously included in the model. The first is lithium demand reduction, caused by an uncertain factor reflecting

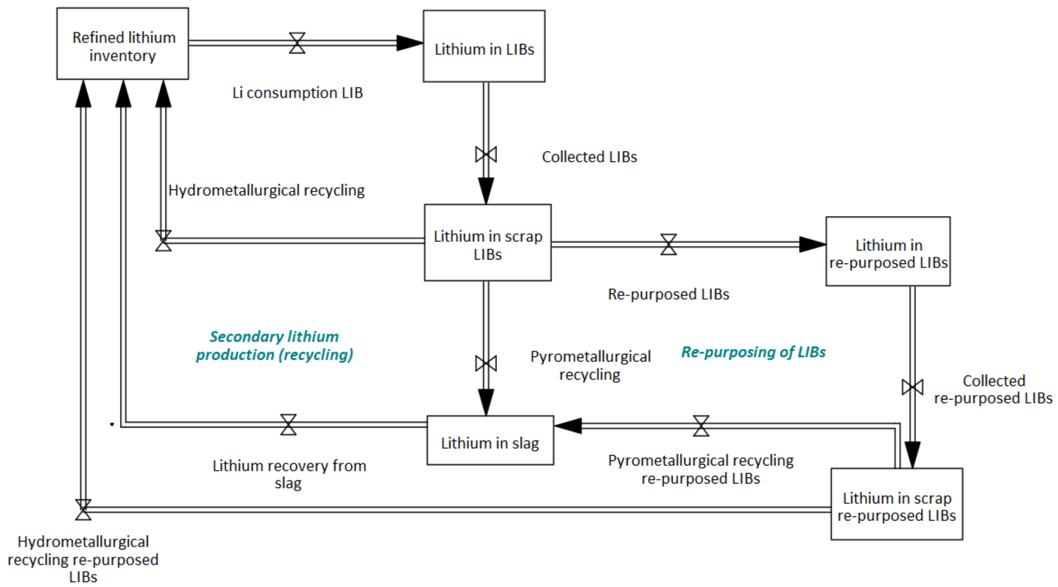

Figure 3.4.: Stocks-flow diagram of implementation recycling and re-purposing.

the reduced lithium demand per kWh, due to technological innovation. The second is the inclusion of three cathode demand scenarios affecting waste batteries' cobalt and nickel content. A shift from cobalt-rich cathodes to nickel-rich types of cathodes was already included in the form of a look-up, varying fractions of demanded cathode types over time, based on data of Bloomberg NEF, used by Van der Linden (2020). Two scenarios have been added. The first one was based on data from the IEA (IEA, 2021d) in which cobalt is reduced somewhat faster and the increase in nickel is limited. The second one is a fictional scenario in which mainly LFP batteries are used, thereby causing a strong reduction in both cobalt and nickel content, as shown in figure 3.5.

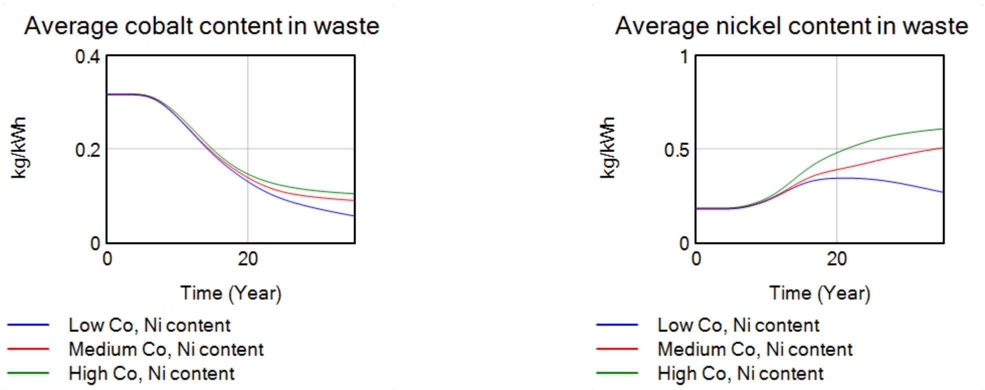

Figure 3.5.: Average cobalt and nickel content in waste resulting from three different cathode demand scenarios.

3.3.1. Economics of recycling

Marginal costs of recycling

Uncertainties in price and costs of different circularity strategies are an essential factor influencing organisations' decisions regarding EoL strategies (Albertsen et al., 2021). The Everbatt model from the Argonne National Laboratory aimed at estimating the costs of closed loop battery recycling and its environmental impacts, was used to estimate the cost ranges for the different types of recycling processes (Dai et al., 2019). The four contributors to the marginal costs of recycling are transportation costs, pre-treatment costs, covering sorting and disassembly, processing costs and potential costs of CO2 emissions.

Since battery transport is classified as hazardous in most countries, it is relatively expensive and therefore taken into account as an endogenous parameter ($C_T(t)$), which has been based on the costs per km (C_{km}) and the average transport distance (d). The average distance is assumed to be decreasing when recycling and re-purposing capacity (RC) increases according to the following equation 3.1. The costs per km are increasing with decreasing distance, for which the relation was determined with experiments in Everbatt (Dai et al., 2019), resulting in a curve determining the costs per kilometer.

$$C_T(t) = d(t_0) * (\frac{RC(t)}{RC(t_0)})^{0.5} * C_{km}(d) \tag{3.1}$$

The pre-treatment costs exist of disassembly costs and sorting costs. The value will be varied over a large uncertainty range during the experiments. It is assumed that pyrometallurgical recycling does not require additional sorting, while hydrometallurgical recycling does (Chen et al., 2019). Therefore, pre-treatment costs for hydrometallurgical recycling are assumed to be 20% larger than the pre-treatment costs for pyrometallurgical recycling.

The processing costs depend largely on the recycling facility its location and scale. Therefore, a large uncertainty range will be taken into account in the analyses, based on experiments done with Everbatt varying different scales (10 to 20 kilotonnes per year) and countries (US, Korea, China and EU) (Dai et al., 2019). Since the experiments showed that for each situation (facility scale and country) hydrometallurgical recycling was around 15% cheaper than pyrometallurgical recycling, the costs for hydrometallurgical recycling are defined as 0.85 * the costs for pyrometallurgical recycling. For pyrometallurgical recycling with lithium recovery, extra costs of lithium recovery need to be included. Data on these costs has not been found yet. However, the recent announcement of Umicore (2022) to include lithium recovery in pyrometallurgical recycling, indicates that the costs weigh up to the revenues. Therefore, the additional costs of lithium recovery from slag were estimated based on lithium prices in 2021. Still, the value will be taken into account as an uncertain parameter in the analysis. Ziemann et al. (2018) and Abdelbaky et al. (2021) reported on the importance of high quality secondary lithium sources in order to achieve primary demand reduction. However, distinguishing between different qualities of lithium is out of scope of this study. It is assumed that the costs of recycling include the purification up to battery grade lithium carbonate. Pre-treatment and processing costs are decreasing over time, since it is assumed that costs will decrease due to learning effects, economies of scale and innovation. This effect is represented by an exogenous innovation factor that will be varied over an uncertainty range in the analysis.

Energy costs are covered within the processing costs. Since the costs of utilities (including energy) are limited to maximum 5% of the total cost (Dai et al., 2019), an in- or decrease in energy price is not expected to have significant effect on the total costs over time. Data on CO2 emissions were retrieved from Everbatt (Dai et al., 2019) and multiplied by the CO2 price in the model, which is determined by the Shared Socioeconomic Pathways (SSPs), that were implemented by Van der Linden (2020).

Revenue of recycling

Profitability largely depends on the mix of battery types and their cathode chemistry (Gaines, 2019; X. Wang et al., 2014). The revenue for EV battery recycling is based on the price of the output cathode materials, since these materials represent the highest value in the LIB (4̃0%) (Chen et al., 2019). Furthermore, the revenue obtained by recycling copper from the batteries is an important driver for recycling (Lander et al., 2021b). Recycling other components (anode, foils and electrolyte) may improve recycling business case and reduce environmental impact, but is not taken into account in this study as a driving factor. Although most revenue nowadays comes from cobalt, nickel and copper, lithium is included because of the purpose of this study and since the expected rise in price might turn lithium into a driving factor for recycling. Above information translates into the following equation to calculate the revenue per recycling type (R_r):

$$R_r(t) = \sum_i A_i(t) * \eta_{i,r} * P_i(t) \tag{3.2}$$

in which A_i refers to the average weight percentage of material i in the battery waste stream, $\eta_{i,r}$ to the recycling efficiency of material i and recycling type r and P_i to the forecasted price of material i. The materials included are cobalt, nickel, copper and lithium. For lithium the price forecast is determined endogenously, as explained in 3.2.3. Since the assumption is that the output of the recycling process will be battery grade lithium carbonate, it is reasonable to base the revenue of recycling on the same price as will be paid for primary lithium, instead of modelling a secondary lithium price. In a later version of the model, there will be distinguished between a primary and secondary lithium price (see 3.3.5). For cobalt, nickel and copper, three price scenarios were included (figures C.3, C.4, C.5). The average weight percentage of the materials is dependent on the mix of cathode types being released in the waste stream and thus on the mix of cathode types being demanded in the year the waste batteries were brought onto the market. The average material content in the waste stream is determined according to the following equation:

$$A_i(t) = \sum_c \alpha_c(t - \tau) * m_{c,i} \tag{3.3}$$

in which c refers to the cathode type, t to the moment when the waste is being released, and τ to the average battery lifetime, α to the percentage of demand fulfilled by a certain cathode type and m to the mass of the material used in the respective cathode type [kg/kWh].

It is important to note that costs are given in dollars per tonne of LIB, while revenues are calculated in dollars per kWh, since the material contents are given in kg per kWh. The energy density of a battery (kWh/tLIB) is therefore an important conversion factor. The main share of the marginal costs for battery recycling are more dependent on the tonnage than on the energy density. Therefore, in the model, a higher energy density of the batteries does not increase the recycling costs, but does increase the revenues. The energy density of a battery depends, among other factors on the cathode chemistry. Therefore, the average energy density of the batteries in the waste stream is based on the relative shares of cathodes in the waste stream, following the structure of equation 3.3. The default values of energy density for each cathode type were retrieved from the Everbatt model (Dai et al., 2019). The average energy density thus changes over time and is coupled to the cathode types demanded in the battery transition.

3.3.2. Economics of re-purposing

The profit forecast for the re-purposing of EV batteries into stationary storage capacity depends on both the costs of the re-purposing process and value of the re-purposed LIB. Costs of re-purposing are the sum of the transportation costs, based on equation 3.1, processing costs (Neubauer et al., 2015), which have been varied during the analysis and are decreasing over time based on an innovation factor, and sorting costs.

Two important factors influencing the value of re-purposed batteries are the demand for LIB energy storage capacity (Albertsen et al., 2021) and the price of new batteries, since a low battery price might harm the business case for re-purposed batteries (Martinez-Laserna et al., 2018). In the model, the maximum value of a re-purposed battery (V_R) is determined by discounting the price of a new battery (P_N) by a health factor (K_h), accounting for the decreased performance of the battery, and a used-product factor (K_u), accounting for the assumption that new products are always preferred over used products (Neubauer & Pesaran, 2011). This function in only correct when there is enough demand for re-purposed batteries in the form of stationary storage capacity. In case the forecasted demand for stationary storage (D_{SS}) is smaller than the supply of re-purposed batteries (S_R), the maximum value of the secondary battery decreases by multiplying it by the quotient of D_{SS} and S_R. This results in equation 3.4.

$$V_R = min(\frac{D_{SS}}{S_R}, 1) * P_N * K_h * K_u \tag{3.4}$$

The price of new batteries is thus also an important factor determining the value of re-purposed batteries. The price of LIBs decreased from 393 $/kWh in 2015 to 132 $/kWh in 2022 and is expected to decrease towards 71 $/kWh in 2050 due to economies of scale in production (BloombergNEF, 2021; Mauler et al., 2021). However, the level of price decline is being slowed down due to increasing material prices (BloombergNEF, 2021). In the model, the increase of the battery price due to more expensive material costs is endogenously modelled, based on the lithium, cobalt and nickel price.

3.3.3. Recycling and re-purposing capacity development

The model's recycling and re-purposing capacity build-up is based on three assumptions. First, it is assumed that operators will only invest in new capacity if they expect the release of waste batteries to be higher than the installed processing capacity at that moment. Second, it is assumed that operators will only invest in new capacity if the profit forecast is positive. Third, since the four EoL processing options will draw from the same source of waste batteries, a division structure had to be defined.

The forecasted availability of waste batteries is determined by the net consumption of lithium for LIBs, delayed by the average lifetime of batteries (τ) and subtracted by operational or prepared recycling and re-purposing capacity (equation 3.5). What is important here is whether the operators anticipate to the fact that not all batteries will be collected and how the waste is divided over the different EoL processing types. Section 4.1.2 will explain how these two factors have been taken into account as structural uncertainty. The amount of recycling or re-purposing capacity that will be taken into preparation is based on the profit forecast for each method and the *Market response factor*, which increases along with the profit forecast per EoL processing type. It indicates to which share of the expected waste stream the market will respond. For example, if this factor equals one, EoL capacity is being prepared for the entire forecasted available waste stream. The decrease in recycling and re-purposing capacity is based on whether the recycling and re-purposing capacities are being used, which is dependent on the availability of waste and whether the recycling and re-purposing activities are still profitable.

$$Available\,waste\,LIBs(t) = LIB\,consumption(t - \tau) - Total\,EoL\,processing\,capacity(t) \tag{3.5}$$

3.3.4. Circularity stocks and flows

The sub-systems, as described in sections 3.3.1 to 3.3.3, ultimately result in flows of secondary lithium and lithium in re-purposed LIBs, as was shown in figure 3.4.

How much lithium is being recycled or re-purposed depends on the recycling and re-purposing capacities built up at a specific moment in time. For simplicity, it is assumed that all recycling and re-purposing capacity will be used, given that sufficient waste LIBs are in stock. The available waste is linearly divided over the different options based on the amount of processing capacity per type. Once LIBs have been re-purposed once, they will be recycled if there is unused recycling capacity left. In case of insufficient EoL processing capacity, LIBs are assumed to be land-filled or incinerated.

Recycled lithium ends up in the same stock as primary lithium, from which lithium can be consumed. Re-purposed LIBs replace part of the demand for lithium in stationary storage capacity. Therefore, the usual demand request in the model is now subtracted by the amount of lithium fulfilled by LIB re-purposing. Since re-purposed LIBs cannot be expected to provide the same capacity as fresh LIBs, the demand is multiplied by the health factor (see section 3.3.2).

3.3.5. Primary and secondary price and demand

Three different sets of assumptions can be distinguished with respect to the distinction between primary and secondary demand and prices:

1. Lithium produced from secondary sources might be of a lower quality than that produced from primary sources, resulting in a lower price for secondary lithium.
2. Lithium produced from either primary or secondary sources results in the same battery-grade material. There is no specific demand for primary or secondary material, but just one demand request for lithium carbonate. Therefore, the market does not care whether lithium was produced from primary or secondary sources, resulting in equal prices for both types.
3. Lithium produced from either primary or secondary sources results in the same battery-grade material. However, a policy may require battery producers to use a specific share of secondary lithium in new batteries. In this case, the market demands a particular share of secondary lithium. This policy-driven demand might result in a higher secondary lithium price if there is a secondary supply shortage. Since the same quality of lithium is still assumed, it is unlikely that prices for secondary lithium will be less than those for primary lithium.

One of the main assumptions throughout this study is that the quality of secondary lithium and primary lithium are equal. Therefore, the first case has been left out of scope. The second case is equal to the base model described in the above sections. The third case describes the situation resulting from one of the policies that have been with the model, being a mandatory share of recycled content (see section 4.2). To test this policy, the distinction between primary and secondary demand and the possible difference in price needs to be included in the model. This structure is thus only active in case the policy is in force.

An additional stock called *Secondary lithium inventory* was added to the model, in which the recycled lithium flows enter. If the policy is not in force, the recycled lithium immediately flows forward to the *Refined lithium inventory*. If the policy is in force, the share of secondary demand determines the consumption of secondary lithium. The share of secondary demand is policy-driven and amounts 4% from 2030 to 2035 and 10% from 2035 onwards, applying only to lithium that is consumed for battery production (European Commission, 2020a). The remaining primary demand is based on the total demand request, minus the consumption of secondary lithium. In case of a surplus of secondary lithium, the remaining stock flows forward to the *Refined lithium inventory*, to ensure this surplus becomes available for primary lithium consumption.

$$P_{sec\,Li} = max(P_{Li}, P_{Li} * \left(\frac{D_{sec}}{S_{sec}}\right)^{\alpha}) \tag{3.6}$$

The *Secondary lithium inventory* is used to calculate the *Secondary Li price* ($P_{Sec\,Li}$). Equation 3.6 follows the same structure used for the primary price (P_{Li}) calculation. The price for secondary lithium thus increases when the secondary supply is insufficient to meet the policy-driven secondary demand. The price increase's exact size is determined by an uncertain factor α. If the secondary supply is sufficient to meet secondary demand, the price of secondary lithium is the same as that of primary lithium. $P_{Sec\,Li}$ determines the profitability of recycling in case the policy is in force. However, it does not influence the secondary demand, since this demand is policy-driven. The implementation of this structure results in an extra balancing feedback loop in the model, shown in figure 3.6.

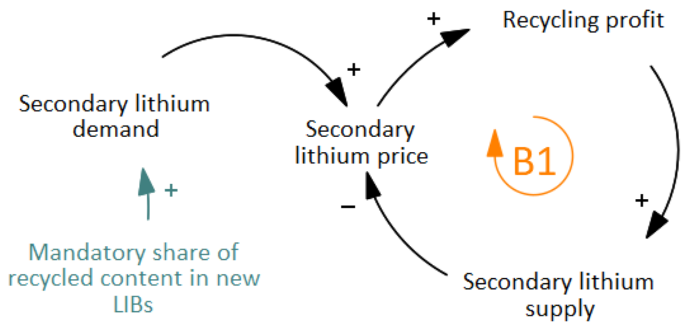

Figure 3.6.: Causal loop diagram showing the feedback loop between secondary demand, price and supply as a result of the policy implementation.

3.4. Model validation

3.4.1. Structural validation

A model can be considered valid if it is suitable for the desired purpose. Forrester and Senge (1980) presents multiple tests to check the validity of SD models. However, in the case of an EMA approach, some validation tests lose relevance due to the purpose of exploratory modelling or are inherently part of the analysis (Auping, 2018). For example, the parameter verification test is less relevant in exploratory modelling since an uncertainty range was given as input to the analysis for many parameters. Which exact value of a parameter suits reality best is of little importance since an ensemble of runs will always be evaluated. Extreme condition tests, aimed at discovering if the model shows expected behaviour even in extreme conditions, are largely covered by the parametric variation during the analysis, given that the input values are sufficiently extreme. In this study, the boundaries do not always reach theoretical limits. However, extreme situations are considered by varying a multitude of parameters simultaneously.

Concerning the remaining structural validation tests, a dimension-consistency and time-step validation test were performed successfully. Boundary adequacy tests were continuously performed during the modelling process. For exploratory modelling, it is essential to include all relevant structural uncertainties or to be specific about which world views have been included (Auping, 2018). This study focuses on examining the possible dynamics of circularity strategies and European policies and not on examining differences in paradigms or world views. Therefore, specific assumptions and implementation choices have been made for most sub-models, and this model does not exhaustively show all possible states of the world. Lastly, structural verification tests were also performed continuously during the modelling and analysis phases, leading to multiple corrections and improvements of the model. Still, the final version is not perfect, and a couple of limitations were found concerning boundary adequacy and structural correctness, which will be discussed in chapter 7.

3.4.2. Behavioural validation

An EMA approach aims to show a considerable variation of what might happen under different uncertain circumstances, thereby explicitly looking into the different behaviours the model produces. Thereby, some behavioural validation tests, like behaviour anomaly tests, surprise behaviour tests, and sensitivity analysis, are inherently part of the analysis (Auping, 2018). In this section, the model's validity is discussed based on a behaviour reproduction test for supply, demand, and the resulting price developments.

An essential driving factor in the model is the price of lithium, which is endogenously determined by the supply and demand sub-models. Therefore, it is important that these sub-models result in realistic projections. Figure 3.7 shows that the uncertainty ranges as specified in section 4.2 result in a broad range of demand and supply forecasts. The forecasting studies of the International Energy Agency and Benchmark Mineral Intelligence fall within the range of results the model creates. The broad ranges allow us to explore the dynamics for both optimistic and pessimistic scenarios.

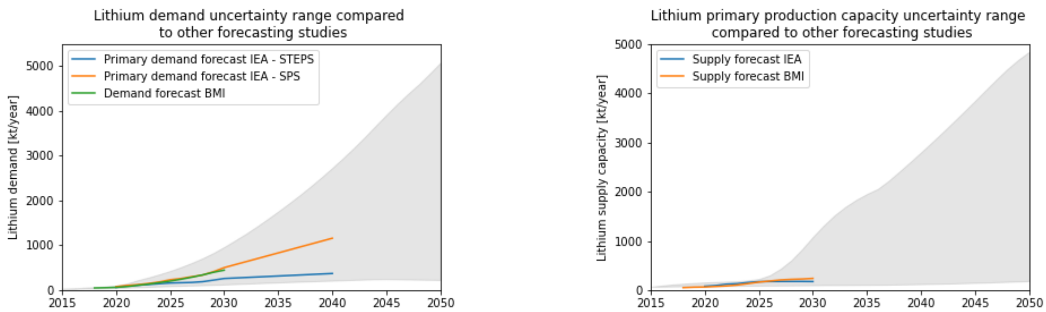

Figure 3.7.: Comparison of demand and supply uncertainty ranges with forecasting studies from the International Energy Agency (IEA) and Benchmark Mineral Intelligence (BMI) (IEA, 2021d; Kramer, 2021)

Figure 3.8 shows the how price develops throughout the model. It shows a large variation in potential situations. However, the bulk of the scenarios leads to price variations between 0 and 250 thousand dollar/ton. Looking at the recent dramatic increase in lithium prices to almost $400.000 per tonne lithium (Spector & Olano, 2022), this does not match the simulation results. In the discussion (section 7.3) will be reflected on the potential reasons for this deviation. On the other hand, the model does include scenarios that approach the current steep price increases. Thereby, the model is still considered valid to explore the dynamics arising from the implementation of circularity strategies.

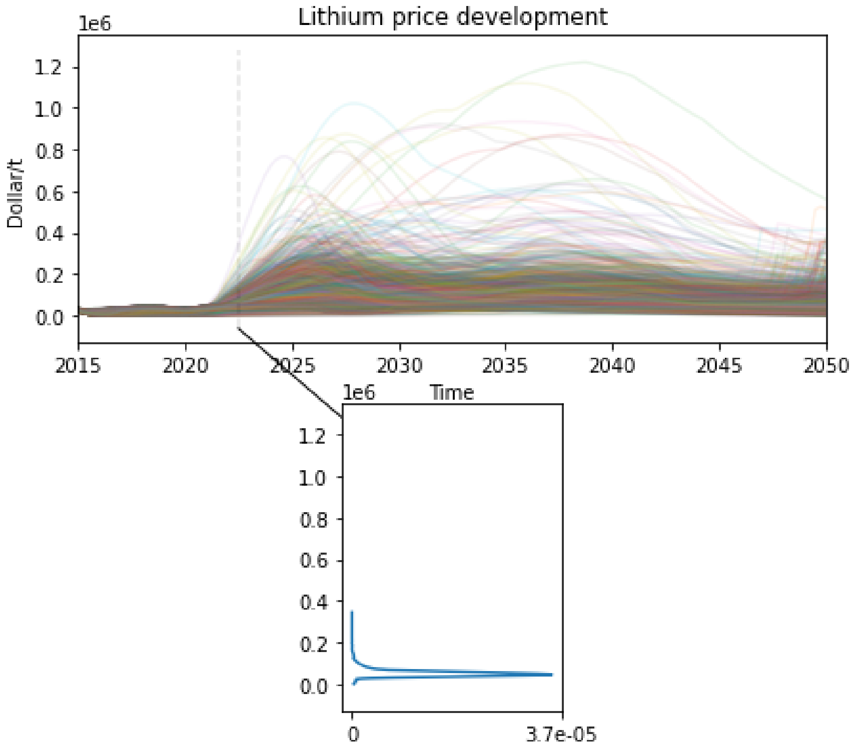

Figure 3.8.: Lithium price development in the model over the full uncertainty space, showing KDE between 2022 and 2023 (n=5000, X=level 1)

3.4.3. Discussion on fitness for purpose

The model used in this study is quite complex and includes many endogenous factors, due to the fact it is an extension of the models built by Van der Linden (2020) and Auping (2011), which did mainly focus on the primary market. By extending the model for the circularity strategies, the model did become more extensive, which means it includes even more assumptions and uncertain factors. Following from this, the model is not deemed valid to predict with any accuracy how the primary and secondary markets for lithium will develop. What the model is designed for, is to explore the potential dynamics between multiple circularity strategies for lithium-ion batteries and between the primary and secondary market for lithium.

Secondly, the model will be used to evaluate the effects of the Battery Regulation, implemented on a European scale. Since the model represents the system on a global level, it is hard to argue that the model is valid for evaluation of the policy on a European scale. However, since Europe is often a world-wide trendsetter when it comes to market standards, it is considered relevant to test the possible effects of the policy with this model. The model is thus deemed valid to explore the effects of the policy as if it were implemented on a global scale. The results will be followed by a qualitative discussion on how local European situation might influence the identified trends. Again, the model cannot predict accurate outcomes of the policy, but it can show the effects of the policy relative to scenarios without policy implementation.

SQ1: What are the relations between circularity strategies for lithium-ion batteries and the existing lithium market dynamics?

The relations between the circularity strategies for lithium-ion batteries and the lithium system, and how these have been implemented in the model are summarised by figure 3.2.

4. XLRM-framework

As introduced in chapter 2, the XLRM framework is the underlying framework of the exploratory modelling and analysis approach. The R, which stands for relations, refers to the model relations, which have been explained in chapter 3. In this chapter, the uncertainty space (X) (section 4.1), policy levers (L) (section 4.2) and output metrics (M) (section 4.3) will be discussed, which together result in an answer to sub-question 2.

> Sub-question central to this chapter:
>
> SQ2: Which uncertainties, policies and outcome metrics need to be taken into account to explore the transition to a circular lithium system?

4.1. Uncertainty space

Thissen and Walker (2013) distinguish two types of uncertainties: those related to the (magnitude of) external factors, referred to as parametric uncertainties, and those related to how the system responds to changes, referred to as structural uncertainties.

4.1.1. Parametric uncertainties

In the experiments performed, two categories of parametric uncertainties can be distinguished. The level 1 uncertainty space consists of 67 parametric uncertainties. The level 2 uncertainty space consists of a selection of parameters from the level 1 uncertainty space, based on the estimated level of uncertainty and the expected level of influence. The level 2 uncertainty space is provided in table 4.2. Some values come from literature, based on which a reasonable margin of uncertainty has been estimated. Other values and ranges are based on assumptions, or the earlier work of Auping (2011) and Van der Linden (2020). The level 1 uncertainties not selected for the level 2 uncertainty space are listed in appendix B.

For the parameters listed in table 4.2, the real values were varied over the range delineated by the minimum and maximum values. That means the values vary across runs but are constant over time within the same run. Four parameters were taken into account in which the values vary over time. For these parameters, shown in table 4.1, two or three different scenarios have been provided as input to the uncertainty space, where each run follows one of these scenarios.

Parameter	Scenarios
Energy price	High, Fluctuating, Declining
Co, Ni & Cu price	High, medium, low
Co & Ni content in cathode mix	High, medium, low
Pace EV uptake	Base, faster uptake

Table 4.1.: Overview of scenario based parameters which have been included in the level 1 and level 2 uncertainty space

4.1.2. Structural uncertainties

Including structural uncertainties leads to different versions of the SD model. Three structural uncertainties have been included in this study.

First, the model assumes that the build-up of EoL capacity follows the forecasted availability of waste. However, multiple processing types will compete for the same type of waste. If all processing options are profitable, there must be some form of waste division over the different types. Two division mechanisms are included. The first and default mechanism is that the relative profitability of the methods linearly determines the shares of waste that are available for these methods, and thus the amount of capacity that will be prepared of a certain type. The second mechanism is also based on relative profitability, but now via a quadratic division. The most profitable processing method will take a larger share, while the least profitable method takes a smaller share compared to the linear division.

A second structural uncertainty included is whether the EoL processing facilities anticipate the expected collected number of LIBs, or the consumed number of LIBs in the past. This would affect the forecasted availability of waste and thus how much recycling and re-purposing capacity builds up, resulting in under or overcapacity.

Thirdly, the distinction between primary and secondary demand explained in section 3.3.5, which is only active when the mandatory share of recycled content is in force, could also be considered a structural uncertainty.

Structural uncertainty	Difference in structure	Included in analysis	Level	Default in level 2
Anticipation on collection rate	With or without anticipation on collection rate	System & policy analysis	1&2	-
Division of waste over EoL options	Linear or quadratic division of waste over types	System & policy analysis	1	Linear division
Primary & secondary demand & price	With or without distinction between primary and secondary demand	Policy analysis	1	No level 2 for policy analysis

Table 4.3.: Overview of structural uncertainties and inclusion in parts of the analysis and level of the uncertainty space

Name parameter	Unit	Min value	Max value	Reference
Additional costs Li recovery from pyro slag	Dollar/t	1500	3000	Estimation based on Umicore (2022)
Average lifetime batteries consumer electronics	Year	2	8	Assumption
Average permit term mining	Year	5	10	Coppola (2022)
Average permit term recycling repurposing	Year	2	5	Assumption
Battery capacity BEV	kWh/Car	20	120	Bloomberg NEF (2019)
Effect of material price on battery price	dmnl	1	2	Assumption
Health factor used batteries	dmnl	0.4	0.8	Neubauer and Pesaran (2011)
Increase in demand stationary storage	dmnl	0.5	0.8	IEA (2021a)
Initial average lifetime EV batteries	Year	8	15	Abdelbaky et al. (2020)
Initial percentage production capacity in preparation	dmnl	0.5	2	USGS (2022)
Innovation factor recycling	1/year	0	0.05	Assumption
Innovation factor repurposing	1/year	0	0.05	Assumption
Innovation factor substitutes	1/Year	0.01	0.1	Assumption
Innovation in mining sector	dmnl	0.7	1	Assumption
Initial market response factor circularity	1/year	0.5	2	Assumption
Market response factor primary production	dmnl	1	5	Assumption
Maximum decrease recycling repurposing capacity	1/year	0.02	0.05	Assumption
Percentage cost on top of marginal cost	dmnl	0.05	0.25	Auping (2011)
Percentage recycling capacity in preparation	dmnl	0	1	Assumption
Political availability of reserves	dmnl	0.1	1	Assumption
Pretreatment costs pyro	Dollar/tLIB	1500	2500	Dai et al. (2019)
Price amplifying factor	dmnl	0.5	3	Auping and Pruyt (2013)
Price averaging period	Year	0.1	0.4	Assumption
Price elasticity long term	1/year	0.1	0.25	Auping and Pruyt (2013)
Processing costs repurposing	Dollar/kWh	20	44	Neubauer et al. (2015)
Recycling costs pyro	Dollar/t	1000	4200	Dai et al. (2019)
Reduction factor lithium	1/Year	0	0.01	Assumption
Relative increase collection rate	dmnl	0.005	0.05	Assumption
Share costs dependent on energy price	dmnl	0.2	0.8	Assumption
Slowing of increase in demand stationary storage	dmnl	0.94	0.96	IEA (2021a)
Substitution threshold batteries[Substitution type]	dmnl	1	3	Assumption
Used product discount factor	dmnl	0.6	0.9	Neubauer and Pesaran (2011)

Table 4.2.: Parametric uncertainties included in both level 1 and level 2 analysis. Dmnl = dimensionless

4.2. The Battery Regulation

In 2020, the European Commission proposed a new Battery Regulation, which is currently debated in Brussels. Although the Battery Regulation was initially planned to come into force in January 2022, the legal procedure is delayed, and it is yet unknown when the process will be completed. This study assumes that the regulation will come into force at the start of 2023. The proposed Battery Regulation has three main objectives: (1) to increase the supply chain resilience by closing the loops of battery materials, (2) to improve sustainability and (3) to limit social and environmental consequences throughout the entire life cycle of batteries.

The European Commission distinguishes thirteen broad categories of measures. Since it is impossible to include all proposed measures from the Battery Regulation in this study, it was chosen to focus on those measures that contribute to the first goal, since it suits the purpose of this study best. The measures all affect the implementation of circularity strategies, thereby affecting the flows of lithium through the system. Furthermore, the measures were evaluated based on quantifiability and alignment with the model's level of aggregation and scope. The different levers will be tested in isolated form as well as in package form. An overview of the included levers and the model implementation is given in table 4.4. The measures will be referred to as the Battery Regulation. Six policy-related uncertainties were included, provided in table B.3. Figure 4.1 shows schematically how the policies affect the system.

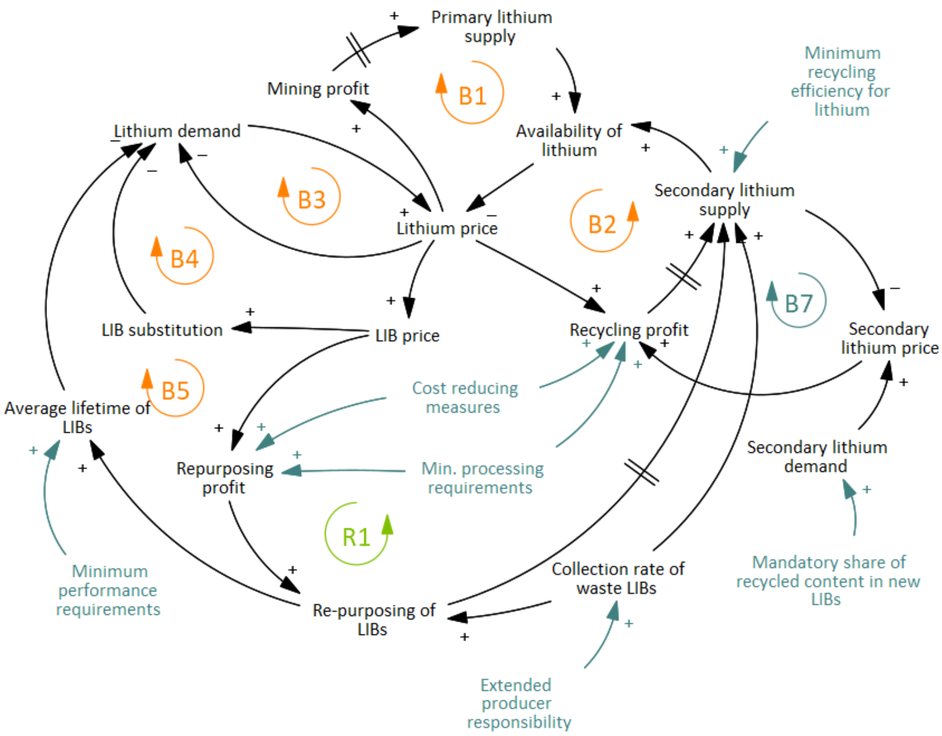

Figure 4.1.: Causal loop diagram of interactions between different sub-models, including the various circularity strategies: reduction, re-purposing and recycling.

#	Measure	Proposed in Battery Regulation	Implementation in model
1	Share of recycled lithium-content in industrial, EV- and automotive batteries (Art. 8)	Mandatory share of recycled content to stimulate the recycling market: 4% in 2030 and 10% in 2035	From 2030 onwards, demand is split into primary and secondary demand as explained in section 3.3.5
2	Cost reduction resulting from new end of waste definition & material passports	EoL batteries will no longer be considered as waste, which lowers the (administrative) costs of re-manufacturing and re-purposing batteries. Material passports for industrial and EV batteries to drive producers towards more sustainable battery production, to facilitate reuse opportunities and increase recycling efficiencies.	Re-purposing costs are decreased with 10-40% (end-of-waste definition) and all pre-treatment costs are reduced by 10-40% (material passports)
3	Minimum performance requirements EV batteries (Art. 10)	Batteries brought onto the European market must fulfil certain quality requirements	Average first lifetime is increased by 10-40%
4	Processing requirements EoL batteries (Art. 56.1 & Art. 57.1)	Collected batteries may not be burnt or land-filled, so all batteries have to be processed by some form of recycling or re-purposing	The outflow via incineration or land-filling are blocked, so all collected batteries stay in stock until they get recycled or re-purposed. The cheapest processing option becomes profitable in case there are no profitable options available yet, because the disposer will have to pay any unprofitable top.
5	Minimum lithium recycling efficiency (Art. 57)	In 2025, each recycling facility should include at least 35% recovery of lithium. In 2030, at least 70%.	All pyrometallurgical recycling facilities will include lithium recovery from 2025, which is also reflected in costs and revenues. No distinction has been made between the different percentages. The recycling efficiency for lithium recovery from slag is varied between 70 and 95%.
6	Extended producer responsibility (Art. 47 & 49)	Battery producers will be held responsible for the collection of all industrial LIBs (EV and stationary storage) and the delivery of these LIBs to a processing facility.	Collection rate is set to 80-95% for all LIBs.

Table 4.4.: Overview of included measures selected from the proposed Battery Regulation (European Commission, 2020d). An overview of the extra uncertainties included in the policy analysis can be found in B.3

4.3. Output metrics

The model yields many output parameters, of which the dynamics are interesting to explore. In chapter 5, the results will be presented in three parts, all with their relevant output metrics. The same output metrics will be used for the policy analysis in chapter 6.

First, the development of the lithium system and the implementation of circularity strategies will be discussed. The output parameters to evaluate the system as a whole are the *Total demand*, *Primary production capacity*, and *Real price Li*. However, it is the interaction between these parameters that is the most interesting, for example, captured in the *Difference between consumption and demand*, indicating whether shortages exist that lead to postponed demand. The implementation of recycling and re-purposing is measured by the *Available EoL processing capacity*, which is defined by equation 4.1. It shows the under or overcapacity for battery recycling and re-purposing concerning the total amount of collected batteries.

$$Available\ EoL\ Processing\ capacity = \frac{Recycling\ capacity + Repurposing\ capacity}{Total\ collected\ waste} \tag{4.1}$$

Secondly, the interaction between circularity strategies will be analysed. The *Difference between profit forecast recycling and re-purposing* will be shown to evaluate the interaction between the circularity strategies. This metric is defined as the difference in normalised profit forecast between the most profitable recycling method and the re-purposing profit. Furthermore, the *Lithium recycling efficiency* (equation 4.2) indicates what proportion of the lithium in LIBs that were offered to a recycling process actually results in secondary lithium production. This metric also illustrates the distribution between different recycling methods because not all methods include lithium recovery.

$$Li\ recycling\ efficiency = \frac{Sec.\ Li\ production}{All\ Li\ offered\ to\ recycling\ process} \tag{4.2}$$

Secondly, the interaction between circularity strategies will be analysed. The *Difference between profit forecast recycling and re-purposing* will be shown to evaluate the interaction between the circularity strategies. This metric is defined as the difference in normalised profit forecast between the most profitable recycling method and the re-purposing profit. Furthermore, the *Lithium recycling efficiency* (equation 4.2) indicates what proportion of the lithium in LIBs that was offered to a recycling process actually results in secondary lithium production. This metric also illustrates the distribution between different recycling methods because not all methods include lithium recovery.

$$Li\ repurposing\ rate = \frac{Li\ being\ repurposed}{Li\ being\ recycled + Li\ being\ repurposed} \tag{4.3}$$

Thirdly, the interaction between the circularity strategies and the lithium system will be evaluated. First, we will look into the share of demand being reduced by re-purposing batteries, indicated by the metric *Demand reduction by re-purposing*. In order to evaluate the contribution of recycling, two output metrics are defined following the definitions used by the European Commission (European Commission, 2018). The first one is the *EoL Recycling Input Rate*, which is defined in equation 4.4. It indicates the contribution of secondary lithium production to the total lithium supply. The recycling of post-production scrap is explicitly excluded from this metric, so it only measures the recycling of lithium originating from waste LIBs. The second one is the *EoL Lithium Recovery Rate*, which is defined in equation 4.5. This metric shows the share of lithium that has been recovered compared to all lithium that ended up in the waste stream. Re-purposing does not count as recovery, but lithium in batteries that have been re-purposed can still be recovered after their second life and thereby contribute to the recovery rate.

$$EoL\ Recycling\ Input\ Rate = \frac{Sec.\ Li\ production}{All\ Li\ production} \tag{4.4}$$

$$EoL\ Li\ Recovery\ Rate = \frac{Sec.\ Li\ production}{Sec.\ Li\ production + Li\ not\ collected + Li\ not\ recycled} \tag{4.5}$$

SQ2: Which uncertainties policies and outcome metrics need to be taken into account to explore the transition to a circular lithium system?

Key insights:

- In level 1 analysis, 66 parametric and structural uncertainties have been taken into account, together resulting in the uncertainty space X. For level 2 analysis, a selection was made out of the 66 uncertainties, resulting in a subset of the uncertainty space comprised of 37 uncertainties.
- From the Battery Regulation, six measures have been extracted and implemented in the model, which are (1) a mandatory share of recycled content, (2) a cost reduction for the recycling and re-purposing process, (3) minimum performance requirements for EV batteries and (4) a ban on incineration and landfilling of batteries, (5) a minimum lithium recycling efficiency for all facilities and (6) an increased collection rate due to the extended producer responsibility.
- Multiple output metrics have been defined to evaluate the transition to a circular lithium system with and without policy implementation. Most important are those reflecting the level of circularity: the Lithium Recycling Efficiency, the Lithium Re-purposing Rate, the EoL Recycling Input Rate, and the EoL Lithium Recovery Rate.

5. Results: System Analysis

In this chapter, the analysis of the results from the exploratory modelling experiments will be presented in order to answer sub-question 4. Within these experiments, the uncertainty space was taken into account, but the policy has not been implemented yet.

Sub-question central to this chapter:

SQ3: Given the uncertain factors, how does the transition to a circular lithium system develop?

The analysis consists of three parts, which contribute to the sub-question's answer. The first part of the analysis focuses on the general development of the lithium system and the implementation of circularity strategies (section 5.1). The second part of the analysis focuses on the interactions between the multiple circularity strategies (section 5.2). This chapter's third part focuses on the interactions between the lithium market dynamics and the circularity strategies (section 5.3).

5.1. General development of the circular lithium system

5.1.1. Lithium demand, supply and price development

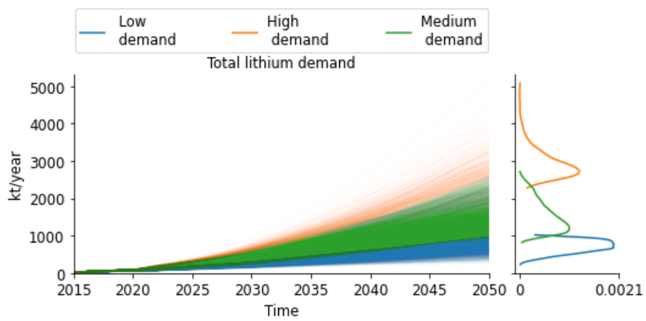

Figure 5.1.: Total lithium demand [kt/year] divided in three clusters: high, medium and low demand (n = 5000, X = 66)

Figure 5.1 shows that the included input scenarios vary greatly in terms of lithium demand. ETFS learns (figure D.2) that this is almost fully dependent on the average battery capacity [kWh/car] demanded by cars. Lithium content reduction and an increased average lifetime of LIBs only have limited influence.

Figure 5.2 shows a large variation in price developments. As discussed in chapter 3.4, most scenarios result in relatively low prices. Generally, there are two periods in which the prices peak, first, between 2022 and 2030, and second between 2035 and 2045. Similar behaviour becomes visible when zooming in on the pink cluster (figure D.3). Time-series clustering was used to discover patterns of how the lithium price develops. However, scenario discovery with PRIM did not lead to any meaningful results. ETFS learns (figure 5.3) that between 2022 and 2030, the uncertainties influencing the demand are most important. This is a logical consequence of the fact that it takes time to scale up primary production capacity, which is thus relatively constant between 2015 and 2025 (figure D.1). Therefore, the demand growth rate is probably the main cause of the price peaks between 2022 and 2030. The pace of scaling up production capacity becomes influential after 2030, which suggests that these peaks are mainly caused when supply fails to scale up sufficiently, even in the long term. Lastly, figure 5.3 shows that substitution becomes important only after 2045.

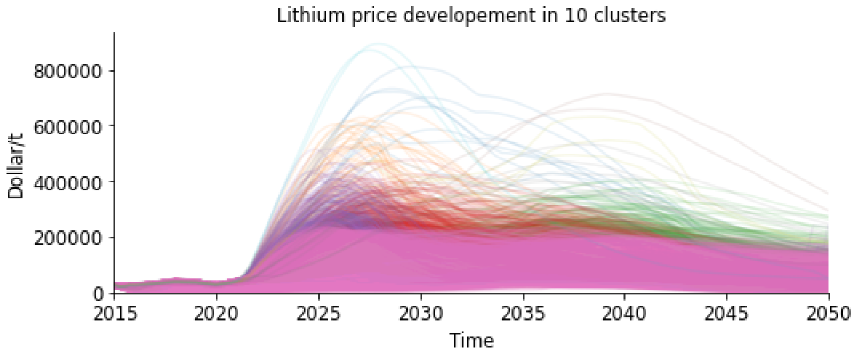

Figure 5.2.: Lithium price [Dollar/t] clustered by behaviour (n = 20000, X = 37).

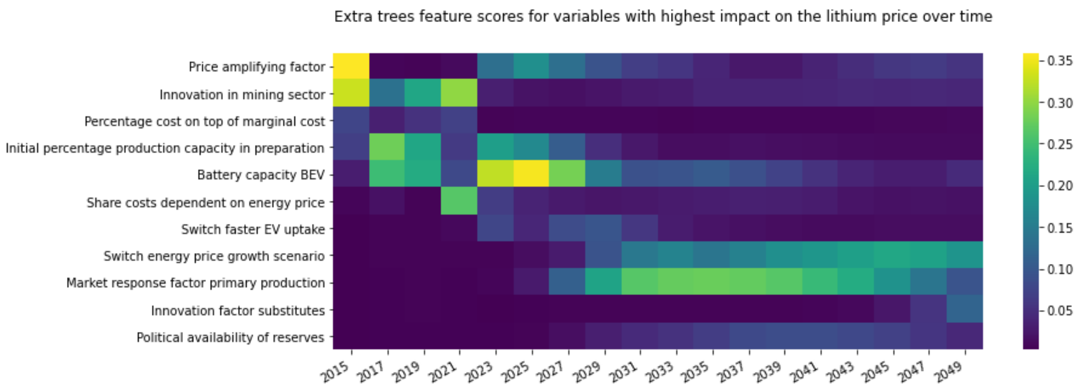

Figure 5.3.: Extra trees feature scoring - Lithium price (n = 20000, X = 37)

Figure 5.4 shows the percentage of scenarios for which there is a difference between consumption and demand, indicating that there is less lithium available than what is demanded by society. It shows that for almost all scenarios, shortages occur between 2020 and 2035. The slight drop in the graph is probably caused by the operationalisation of supply capacity prepared in the first years. ETFS for the difference between consumption and demand (figure D.4) confirms that until 2030, demand is the most influencing factor, while after 2030, the shortage is mainly caused by insufficiently scaling up primary production capacity.

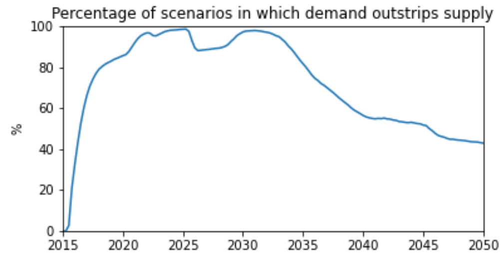

Figure 5.4.: Percentage of scenarios (n=5000, X = 66) for which there is a difference between consumption and demand.

5.1.2. Recycling and re-purposing capacity development

The recycling and re-purposing capacity development are dependent on two structural uncertainties. There is not much difference between the linear or quadratic allocation of recycling capacity over the different types, but whether the market anticipates the collection rate does have a large impact. Figure 5.5 shows that no anticipation leads to overcapacity because the actual number of batteries ending up in the waste stream is lower than expected. In case they do anticipate, the market is always running behind since the collection rate slightly increases over time in the model. ETFS (figure D.5) confirms that the collection rate is very important in determining the total available recycling and re-purposing capacity in the model.

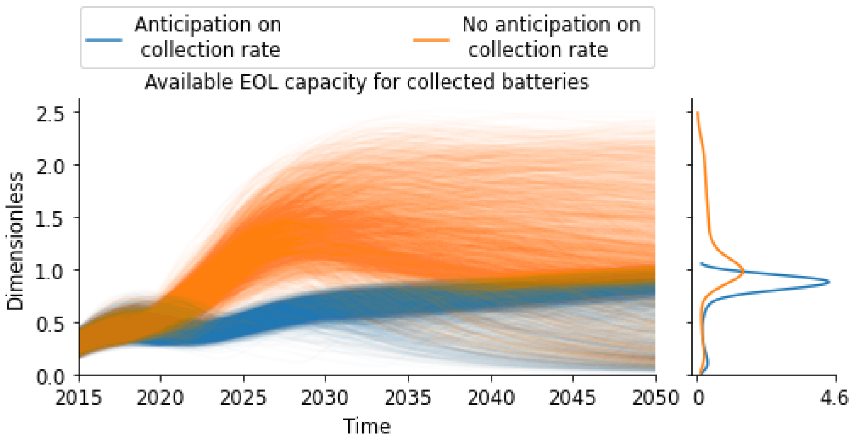

Figure 5.5.: Available recycling and re-purposing capacity divided by the number of collected batteries with and without anticipation on the collection rate (n = 5000, X = 66)

5.2. Interaction between circularity strategies

5.2.1. Recycling vs. re-purposing

The competition between the recycling and re-purposing business cases becomes visible in figure 5.6, showing the difference in normalised profit forecast between the most profitable recycling type and re-purposing. A positive difference indicates that recycling is economically more attractive than re-purposing. From 2025, both processing methods are quite competitive within the uncertainty space. High material prices for Co, Ni and Cu lead to a slight shift favouring recycling, indicating that the indirect effect of the material prices on the battery prices is less strong than the direct effect of material prices on recycling revenues. The importance of the material prices on the profit forecasts of the various recycling types and re-purposing is confirmed by ETFS (figure D.6 and D.7).

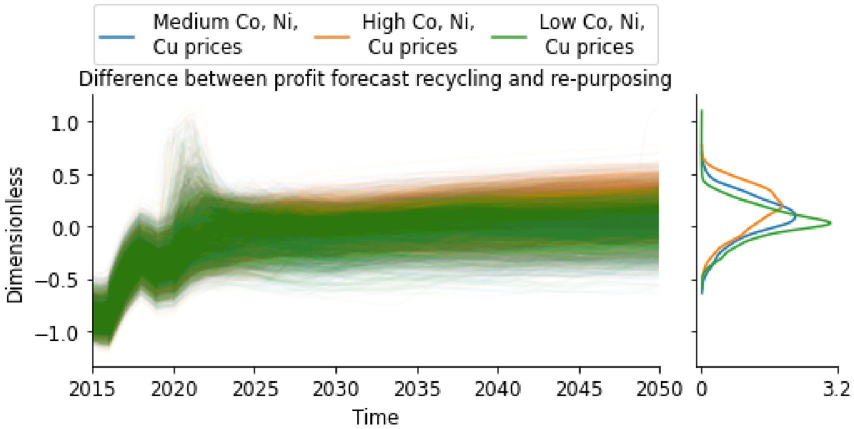

Figure 5.6.: Difference in normalised profit forecast between most profitable recycling type and re-purposing (n = 5000, X = 66). Note: The extreme decrease in re-purposing profitability in 2020 is a result of the model its forecasting structure and should be neglected.

The lithium re-purposing rate shows the proportion of batteries that is repurposed relative to the total number of batteries that is either repurposed or recycled. Figure 5.7 shows that in many scenarios an increasingly smaller proportion of batteries are re-purposed before being recycled, stimulated by high material prices.

5.2.2. Recycling vs. reduction

The lithium recycling efficiency gives insight in which share of the lithium is being recovered within the total recycling flow. A high recycling efficiency means that more LIB recycling facilities include lithium recovery. Interestingly, figure 5.8 shows that for the fictional low cobalt and low nickel scenario, the recycling efficiency shifts upwards, indicating that an increased share of the recycling facilities includes lithium recovery. However, as is shown in figure 5.9 the overall lithium recovery rate shifts downwards, indicating that less batteries are offered to a recycling process. This is not necessarily problematic if it means more batteries will then be re-purposed, but also the total EoL processing capacity shifted downwards (figure D.9).

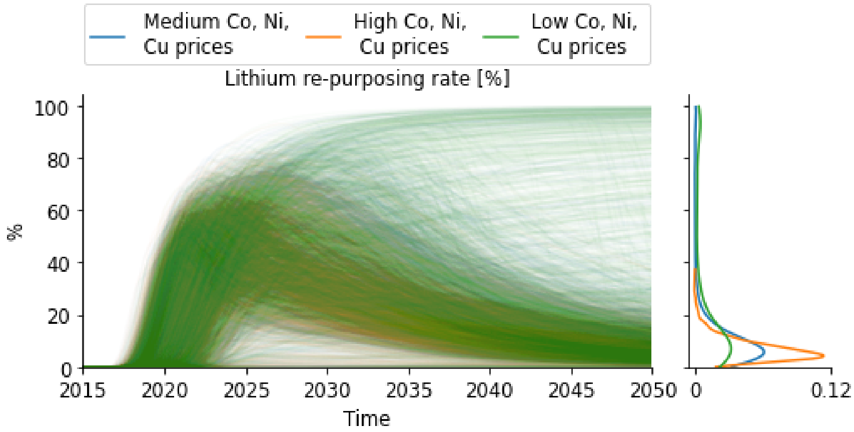

Figure 5.7.: Lithium re-purposing rate grouped by material price scenarios (n = 5000, X = 66)

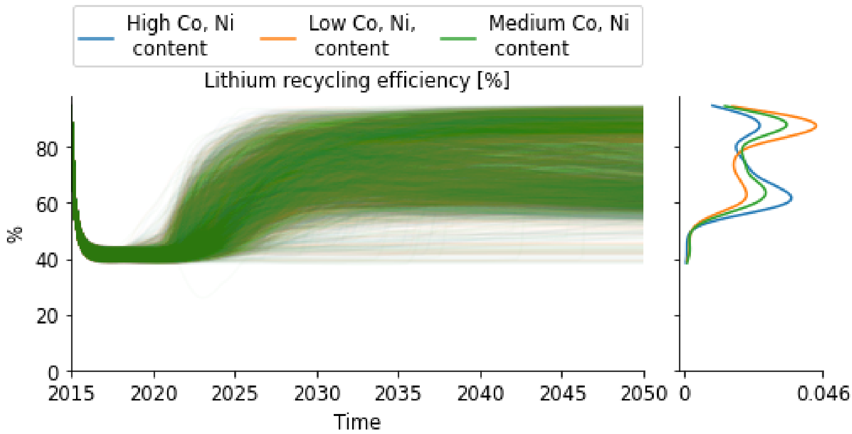

Figure 5.8.: Lithium recycling efficiency grouped by cathode demand scenarios (n = 5000, X = 66)

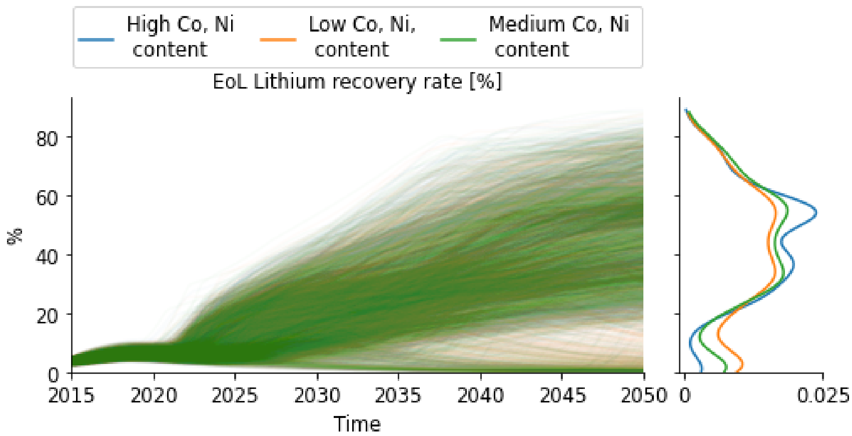

Figure 5.9.: Lithium recovery rate grouped by cathode demand scenarios (n = 5000, X = 66)

5.3. Interactions between the lithium system and the circularity strategies

In the causal loop diagram in figure 3.2, three interactions of the circularity strategies with the primary lithium system can be identified. Firstly, the lithium price partly determines the profitability of recycling and re-purposing. Secondly, secondary supply of lithium contributes to the total availability of lithium. Thirdly, re-purposing increases the lifetime of batteries and thereby replaces part of the demand for primary lithium. These three interactions will be discussed below. Furthermore the over all lithium recovery rate will be discussed, since the system as a whole benefits from not wasting lithium.

5.3.1. Effect of lithium price on circularity strategies

ETFS for the normalised profit forecasts of hydrometallurgical recycling and pyrometallurgical recycling with lithium recovery shows that the battery capacity for cars is one of the most important factors between 2025 and 2027 (figure 5.10). Figure 5.3 shows that during these years, the battery capacity demand is highly influencing the price. This indicates that a fast demand increase has a positive impact on the profit forecast for lithium recycling. However, after 2027, material prices scenarios for cobalt, nickel and copper, and the level of innovation within the recycling industry have a much stronger effect. When we look at the ETFS for the development of recycling capacity, the battery capacity for EV is very important over the full time range (figure D.8). However, this is probably not related to the lithium price, but to the fact that the capacity develops based on the amount of waste that is being released, which is of course a larger amount in case there is a high level of battery consumption.

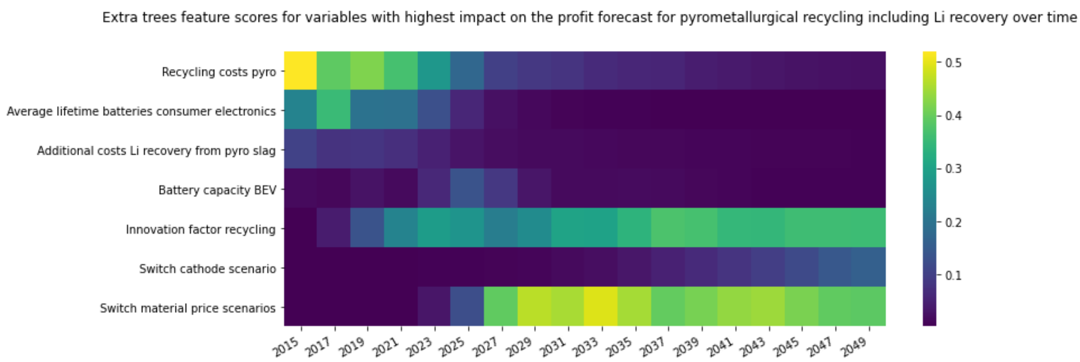

Figure 5.10.: ETFS for normalised profit forecast pyrometallurgical recycling including lithium recovery (n = 20000, X = 37)

5.3.2. Contribution of circularity strategies

Figure 5.11 shows that in the most optimistic scenarios, EoL recycling contributes up to 50% to the total lithium supply. In most cases, the recycling input rate is around 30% in 2050. In general, due to continuously increasing demand towards 2050, recycling will always be running behind and will never reach 100%. The influence of recycling on the price development

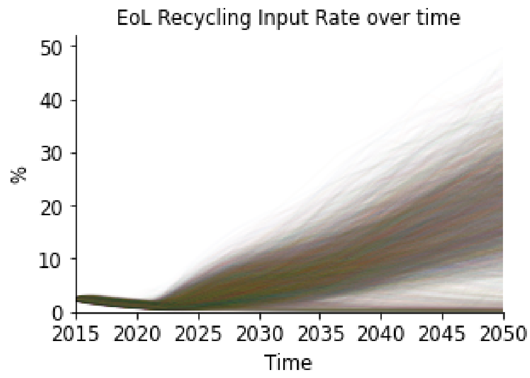

Figure 5.11.: EoL Recycling Input Rate (n = 5000, X = 66)

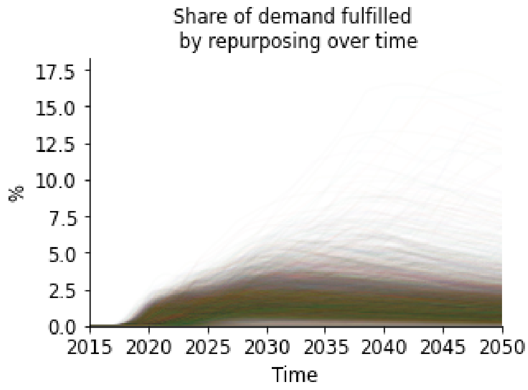

Figure 5.12.: Share of demand that fulfilled by re-purposing (n = 5000, X = 66)

is therefore also limited. In figure 5.12 is shown that re-purposing probably will only have a limited impact by replacing lithium demand. In most scenarios, the maximum percentage of demand that can be fulfilled by repurposed batteries is 5%. It shows that the contribution of re-purposing and recycling to reduce the potential gap between supply and demand is limited on the short term. Thereby, the price dampening effect will also be limited.

5.3.3. Lithium recovery rate

In most of the scenarios, the lithium recovery rate is increasing over time, as shown in figure 5.13. Scenario discovery was performed for each cluster, which did only reveal that the split between a medium and a high lithium recovery rate is primarily caused by the relative increase in collection rate. For the cluster with a recovery rate moving towards zero, no meaningful boxes were found, probably due to the limited number of scenarios in this cluster. However, looking at how it has been implemented in the model, this result only occurs when recycling does not become profitable over the full time frame.

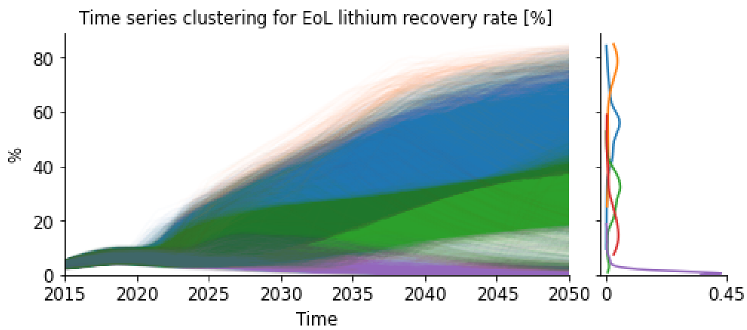

Figure 5.13.: Time series clustering result for the lithium recovery rate (n = 20000, X = 37)

SQ3: Given the uncertain factors how does the transition to a circular lithium system develop?

Key insights on general development of the circular lithium system:

- Between 2022 and 2030, the lithium prices are mainly determined by the level of the demand, while after 2030, the pace at which the primary production capacity increases, becomes more influential.
- In almost 100% of the scenarios, there is a difference between consumption and demand, indicating a shortage of lithium to some extent.
- In the model, the development of recycling and re-purposing capacity and the overall lithium recovery rate is very dependent on the collection rate. In most scenarios, recycling and re-purposing capacity increases over time.

Key insights on the interactions between the circularity strategies:

- Recycling and re-purposing are quite competitive to each other. High material prices are favouring recycling over re-purposing, leading to a decreasing trend in the lithium re-purposing rate.
- Cobalt and nickel reduction in battery waste results in a shift to more recycling facilities including lithium recovery. However, it shifted the total level of recycling downwards.

Key insights on the interactions between the implementation of the circularity strategies and the lithium system:

- The profit forecasts of circularity strategies are sensitive to the lithium prices only between 2025 and 2030, after which the material price scenarios for Co, Ni, and Cu become dominant.
- Contributions of lithium recycling to the increase of supply and LIB re-purposing to the reduction of demand are limited due to the increasing demand until 2050.
- There is only a limited number of scenarios in which no lithium is being recovered in 2050. In most scenarios, the lithium recovery rate is increasing, mainly determined by the collection rate.

6. Results: Policy Analysis

In this chapter, the policy analysis will be discussed. First, the dynamics resulting from each of the individual measures are shown in comparison to the scenarios where no policy has been implemented. Second, the dynamics resulting from the full policy package and the interactions between multiple individual measures are shown.

> Sub-question central to this chapter:
>
> SQ4: Given the uncertain factors, how does the European battery circularity policy affect the the transition to a circular lithium system compared to a situation with no policy implementation?

Since the model is representing the lithium system on a global scale, the results presented in this chapter learn something about the dynamics as if the policy would have been implemented globally. In the discussion, section 7.3.2 will elaborate upon the European context and the effects that can be expected from the Battery Regulation in Europe.

6.1. Exploring the effect of individual measures

6.1.1. Mandatory recycled content

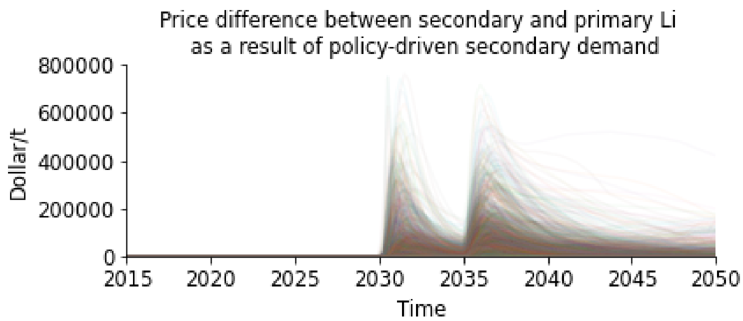

Figure 6.1.: Price difference between primary and secondary lithium (n = 2925, X = 72, 75 extreme scenarios were left out to make bulk visible)

The mandatory recycled content regulation entails that battery producers should use at least 4% (2030) or 10% (2035) of secondary lithium for their production. Figure 6.1 shows the effect of the policy. If the price difference is zero, the policy is ineffective. If the price difference is positive, it indicates that there is insufficient secondary lithium available to meet the policy-driven secondary demand.

Although for a number of scenarios the price increases are high, figure 6.9 shows that the policy may also be redundant. Logically speaking, the policy is only effective when the recycling input rate is lower than 4% in 2030 and 10% in 2035. This means that the policy is mainly effective when the recycling capacity development has been very limited until the moment of implementation. In those situations, it ensures a certain percentage of lithium recovery. However, the recovery rate may also decrease again as shown in figure 6.2. This can be explained by the feedback loop as shown in figure 3.6. When secondary supply capacity is sufficient to meet the targets, prices return to the normal level. In case the processes are not profitable with normal price levels, recycling capacity may be broken down.

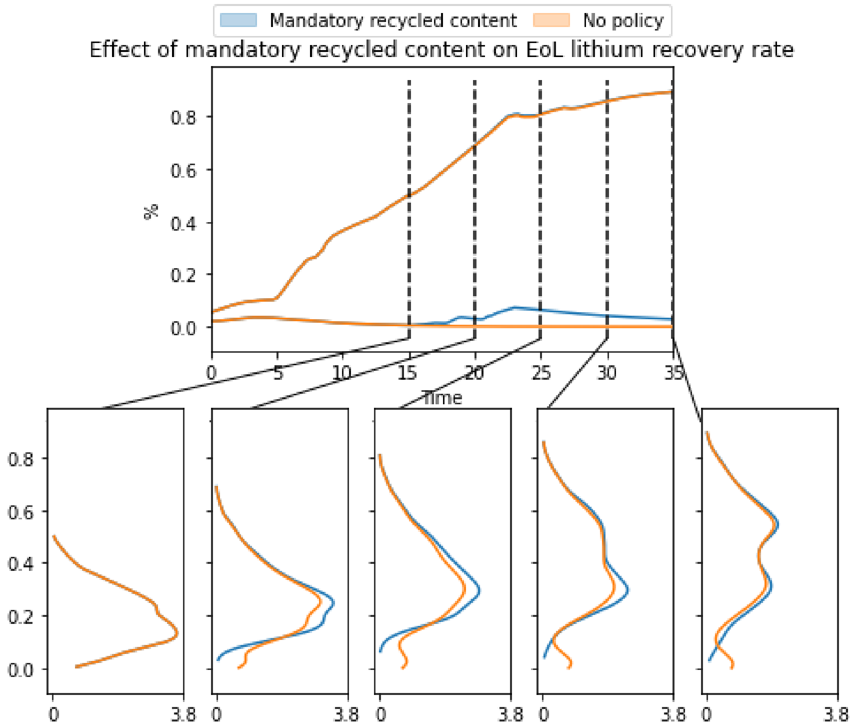

Figure 6.2.: Lithium recovery rate with and without implementation of mandatory share recycled content

6.1.2. Cost reduction

Figure 6.3 shows the effect of the cost reductions on the competition between recycling and re-purposing. At the moment of implementation, the measure seems to be slightly favouring re-purposing. However, towards 2050, it does not result in a higher re-purposing rate (figure E.1).

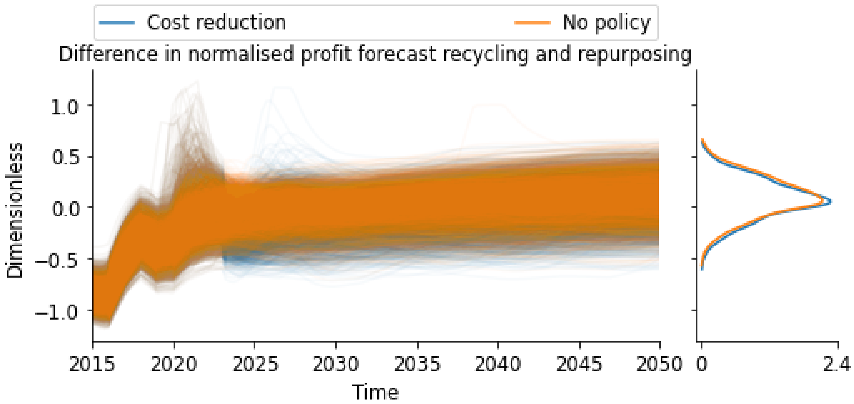

Figure 6.3.: Difference between normalised profit forecast recycling and re-purposing with and without policy-driven cost reduction (n = 3000*2, X = 72)

6.1.3. Minimum performance requirements

The minimum performance requirements were translated into the model as a 10-40% increase in average lifetime of EV batteries. Figure 6.4 shows that it results in a downwards shift of the recycling input rate in 2050. This indicates that an over all delay in secondary lithium production, logically following from a longer battery lifetime. However, it also reduces the total lithium demand, because batteries have to be replaced less often. This effect is shown in figure 6.5.

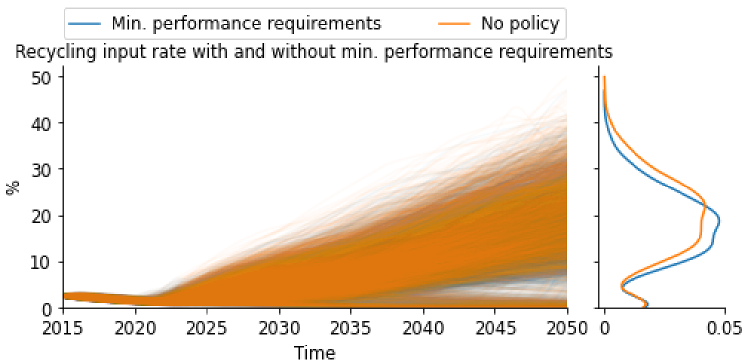

Figure 6.4.: Effect of min. performance requirements on EoL Recycling Input Rate (n = 3000*2, X = 72)

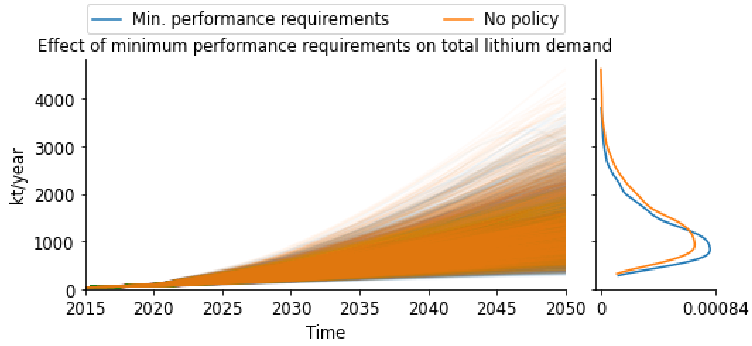

Figure 6.5.: Effect of min. performance requirements on total lithium demand (n = 3000*2, X = 72)

6.1.4. Minimum EoL processing requirements

Minimum requirements for EoL processing entails that all batteries should at least be recycled, which means that batteries can no longer be land-filled or incinerated. Figure E.2 shows that the change of obtaining a high lithium recovery rate becomes higher. However, there is no increase in recycling capacity. This means that the measure does not result in more recovery, but in less outflow in the model and thus higher accumulation of the waste stock. The model needs to be improved to make sure an accumulation of waste stock results in more recycling or re-purposing capacity.

6.1.5. Minimum lithium recycling efficiency

Pyrometallurgical recycling now always includes lithium recovery from slag. Obviously, this leads to a significantly higher recycling efficiency (figure E.3) and thereby also to an increase in the lithium recovery rate, as shown in figure 6.6. However, it has no effect on the proportion of scenarios in which no recycling takes place at all.

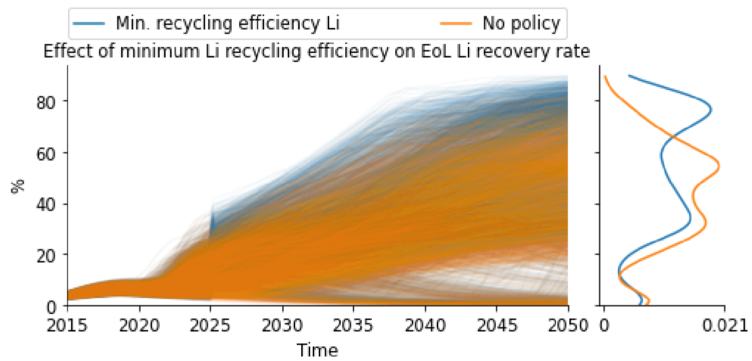

Figure 6.6.: Effect of minimum recycling efficiency on EoL lithium recovery rate (n = 3000*2, X = 72)

6.1.6. Extended producer responsibility

The extended producer responsibility results in a sharp increase in the collection rate. This potentially leads to an increased EoL lithium recovery rate and EoL recycling input rate. However, first, enough capacity should be available to process the large number of collected batteries. Figure 6.7 shows that a sharp increase in battery collection may lead to a period of insufficient recycling and re-purposing capacity.

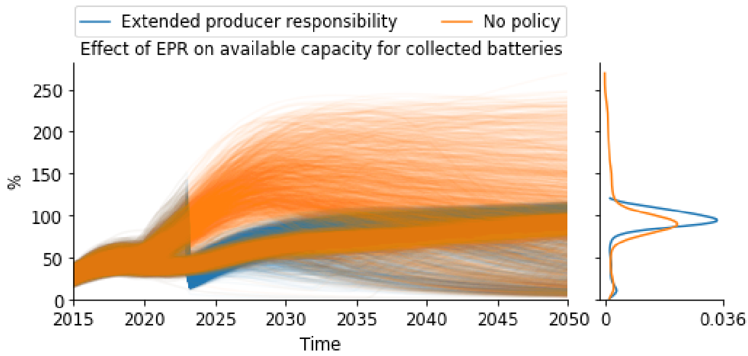

Figure 6.7.: Effect of extended producer responsibility on available processing capacity (n = 3000*2, X = 72)

6.2. Exploring the effect of the full policy

6.2.1. Effect on implementation of circularity strategies

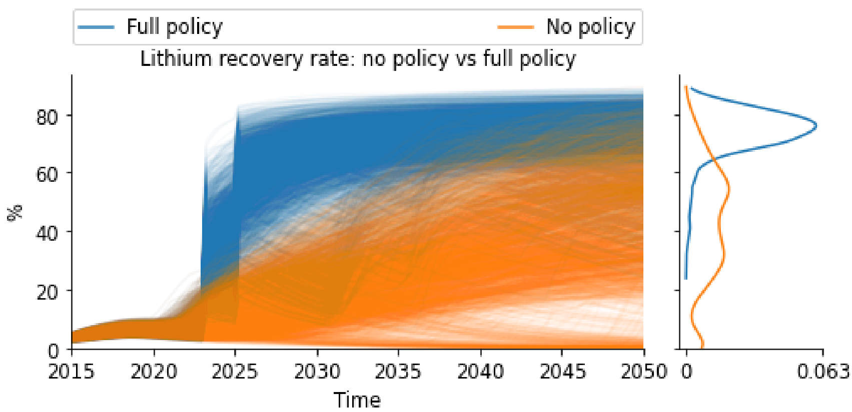

Figure 6.8.: Effect of full policy package on the EoL lithium recovery rate (n = 3000*2, X = 72)

In this paragraph, the effect of the entire policy package will be explored. Figure 6.8 shows a large increase in the EoL lithium recovery rate. Thereby, it shows that the policy is expected to be quite effective to prevent the spilling of lithium when batteries reach their end-of-life.

This large effect is thus the sum of a high collection rate, ban on incineration and land-filling and a minimum recycling efficiency for lithium in each recycling facility. The mandatory share of recycled content might also contribute. However, figure 6.9 shows that when the measure is part of the full package, it is ineffective in a larger share of the scenarios. This can be explained by the fact that now other measures do part of the job when it comes to sufficient secondary supply.

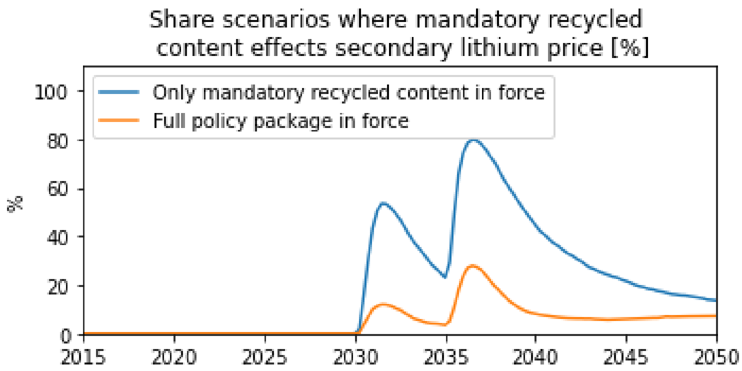

Figure 6.9.: The share of scenarios in which the mandatory recycled content policy is effective. It shows that in case the full package is implemented, the mandatory share of recycled content becomes redundant in more scenarios.

From an environmental and circularity perspective, it is beneficial to first re-purpose batteries, before recycling them. In figure 6.10 it is shown that the Battery Regulation, as it has been implemented in this study, results a downward shift of the LIB re-purposing rate towards 2050.

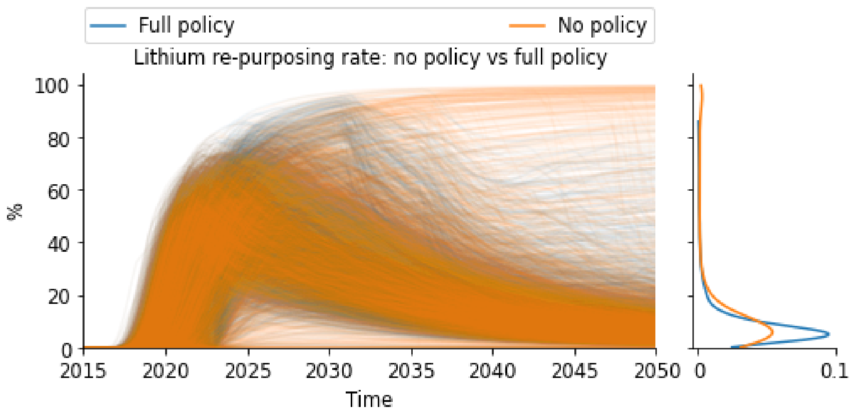

Figure 6.10.: Effect of full policy package on the LIB re-purposing rate (n = 3000*2, X = 72)

6.2.2. Effect on the lithium system

Although the EoL Recycling Input Rate will be delayed by the minimum performance requirements for LIBs, it is shown in figure 6.11 that the sum of all the measures has a positive effect on the average recycling input rate. However, it also shows that the maximum contribution of recycling to the total supply is still limited to 50%. It is therefore important that the Battery Regulation also reduces demand. The share of demand that can be fulfilled by re-purposing only slightly increases between 2025 and 2040 (figure E.4. Over all the number of scenarios in which shortages occur is being reduced by the policy, as shown in figure 6.12. Figure 6.13 shows that it also reduces the number of scenarios in which shortages of more than 10 kt occur.

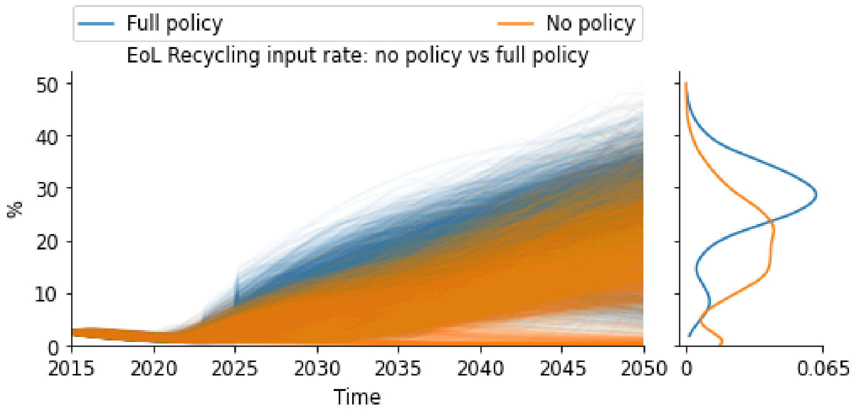

Figure 6.11.: Effect of full policy package on EoL Recycling Input Rate (n = 3000*2, X = 72)

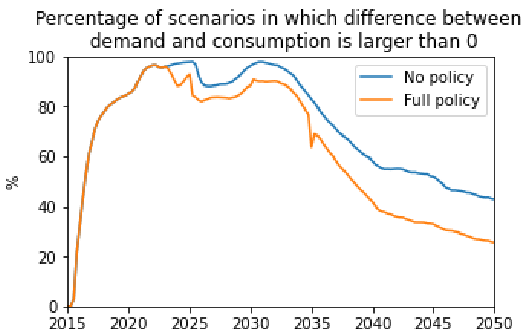

Figure 6.12.: Share of scenarios in which the lithium shortage is larger than 0 t

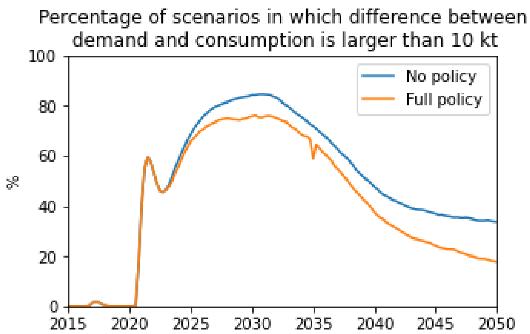

Figure 6.13.: Share of scenarios in which the lithium shortage is larger than 10kt

SQ4: Given the uncertain factors how does the European battery circularity policy affect the the transition to a circular lithium system in compared to a situation with no policy implementation?

Key insights individual measures:

- The mandatory share of recycled content has a stimulating effect on the recycling business, but only when secondary demand outstrips secondary supply. It is robust in preventing situations with no lithium recovery.
- The cost reductions as implemented in the model favour the business case for re-purposing on the short term, but it does not affect the LIB re-purposing rate.
- Minimum performance requirements slow down secondary supply, but also result in the desired demand reduction.
- A ban on the land-filling or incineration of batteries leaves no other options than recycling or re-purposing. However the implementation in the model should be improved to show this effect.
- The minimum recycling efficiency for all recycling facilities increases the EoL lithium recovery rate and the EoL Recycling Input Rate.
- The Extended Producer Responsibility has a large positive effect on the output metrics due to the large increase in collection rate. In the short term, this may well lead to a shortage of processing capacity.

Key insights full policy:

- The sum of measures has a very positive effect on the EoL lithium recovery rate, because it is preventing losses in the system in multiple ways. However, it seems less effective in prioritising re-purposing over recycling.
- Although the sum of measures increases the average EoL Recycling Input Rate, it is still limited to 50% in the most optimistic scenario.
- The sum of measures is able to prevent shortages in up to 20% of the scenarios.

7. Discussion

In this chapter will first be reflected on the approach and methods used for this study (section 7.1). Then, the limitations of the model will be discussed in section 7.2. Thirdly, section 7.3 discusses to what extent the modelling results are expected to hold in the real world situation, including an elaborate discussion on the potential effectiveness of the Battery Regulation in the European context. Additionally, the results will be put in the broader environmental context to evaluate what it means for the sustainability of the energy transition (section 7.4). The entire discussion results in suggestions for further research, presented in section 7.5.

7.1. ESDMA approach

The exploratory system dynamics modelling and analysis approach proved a useful approach to gain insights in the market dynamics and relations between the primary lithium system and the circularity strategies for LIBs. However, there are also some methodological limitations. In this section will be elaborated upon the suitability of SD and EMA for this study.

7.1.1. SD for modelling the circular lithium system

The system dynamics model used for this study has a relatively high level of aggregation because it covers the entire global lithium system. By including circularity strategies, it was required to couple the material supply chain to the product-based waste supply chain. Although this model showed that it is possible to interconnect these systems, it does add to the complexity of the model. Furthermore, the coupling asks for choices and assumptions regarding the aggregation level. This study chose to focus only on the circularity of LIBs since batteries cover most of the lithium market. However, for other materials, the occurrence might be more diverse, requiring the inclusion of multiple products. Since the appropriate circularity strategies are different for each product type, it becomes rather complex soon. What makes it even more complex is that the design of products might change over time, which affects the circularity strategies both from an economic and technological perspective. Finding the right aggregation level has been a challenge throughout this study. It resulted in a couple of model limitations, which are discussed in section 7.2. Analysing circularity strategies and the waste management supply chain might therefore also benefit from a more dis-aggregated approach than the approach taken in this study.

7.1.2. EMA for analysing the circular lithium system

EMA provides many tools to evaluate complex systems under various circumstances. Visual analysis and ETFS have yielded multiple insights about the system's dynamics. Unfortunately, scenario discovery with PRIM did not yield much information, which probably has been caused by the dynamic complexity of the model. Also, the study included too many uncertain parameters to use SOBOL sensitivity analysis, so it was necessary to divert to ETFS. Although the validity of ETFS has been tested (appendix A), it is still less accurate than SOBOL. Furthermore, choices have been made to reduce the number of dimensions in the analysis. Therefore, the influence of some uncertainties might have been underestimated due to exclusion from the sensitivity analysis.

7.2. Limitations of the model

"Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful." This quote from George Box (Box and Draper (1987) p. 424) illustrates that no model in the world is perfect, because it is by definition a simplification of a (sub)-system of the real world. The model that was used for this study is no different. However, some of the structures in the model would benefit from improvements in order to increase the validity of the model, which are being discussed in this chapter.

7.2.1. Primary lithium system

The demand, primary supply and price structure are primarily based on previous models built for geologically scarce metals copper, cobalt and nickel. The supply chain for lithium is significantly different due to different types of deposits (brines and pegmatites) and the relatively high concentration in seawater. Because the focus of this study was on the development of the model's circularity strategies, the primary supply chain structures have only been adjusted to a basic level deemed necessary for this study. However, because of the different natures of the several lithium sources, one might want to disaggregate the types of deposits to provide a more accurate view on the availability and profitability of the deposits. Additionally, the bottom-up demand structure can be improved by updating the input data and adding some other applications of LIBs, like electric bicycles. Furthermore, the opportunity cost mechanism was assumed. However, it is questionable whether all relevant costs of primary production are correctly included from an environmental and social perspective.

7.2.2. Recycling and re-purposing capacity development

The implementation of the development and usage of recycling and re-purposing capacity can be improved. The pace at which the market responds to the profit forecast depends on the proxy *Market response factors*. It is a significant simplification of very complex interactions of factors making an actor decide to invest in a facility for mining, recycling or re-purposing. Related to this is that recycling and re-purposing have been considered one-stage processes. However, the multiple stages of recycling and re-purposing (e.g., collection, sorting and pre-treatment) involve multiple actors. Further dis-aggregation of these dynamics did not match the level of aggregation of this study. However, in future research, an agent-based modelling approach might be helpful to investigate the drivers behind the market response factors for the different actors.

Furthermore, capacity development is based on the profit forecast at one moment in time. However, companies would base the investment decision on the expected profitability over 30 years. This could mean that they would already invest when the process is not profitable yet, which is compensated by profitability over the years. The other way around, the model builds up re-purposing capacity in the early years, when LIBs are still high. However, companies would already foresee that profitability will decrease in the future.

Additionally, in situations where one of the methods becomes (slightly) profitable, after first being loss-making for an extended period, the model reacts abruptly to the vast amount of waste for which no treatment capacity is yet available. Then, when profitability has declined, the capacity is in the pipeline and is thus developed. Although structures are in place to allow capacity to decrease again if the profit forecast is negative, this is much slower than the build-up. So these structures could be improved for a more realistic and gradual build-up.

Lastly, the structure determining how much capacity will be prepared per processing type can be improved. Next to the linear and quadratic division, a ”winner takes all” structure could be tested, because some authors argue that re-purposing would only occur if recycling is less profitable (Neubauer & Pesaran, 2011; S. I. Sun et al., 2018). These capacities also determine the division of waste over the different processing types. However, capacity development was based on the profitability at the moment in time it was decided to develop the capacity. An improvement of the model would be to base the actual division of waste over the different processing capacities in the stock-flow structure on the profits at that moment in time.

7.2.3. Challenges arising from aggregation level

In general, it was found that modelling product-based systems raises challenges regarding the aggregation level. In this study, the circularity strategies included were limited to those for LIBs. Recycling or re-purposing of other lithium-containing products was thus left out of scope, which inherently limits the EoL recycling input rate, because the lithium consumed for non-LIB purposes flows out of the system. In further research, more product types might be taken into account.

It was chosen not to disaggregate over the different applications of LIBs (consumer electronics, EV, stationary storage) in the stock-flow structure, because the chemical composition is similar. Furthermore, the assumption was that most LIBs would be for EV purposes. While performing the analysis, it was found that in the early years, when recycling is loss-making, only re-purposing capacity is being developed. However, the LIBs released in the first years are mainly LIBs for consumer electronics. These LIBs are not suitable for re-purposing. In future research, it would thus be beneficial to disaggregate across the different uses of LIBs in the stock-flow structure to avoid this type of inaccuracy.

The multitude of battery technologies is one of the factors making recycling and re-purposing rather complex. Although experiments have been conducted with different cathode mix scenarios to show some technological development and its effect on recycling revenue, this does not include the consequences of developments in battery design that require modification of the EoL processes and thus affect costs.

Not only do technological differences between products add to the complexity of modelling circularity strategies, but also the multitude of processing options. Direct recycling is a promising method to revive spent cathodes without having to break them down entirely. Including this recycling option in a future version of this model would contribute to its completeness.

Lastly, the model aggregates over the types of cathodes ending up in the waste stream and assumes that each EoL processing facility receives a perfect mix of cathode types. In reality, there will be pre-treatment and sorting creates waste streams with varying potential revenues. The waste market works with gate fees that can be either negative or positive, which means that recyclers receive money for processing low-grade streams and may have to pay for high-grade streams. This model aims to evaluate the profitability of recycling under different conditions at a high level of aggregation. The gate fees, which ensure a fair distribution of profits across the various steps, are therefore not considered. In reality, this might affect the profitability of both recycling and re-purposing.

7.2.4. Policy implementation

Policies were implemented as exogenous factors, coming into force in an on-and-off manner. In reality, the market would respond to the announcement of a new policy, and policymakers would respond to the market dynamics. This causes an unrealistic delay in the effectiveness of the policy. For example, the mandatory share of recycled content may already have stimulated recyclers to include lithium recovery before it eventually comes into force. In that case, it might even be that the policy does not result in a price increase for secondary lithium because the policy announcement has already increased recycling capacity.

Concerning the structural implementations of the different measures, improvements are possible. For example, the ban on incineration and land-filling would lead to compulsory recycling or re-purposing. Therefore, it is built into the model that if all methods are loss-making, the least loss-making method automatically becomes profitable. However, this implementation does not represent the actual situation well enough. It leads to situations where a processing method is profitable at one moment but suddenly no longer profitable a moment later. This means that the loss-making method starts to phase out again. Whereas, if there is insufficient processing capacity, all methods should be automatically profitable, since the disposer would pay the unprofitable gap now that incineration and landfill are banned. This leads to erratic and unrealistic behaviour as can also be seen in figure 6.8.

In addition, batteries pile up in the waste stock if there is too little processing capacity. Since battery storage is expensive, this should lead to the development of additional processing capacity, which is not included in the model. Therefore, these structures need to be improved to correctly assess the impact of the ban on land-filling and incineration.

Furthermore, more research is required to estimate better which cost reductions the Battery Regulation may realise. Lastly, the extended producer responsibility makes producers pay for the collection and disposal of batteries. These costs would potentially increase the battery price, which was not included in this model.

7.2.5. Input data and parametrisation

In the model of Van der Linden (2020), data from Bloomberg NEF was used. This data have not been updated due to a lack of access, although this would have been beneficial, since the EV transition develops fast. In addition, some of the ranges chosen for the uncertain input parameters could be better substantiated, for example by subjecting those to expert validation. Also, as was discussed in chapter 3.4.2, the bulk of the ensemble does not match with current price developments. A critical evaluation of the chosen ranges, to make the ranges more realistic and filter out overly pessimistic or optimistic unrealistic scenarios, would be an important improvement step.

7.3. Discussion of the results

7.3.1. The lithium system and its circularity strategies

It was shown that in the short term, the lithium price depends mainly on the level of demand because the supply capacity is relatively inelastic. This result will likely hold in the real world since expanding supply capacity costs time and faces social and political resistance. Furthermore, the level of demand turned out to be almost solely dependent on the average battery capacity demanded by EV. This is a logical result since it was one of the leading, broadly varied, uncertain parameters influencing the demand. In the real world, the demand is determined by many more parameters. Substitution comes into play relatively late. Although it will indeed take time before the substitutes will be competitive, the innovation might be boosted by high lithium prices. This feedback loop is not included in the current model.

The general price behaviour for most of the scenarios does not match the current real world situation. This might be a result of the parametrisation of the model. The energy price scenarios take into account the high oil prices based on data until 2022. However, the energy price's effect on the marginal costs of mining might have been underestimated. It might also be the result of the largely unstable state the world is currently in, due to the war in Ukraine. These types of external factors disturbing the world market are not included in the model, but may explain the underestimation of the lithium price.

Concerning the recycling and re-purposing capacity, it was shown that the collection rate and whether the market anticipates the collection rate is essential. This is primarily the result of the structural implementations in the model. Still, the notion that the collection rate is of significant importance for the level of recycling and re-purposing, will hold in the real world.

It was shown that recycling and re-purposing compete, where high material prices favour recycling to a larger extent than re-purposing. Since battery prices are determined by many more factors than the cathode material prices, this effect is considered realistic.

Gaines (2019) expected that the trend towards low cobalt LIBs might harm the business case for recycling. Interestingly, it was shown that the recycling efficiency shifted upwards for the fictional low cobalt and low nickel scenario. This can be explained by the fact that the share of revenue originating from lithium becomes larger when cobalt and nickel contents decrease, making lithium thus more critical for the recycling business case. However, low cobalt and nickel content decreased the total level of recycling, which confirms the concerns of Gaines (2019). These dynamics show the importance of clearly defined goals and a thorough understanding of the various output metrics.

The profitability of recycling showed to be more sensitive to the cobalt, nickel and copper price, than to the lithium price. This is probably because the copper, cobalt and nickel prices are entered into the model as scenarios, with all three prices being either high, medium or low. It is thus not surprising that the profit forecasts are highly sensitive to the material price scenarios. Nevertheless, these prices are likely to have a large impact in the real-world as well.

Lastly, it was shown that the contributions of circularity strategies to increase supply and reduce demand are limited in the short-term, but increasing towards 2050, confirming the conclusion of Watari et al. (2019). It must be noted that part of this limitation is caused by the outflow of lithium used for non-LIB purposes. However, the primary cause is likely to be that it takes time before sufficient lithium has been used to exploit as a secondary source. The role of primary production will thus stay essential to meet the lithium demand until 2050. It might be that after 2050, when demand stabilises and sufficient consumption of lithium has taken place, circularity strategies will be able to fulfil a larger share of the demand. Further research might look into the dynamics after 2050.

7.3.2. The Battery Regulation in the European context

In chapter 6, the effect of the Battery Regulation was shown for the hypothetical situation that these measures are implemented on a global scale. In general, the effects of the Battery Regulation on the world market, as shown with the model, will be less intense in case the policy is just implemented on the European scale. On the other hand, it could be that some of the measures do have a significant effect on the global market. For example, LIBs imported to Europe will also have to comply with the regulation regarding a mandatory share of recycled content. Still, the results shown with the global model cannot be automatically projected onto the European situation. Therefore, this section discusses whether the results will likely hold in the European context.

Due to a lack of primary supply in Europe, secondary production is one of Europe's strategies to become less dependent on other parts of the world. Hoarau and Lorang (2022) evaluated the impact of the mandatory share of recycled content for the European market with a material flow analysis approach and concluded that the targets of 4 and 10% recycled lithium in 2030 and 2035 might be unrealistic to achieve. Although the authors acknowledge that ambitious targets stimulate the recycling industry, they recommend lowering the targets in order to keep the policy credible and feasible. The results from this study show that the targets may indeed be unachievable at the moment of implementation. However, precisely in those cases, prices for secondary lithium might go up and provide a push to the recycling market. Lowering the targets would, from this point of view, increase the chance of the policy becoming obsolete. Nevertheless, it then still ensures that secondary lithium is refined up to battery-grade quality, guaranteeing closed-loop recycling.

Melin et al. (2021) express the concern that the Battery Regulation does not specify where the required origin of recycled material. The model implemented the measure so that lithium from post-production scrap did not add to the secondary lithium inventory. However, if the law could be met with sufficient post-production scrap, this potentially destroys any incentivising effect on recycling development. Also, importing recycled content is mentioned as an option. This would be a risk for the European recycling industry, since processing costs are higher in Europe than in other parts of the world (Dai et al., 2019).

The extended producer responsibility forms an essential base of Europe's Battery Regulation. It demands that producers collect "all" industrial batteries they have brought to the market. However, no specific collection target has been formulated. In the model, a high collection rate was chosen to show the effect in case almost all LIBs were collected. However, the question is how the lack of a specific target works out in practice. The shown effects may thus be an overestimation of reality.

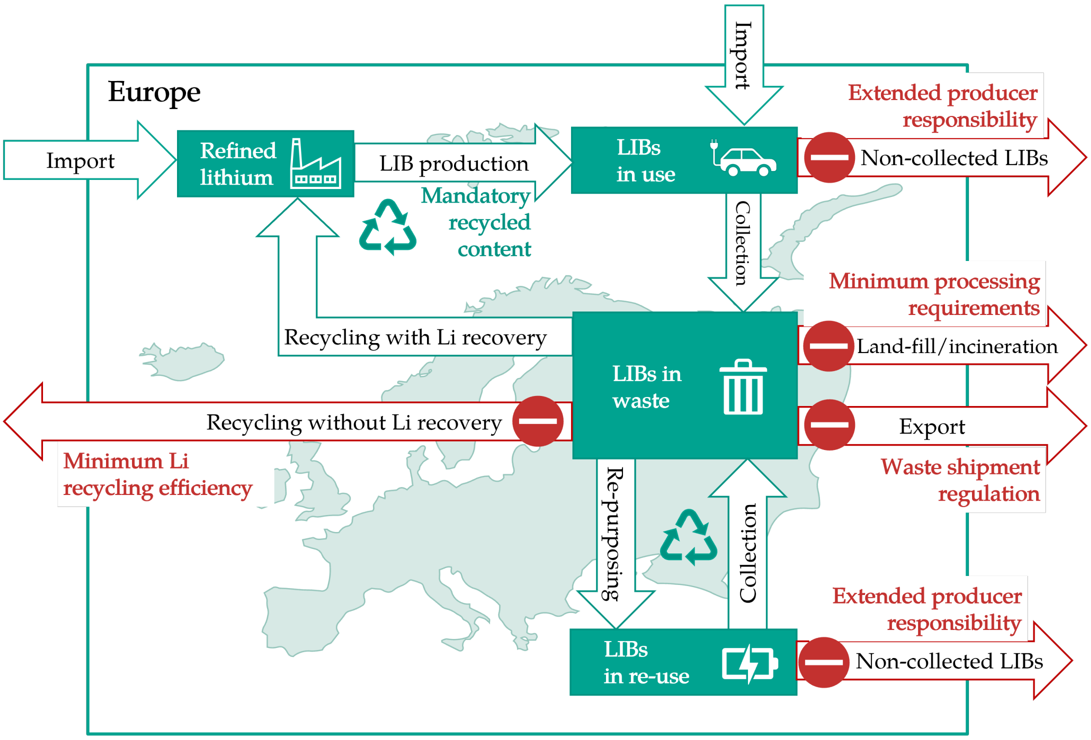

Figure 7.1.: Schematic stock flow diagram showing the routes via which Europe may waste lithium and the measures from the Battery Regulation blocking these routes.

However, the collection is only the first step towards a circular lithium system. If all collected LIBs were incinerated, the lithium recovery rate would still be zero. The effectiveness thus depends on whether European producers have any alternatives left next to recycling and re-purposing. It seems that the Battery Regulation can block multiple of these alternative routes, shown in figure 7.1. The minimum processing requirements prevent LIBs from getting incinerated or land-filled. The minimum recycling efficiency for each facility prevents recycling from taking place without lithium recovery. The only option left would be to export the waste LIBs. According to the Battery Regulation, export is allowed when it complies with the Waste Shipment Regulation, for which new rules have been announced as well (European Commission, 2021). The exporting party must then demonstrate that the processing takes place under conditions that fulfil the requirements of the Battery Regulation. A more detailed analysis of the Waste Shipment Regulation would be required to assess this potential outflow of LIBs. However, exporting LIBs to circumvent the Battery Regulation becomes increasingly complicated.

It must be noted that the lithium recovery rate for the full policy implementation does not correctly represent the actual recovery rate, because the lithium that accumulates in the waste stock is not accounted for. However, the market would likely respond by increasing the EoL processing capacity. This would mean that the lithium recovery rate might be a correct representation. However, the model then underestimates the absolute amount of lithium that can be recovered in those scenarios where lithium accumulates in the waste stock.

The Battery Regulation seems to be a complete policy package, resulting in recycling and re-purposing as the only options left in Europe. Still, the economic differences between recycling and re-purposing are relevant, since producers would opt for the cheapest processing option. The modelling results showed that the measures could not guarantee that re-purposing will be prioritised over recycling. The cost-reducing measures might be more effective in stimulating re-manufacturing and re-purposing in Europe due to the generally high processing costs. However, it can still be considered a risk that the mandatory share of recycled content and high material prices add to the attractiveness of recycling.

Because the Battery Regulation potentially closes all alternative routes, it is also likely to eliminate the risk of decreased recycling levels due to cobalt and nickel reduction in waste LIBs. At most, the reduction of cobalt and nickel then has a positive effect on the re-purposing rate, as a lower value of the battery materials is less harmful to the re-purposing business case than to the recycling business case.

Furthermore, it was shown that, on average, the Battery Regulation increases the contribution of circularity strategies to the lithium system, reflected in the EoL recycling input rate. For Europe, the contribution of the circularity strategies might be of relatively higher importance compared to the global situation, since Europe is very dependent on non-European countries for the primary supply. At the same time, these results emphasise, that shortages cannot be prevented by the efficient implementation of circularity strategies alone. Even with a successful implementation of the Battery Regulation, the contribution is limited as long as the lithium demand grows.

7.4. The broader context: critical metals for the energy transition

This study started with the notion that moving away from fossil fuels, shifts the dependence on oil and gas towards dependence on critical metals. Today's high lithium prices illustrate the acceleration of the energy transition. Since scaling up primary production capacity takes time and recycling and re-purposing have a limited contribution in the short term, it would be a robust strategy to look at the highest rungs of the circularity ladder. There, one finds the strategies *Refuse*, *Rethink* and *Reduce*.

Bosch et al. (2018) analysed the material requirements for the Dutch energy transition and concluded that the Netherlands would need all rungs of the circularity ladder to fulfil the transition. The results of this study confirm that mainly in the short term, it would be a robust strategy for Europe to investigate which sectors' demand for lithium can be reduced, without compromising the energy transition. Examples of rethinking the system to reduce demand, would be to stimulate shared mobility, look for less material-intensive electricity storage methods, or simply by reducing our energy demand, so that less green technology is required to fulfil the energy transition. The critical material resilience strategy currently consists of four policy directions: improving the resilience of supply chains, improving the circular use of resources, increasing the domestic mining and refining capacity and diversifying the supply from third countries. Less material-intensive product design is part of the circular policy direction, and this is thus one of the aspects of circularity that deserves more focus from policy-makers. Future research might evaluate to what extent the European Union is considering demand reduction as a solution and investigate promising demand-reducing options.

7.5. Suggestions for further research

Since it was the first time this model has been expanded for circularity strategies, future research might focus on improving these structures and overcoming the limitations as described in previous sections. The complexity of the waste market might benefit from research at a lower aggregation level, for example by studying the investment decisions of recycling and re-purposing companies with an agent-based modelling approach. Additionally, regionalisation would be beneficial, not only to evaluate the Battery Regulation on the scale it will be implemented, but also to investigate the supply risk for Europe as a result of its dependence on non-European countries. Furthermore, looking into the dynamics arising after 2050 would be interesting, because the demand stabilisation might result in different market dynamics and a more significant potential for circularity strategies.

8. Conclusion & Recommendations

8.1. Conclusion

This study used an exploratory system dynamics modelling approach to investigate how the European battery circularity policy will affect the implementation of interacting circularity strategies and the lithium market dynamics towards 2050. Overall, the Battery Regulation turned out to be robust when it comes to ensuring an increase in the end-of-life lithium recovery rate. However, the measures tested in this study cannot guarantee that re-purposing will be prioritised over recycling. The implementation of circularity strategies certainly contributes to the increase of supply and the reduction of demand. However, as long as lithium demand continues to grow, their contribution is limited.

The model allowed to explore the interactions between the various implemented circularity strategies under a broad ensemble of uncertain conditions. First, it was shown that there is a form of competition between the various recycling types and re-purposing, where the profit forecast for the several recycling types responds more strongly to increasing material prices than the profit forecast for re-purposing. While the Battery Regulations' cost-reducing measures are expected to be more favourable to re-purposing, the mandatory share of recycled content may instead encourage recycling. Second, it was shown that reducing cobalt and nickel in batteries might positively affect the share of recycling facilities that includes lithium recovery, but might negatively affect the total level of recycling and re-purposing. However, once the Battery Regulation will be implemented, all recycling facilities will have to include lithium recovery to a certain extent, and the ban on incineration and land-filling guarantees that lithium-ion batteries will either be recycled or re-purposed. Thereby, cobalt content reduction in lithium-ion batteries, is not expected to greatly affect the level of recycling in Europe. At best, it may have a positive effect on the position of re-purposing with respect to recycling.

With respect to the lithium market dynamics, it was shown that the contributions of recycling to the supply capacity and re-purposing to demand reduction are limited in case demand continues to grow towards 2050, simply because not enough lithium has been used yet to subsequently be exploited as a secondary resource. Nevertheless, the Battery Regulation did reduce the number of scenarios in which there is a gap between lithium availability and demand, indicating that the implementation of circularity strategies may prevent shortages in part of the scenarios.

For the European context, it was discussed that the full package of measures as formulated in the announced Battery Regulation, is likely to ensure at least a minimum percentage of lithium recovery, even in adverse uncertain conditions. This is caused by the sum of the extended producer responsibility, a ban on land-filling and incineration, a minimum percentage lithium recovery in each recycling process and the mandatory share of recycled content in fresh batteries. Adding to this that the Waste Shipment Regulation is expected to complicate the export of waste batteries, no other options remain than to recycle or repurpose end-of-life batteries within Europe.

The scientific contribution of this study lies not only in evaluating the transition to a circular lithium system, but also in the application of an exploratory modelling approach to link the material-based system to the product-based circularity strategies. Interconnecting the material and product-based system elements added to the complexity of the model. Finding the right aggregation level was challenging, and the choices made during the modelling process led to several limitations. Future research might investigate the system with a more disaggregated approach. Furthermore, the European policy was evaluated with a global model, and therefore further research is recommended to test the policies on a regional level. Despite the limitations, building and using the model allowed the modeller to generate insights about the interactions between circularity strategies for lithium-ion batteries and the lithium system, and to evaluate the potential effectiveness of the Battery Regulation.

8.2. Recommendations

Based on the conclusions above, two recommendations have been formulated for the European Commission. Firstly, the competing interactions between reduction, lifetime extending strategies, and recycling is an important consideration to prevent one strategy coming at the expense of another. Therefore, it is recommended to better ensure the prioritisation of circularity strategies, in accordance with the circularity ladder. In doing so, it is essential to distinguish well between the different output metrics, all providing different pieces of information concerning the level of circularity of the system.

In the short term, the contribution of circularity strategies to the availability of lithium turned out to be limited. In addition, scaling up primary production capacity takes time and competitive substitution options for battery electric vehicles are not likely to be available soon either. It would therefore be a robust strategy to devote extra focus to the highest rungs of the circularity ladder, being *Refuse, Rethink and Reduce*. The European Commission is thus advised to consider in which sectors the use of lithium and other critical raw materials can be reduced, without compromising on the energy transition. Because for everything Europe does not need, Europe cannot depend on either.

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A. ETFS validation

As explained in section 2.3, is Extra Tree Feature Scoring a less computationally expensive alternative to SOBOL sensitivity analysis (Jaxa-Rozen & Kwakkel, 2018). In this section will be investigated whether the feature scores are reliable enough to base the results upon. Three experiments were performed to gain confidence in the validity of the feature scores [1].

Three experiments have been performed to test the validity of Extra Trees Feature Scoring to replace SOBOL sensitivity analysis. First, the experiments with the model were performed for two entirely different sets of 20000 scenarios. For both of these sets, ETFS was used to obtain the feature scores of all time series outcomes of interest. For each outcome, the top three parameters with the highest feature scores at a certain moment in time were plotted. For each outcome parameter, the scores obtained with the two sets of scenarios were compared. An example is shown in figure A.1 and A.2 showing the feature scores of the most influencing parameters on the lithium recovery rate for set 1 and 2 respectively. For most parameters, the differences remain limited to a change in order for a couple of parameters with low features scores which are close to each other. For the lithium recovery rate, set 2 reveals two additional parameters which are at a certain point in time included in the top 3, however, both with relatively low feature scores. It shows that the most influencing parameters are the same for both sets, providing sufficient confidence that in general, ETFS shows a sufficiently constant result.

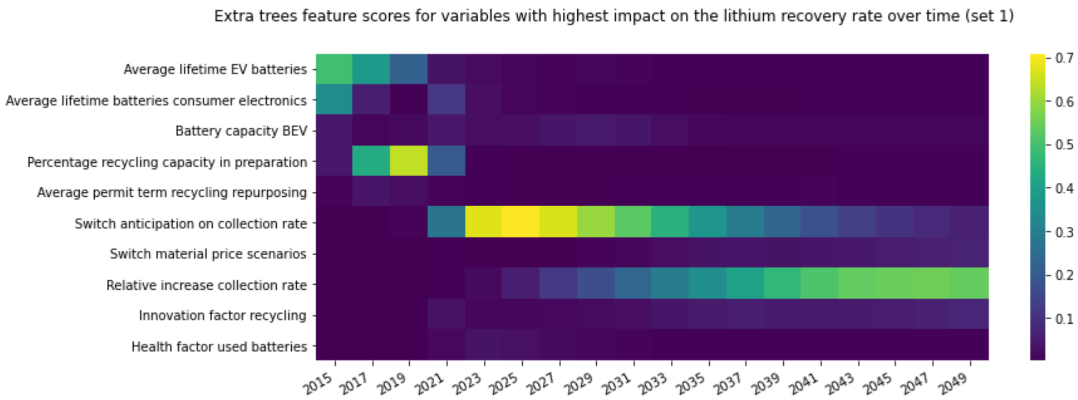

Figure A.1.: Extra trees feature scores of uncertainties with highest impact on the Lithium Recovery Rate (Set 1, n = 20000)

Second, for one of the scenario sets (set 1), the feature scores have been calculated for 100 different ensembles of scenarios which where randomly drawn from the full set of 20000

[1] These experiments have been performed with an earlier version of the model. However, the latest adjustments to the final model are not expected to influence the results of these experiments.

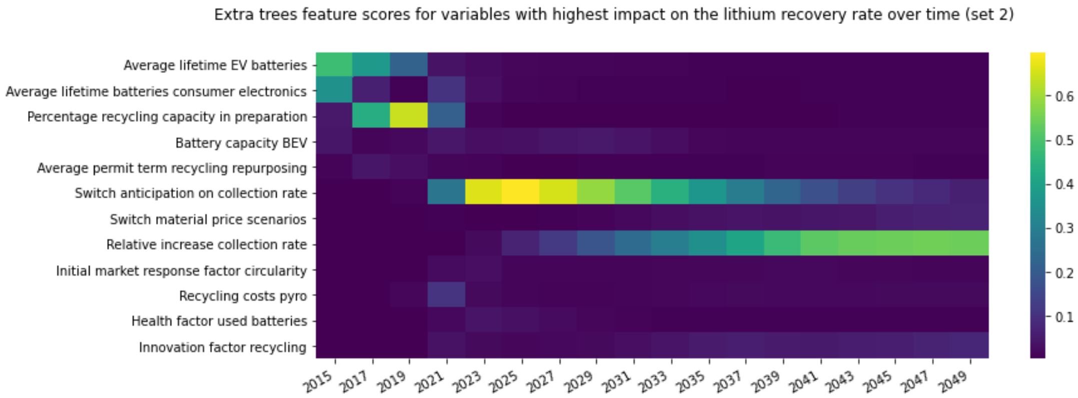

Figure A.2.: Extra trees feature scores of uncertainties with highest impact on the Lithium Recovery Rate (Set 2, n = 20000)

scenarios. All ensembles had an equal size to the entire set (n=20000), but were different in order and may contain duplicates. Since the sequence in which the scenarios are fed into the algorithm may influence the feature scores, this experiment checks whether similar scores are generated despite of ensemble. If the difference in scores is limited, this contributes to the confidence in the validity replacing SOBOL sensitivity analysis by EFTS. Figure A.3 shows the confidence intervals for the parameters which belong to the top three parameters with the highest feature score at a certain moment in time. However, the confidence intervals have been calculated at one moment in time, in this case the year 2040. Because the confidence intervals might differ over time, for one parameter, the relative increase in collection rate, is shown how the confidence interval develops over time in figure A.4. Both figures show that the variation in scores in the 100 different ensembles is quite limited, which thus provides us with confidence that the results of ETFS are reliable enough to be used.

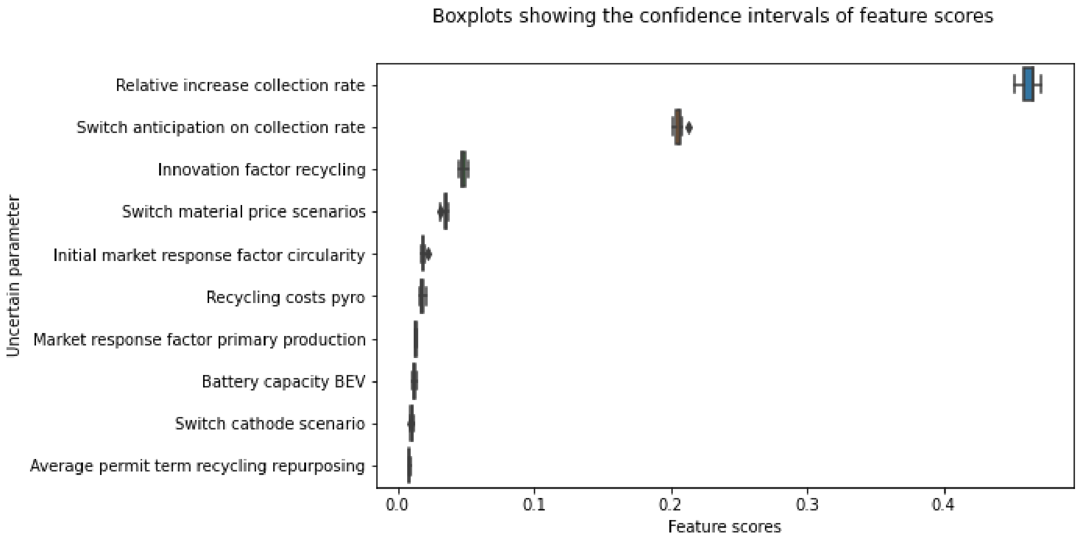

Figure A.3.: Confidence intervals for feature scores of most influencing parameters on Lithium Recovery Rate (Set 1, n = 20000, m = 100, t = 2040)

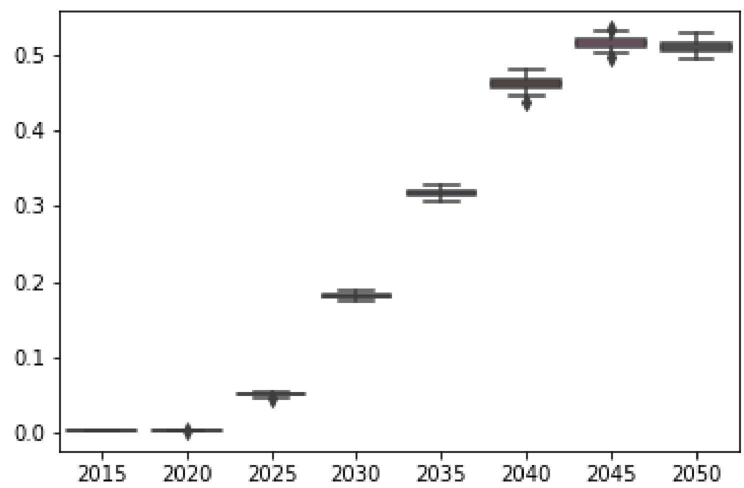

Figure A.4.: Confidence intervals for feature scores of the relative increase in collection rate, showing the impact on the lithium recovery rate over time (Set 1, n = 20000, m = 100)

B. Parametric uncertainties

Name parameter	Default value	Unit	Min value	Max value	Reference
Administration time	15	Year	10	20	Auping and Pruyt (2013)
Average battery lifetime second use	10	Year	8	12	Neubauer et al. (2015)
Average lifetime batteries stationary storage	10	Year	8	15	Assumption
Average time scrap to recycling	0.4	Year	0.38	0.42	Assumption
Battery capacity Ebus	200	kWh/Car	150	220	Bloomberg NEF (2019) via Van der Linden (2020)
Battery capacity Etruck	70	kWh/Car	70	150	Bloomberg NEF (2019) via Van der Linden (2020)
Battery capacity PHEV	12.5	kWh/Car	10	30	Bloomberg NEF (2019) via Van der Linden (2020)
High delay order (categorical)	10	dmnl	9, 10, 11	-	Assumption
Long term substitution strength	0.05	1/Year	0.01	0.05	Van der Linden (2020)
Low delay order (categorical)	3	dmnl	3, 4, 5	-	Assumption
Market response factor capacity decrease	0.2	1/year	0.2	1	Assumption
Maximum decrease production capacity	0.03	1/year	0.02	0.05	Assumption
Number of buses per person	0.0016	Bus/Person	0.001	0.002	EEA (2018) via Van der Linden (2020)
Number of cars per dollar GDP	4.87E-06	Car/(Dollar/Year)	3.90E-06	5.84E-06	Sivak (2013) via Van der Linden (2020)
Percentage lost during operations	0.05	dmnl	0.04	0.08	Assumption
Percentage of primary scrap	0.05	dmnl	0.01	0.2	Assumption
Period for long term effect on demand	10	Year	5	15	Auping and Pruyt (2013)
Price elasticity short term	0.05	1/year	0.02	0.08	Auping and Pruyt (2013)
RE Co hydro	0.98	dmnl	0.85	0.99	Dai et al. (2019)
RE Co pyro	0.98	dmnl	0.85	0.99	Dai et al. (2019)
RE Li hydro	0.9	dmnl	0.85	0.95	Dai et al. (2019)
RE Li pyro with Li recovery	0.9	dmnl	0.7	0.95	Chen et al. (2019)
RE Ni hydro	0.98	dmnl	0.85	0.99	Dai et al. (2019)
RE Ni pyro	0.98	dmnl	0.85	0.99	Dai et al. (2019)
Recycling efficiency copper	0.9	dmnl	0.8	0.95	Dai et al. (2019)
Short forecasting period	1	Year	0.5	1.5	Assumption
Short term substitution strength	0.06	1/year	0.02	0.06	Assumption
Shared socio-economic pathways (categorical)	2	dmnl	1, 2, 3, 4, 5	-	Van der Linden (2020)

Table B.2.: Level 1 uncertainties that were not included in level 2 analysis. For level 2 analysis, the default values as presented in the third column were used. dmnl = dimensionless

Parametric uncertainty	Unit	Min value	Max value	Reference
Secondary premium amplifying factor	dimensionless	0.5	1.5	Assumption
Policy driven administrative cost decrease	dimensionless	0.1	0.4	Assumption
Material passport cost decrease	dimensionless	0.1	0.4	Assumption
Collection rate with EPR	dimensionless	0.8	0.95	Assumption
Policy-driven lifetime increase	dimensionless	1.1	1.4	Assumption
Minimum profit due to minimum processing requirements	dimensionless	0.05	0.3	Assumption

Table B.3.: Overview of extra uncertainties included for the policy analysis

C. Figures chapter 3

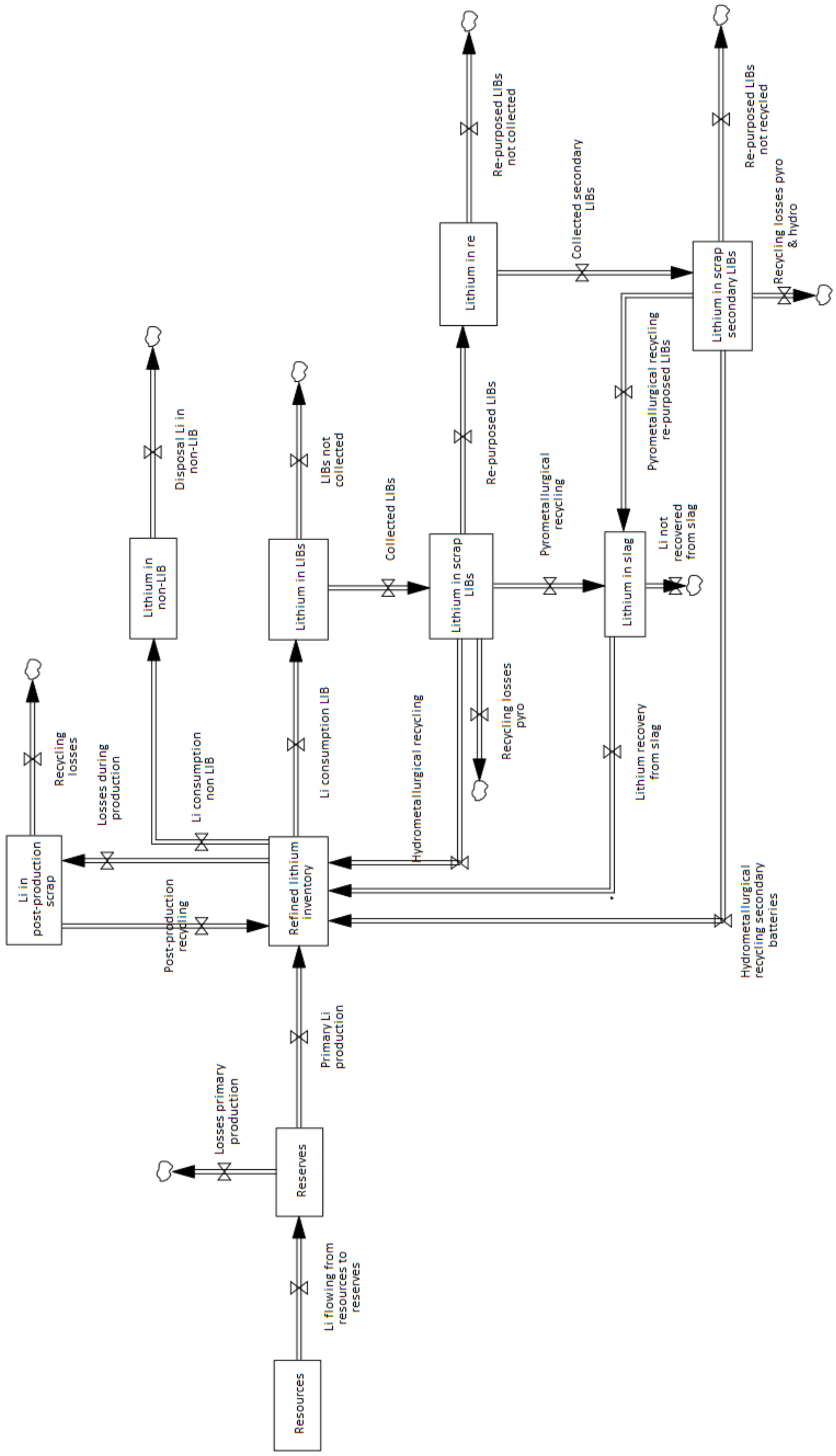

Figure C.1.: Full stock-flow diagram

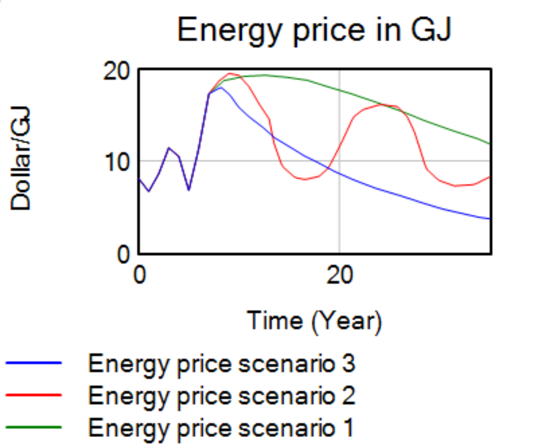

Figure C.2.: Energy price scenarios. Values until 2022 based on Our World in Data (2021), shapes of the curves based on Van der Linden (2020)

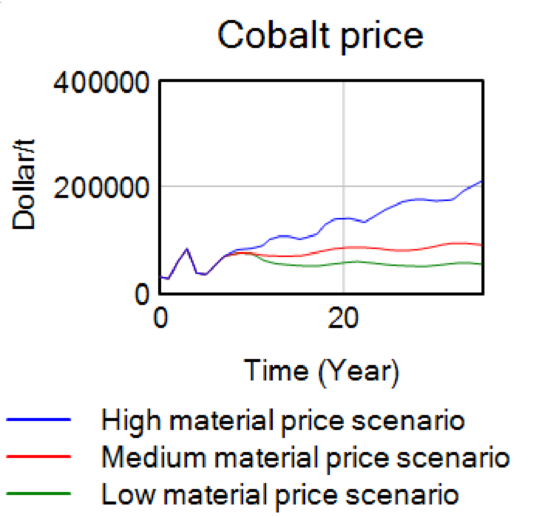

Figure C.3.: Cobalt price scenarios. Values until 2021 based on Statista (2021a), fluctuations assumed based on Van der Linden (2020)

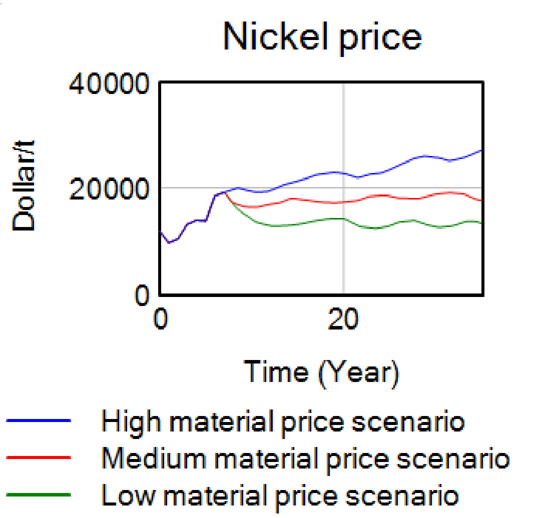

Figure C.4.: Nickel price scenarios. Values until 2021 based on Statista (2021b), fluctuations assumed based on Van der Linden (2020)

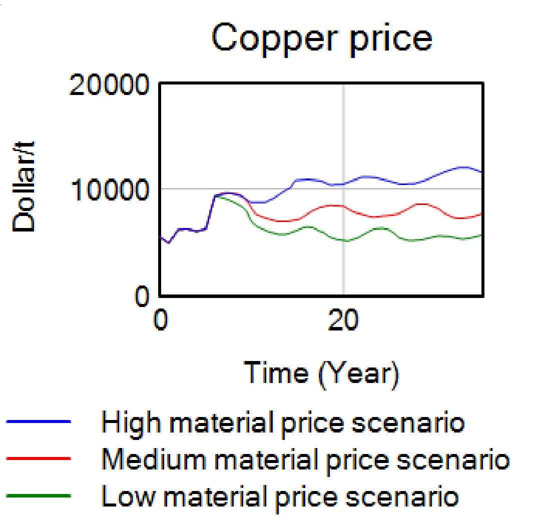

Figure C.5.: Copper price scenarios. Values until 2021 based on Statista (2022a), fluctuations assumed based on Van der Linden (2020)

D. Figures chapter 5

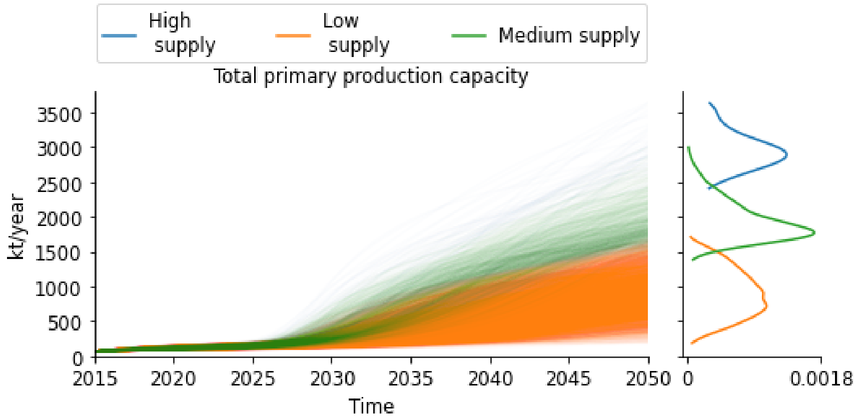

Figure D.1.: Primary production capacity [kt/year] divided in three clusters: high, medium and low supply (n=5000, X = 66)

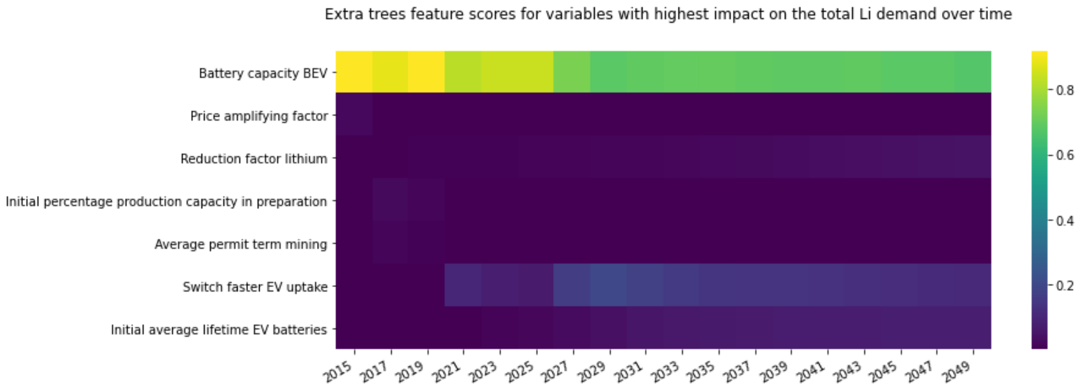

Figure D.2.: Extra trees feature scoring - Total demand lithium (n = 20000, X = 37)

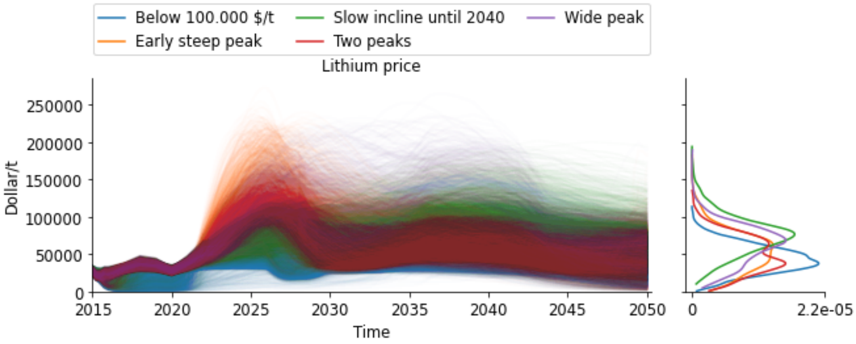

Figure D.3.: Lithium price [Dollar/t] for bulk of the scenarios (n=19336, X=37).

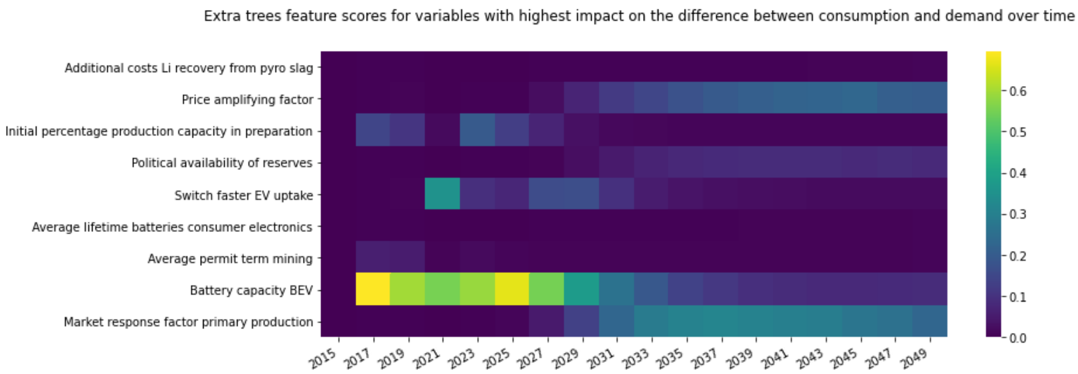

Figure D.4.: ETFS difference between consumption and demand (n = 20000, X=37)

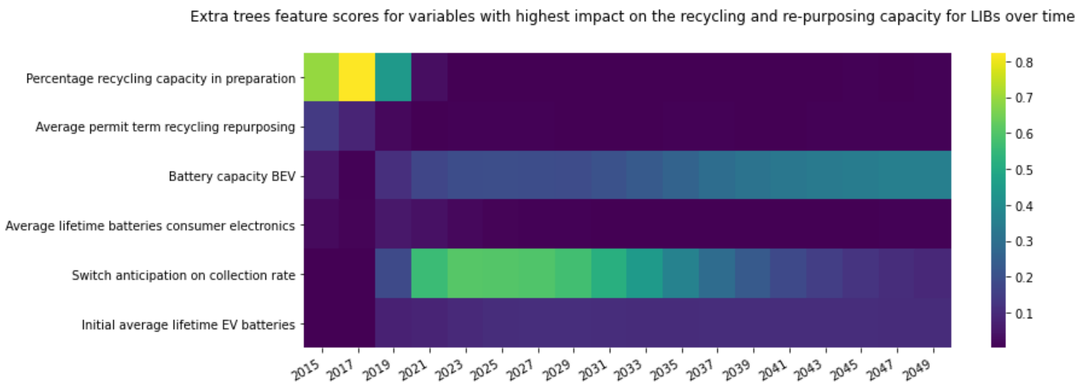

Figure D.5.: ETFS total recycling and re-purposing capacity (n=20000, X=66)

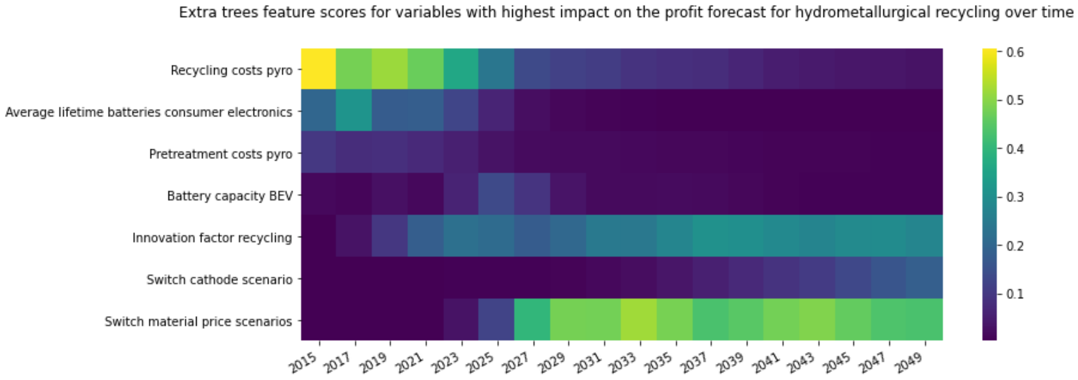

Figure D.6.: Extra trees feature scoring - Normalised profit forecast hydrometallurgical recycling (n = 20000, X = 37)

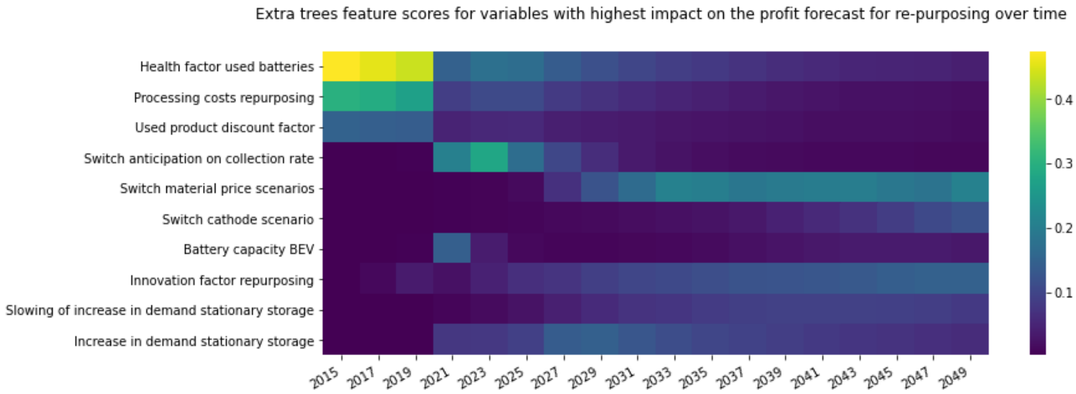

Figure D.7.: Extra trees feature scoring - Normalised profit forecast re-purposing (n = 20000, X = 37)

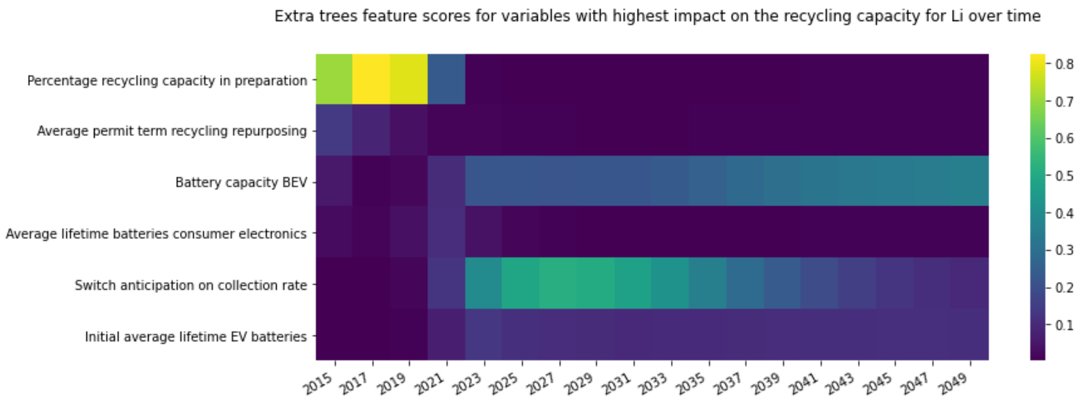

Figure D.8.: ETFS for total capacity for secondary lithium production (n=20000, X= 37)

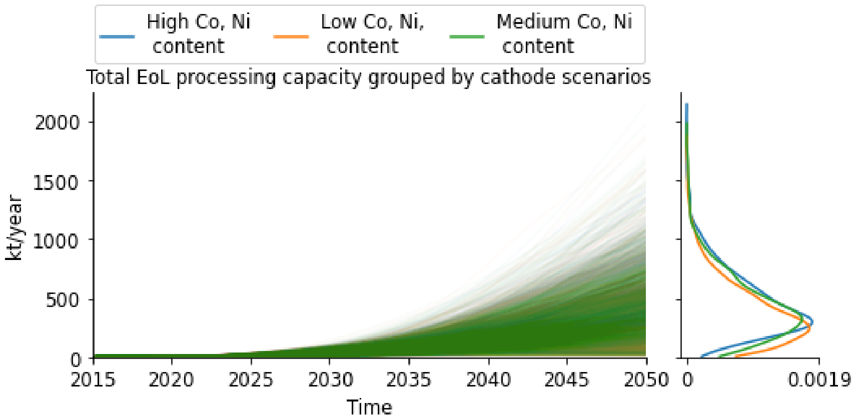

Figure D.9.: Total recycling and re-purposing capacity grouped by cathode demand scenarios (n = 5000, X = 66)

E. Figures chapter 6

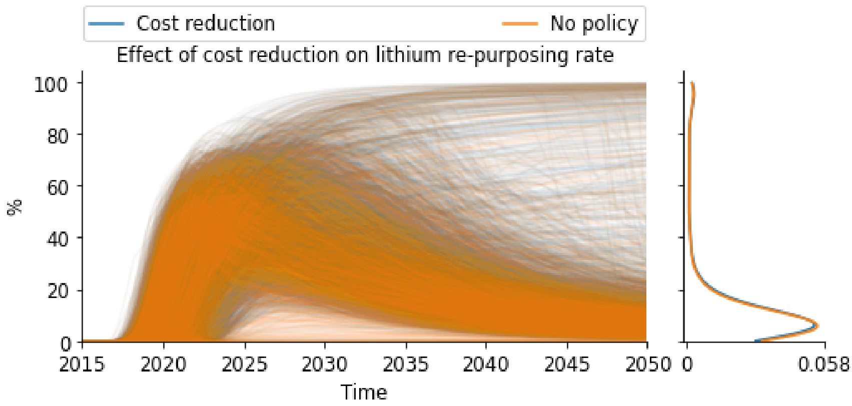

Figure E.1.: Effect of cost reduction on lithium re-purposing rate (n=3000*2, X=72)

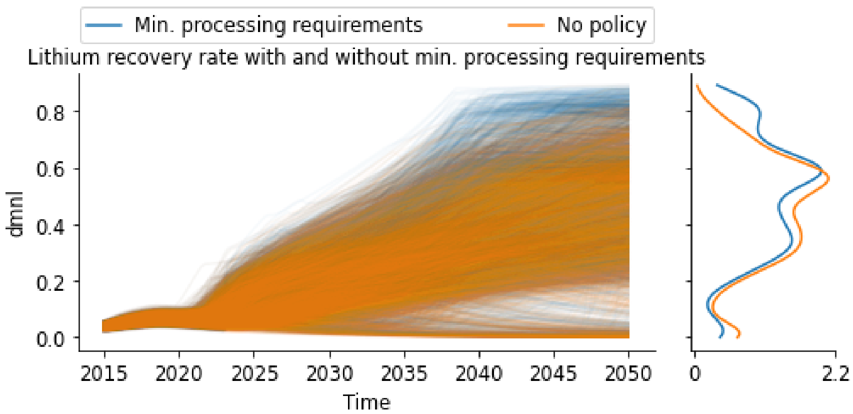

Figure E.2.: Lithium recovery rate with and without minimum EoL processing requirements (n=3000*2)

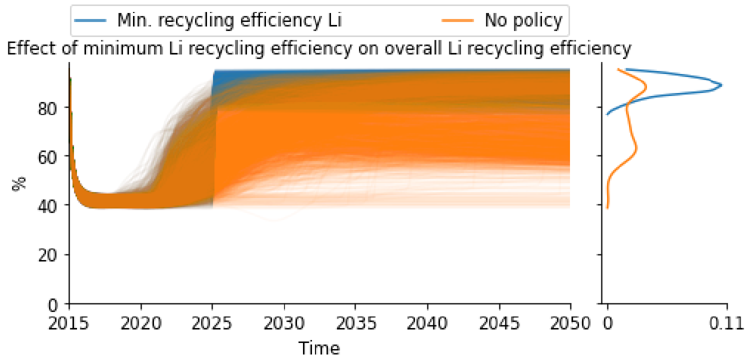

Figure E.3.: Effect of minimum recycling efficiency per facility on overall lithium recycling efficiency (n=3000*2, X=72)

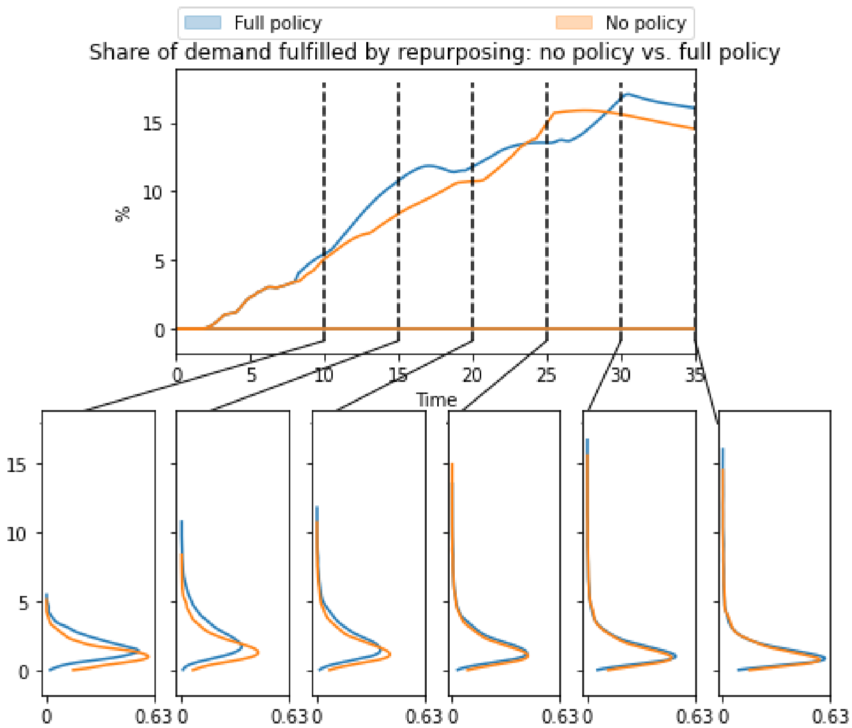

Figure E.4.: Effect of full policy package on the share of demand that can be fulfilled by re-purposing (n=3000*2, X=72)