# Dynamic Material Flow Analysis for Battery Cell Circularity in Mining Equipment

Master’s thesis in Management and Economics of Innovation

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Cover: A large open pit mine (Obtained from Pixabay (2014) with permission).

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## ABSTRACT

Over the last decade, electric vehicles (EVs) have advanced considerably, with predictions of continued rapid growth. However, the batteries driving this electrification contain rare materials like lithium, nickel, and graphite, which are expected to face increased demand. This surge in demand poses challenges related to material supply and resource constraints. Circular economy principles can reduce the constraints and extending battery life through reuse and recycling loops. The mining industry exemplifies this transition, substituting diesel-powered equipment with electric alternatives in mines. This study therefore aims to investigate the resource implications of increased circularity for battery cells in mining equipment until 2050. Specific objectives include developing a dynamic material flow analysis (dMFA) model, examining effects under different reuse scenarios, and analyzing recycling rate implications.

Results from the dMFA model show that life extension practices, such as reuse in other machines and battery energy storage solutions (BESS), can considerably reduce the demand for primary materials when electrifying the mining sector. For example, life extension possibilities in other mining equipment could in 2050 result in a lower demand for primary material, corresponding to a reduction of 17%. In the other scenarios, this level of reduction is affected by collection rate, recycling rate and the possibility of reusing batteries in BESS. However, practical challenges in infrastructure and compatibility arise with increased battery cell flows.

The results further underscore the challenges arising from mining electrification, including infrastructure overhaul, longevity of operational mines, and practical issues in battery reuse. The thesis highlights the role of legislation in advancing recycling and technological adoption, emphasizing the need for clear legal frameworks. Collection rate mandates and product-service systems can incentivize businesses to enhance recycling efforts. Despite uncertainties in the dMFA model, the findings offer guidance for stakeholders and policymakers in enhancing sustainability within the mining sector. Future research is suggested to delve into the feasibility of life extension strategies and conduct life cycle assessments to investigate environmental impacts of electrifying mining equipment.

Keywords: Mining electrification, battery electric vehicles, LFP batteries, circular economy, battery reuse, battery recycling, battery life extension, material flow analysis

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# 1. Introduction

Over the past decade, electric vehicles have seen remarkable progress in vehicle design, battery technology, and charging infrastructure with predictions of further exponential acceleration (Tan, et al., 2023). However, the batteries that enable such electrification contain several scarce and critical materials, such as lithium, nickel, cobalt, and graphite. Demand for these materials is expected to increase substantially over the coming decades (Xu et al., 2020). For example, lithium used in, e.g., lithium iron phosphate (LFP) batteries is a key material for batteries in electric vehicles (EVs), gadgets, and battery storage solutions (Goonan, 2012). This means that as the demand for lithium batteries rises worldwide, there is a risk of creating production systems that rely heavily on scarce minerals (Kushnir & Sandén, 2012). Although a considerably amount of research does not recognize a resource limitation of lithium (Peiró, Méndez, & Ayres, 2013; Wanger, 2011), other academics are less certain of its sufficiency (McNeil et al., 2023). Further, Kushnir and Sandén (2012) highlight the challenge in material flow rate into the system, constrained both by limited extraction rates and recycling capability. Xu et al. (2020) also point to potential bottlenecks in material supply, although influenced by uncertainties in the rates of EV fleet development and battery chemistry innovation. The challenges put forth by Xu et al. (2020) include potential shortages of lithium and cobalt before 2025 with reserves possibly depleted by 2050 in some scenarios, and they assess the success of the EV transition to hinge on sustainable material supply growth.

In order to decrease the dependency on critical materials and reduce the risks for supply constraints, policymakers are implementing targets for battery circularity. For example, the EU Batteries Regulation from 2023 promotes the transition to a circular economy, with the aim to secure supply of raw materials and strengthen self-sufficiency within the EU through increased levels of reuse and recycling (European Commission, 2023a). Adopting strategies aligned with circular economy principles can effectively diminish the need for new batteries in EVs as well as in other applications (Nurdiwati & Agrawal, 2023). In line with this strive, companies can gain from extending battery life through reuse loops (Martinez-Laserna, et al., 2018), thereby securing access to valuable materials. Implementing such extended usage is particularly important since many industries are currently transitioning towards electrification simultaneously. The intensified competition increases the importance for companies to secure supply of required materials to enable such a transition, e.g., by maintaining ownership of the materials through in-house reuse and recycling.

The mining industry is an example of a sector focusing on electrification and the implementation of circular solutions (Leonida, 2023). Substituting diesel-powered equipment with electric equipment in hard rock underground mines has gained widespread recognition as an important measure to improve working conditions and mitigate greenhouse-gas emissions (Halim, et al., 2022). However, it is currently unclear how beneficial such solutions are; therefore, a quantitative evaluation is needed. Within this thesis, a quantitative evaluation is performed in collaboration with a major mining equipment manufacturer to gain insights into the effectiveness of these solutions. As regulatory pressure rises and companies aim for resource efficiency and economic benefits, it becomes increasingly important for companies to measure the material flows of products throughout their entire life cycle, including extended use and second-life applications. For this purpose, material flow analysis (MFA) can be a useful method for quantifying the inventories and dynamics of a more circular system. MFAs can be used to better manage resources, decrease waste, and minimize environmental impact (Brunner & Rechberger, 2004). For example, analyzing the anticipated evolution of EV battery waste streams can help informing decisions on recycling, reuse infrastructure, and strategic planning (Abdelbaky, Peeters, & Dewuld, 2021). Apart from being beneficial to the company, this understanding is also vital for informed policymaking, assessing supply risks, and evaluating the social and environmental impacts of establishing a circular battery value chain (Xu, et al., 2020).

Prior research has predominantly focused on estimating global and regional demand for EV battery materials, utilizing MFA (Xu, et al., 2020; Ziemann, et al., 2018). These studies have underscored resource challenges, especially with lithium and cobalt, while highlighting the potential of EV battery recycling. Prior research in the field of lithium-ion battery management has primarily focused on evaluating reuse and recycling strategies, particularly in the context of EVs (Dunn et al,. 2021; Aguilar Lopez et al., 2023; Baars et al., 2021). Aguilar Lopez et al. (2023) utilized a stock-driven dynamic MFA (dMFA) to assess shifting material challenges and strategic trade-offs over time in the EV industry. Their MFA model is designed to evaluate the demand, usage, and flow of critical materials (such as cobalt, nickel, and lithium) used in Lithium-ion Batteries (LIBs). This analysis is particularly focused on understanding how these materials are consumed and cycled through the production, usage, and recycling of EV batteries. Baars et al. (2021) also conducted an MFA focusing on cobalt in EV batteries and they identify and analyze four strategies: (i) technology-driven substitution and (ii) reduction of cobalt, (iii) new business models for battery reuse/recycling, and (iv) policy-driven strategies to enhance recycling. These strategies, particularly focused on extending the lifecycle and efficient use of resources in EV batteries, aim to reduce dependence on critical raw materials like cobalt and mitigate environmental impacts.

Few battery cell-focused MFAs specific to the possibilities and challenges of the mining industry exist. An exception is Helander and Ljunggren (2023), who apply dMFA to assess the effects on the demand for new products and raw material from growing a product-service (PSS) system. The study focused on reuse and recycling of LIB subpacks for mining equipment and applied dMFA in order to consider various cycles of product reuse and recycling within a closed-loop system. The study primarily investigates the flow and implications of materials such as lithium, cobalt, and nickel.

## 1.1 Aim and objectives

The overarching aim of the thesis is to investigate the resource implications over time of increased material and product circularity for battery cells in mining equipment. The aim is achieved through developing a dMFA model and performing a scenario analysis of material flow and stock levels for battery cells until 2050. This model will serve as a tool for future in-depth analysis by the case company. Based on this aim, the specific research objectives (ROs) to be fulfilled are:

**RO1:** *Develop a dMFA model for battery cells in mining equipment that allows for altering parameter values and performing scenario analysis.*

**RO2:** *Apply the developed dMFA model to investigate the effects on material and product flows over time when considering varying product lifetimes across the following reuse scenarios:*

1. *Immediate LFP battery cell recycling with no reuse*
2. *Reuse of LFP battery cells through extended 1st life applications*
3. *Reuse of LFP battery cells through extended 1st life applications plus additional 2nd life use in battery energy storage systems (BESS)*

**RO3:** *Analyse the effects of different recycling rates for battery cell materials in the reuse scenarios.*

The analysed scenarios are illustrated in Table 1.1. Compared to the previous study by Helander and Ljunggren (2023), this study considers a different battery chemistry (LFP instead of NMC) and applies several different assumptions regarding the system. For example, their study does not consider changes in the diffusion curve and focuses on lithium, nickel and cobalt, whereas this study varies the diffusion curve and examines flows of lithium and aluminum. Also, Helander and Ljunggren (2023) analyzed three scenarios: business as usual, reuse, and battery reuse with additional stationary storage. These scenarios align with the 'No Reuse', 'Extended 1st Life', and 'Extended 1st Life + BESS' scenarios examined in this study. However, this paper introduces an additional variable, the recycling rate, thereby extending the analysis to include six scenarios (see section 3.2.2). Moreover, this study conducts further sensitivity analyses to assess the impacts of variations in factors such as life extension in rigs, battery lifetime, and the adoption rates of BEV.

*Table 1.1: Overview of the analysed scenarios.*

| | **No reuse** | **Extended 1st life** | **Extended 1st life + BESS** |
|---|---|---|---|
| **Medium recycling efficiency** | Scenario 1A | Scenario 2A | Scenario 3A |
| **High recycling efficiency** | Scenario 2A | Scenario 2B | Scenario 3B |

## 1.2 Limitations

One of the main limitations of the thesis is that the data derived from a specific company is assumed to represent the entire industry. Due to confidentiality concerns, the results from the company have been extrapolated to the entire industry. For the same reason, the rationale behind some of the assumed values cannot be fully disclosed. Lastly, while the thesis examines material and product flows, it does not consider environmental impacts (e.g., acidification and biodiversity losses) nor economic costs.

# 2. Background

The following sections describe the circular economy, MFA, battery electric vehicle (BEV) technology, battery recycling strategies, BEV applications within the mining industry and earlier research.

## 2.1 Circular economy

As global concerns about resource depletion and environmental degradation intensify, the concept of circular economy has emerged to address these pressing issues (Korhonen, Honkasalo, & Seppälä, 2018). Since the establishment of the circular economy notion, the concept has evolved and now acknowledges the constraints on planetary resource and energy utilization and underlines the importance of perceiving the planet as a "system" (Bocken, et al., 2016; Kirchherr, Reike, & Hekkert, 2017). The circular economy concept differs from the linear model of take-make-use-dispose, refocusing to making profits through circular material and product flows (Bakker et al., 2014). Further, as argued for by Bocken, et al., (2016), business models developed around circular economy concepts can facilitate economically sustainable methods for ongoing product and material reuse, as well as incorporating renewable resources.

Several researchers differentiate between two distinct loops within closed-loop systems: the reuse of goods and the recycling of materials (Stahel, 2010; Ellen MacArthur Foundation, 2023). Reuse of goods can be achieved by creating durable goods and implementing life-extension measures, such as service and repair. Recycling of material seals the loop between end-of-use and new material production and reduces primary material needs (Bocken et al., 2016). Further, Bocken et al. (2016) distinguishes a third strategy for the increased resource efficiency; that of reducing the resources needed per product. This is also known as dematerialization and can play a crucial role in fostering environmental sustainability in industries through alleviating scarcity constraints and reducing waste (De Bruyn, 2002). Together, prolonging product lifetimes, reusing goods, recycling materials, and increasing resource efficiency can contribute to decreasing, slowing, and closing material loops (Bocken, de Pauw, Bakker, & van der Grinten, 2016).

The circular economy concept is becoming increasingly important for companies as it offers a sustainable approach to resource management, reducing material use and recapturing "waste" as a resource to manufacture new materials and products (Ellen MacArthur Foundation, 2023). By keeping materials and products in circulation for as long as possible, the circular economy approach can help companies contribute to climate change mitigation, biodiversity conservation, and the reduction of waste and pollution. MFA is a method that could aid the understanding of material use, reuse, recycling, and disposal, enabling the evaluation of circular economy initiatives and their influence on material requirements (Millette, Williams, & Eiríkur Hull, 2019).

## 2.2 Material flow analysis

MFA is the systematic assessment of flows and stocks of materials within a system defined in space and time (Brunner & Rechberger, 2004). This analytical approach relies on tracking physical quantities of stocks, inflows, and outflows within a system (Ayres & Ayres, 2002). MFA is based on mass balance equations that encompass material inputs and outputs of processes as well as the stock and its changes in the system. Moreover, MFA connects the sources, the pathways, the intermediate and final sinks of a material, providing an overview of how materials move through a defined system. This is useful for assessing resource utilization, environmental impacts, and potential opportunities for sustainable resource management (Brunner & Rechberger, 2004). Brunner and Rechberger (2004) describe that it is important to note that the steps in an MFA are not strictly linear; rather, they should be performed iteratively. Selections and decisions made during the MFA need continuous monitoring and adjustment to align with the project objectives. Refinements and data improvements should be ongoing until a desired level of data quality is achieved (Brunner & Rechberger, 2004). There are some central concepts within MFA, for which definitions are provided below based on Brunner & Rechberg (2004):

- **Substance** - Single type of matter characterized by uniform units (e.g., atoms or molecules).
- **Goods** - Substances or mixtures of substances with assigned economic values (positive or negative). While goods can also include energy, services, and information, MFA considers only material goods.
- **Materials** - Substances and material goods.
- **Process** - Transport, transformation, or storage of materials.
- **Flow** - Flows link processes together and are usually defined as moved mass per time unit. Flows crossing system boundaries are defined as imports/exports, while inputs/outputs are flows entering/exiting a process.
- **Stocks** - Stocks in a system represent material reservoirs. Through flows, stocks can remain constant, grow, or shrink.
- **System** - A system is defined as a bounded group of material flows, stocks, and processes. The system boundary can consist of both geographical and virtual boarders and is defined in space and time.

The steps involved in performing an MFA vary, and there is no universally agreed-upon methodological framework (Ayres & Ayres, 2002). However, Ayres & Ayres (2002) present four general steps that are typically followed: (i) goal and system definition, (ii) process chain analysis, (iii) accounting and balancing, and (iv) modelling and evaluation. A more detailed procedure for conducting an MFA is described by Brunner & Rechberger (2004) and shown in Figure 2.1.

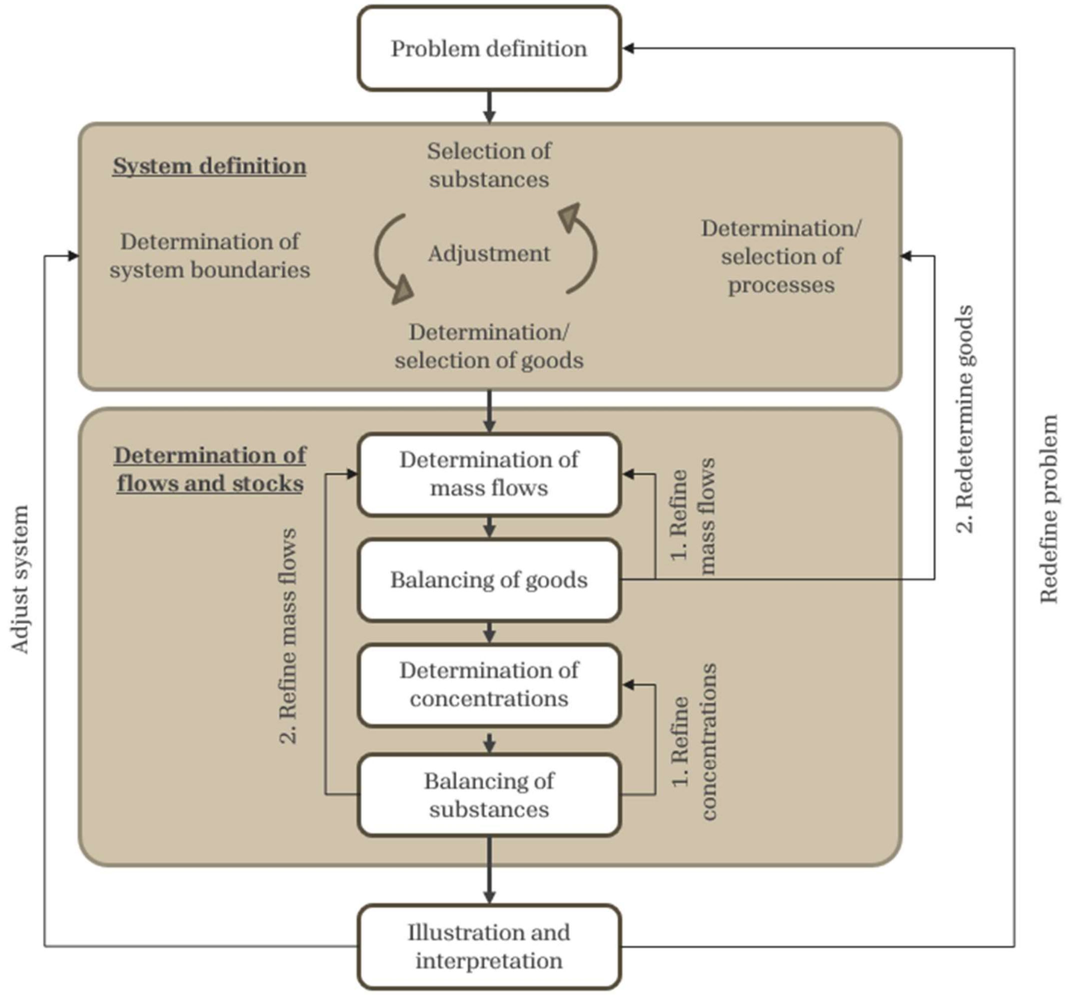

*Figure 2.1: Procedures for MFA – Figure produced by the authors based on a description by Brunner & Reschberger, (2016).*

While MFA can be applied as a stand-alone methodology, it can also be integrated with, e.g., environmentally extended input-output analysis, scenario development, and life cycle assessment. Such integrated assessment approaches might even emerge as novel tools for studies on sustainable development and circular economy (Graedel, 2019).

When performing an MFA, there are three different ways to model the system's flows and stocks: (i) accounting, which involves registering flows and stocks in retrospect, (ii) static modelling, where a steady state is assumed for stocks, flows and their relations, and (iii) dynamic modeling, which incorporates time as a modeling parameter, enabling the prediction of future scenarios (Ayres & Ayres, 2002). In this study, a dMFA will be conducted. Compared to a conventional MFA, a dMFA considers possible changes in material stocks and flows over time. With a dynamic model, outcomes of measures can be predicted and analyzed for a particular future year. Moreover, the time it will take for implemented measures to start showing their intended effects can be estimated (Ayres & Ayres, 2002). A dynamic model is particularly well-suited for conducting scenario analyses, which involves exploring different possible future situations.

The dMFA model in this thesis builds on the stock dynamics method, where the lifespan and stock demand for units dictate how many new units are required and how many retire (Müller, 2006). This method is deemed suitable since the demand for battery cells can be determined based on the projected number of required machines in the future, and this data is available to feed the model.

## 2.3 Lithium-ion batteries

In the transition towards a more sustainable society, electrification of the transport sector as well as grid-level energy storage systems are crucial for maintaining a balance between power generation and consumption. Due to their swift response, modular nature, and adaptable operation, batteries hold great promise for integration into these evolving systems (Chen, et al., 2020). Batteries used in EVs primarily encompass lead-acid batteries, nickel-metal hydride (Ni-MH) batteries, and lithium-ion batteries (Nykvist & Nilsson, 2015). As described in section 2.1, lithium-ion batteries stand as a competitive option for energy storage in EVs due to their exceptional attributes such as high energy efficiency, negligible memory effect, long lasting cycle life, and high-power density (Ding et al., 2019). These benefits result in lithium-ion batteries currently holding a dominant position in the market for commercial automotive batteries and this kind of batteries can be found in prominent EVs like the BMW i3, Tesla, etc. (Fui Tie & Wei Tan, 2013). Out of several different battery chemistries involving lithium, lithium iron phosphate (LFP) is commonly regarded as an attractive material combination (Vartanian & Bentley, 2011).

### 2.3.1 Batteries and cells

A battery “cell” refers to the fundamental electrochemical unit of a battery, whereas a “battery” is composed of one or several cells and other materials. Within a battery, the cells can be interconnected either in series, in parallel, or in a combination of both, determined by the requirements and intended use of the battery. Battery cells operate through harnessing the chemical energy within materials and transforming it into electrical energy through electrochemical redox reactions between, at least, two active components (Beard, 2019). The structure of the cell comprises three primary components: anode, cathode, and electrolyte. The anode serves as the reducing electrode, releasing electrons to the external circuit and undergoing oxidation during the electrochemical reaction. The cathode, on the other hand, serves as the oxidizing electrode, accepting electrons from the external circuit while undergoing reduction itself. Finally, the purpose of the electrolyte is that of an ionic conductor, creating the necessary environment for ion transfer between the two electrodes (Beard, 2019). When oxidation and reduction occur at the electrodes, a flow of electrical energy is created and it is this flow of electrons that generate the electric current (Bates, 2012). The performance of a cell is to a great extent limited by the selection of these components as the qualities and combination of different active materials exert a substantial influence on the potential to generate energy (Berg, Villevieille, Streich, Trabesinger, & Novák, 2015). As described by Beard (2019), restrictions to which combination of anode and cathode materials are possible arise due to, among other things, the overall reactivity, kinetics, and cost. Main considerations when selecting the electrode materials are conductivity, efficiency, and cost. Bearing these characteristics in mind, lithium is appealing as metal of choice for battery electrodes due to its light weight and electrochemical properties (Beard, 2019).

### 2.3.2 Lithium iron phosphate battery cells

LFP batteries are constructed as described in section 2.3.1 with interconnected cells arranged in parallel or series. For LFP batteries, graphite is used in the anode and LiFePO4 in the cathode. The lithium ions that carry the charge in LFP batteries move through the electrolyte, typically containing a dissolved lithium salt, and interact with the electrode active materials. During charging, lithium ions migrate from the negative electrode (anode) to the positive electrode (cathode) while electrons travel through an external circuit, leading to reduction reactions as visualized in Figure 2.2.

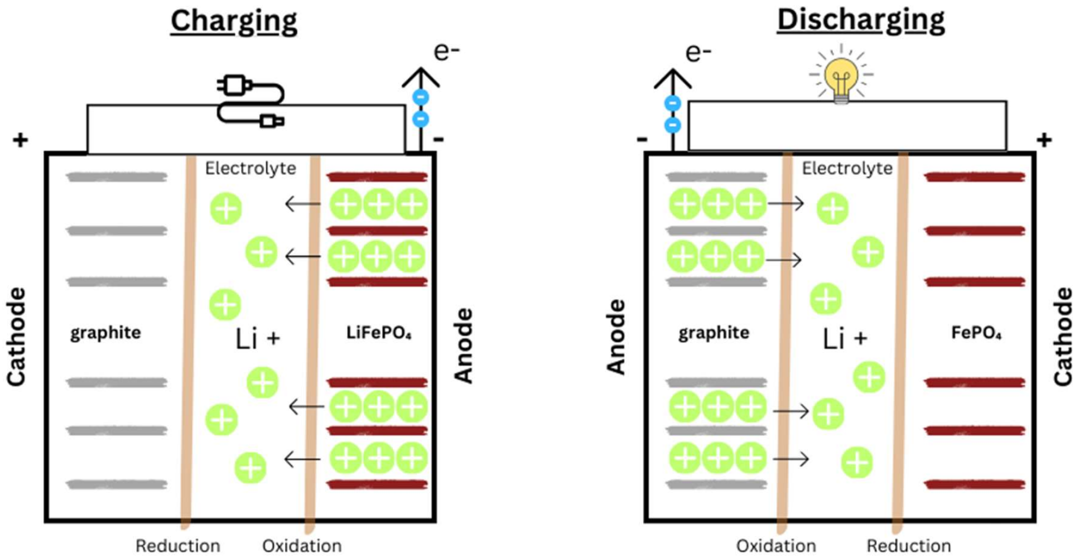

*Figure 2.2: Charge-discharge process of a lithium-ion cell – Figure produced by the authors based on the description by Gulzar, et al., (2016).*

Together with nickel cobalt manganese oxide (NMC), LFP batteries are presently the most commonly used LIBs in electrical vehicles. When comparing LFP batteries with NMC (Table 2.1), they are considered relatively similar in terms of performance when measuring the energy output during their expected lifetime. Whilst NMC are slightly stronger in terms of energy density, LFP come on top in terms of higher safety and slower degradation. The slower degradation has implications on increasing its lifespan and, hence, the amount of energy that can be channeled before it reaches end of life (EoL) (Lane, 2023). LFP batteries are known for offering high current, high temperature resistance, and enhanced safety even in harsh operating conditions (Electronic Design, 2021). Yet another benefit of the LFP chemistry concerns resource constraints; compared to the nickel and cobolt in NMC batteries, the iron phosphate used in LFP batteries is much more abundant and lower in cost (Tesla Economist, 2021). Consequently, LFP is often considered as a promising alternative for future development and application within BEVs (Quan, et al., 2022).

*Table 2.1: Comparison of five aspects of NMC and LFP batteries (Lane, 2023)*

| | **NMC** | **LFP** |
|---|---|---|
| Lifespan | Faster degradation, lower lifetime | Slower degradation, longer lifetime |
| Safety | Decreased stability at higher temperatures | Less likely to experience thermal runaway |
| Upfront cost | Lower upfront cost due to more extensive economies of scale | Higher upfront cost due to worse economies of scale |
| Value | 32 MWh energy output during warranty period (LG Chem Prime) | 58 MWh energy output during warranty period (sonnenCore) |

## 2.4 Battery electrical vehicles

This section introduces electrification of vehicles and its impact on the global sustainability challenge. From the broader trend of electrifying transportation, the section then delves into the unique challenges and opportunities associated with vehicle electrification in the mining industry.

### 2.4.1 Vehicle electrification

The transport industry accounted for approximately 21% of global carbon dioxide emissions in 2022 (Tieso, 2023). With increasing globalization and interconnectedness across borders, global trade can only be expected to grow (Kumar A. , 2023). Electrical Vehicles (EVs) are widely considered to be low in emissions and with the potential to contribute to the transition towards sustainable transportation (She et al., 2017). EVs encompass several categories, primarily pure or battery electric vehicles (PEVs or BEVs), hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs) (Shahan, 2016). BEVs rely entirely on a traction battery for power (Mersky et al., 2016) and consequently provides benefits compared to vehicles relying on the combustion of fossil fuels for addressing environmental concerns and the energy crisis, given their zero emissions and independence from oil consumption (Lin & Wu, 2018). EV batteries must deliver high levels of continuous power, which requires high energy capacity (Saxena et al, 2015).

### 2.4.2 BEVs in the mining industry

Presently, the mining industry predominantly depends on vehicles powered by fossil fuels and within the mining industry, vehicle emissions constitute on average half of a mine’s overall direct emissions (Ertugrul et al., 2020). Apart from the negative impact from high carbon emissions, examples of more mining-specific drawbacks from vehicles with internal combustion engines (ICEs) are low efficiency, limited overload capacity, expensive and demanding maintenance, considerable noise, and substantial heat generation. Furthermore, diesel vehicles present challenges in terms of data collection, remote monitoring, and autonomous controlling (International Council on Mining and Metals (ICMM), 2023). In comparison, BEVs present several advantages for the mining industry apart from the potential to reduce the carbon footprint of the mine. The main benefits of BEVs are: (1) Improved energy efficiency; (2) consistent torque; (3) rapid response to changes in load and improved overload capacity; (4) absence of exhaust emissions; (5) lower emissions; (6) lower energy costs; (7) reduced maintenance requirements; and (8) minimal noise and vibration (Paraszczak, Svedlund, Fytas, & Laflamme, 2014). Due to these benefits, battery-powered mining vehicles are rising in demand from customers and the original equipment manufacturers (OEMs) are looking to meet the demand (Leonida, 2021).

The potential of introducing BEVs in the mining sector has become increasingly acknowledged over the past decade and manufacturers have already introduced an extensive array of electric vehicles adopted to diverse mining applications (The Global Mining Guidelines Group, 2022). Enabled by recent years’ advancements in battery technology, the production of reliable BEVs has been feasible since 2016 (Leonida, 2020). Furthermore, initiatives such as the European Union’s Sustainable Intelligent Mining Systems, and the global International Council on Mining and Metals aim to establish conditions for the industry OEMs to further advance the next generation of mining vehicles. The vehicles currently developed are adaptable to various mining techniques and can, according to the Global Mining Guidelines Group (2022), generally be categorized into “on-board charging” and “off-board charging”. These two main categories may then be further divided depending on how the charging is performed (Fig. 2.3).

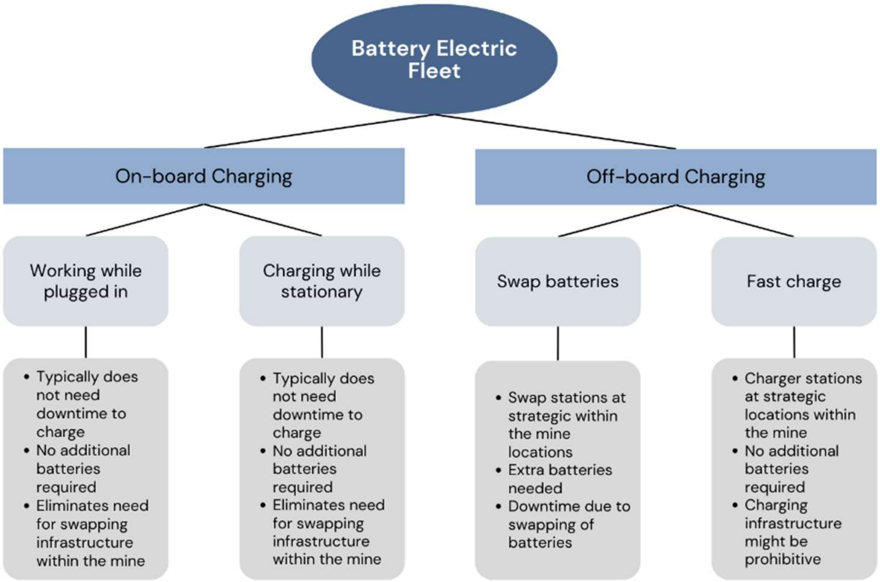

*Figure 2.3: Electric vehicle fleet designs for mining, divided by charging type – Figure produced by the authors as described by Global Mining Guidelines Group (2022).*

Despite the many advantages of BEVs, the electrical mining vehicles currently accessible (as well as those in later stages of development) are currently not universally applicable substitutes to ICE vehicles and each of the above solutions come with its respective drawbacks. In on-board charging, plugged-in vehicles are limited in range, but it eliminates the need for charging downtime and the associated infrastructure requirements. Stationary charging, on the other hand, also decreases infrastructural demands but is associated with significant downtimes. For off-board charging, battery swapping requires more advanced infrastructural set-up, but the downtime is decreased, and the range expanded. On the other hand, the fast charge solution still involves charging downtime but comes with a reduced need for battery-swap infrastructure (Paraszczak, Svedlund, Fytas, & Laflamme, 2014). Further, significant drawbacks related to fast charge solutions are its prohibitively high demands on the electrical grid capacity and accelerated degradation of cell life (Botsford & Szczpanek, 2009).

## 2.5 Battery reuse

To extend the use of individual batteries, and thereby reducing the material and production needs, reuse is a potential strategy, both in the mining industry and more generally. Extending a battery's lifespan can be achieved either through remanufacturing or repairing, or by utilization in a secondary application (Kastanaki & Giannis, 2023). Extending battery life can be beneficial as it postpones recycling until associated processes mature further and higher recycling efficiencies can be achieved, potentially leading to a lower need of new batteries and of primary material (Kastanaki & Giannis, 2023). Discarded batteries initially used in BEVs, now with diminished capacity in the 20–80% range, can find new life in low-speed vehicles through a cascading utilization approach (Wang, et al., 2022). However, the decrease in battery capacity over time poses safety risks and increased costs (Xiong et al., 2020).

To tackle these issues, battery management systems (BMSs) are increasingly used to improve health and safety management (Sulzer et al., 2021). Secondary life applications can also involve repurposing batteries for applications like BESS (Kastanaki & Giannis, 2023).

BESS are typically applied to achieve several objectives within renewable energy systems. These objectives include the distribution and improvement of reliability for renewable energy sources, maintaining a steady voltage and power output, improving the system's ability to respond dynamically to changes or fluctuations, and ensuring the stability and smooth operation of the entire renewable energy system (Rafaq, Basit, Mohammed, & Jung, 2022).

A BESS primarily consists of batteries (including the battery management system, BMS), a power converter system (PCS), an energy management system (EMS), and various auxiliary components (Chen, Li, & Chen, 2023). BESS relies on a PCS to integrate renewable energy into the grid by converting voltage types. PCS includes a control system, semiconductor switches, passive components, thermal management, safety features, and enclosures. It plays an important role in connecting different energy sources with varying voltage levels and frequencies to the standard AC grid output (Rafaq, Basit, Mohammed, & Jung, 2022). The EMS optimizes BESS performance by intelligently coordinating individual batteries. Considering factors like degradation and variable efficiencies, EMS aims to extend BESS lifetime and enhance efficiency for seamless integration into power systems (Nebuloni, et al., 2023).

There is an exponential growth of BESS capacity (McKinsey & Company, 2023). Repurposing used batteries for a second life could notably decrease the need for new LIBs in BESS. However, there are concerns regarding the feasibility of current technologies for commercialization of second use of batteries, and the business model through which using repurposed batteries can attain profitability. There are also concerns regarding the technical feasibility and the differences between retired and new LIBs (Geng, et al., 2022). Some critical battery features include efficiency, lifespan (measured in cycles and years), operating temperature, depth of discharge (referring to how much they are discharged), self-discharge rate (how quickly they lose charge when stored), and energy density (Divya & Østergaard, 2009).

## 2.6 Recycling of LFP battery cells

Recycling of LFP batteries can recover valuable materials, reducing the need for natural resources, and reducing environmental impacts (Wang, et al., 2022). Despite increasing utilization rates for LIBs and electric vehicles, increases in their recycling have not been as swift. Unless increased, this moderate recycling rate could become an intensified issue as the number of LIBs reaching EoL rises (Chen, et al., 2019). Current recycling efforts predominantly concentrate on recycling high-value materials, which, in the case of LFP, is lithium. However, current recycling infrastructure oftentimes do not recycle lithium due to high process costs, which results in low recycling levels for the battery cell as a whole (Heelan, et al., 2016).

Recycling of retired LIBs, including LFP, has partly been low since the current economic and infrastructural situation does not offer enough incentives to neither manufacturers nor waste managers to engage in recycling. Another reason for the low recycling rates is that the batteries contain toxic and flammable materials, which pose severe risks to both human health and the environment if not carefully taken care of (Tang, Ren, Duan, Li, & Li, 2020). The processes applied currently leave room for improvement in energy efficiency and decrease in caustic chemicals, which cause additional pollution as well as a climate impacts (Zu, et al., 2020). However, the perception of LIB collection and recycling rates is somewhat distorted since discarded LIBs are commonly exported to external markets. Thus, when the batteries eventually are recycled it is likely in a country different to where it had its primary use and nations like China and South Korea already have established recycling systems for LIBs (Melin, 2023).

Outdated legislation may hinder technological innovation and impede the recycling of batteries (Green, 2017). In the EU, the Batteries Directive aims to unify recycling ambitions across member states, emphasizing producer responsibility, setting targets for battery collection, and stating recycling quality standards. The directive further state producer responsibility and labelling requirements, forcing the producers to inform consumers on the chemical composition and proper disposal of the batteries, as well as finance the costs associated with collection, treatment, and recycling (European Parliament, 2022). Additionally, various US states have implemented specific regulations for battery recycling, such as requirements for retailers to accept used batteries (Green, 2017).

Current recycling methods for LFP batteries primarily consist of pyrometallurgy, hydrometallurgy, and direct recycling (Costa, et al., 2021), which are further described in the following subsections along with their associated advantages and challenges.

### 2.6.1 Pyrometallurgical recycling

Pyrometallurgical recycling of LFP cells involves the use of high temperatures to extract metals or other compounds from spent LFP batteries (Zhou, Li, & Xu, 2021). The process typically involves crushing the batteries and then heating them at high temperatures in a furnace to break down the cathode material (Kumar, et al., 2022). This resulting material is then treated with chemicals to extract the lithium, which can be further processed to produce material for new batteries (Mao, et al., 2022).

Since the retired batteries are burnt without any sorting or pre-treatment, it has practical advantages for large-scale operations. However, this comes at the cost of difficult lithium extraction as well as with a high energy demand and notable carbon dioxide emissions (Zhou, Li, & Xu, 2021). These drawbacks are primarily associated with the most common pyrometallurgical recycling method of smelting. Recent developments in pyrometallurgy have addressed these challenges by recovering lithium through a roasting process, which converts insoluble lithium into a water-soluble form, increasing the recovery rates (Dang, et al., 2018).

The pyrometallurgical technology as a means for recycling lithium is still in its early development stages due to low lithium yields, high emissions and high energy demand. Different processes can achieve lithium recovery rates of 76-97% at different energy and economical costs (Holzer et al., 2021). Additionally, since the economic value of metals in LFP cathode material is notably lower than in NCM cathode materials, LFP recycling is considered both technically and economically more unattractive (Wang, et al., 2022).

### 2.6.2 Hydrometallurgical recycling

Hydrometallurgical recycling broadly begins by categorizing batteries by type, after which they are disassembled and fully discharged through a procedure called deep discharge to prevent potential safety hazards. The demolishing of batteries can be achieved through methods such as crushing, sieving, milling, froth flotation, pneumatic separation, magnetic separation, and densiometric splitting (Costa, et al., 2021). The valuable metals liberated after the previous step are thereafter dissolved in an aqueous solution using chemical reagents, including leaching, liquid-solid separation, solution purification, metal extraction, and wastewater treatment.

Hydrometallurgy has an advantage compared to pyrometallurgy that can be conducted at ambient temperature and pressure. Furthermore, hydrometallurgy has a higher recovery efficiency and lower energy requirements compared to pyrometallurgy. Due to profitability issues and intricate processes of pre-treatment, coupled with the costs of the subsequent mandatory wastewater treatment, the widespread adoption of hydrometallurgical recycling is limited (Yao, et al., 2018).

Currently existing hydrometallurgical recovery techniques for LFP batteries can be categorized into three main groups: inorganic acids, organic acids, and oxidation reagents (Wang, et al., 2022). In comparison to inorganic acids, organic acids exhibit benefits regarding renewability and eco-friendliness since it generates fewer secondary pollutants (Yao, et al., 2018). With the aim to reduce energy expenses and environmental impact, “green leaching agents”, such as organic acids, bioleaching agents, and deep eutectic solvents are currently being evaluated with the aspirations of achieving higher recycling efficiencies. Through the selective recycling of high-purity metals made available with hydrometallurgical approaches, lithium recovery rates up to 100% can be obtained (Kumar, et al., 2022).

### 2.6.3 Direct recycling

As opposed to hydro- and pyrometallurgical recycling, direct recycling aims to recover and preserve the active materials (Gao, Tran, & Chen, 2022). The initial pre-treatment resembles that of hydrometallurgy but rather than chemically dismantling, the active materials are purified and revived through a process called re-lithiation (Sloop, et al., 2022). Following the pre-treatment and subsequent separation, there are several methods for repairing and restoring the recovered active materials, such as lithium (Nie, et al., 2015). Direct recycling has emerged as an attractive method due to its energy efficiency. Furthermore, it enables the preservation of a considerably portion of the energy stored within the materials from the original manufacturing (Tang, Ren, Duan, Li, & Li, 2020). The major drawback of this technology is its nascency and insufficient scale, without agreements or conventions for this type of recycling (Xu, et al., 2022). However, several processes for direct recycling are under development, currently achieving 78-99% recovery rates for lithium (Wu, et al., 2023).

# 3. Methodology

This chapter is organized into five main sections. Section 3.1 outlines and justifies the overall research design. Section 3.2 presents the case study and the various scenarios to be examined. In Section 3.3, the development of the dMFA model is explained. Section 3.4 details the data collection for the model. Finally, Section 3.5 describes the sensitivity analysis performed.

## 3.1 Research design

In order to explore how different reuse scenarios and recycling efficiencies influence the material flows for mining equipment batteries, a case study has been deemed a suitable research approach for this study. A case study offers the opportunity to gather real-life data to deduct theoretical implications within the selected field and facilitates the gathering of insights of practical use (Ridder, 2019). Further, the approach falls under the category of quantitative research as it primarily explores numerical patterns related to battery material flows (The University of Texas at Arlington, 2023). Further, an analytical research design is applied as scenarios are constructed and altered within the dMFA model in order to assess the impacts and outcomes from altering selected input parameters (Ridder, 2019). The thesis will result in outcomes in terms of factual results, as well as in a model implemented as an Excel tool that can be used and modified for future use by the case company.

The research approach of choice for this study is abductive, which according to Bell et al. (2022) addresses several constraints related to inductive and deductive methods in business research. Abductive reasoning is used to generate hypotheses with a starting point in surprising insights that emerge when researchers encounter empirical phenomena that cannot be explained by existing theories (Saunders, Lewis, & Thornhill, 2012). Researchers following abductive practices have increased flexibility in deriving theory from data, allowing for unexpected results. Furthermore, when an iterative process between literature and empirical evidence is adopted, the abductive development of theory throughout the study is promoted (Sheperd & Suddaby, 2016).

Historically, the dynamic interaction between history and empirical observation faced criticism for perceived lack of academic validity and being considered a “soft” approach (Yin, 1994). However, recent years have seen a growing importance of the interplay between conceptual and experimental research, especially in abductive research designs (Dubois & Gadde, 2002). Critics argue that case studies are too adapted to specific situations, hindering broader generalization (Weick, 1969). Yet, more contemporary perspectives suggest that general findings may not be universally applicable over time, recognizing situation-specific insights as valuable even when aiming for generalizability (Cronbach, 1975).

In this study, focusing on a specific industry, the use of a case study methodology aligns with criteria outlined by Bell, Harley, and Bryman (2022), emphasizing the possibility to delimit a bounded situation and emphasize distinguishing features. Case studies are deemed suitable for business research, involving a thorough examination of specific and isolated situations (Bell, Harley, & Bryman, 2022).

Additionally, the Excel model created for the thesis aims to be applicable for future case-based analyses of material flows and stock levels for battery cells, as advocated for by Dubois and Gadde (2022). As described by Graedel (2019), an MFA can serve as a foundation for a further, detailed analysis of carbon emissions, something the case company is interesting in conducting for the battery cells in the near the future.

## 3.2 Case description

In order to gain access to valuable insights and data, this thesis has been conducted in collaboration with a leading company within the production of mining equipment. However, due to confidentiality, the research scope has been expanded to consider the mining industry at a global level and sensitive information has been omitted.

### 3.2.1 Mining applications

While mining involves several operations, and can occur both above and below ground, the focus of the thesis is limited to underground mining. Like the mining industry in general, the case company is currently working on electrification of their underground vehicles and this study considers three main vehicle types: trucks, loaders, and rigs, all of which come in different sizes and adaptations to different mines (Figs. 3.1-3.3). Underground mining trucks and loaders require more precise maneuvering in the tighter environments they operate in and serve various purposes, such as excavation, loading rocks or extracted materials into trucks, and transporting materials to the surface. Rigs typically have a wider array of possible applications, depending on how they are built and are used for drilling and mine development rather than load and transport. For the purpose of the thesis, a differentiation was made between size classes only when the number of battery cells they require differed. Further, within the thesis, the decision was made to study only BEVs and no hybrid electric vehicles. Within the category ‘trucks’, both the regular trucks and trolley-electric trucks have been included since trolleys are not hybrid vehicles.

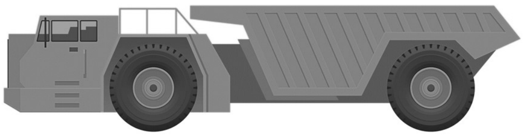

*Figure 3.1 Example of a mining truck (Obtained from Shutterstock (2023) with permission).*

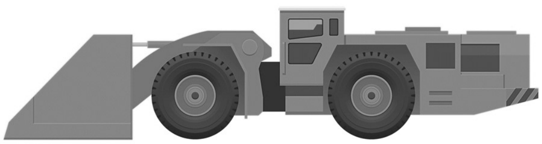

*Figure 3.2 Example of a mining loader (Obtained from Shutterstock (2023) with permission).*

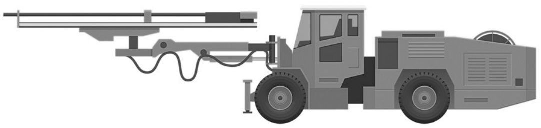

*Figure 3.3 Example of mining rig (Obtained from Shutterstock (2023) with permission).*

Each vehicle type employs a battery that contains a varying number of packs depending on the vehicle. Furthermore, the number of modules per pack and the number of cells per module can vary. The battery packs serve as mechanical protection and isolation for the battery modules. The battery modules in turn consists of battery cells. When a battery module reaches its EoL, the whole module is swapped. However, within the dMFA model, the product flows and calculations are made on cell level as they correspond to the largest common building block for the three vehicle types. Using battery cells as the fundamental components thus allows for studying the material flows on an common basis. The case company explains that in the mining industry cascade utilization in different machines is becoming an interesting business case to consider, as it might provide financial as well as environmental benefits. Further, company experts explained that the battery capacity needed is the highest in trucks, less in loaders, and the least battery capacity need can be found in drilling rigs.

### 3.2.2 Scenarios description

The material flows are analyzed for scenario 1 (only recycling), scenario 2 (extended life plus recycling), and scenario 3 (extended life, BESS, plus recycling). All scenarios and flows are described more in detail below and illustrated in Fig 3.4. The share of battery cells that can be used through life extension is determined by the lifetime function of the battery cell for a specific vehicle type and its estimated state of health (SoH) at EoL. Due to the capacity requirements being highest in trucks, second highest in loaders, lower in rigs, and lowest in BESS, battery cells from applications with higher capacity requirements can have an extended life in an application with lower capacity requirements. According to the case company, batteries are estimated to reach a replacement threshold when the battery capacity reaches around 70% for vehicles and 25% for BESS. The translation of SoH into lifetimes in years is dependent on how many charges cycles the batteries go through but was estimated at 3-7 years depending on which machines they are used in, as well as their previous applications. The case company has proposed a model in which it is feasible to extend the life of cells in both 1st extended use, 2nd extended use, and in BESS. This form of reuse is currently not implemented but is part of the case company's plan for the future. Consequently, the decision was made to construct the model, even on an industry-wide scale, with the assumption that this kind of reuse is possible.

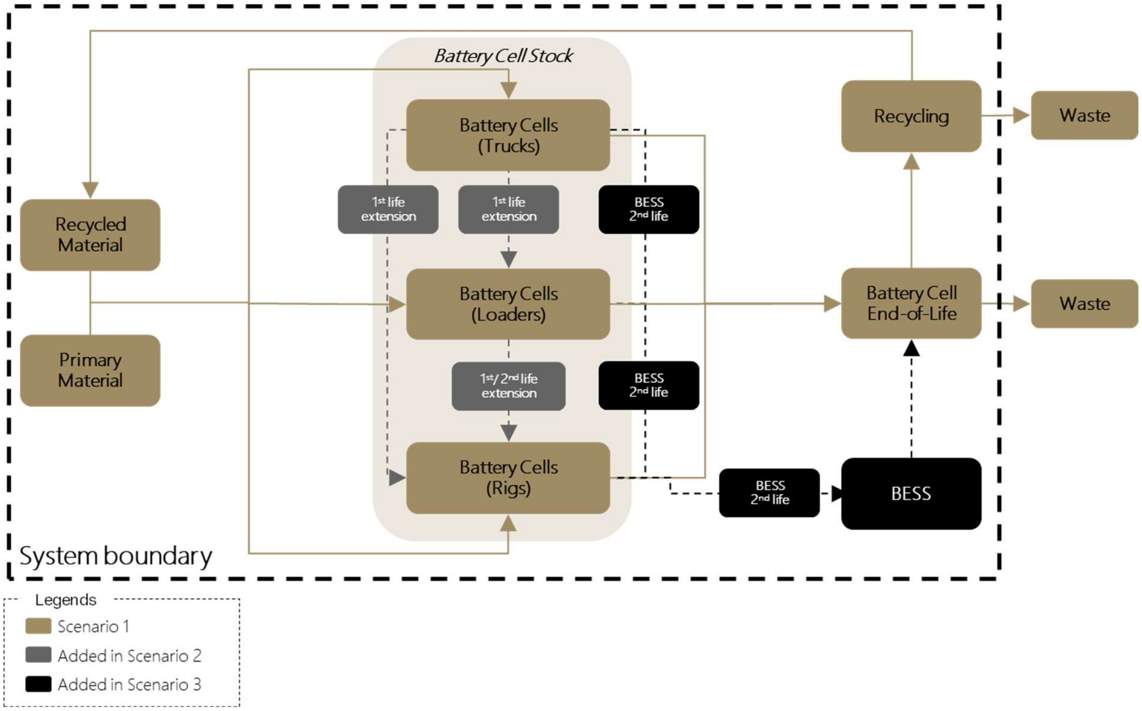

*Figure 3.4: Flow chart describing the potential flows for battery cells in scenarios 1, 2, and 3.*

In this thesis, the case study is performed by modelling six different scenarios and investigating a range of potential results for material flows and stock levels arising from various EoL strategies. The six scenarios are constructed through combining the two parameters (i) reuse approach and (ii) recycling rate as presented in Table 1.1. This results in six scenarios. Below, the rationale behind the three scenarios are descibed in more detail.

In Scenario 1, the system exclusively engages in first use application and battery cell recycling. First use application means that the cells entering the system are employed in one of three machines until they reach a too low SoH for the application. Subsequently, these cells are directed to recycling, with a proportion returning to the system as new cells based on the recycling rate. This approach results in a reduced demand for primary cells and substances.

In Scenario 2, the system also includes extended life after the first use but before the battery cells are sent to recycling. A summary of the assumed values for the share of batteries that flow in the different directions can be found in Table 3.1. In Scenario 2, battery cells first serve in one of three types of machinery, then enter an extended life phase. For trucks, 85% of cells are repurposed equally between loaders and rigs. Surplus cells, or the 15% from trucks unfit for extended use, are sent to recycling. Similarly, 85% of loader cells are reassigned to rigs, and all rig cells eventually go to recycling. Reused cells from earlier uses are prioritized to meet demand, except in trucks. The recycling process dictates how many cells return as new, reducing the need for primary resources.

Scenario 3 extends this model to include first life, extended life, BESS usage, and recycling. It is similar to Scenario 2, but here, 90% of cells destined for recycling are first used in BESS applications until their SoH becomes too low. The remaining 10% are recycled directly. Post-BESS, all cells are recycled, contributing a share of new cells back to the system.

*Table 3.1 Summary percentages determining the flows in the three scenarios.*

| | **Scenario 1** | **Scenario 2** | **Scenario 3** |
|---|---|---|---|
| Fit for extended 1st life from trucks and loaders | No reuse | 85% | 85% |
| Not fit for extended 1st life from trucks and loaders | No reuse | 15% | 15% |
| Fit for extended 2nd life from loaders | No reuse | 85% | 85% |
| Not fit for 2nd extended life from loaders | No reuse | 15% | 15% |
| Fit for BESS, out of cells not fit for 1st or 2nd extended life | No reuse | No 2nd life | 90% |

### 3.2.3 Recycling

The difference between scenarios 1A-3A and 1B-3B is the recycling rate. The recycling rate is composed of the collection rate for battery cells, as well as the recycling efficiency for the specific materials. The distinction between collection rate and recycling rate was made due to the differences and potential challenges for the two factors:

- **Recycling efficiency**: LIB recycling is a rapidly evolving field, expected to undergo substantial transformations as it addresses challenges such as technical and economic feasibility, and the potential for scaling. Currently, hydro- and pyrometallurgy appear to be the most promising routes for recovering valuable materials but alternative approaches are being explored (Neumann, et al., 2022), which would impact the flows of recycled materials in the dMFA model.
- **Collection rate**: Large-scale LIB recycling is in its early stages and to encourage robust recycling value chains, funding and policy instruments are required to compete with primary material supply chains in terms of cost, quality, and reliability (Beaudet, Larouce, Amouzegar, Bouchard, & Zaghib, 2020). The European Union is actively pursuing the expansion of battery collection and recycling by introducing new legislation to align recycling efforts across Europe

(Cheret, 2007). Consequently, the collection rates for EV battery cells are likely to increase, which would influence the material flows and stock levels in the dMFA model.

As discussed in section 2.6, there are several methods available for recycling LFP battery cells with their respective advantages and challenges. While both pyrometallurgical and hydrometallurgical currently present an unattractive business case for recycling of LFP batteries from an economic perspective, the practically attainable recycling process efficiencies are promisingly high. Current processes achieve between 76% and 97% with pyrometallurgical recycling and up to 100% with hydrometallurgical recycling (Holzer et al., 2021; Kumar A., 2023). However, an important distinction to be made is that pyrometallurgical processes are currently not commercialized on a large scale (Makuza et al., 2021) while hydrometallurgical recycling is currently being industrialized (Marcinov, et al., 2023). Within this thesis, a “medium” recycling rate of 97% and a “high” recycling rate of 100% were assumed. The underlying reasoning is the technical feasibility of achieving such high recycling efficiencies, as well as the anticipation of rapidly increasing adoption rates of these processes. Further, the high assumed recycling rates and the low range between them were assumed in relation to a relatively low collection rate (see further below). Consequently, while relatively few batteries are collected, those that are collected are assumed to have high efficiency in recycling.

The definition of the collection rate within the thesis aims to take various factors into consideration. For example, it aims to encompass the share of batteries that are physically collected, the portion that end up being recycled, and the subset recycled through a process where the materials of interest for the thesis (lithium and aluminum) are being recovered. On the one hand, the mining industry involves a higher degree of clear ownership of larger batteries compared to the situation for personal EVs. Evolvement of battery-ownership models would thereby be facilitated, and this has the potential to facilitate collection (Engel, Hertzke, & Siccardo, 2019) and could consequently justify a higher collection rate. On the other hand, LFP batteries containing fewer valuable metals might justify a lower assumed collection rate compared to, for example, NMC batteries (Wang, et al., 2022). Further, lithium and aluminum are primarily recovered through hydrometallurgical processes and although development of these methods is currently ongoing, their potential and capacity is still uncertain (Holzer et al., 2021; Kumar A., 2023).

Considering the above, the collection rates for the thesis were grounded in estimations made by Zhang et al. (2021), who defined a "high collection rate" as falling between 44-54%, and a "low collection rate" ranging from 18.06% to 19.24%. However, this low estimate for the collection rate is deemed less likely due to governmental initiatives, such as penalties, being in place (Zhang et al., 2021). Consequently, the thesis adopts a "medium" collection rate of 35%, falling within the interval between the high and low rates proposed by Zhang et al. (2021). Similarly, a "high" collection rate of 50% is assumed, aligning with the higher range provided by Zhang et al. (2021).

It can be noted that the collection rate has a greater impact on the recycling rate compared to recycling efficiency for the respective materials. In scenario 1A-3A, the collection rate is set to 35%, the recycling efficiency for lithium to 97%, and the recycling efficiency for aluminum to 99%. In scenario 1B-3B, the collection rate is set to 50%, the recycling efficiency for lithium to 99%, and the recycling efficiency for aluminum to 99.9%. This results in the four recycling rates marked in blue, presented in Table 3.2. As a consequence of increasing both the collection rate and the recycling efficiency, the recycling rate is increased by +48.80% for lithium and +44.16% for aluminum. When the collection rate is kept at 35% but the recycling efficiency is increased, the corresponding increases in recycling efficiency are +2.06% more for lithium and +0.91% more for aluminum. When instead increasing the collection rate from 35% to 50% but keeping the recycling efficiencies at their lower values, the increase in recycling efficiencies is +42.86% for lithium and +42.86% for aluminum.

*Table 3.2 Recycling rates as a result of varying collection rates and recycling efficiencies.*

| | **Lithium: 97% efficiency** | **Aluminum: 99% efficiency** | **Lithium: 99% efficiency** | **Aluminum: 99.9% efficiency** |
|---|---|---|---|---|
| **35% Collection rate** | 33.95% | 34.65% | 34.65%<br>(+2.06%) | 34.97%<br>(+0.91%) |
| **50% Collection rate** | 48.5%<br>(+42.86%) | 49.50%<br>(+42.86%) | 49.50%<br>(+48.80%) | 49.95%<br>(44.16%) |

## 3.3 Material flow analysis

In the following subsections, each step of the MFA is described, following the framework described in Section 2.2. As suggested by Brunner and Rechberger (2004), the process of conducting the study has been iterative and the dMFA model has been developed with support from the case company.

### 3.3.1 Problem definition

The problem definition and the aim of the MFA are the same as the as for the thesis and are stated in section 1.1, Aim and Objectives.

### 3.3.2 System definition

As part of the system definition, there are four things that need to be selected according to Brunner and Rechberger (2004): Goods, substances, processes, and system boundaries. For this study, the chosen goods are the battery cells. The substances considered in this study are lithium and aluminum. Lithium is the primary element in the battery's cathode, and aluminum is a material in the battery module case structures. Both these materials are on the 2023 list of critical raw materials for the EU and are thus deemed important to Europe's economy but having high supply risks (European Commission, 2023b). The amount of aluminum per cells is an average of the different battery modules considered in the vehicle model. In Table 3.3, the substance split for each cell is presented.

*Table 3.3 – Substance split per cell.*

| Substance | Amount (g/cell) |
|---|---|
| Lithium | 101 |
| Aluminum | 474 |

When deciding on a system boundary, Brunner and Rechberger (2004) describe that a guideline is to select a system that is small, but still includes all central processes and material flows. The system boundaries should also be based on the goal of the study. As this study aims to explore material and product flows in the mining industry over time, considering varying product lifetimes across different reuse and recycling scenarios, the boundaries are the lifecycle of a battery cell. The case described in this thesis has been limited to include only the material flows between the nodes in which the batteries are used. Consequently, both transportation and manufacturing of the cells are considered out of scope. The rationale behind this decision is that the transport and manufacturing steps do not impact the volumes of material, other than through potential losses. However, these potential losses were considered difficult to estimate and likely minor. The defined system also involves some steps outside of the company and the mining industry, like BESS and recycling. However, this dMFA model only looks at the materials from batteries within the mining sector in those processes. This limitation of material flows to stay within the specific industry is a method also employed by Aguilar Lopez et al. (2023). It avoids the need for additional modelling of other industries and their trade flows. In the dMFA model, the material recycled is used to manufacture new cells that are then used in the same vehicles, hence the system is a closed loop. This assumption is likely relevant, as there are benefits for mining companies to maintain ownership of the battery materials. However, the recycled material might also end up in batteries used in other industries and the share of recycled materials in the inflow might therefore in reality be dependent also on recycling rates of other industries.

The system's complexity and study's objective dictate the number of stocks and flows involved. In this thesis, four battery cell stocks are considered, as well as the battery cells flows in, out and between these. The four battery cell stocks are:

- Stock in trucks
- Stock in loaders
- Stock in rigs
- Stock in BESS

### 3.3.3 Determination of Flows and Stocks

As described by Brunner and Rechberger (2004), determining flows and stocks involves the following steps: determining mass flows, balancing goods, determining concentrations, and balancing substances. However, this study considers changes over time in a dMFA, which implies a different approach for determining flows and stocks. In a stock dynamics approach, demand for goods plays a crucial role in combination with the goods' lifespan, since it dictates the need for additional units and the retirement of existing ones. The introduction of new goods also affects the amount of material required. These material inputs, along with the lifespan of the units, are used to compute the accumulation and reduction of material and product stocks (Müller, 2006). This stock-driven approach can mathematically be described by the equations below:

$$Inflow_t = stock_t - stock_{t-1} + Outflow_t \tag{1}$$

$$Outflow_t = \sum_{t'=t_0}^{t'=t-1} Inflow_{t'} \times (1 - S_{t-t'}) \tag{2}$$

In the equations, inflow$_t$ or inflow$_{t'}$ refers to the new battery cells at year $t$ or $t'$; stock$_\mathrm{t}$ or stock$_{t-1}$ refers to the battery cells in use in a machine at year $t$ or $t-1$; outflow$_\mathrm{t}$ refers to the battery cells for which the SoH is below the application's performance requirements at year $t$; and $S_{t-t'}$ refers to the probability that the previously installed capacities reach their EoL after $t - t'$ years.

The general modelling framework follows the one outlined by Helander and Ljunggren (2023) and each of the machines have a different demand for battery cells, deciding the needed inflow of cells to the system. The stock's need also determines how many cells that then flow through the different processes and to recycling. Trucks exclusively receive and use new or recycled battery cells. Thus, the inflow and outflow of battery cells in trucks is calculated using equation (1) and (2), in all scenarios. In scenario 1, equation (1) and (2) is enough for all machines as there is no reuse and the inflow and outflow in machines can be calculated using these equations. However, when it comes to loaders and rigs in scenario 2 and 3, the model gives priority to using available reused battery cells (extended life cells) as incoming cells and then adds new cells as needed to meet the required stock.

Lastly, after the collection rate is accounted for, the remaining cells eventually end up in recycling. The recycling stage has an efficiency rate that determines how much of the recycled cell that can be used to produce new cells to the system. The efficiency rate varies between 'low' and 'high' in the different scenarios shown in Table 3.2. The efficiency rate includes the losses in collection and recycling processes. Out of the recycled cells, an equal amount goes into each machine as part of the inflow of new cells. The number of primary cells needed each year then depends on how many recycled cells that flow back into the system according to equation (3) below:

$$Inflow\ primary_t = Inflow_t - Inflow\ recyled_t \tag{3}$$

Within the thesis, the demand for goods is based on the globally installed base of BEVs in mining. Data of the current installed base and predications until 2025 is gathered from interviews with Global Data (Kurtz, D., personal communication, November 8, 2023). The predictions until 2050 are extrapolated from this forecast and cross-referenced with the growing need of minerals predicted by the case company, combined with adoption rates of BEV of passenger cars. These adoption rates for BEVs in passenger cars are estimated as the average of seven public sources: EVAdoption (2023), Today's trucking (2022), The Next Silicon Valley (2017), IEA (2021a), Axios Generate (2021), FreeingEnergy (2019), and IEA (2021b). A weighted average was then calculated based on the average from the public sources and input from case company experts. The BEV stock is then multiplied by number of cells per module and number of modules per machine to arrive at the stock of cells used as input in the dMFA model.

Based on information provided by the case company concerning estimated battery lifetimes in different mining equipment, across the time horizon of the dMFA model, so-called 'survival functions' ($S$ in equations (1) and (2)) were constructed for each of the different battery use-case scenarios. The survival functions are modeled using a Gaussian distribution function *f*(*t*). The standard deviation used was ¼ of the expected lifetime of the batteries in each application.

$$f(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(t-\mu)^2}{2\sigma^2}} \tag{4}$$

In eqution (4), *f*(*t*) represents the probability distribution function, $\sigma$ denotes the standard deviation, and $\mu$ represents the mean lifetime. The survival rate $S$ at time $t$ is derived from:

$$S(t) = 1 - \sum_{t=0}^{t} f(t) \tag{5}$$

The survival function (5) describes the share of a cohort still in use in certain year. In total, 14 survival functions were constructed in order to capture the differences in lifetime based on in which application the battery was used, as well as its level of previous use (primary battery, first life extension, and second life extension) (Table 3.4).

*Table 3.4 –Life stages for which survival functions were created.*

| **Starting in truck** | **Starting in loader** | **Starting in rig** |
|---|---|---|
| Only truck | Only loader | Only rig |
| Truck → Loader | Loader → Rig | Rig → BESS |
| Truck → Rig | Loader → BESS | |
| Truck → BESS | Loader → Rig → BESS | |
| Truck → Loader → Rig | | |
| Truck → Loader → BESS | | |
| Truck → Loader → Rig → BESS | | |

## 3.4 Data collection

Two main data types were collected: (1) Primary data, mainly from interviews and emails within the case company, and (2) secondary data, mainly through desktop research. Both primary and secondary data collection was performed with a purposive sampling strategy for the data points to be relevant as input to the model (Bell, Harley, & Bryman, 2022). Due to confidentiality, the assumed values of several data points used in the underlying Excel model cannot be disclosed.

### 3.4.1 Primary data collection

The primary data collection consisted mainly of obtaining information from topic experts within the case company, together with which the thesis was performed. In addition, one session for data collection was held together with a collaborating company, Global Data, in order to obtain data on installed base of machines for the mining industry on a global level. Most of the data collection within the case company was performed via email communication. Email was deemed a suitable method as the data sought for was of quantitative character and did not require the more qualitative aspects that can be communicated through face-to-face interviews. According to Guest et al. (2020), emails can result in less data being gathered. However, neither long response times nor missing data became an issue for this thesis.

For data collection of less straight forward nature, involving assumptions and estimations, interviews and working sessions were arranged. Working sessions were also deemed the most suitable form of communication for topics that required a deeper understanding of the background to the numbers. The topics covered and the data collection through these sessions are presented in Table 3.4. These working sessions were conducted in a way that combined the benefits of semi-structured interviews and iterative collaboration with topic experts from the case company. Semi-structured interviews, commonly used in social science and clinical research, offer a balance of structure and flexibility. This approach, highlighted by Magaldi & Berler (2020), allows for exploration of emerging themes, reducing the risk of overlooking insights. Following Bell, Harley, and Bryman’s (2022) recommendation, an interview guide was prepared for each session, covering topics and incorporating follow-up questions during the interviews. This conversational style increased collaboration and the possibility of iteratively agreeing upon reasonable quantitative values.

Conducted online due to international locations, each session lasted 30-60 minutes. Both authors participated, with one focusing on conducting interviews and the other on note-taking. As suggested by Bell, Harley, and Bryman (2022), having two interviewers promotes a more casual ambiance, fostering information sharing. The sessions were not recorded to maintain a relaxed atmosphere. In cases of incomplete answers or potential misunderstandings discovered post-interview, follow-up emails with additional questions were sent for clarification.

During the data collection, 20 interviews or collaborative sessions were held, and 8 different sources were contacted via email as listed in Table 3.4-3.5. In addition, over 20 working sessions were carried out, primarily together with employees within the case company and the dedicated supervisor. These interactions provided valuable opportunities to validate and cross-reference the data collected, increasing the reliability of the data.

*Table 3.4 – Summary of interviews/working sessions for primary data collection.*

| **Interview/ Session** | **Company (Function)** | **Topics covered** |
|---|---|---|
| **A** | Case company<br>(Strategy) | Weekly guidance (17 sessions)<br>Sanity checking of data and results |
| **B** | Case company<br>(Business & Market intelligence) | Market size for mining equipment<br>Growth trends<br>Adoption rate of BEVs |
| **C** | Global Data<br>(Market intelligence) | Historical installed base of mining equipment<br>Expected installed base of mining equipment |

*Table 3.5 – Summary of emails sent for primary data collection.*

| **Email** | **Company (Function)** | **Topics covered** |
|---|---|---|
| 1 | Case company<br>(Business & Market Intelligence) | Installed base of mining machines |
| 2 | Case company<br>(Business & Market intelligence) | Rationale for estimating the installed base over time |
| 3 | Case company<br>(BEV and electrification) | Machine technicalities<br>Expected battery lifetimes<br>Timeline of BEV adoption |
| 4 | Case company<br>(BEV and electrification) | Battery modules per vehicle type<br>New model adoption<br>Split between size classes |
| 5 | Case company<br>(Data analytics) | Decline rates in state of health<br>BEV adoption rates |
| 6 | Case company<br>(Sales) | Size class split<br>New model adoption |

| | | |
|---|---|---|
| | | BEV adoption rates |
| 7 | Case company (Engineering and technical support) | BESS lifetimes<br>Recycling recovery rates |
| 8 | Case company (Sustainability) | Electrification regulations/legislation |

### 3.4.2 Secondary data collection

Secondary data collection, as advocated by Boslaugh (2007), complements primary data by offering cost-effectiveness and broad reach. However, using data not initially generated for the research questions may pose limitations in representing different locations, times, or settings (Boslaugh, 2007). To address this, critical datapoints were validated with the case company representatives. These included material intensity of batteries, reuse rates, battery lifetimes, recycling efficiencies, installed base of machines, growth rates, and BEV adoption rates in mining.

The literature review, following Egger et al.'s (2008) framework, involved targeted keyword searches on Google Scholar. Articles found provided related literature on battery circularity, vehicle electrification, battery chemistry, circular economy, and the mining industry. Source quality was ensured through reference checks and alignment with other findings once a potentially relevant study was identified.

## 3.5 Sensitivity analysis

The uncertainties surrounding the parameters for both the reuse approach and recycling rate warrant a sensitivity analysis across the six scenarios presented in Table 3.1. The uncertainties surrounding the parameters for both the reuse approach and recycling rate warrant a sensitivity analysis across the six scenarios presented in Table 3.1. An additional three parameters characterized by a potentially large influence on the results have been selected for sensitivity analysis in accordance with the case company topic experts, shown in Table 3.6 and described more in detail below. The purpose of the sensitivity analysis is twofold: To quantify the influence of changes by systematically varying an isolated input parameter and observing the corresponding impact of changes in the parameters, and to ensuring the robustness of the dMFA model across a range of inputs.

The rationale for the selection of parameters for sensitivity analysis is as follows:

- **1st life extension in rigs**: Due to a difference in the design of the modules used in the case company's trucks and loaders compared with those used in its drilling rigs, the transitioning of reused battery cells for their life extension is not as straight forward as batteries going from trucks to loaders. According to case company experts, life extension from trucks or loaders to rigs will eventually be made possible, but a fixed timeline for this is currently not in place and is consequently uncertain. The time and possibility to extend battery lives through applications in rigs will influence the material flows of the dMFA model.

- **Battery lifetime development:** To address the growing demands of the electric vehicle market, batteries must possess high energy density, rapid charging capabilities, extended lifetimes, and cost-effectiveness. Consequently, extensive material research on battery cells is conducted to consistently improve battery performance and align with these criteria (Ahlberg Tidblad, et al., 2021). Given the inherent difficulty in estimating battery lifetimes, particularly in this context where electric machines are a novel phenomenon with limited data, conducting sensitivity analysis becomes relevant.
- **BEV adoption rate**: The electrification of mines will require substantia investment in infrastructure, technology, and skilled labor, as well as collaboration among key players across industry and government (Ertugrul, Pourmousavi Kani, Davis, Sbarbaro, & Morán, 2020). As a result, several scenarios for the adoption of EVs in the mining industry can be argued for, significantly influencing the material flows of battery cells. One scenario discussed with case company experts is the perspective of legislative demands, mandating a transition towards 100% electrification. With both California (Powell, 2022) and the UK (Dron, 2023) aiming to make all new cars zero-emission by 2035, and with China's target of a 20% sales share for NEVs already by 2025, assuming similar ambitions for the mining industry by 2050 is not unrealistic. Due to the high level of uncertainty in this parameter, a sensitivity analysis was deemed appropriate.

*Table 3.6: Parameters for sensitivity analysis with the corresponding low and high estimates.*

| **Parameter** | **Low estimate** | **High estimate** |
|---|---|---|
| 1st life extension in rigs | Not possible | Possible |
| Battery lifetime development | 3 years for trucks<br>4 years for loaders<br>7 years for rigs | 5 years for trucks<br>6 years for loaders<br>10 years for rigs |
| BEV adoption rate | 65% adoption in 2050 | 100% adoption in 2050 |

When performing the sensitivity analysis on the above-discussed parameters, results are derived in relation to scenarios 1A, 2A, and 3A. The reason for this was to isolate the changes stemming from the sensitivity parameter under investigation and simplify the outputs.

# 4. Results and discussion

This section presents the results and contains a discussion about their implications for the system, the industry, and relevant stakeholders. First, growth and electrification trends for the mining industry are discussed, followed by the implications in the six different scenarios for the stocks and flows of battery cells and two of its constituting materials, lithium and aluminum. The section also includes the results of the sensitivity analysis.

## 4.1. Growth and electrification trends for mining vehicles

As outlined in the method, the number of BEVs and ICE vehicles for 2020-2050 were calculated using the 2020 base figures, projected industry growth rates up to 2050 from Global Data (Kurtz, D., personal communication, November 8 2023), and case company expert insights. The calculation of BEV stock levels considered the BEV adoption rate and the expansion of the EV installed base in conjunction with the industry growth rate. Worth mentioning is that 2% installed base growth rate, suggested by case company and industry experts from Global Data, constitutes an important assumption in the calculations.

Based on discussions with case company experts, it is reasonable to assume a more conservative adoption rate for the mining industry compared to that for personal EVs. Replacing mining vehicles with EVs involves more complex changes to the mining infrastructure. This encompasses considerations such as charging infrastructure, battery switching solutions, and adapting operational workflows to accommodate the requirements of electric mining vehicles. Operational mines are less likely to be redesigned to incorporate the infrastructure required for BEVs compared to when designing future mines. S&P Global (2023) estimates an average time of 15.7 years from the discovery of a mine until the start of production (with a range between 6 and 32 years). The potential longevity of a mine implies that the electrification transformation of the mining industry is likely to be slower than the transition of personal vehicle electrification. Additionally, the diversity of mining operations worldwide contributes to the slower adoption. Mines vary widely in extraction methods as well as stakeholder structure, making electrifying operations a more attractive alternative in some situations compared to others.

Further, as mentioned by Green (2017), ambiguity and disparities between countries concerning battery legislations and regulations risks impeding the progress of battery adoption. Currently, there are no mandates specific to the mining industry related to emission reductions, but such regulations be implemented, the adoption rate for BEVs could increase considerably. After consulting with case company experts, the thesis assumes a more conservative adoption rate.

In the dMFA model, the adoption rate for BEVs was calculated as a weighted average of the BEV adoption rate estimations for personal EVs from seven sources, and estimated adoption rates made by the case company. Three of the public data sources considered were estimations from the International Energy Agency (IEA, 2021a), including their low and high estimate for personal EV adoption, as well as estimates for adoptions of heavy trucks. Including the other four sources (Today's trucking 2022; The Next Silicon Valley, 2017; Axios Generate, 2021; FreeingEnergy, 2019) estimated adoption rates for new EV sales in 2025 are between 7% and 17% of total sales and values for 2050 between 65% and 99%. These differences in the estimates provided by the same source, ranging between 65% to 90% for the year of 2050, clearly demonstrates the uncertainties behind the estimations. Considering this range, and the unclear relevance for the mining industry, the estimated adoption rate was projected to 10% in 2025 and 67% in 2050 (Fig. 4.1).

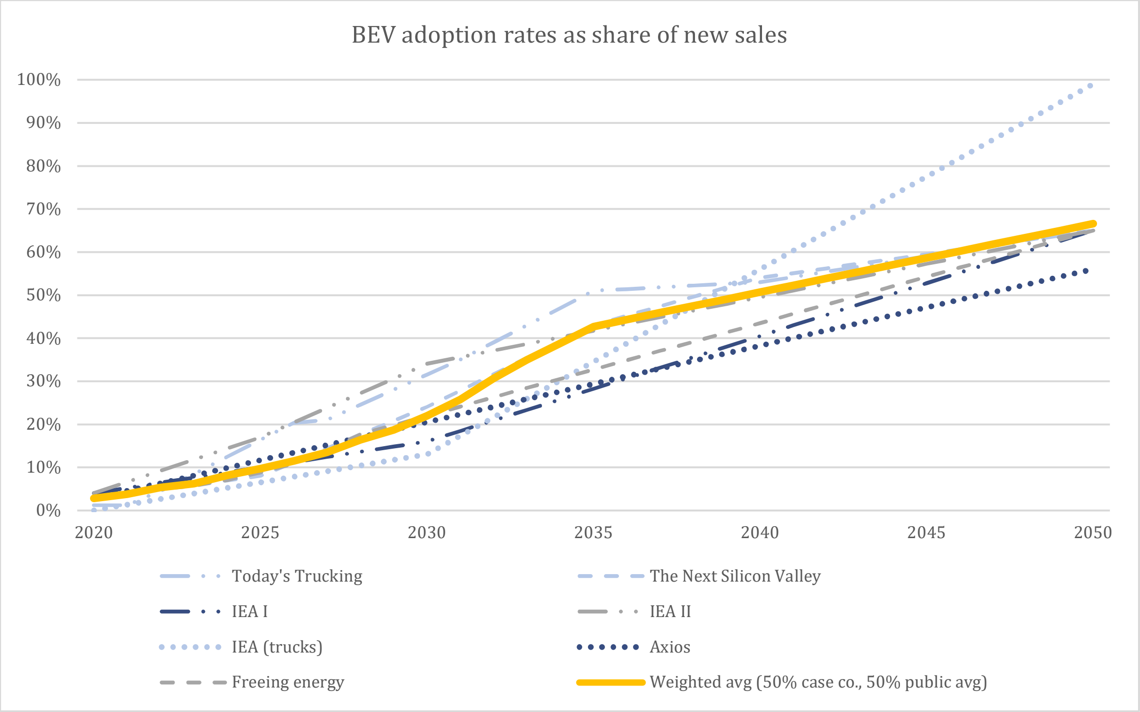

*Figure 4.1 BEV adoption rate estimations from eight sources. Weighted average calculated as 50% case company estimate and 50% average of estimates by seven public sources (EVAdoption, 2023; Today's trucking 2022; The Next Silicon Valley, 2017; IEA, 2021a; IEA, 2021b; Axios Generate, 2021; FreeingEnergy, 2019).*

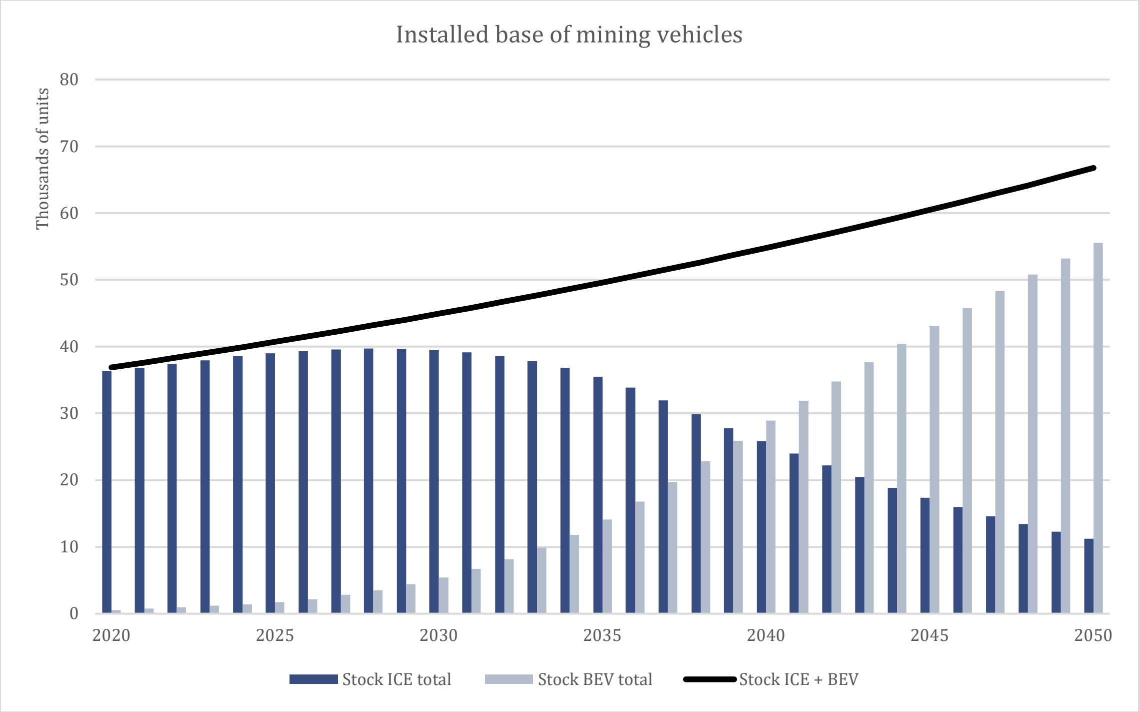

*Figure 4.2 Growth of total installed base of mining equipment (ICE and BEV) for 2020-2050.*

The global stock of mining equipment consisted of approximately 36 400 ICE units and 500 BEV units in 2020 (Fig. 4.2). Applying the industry growth rate and the BEV adoption rate, the installed base of ICEs is estimated to increase between 2020-2029, although at a lower rate compared to the industry at large, before reaching its highest point at 39 700 in 2029. The ICE installed base is thereafter expected to decrease, reaching a final value in 2050 of roughly 11 200 units.

For the BEV equipment, growth was estimated for the entire period between 2020 to 2050, reaching an inflection point in 2038 after which the growth rate begins to slow down. The absolute number of BEVs surpasses the absolute number of ICEs in 2040, after which it remains at a higher level throughout the period. The total installed base of mining BEVs in 2050 is estimated to approximately 55 500 units, resulting in a BEV-to-ICE ratio of around 5:1. The total BEV stock resulting from these considerations (Fig. 4.3) is the machinery stock from which all six scenarios depart.

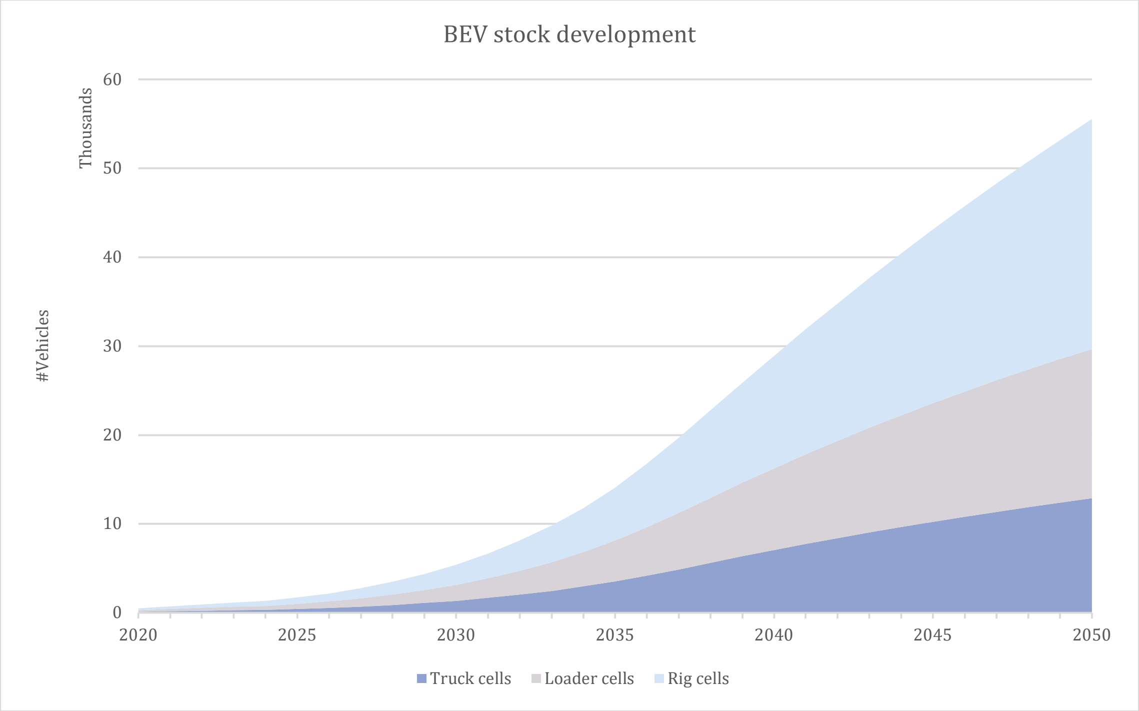

*Figure 4.3: BEV stock by machine type.*

## 4.2 Battery cell stock estimations

The stock of battery cells in machines remains the same in all six scenarios, but the total cell stock differs in scenario 3 as the cells also go to BESS before recycling, and additional use phase (Figs. 4.4-4.6). In scenarios 1 and 2, the growing stock of battery cells increases from 1.2 million in 2020 to 126.9 million in 2050. In scenario 3, additional reuse in BESS leads to higher growth, reaching 160.2 million cells in total by 2050, with 33.3 million cells in BESS. The number of cells going to BESS will continue to grow as there is no limitation to the need for battery cells in this application in the dMFA model, so all cells with sufficient SoH at EoL proceeds to BESS. Consequently, as long as there is an increase in the number of battery cells entering the system, the inflow of cells to BESS will continue to grow. Given the anticipated expansion of BESS (McKinsey & Company, 2023), assuming no limit to the BESS inflow was considered reasonable.

Despite the consistency in total number of cells in use across the three scenarios, variations emerge in the distribution between new cells, cells in 1st extended use, and cells in 2nd extended use. Scenario 1 exclusively features new cells in use, as it omits any life extension possibilities. Scenarios 2 and 3 have similar distributions of new cells, cells in 1st extended life, and cells in 2nd extended life. In 2050, 27% of the total stock can be satisfied by reused cells. Trucks have 100% new batteries, while loaders have 86% new cells and 14% 1st extended life cells. Rigs have 0% new cells and 100% cells from 1st extended life (cells that have been in one machine previously), and 0% in 2nd extended life (cells that have been in both trucks and loaders before). However, rigs have up to 19% 2nd extended life cells in year 2031 (Fig. 4.6), but this decreases to 0%. This trend suggests that in the long run, rigs will no longer require 2nd extended life cells, as they will entirely operate on 1st extended life cells. Instead, these cells could go into other applications, such as in BESS.

Notably, rigs do not require any new cells post 2023 in scenarios 2 and 3, as the stock requirements are met through life-extended cells previously deployed in trucks and loaders. Cells in 2nd extended use are very few in comparison to cells in 1st extended use. For loaders, while the majority of the stock need is met by new cells, an increasing proportion is gradually satisfied by cells having had a previous 1st life in trucks. The implication is that, if companies can establish the necessary infrastructure and technology to transition batteries, there would be no production costs associated with acquiring new batteries for rigs and lower costs for acquiring batteries for trucks. However, this transition may not be feasible today, and the associated cost and environmental benefits of such an implementation remain to be predicted.

While there are more rigs than loaders and trucks (Fig. 4.3), the number of battery cells in use is lower in rigs than in the other two machine types (Figs. 4.4-4.6). The reason for this is that rigs require fewer battery cells per machines, according to estimations by the case company (although this might change in the next 30 years as machines and batteries undergo development). For example, as noted by Berg et al. (2015), cell performance is significantly influenced by the selection of components and materials. Technical advances, such as using different materials in the cell, could enhance energy output per cell, potentially reducing the number of cells in machines and affecting future product and material flow. Technical improvements may also alter the lifetimes of cells, although this development may vary across machines.

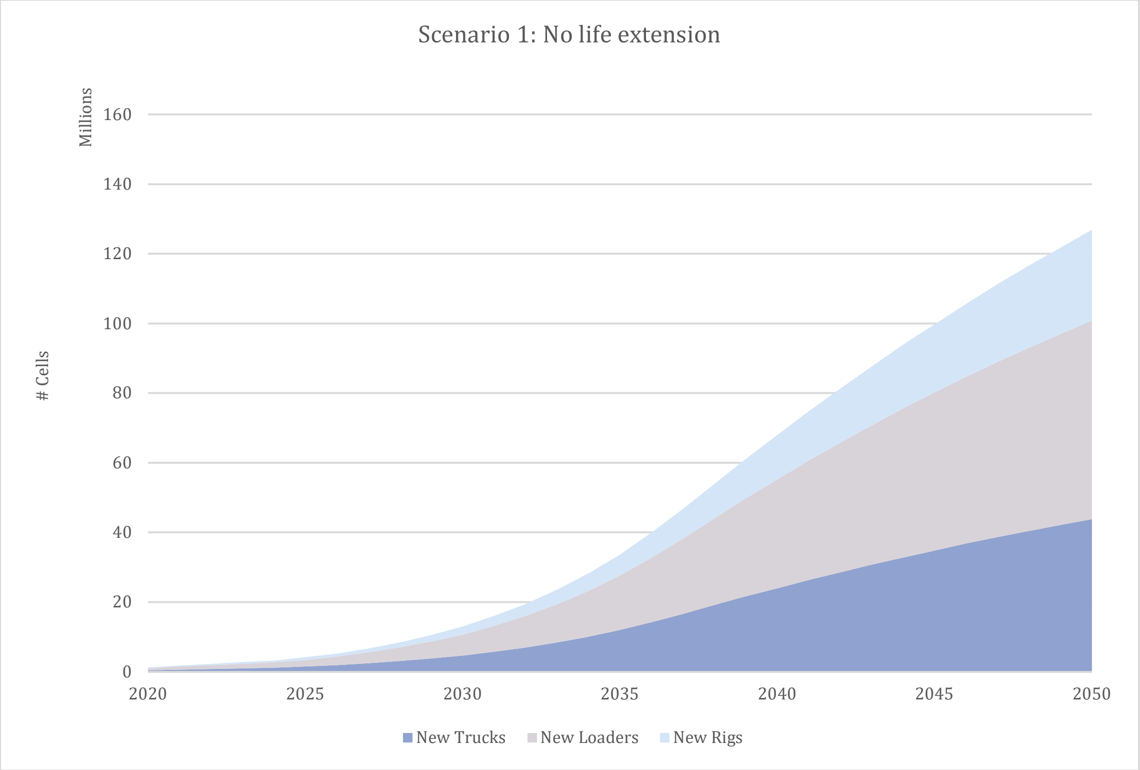

*Figure 4.4: Scenario 1: No life extension, cells in use per application and life phase.*

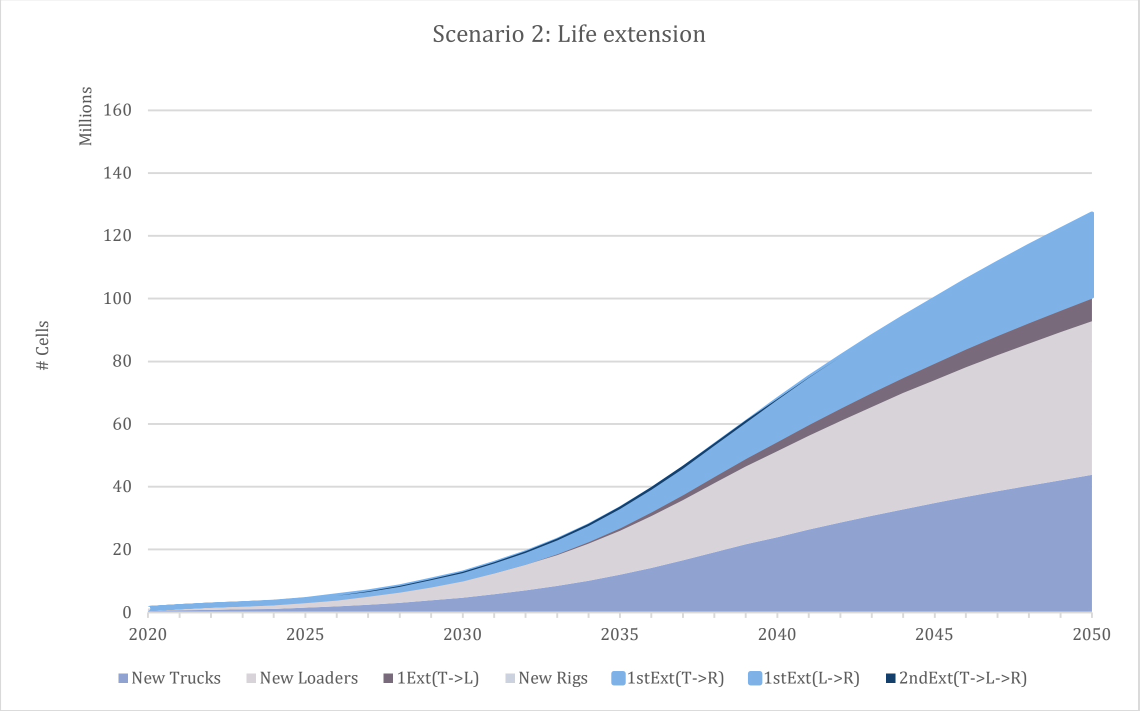

*Figure 4.5: Scenario 2: Life extension, cells in use per application and life phase.*

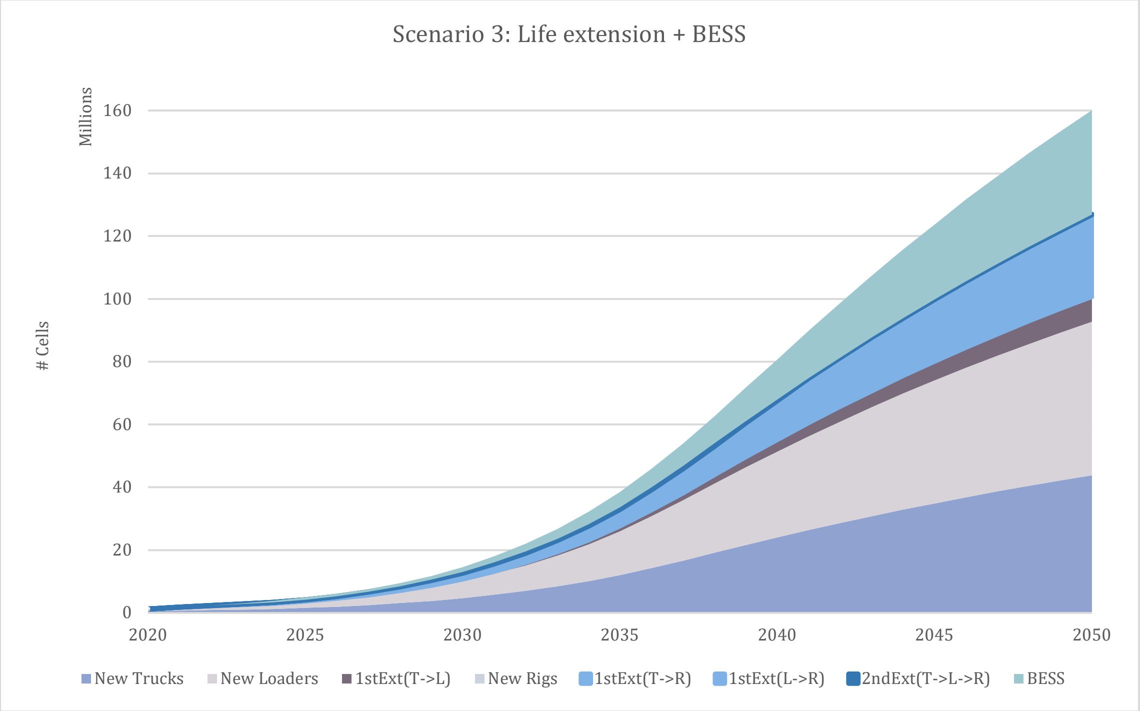

*Figure 4.6: Scenario 3: Life extension + BESS, cells in use divided by application and life phase.*

One of the main implications from the life extensions in scenarios 2 and 3 is a higher number of cells flowing into the machines each year (Fig. 4.7). In 2050, there is 13.5 million more cells flowing into the machines compared to scenario 1; a mixture of new, 1st extended life cells, and 2nd extended life cells. Consequently, although reuse lowers the amount of primary material, it increases the pressure on the infrastructure as material flows between machines increase. This could potentially create an economic and environmental trade-off between the production of new battery cells versus the transport and re-installation of reused cells. Additionally, having more cells in 1st or 2nd extended life introduces increased labour intensity. The estimation that a 1st extended life battery in loaders will last only 25% as long as a new battery suggests four times more frequent battery pack replacements, leading to additional labour. This can impact operational costs and productivity of the mining industry. On the other hand, it could also provide an opportunity for mining OEMs to strengthen customer relations, increase ownership, secure access to scarce materials, and improve resource utilization, for example through the implementation of product-service-systems (PSS) (Helander & Ljunggren, 2023).

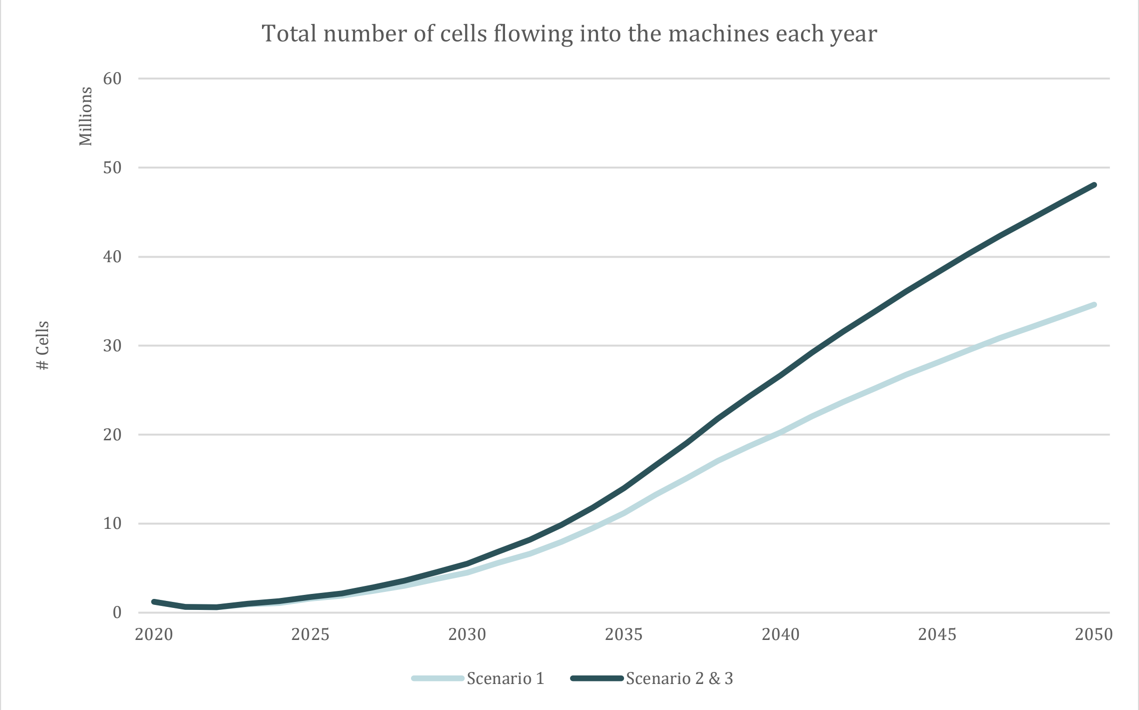

*Figure 4.7: Total number of cells flowing into machines each year.*

The mining industry's contribution to BESS could help addressing the growing demand for batteries in this application. This approach not only supports the projected growth in demand for BESS but also underscores the mining industry's potential to lessen demand for primary materials, promoting sustainability. The rapid technical development of EMS, discussed by Nebuoloni et al. (2023), enhances the feasibility and efficiency of extending battery cell life in BESS from mining equipment.

As the dMFA model is based on the installed base of the entire industry, it makes no distinction between the stock of different mines nor different companies. In reality, the companies' batteries are not interchangeable, and a battery used in one mine might not be used in an extended life at a different site due to compatibility issues, increased costs, and logistics. While transporting batteries worldwide would escalate costs for a single OEM, it would not be a compatibility issues between batteries from different mines. However, the compatibility issues between OEMs provides an opportunity for companies as it can create a lock-in effect, pushing miners to operates their mines using machines from one single OEM, which can be advantageous. It also encourages companies to focus on optimizing the performance and lifespan of their own batteries, fostering a sense of ownership and responsibility for the longevity and efficiency of their energy storage assets. However, there might be advantages for the industry as a whole to increase interchangeability and standardization as it will lead to resource optimization and, as shown in the dMFA model, lower the need for primary battery cells.

## 4.3 Battery cell and material requirements

The result of the study shows that the introduction of life extension impacts the material flows in several ways. However, the requirements of primary lithium and aluminum are strongly connected to the requirement of battery cells, in combination with the assumed recycling rates. Due to assumptions of lower recycling efficiency rates for lithium compared to aluminum, lithium has a slightly lower recycling share compared to aluminum in all scenarios. The study shows that the demand for new cells is approximately 23% lower in scenarios 2 and 3 compared to scenarios 1A and 1B because of life extension not being possible in scenarios 1A and B. The total demand for both materials was the same regardless of recycling rate (since the dMFA model assumes the same stock for all scenarios) but differed between scenario 1 compared to scenarios 2 and 3.

As illustrated in Figures 4.8-4.10, the total amount of recycled cells flowing in, and consequently also of recycled material, is projected to be substantially larger in scenario 1A+B compared to scenarios 2A+B and 3A+B. This is because cells in scenario 1A+B have no life extension or usage in BESS and hence reach the recycling stage faster than in the other scenarios. For the same reason, scenario 3A+B has the lowest number of recycled cells flowing in; the cells have a longer total life as they linger in reuse and BESS. Consequently, they reach the recycling stage later, causing a delay in the re-entry of recycled material into the system. However, this delay between scenario 2A and 3A is shorter compared to the difference noted between scenarios 1A and 2A, since the lifetimes in BESS are comparatively shorter.

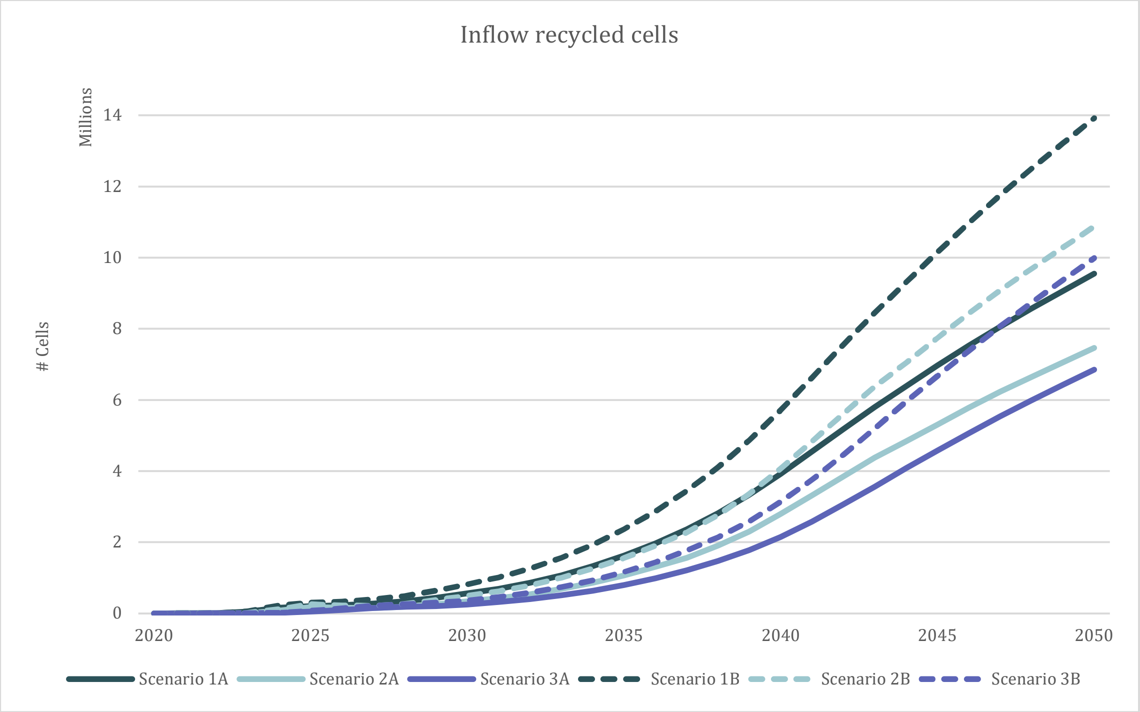

*Figure 4.8: Inflow of recycled cells to the system per scenario.*

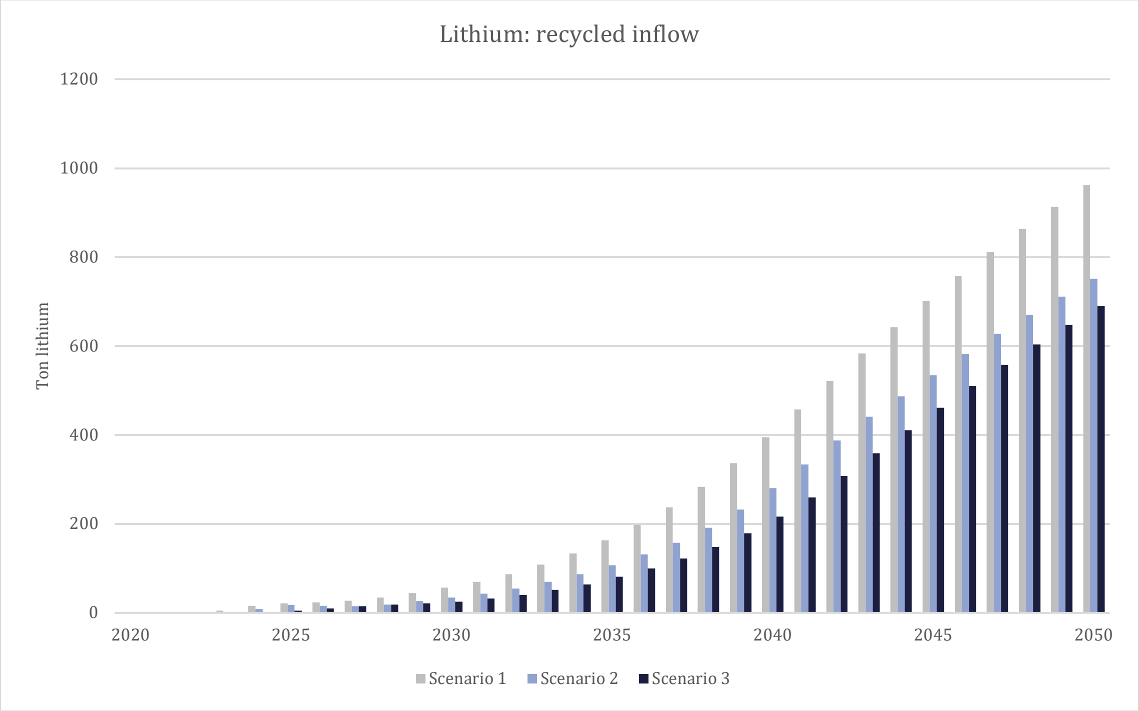

*Figure 4.9: Inflow per year of recycled lithium demand for scenarios 1, 2, and 3*

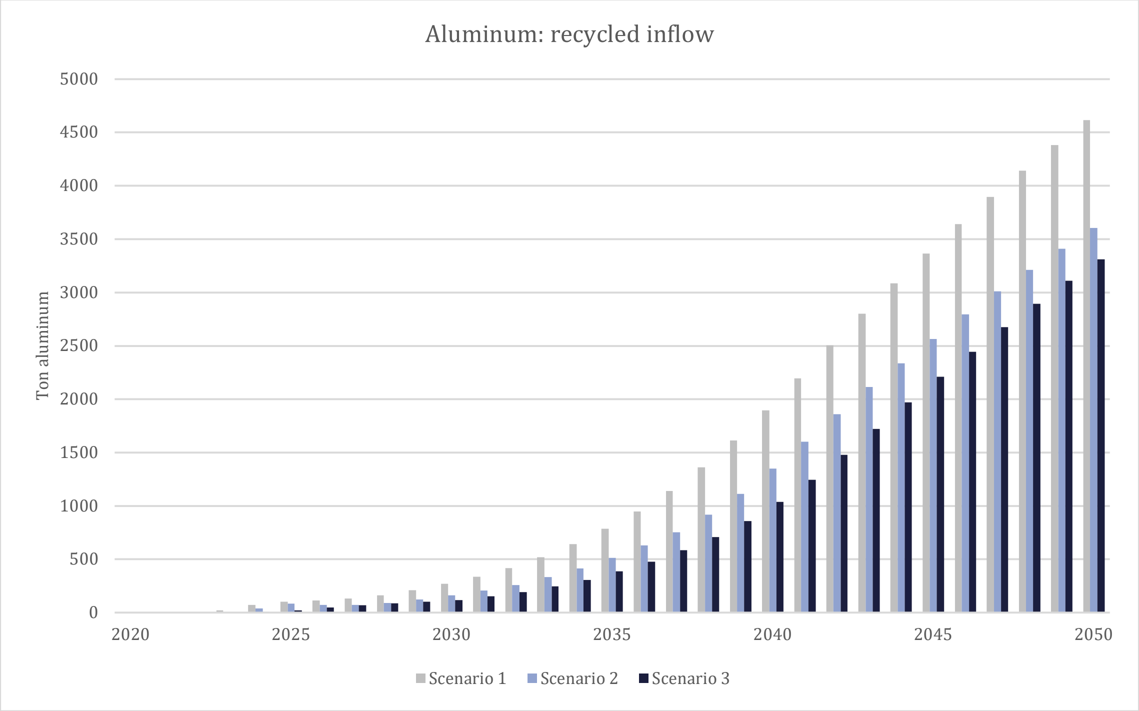

*Figure 4.10: Inflow per year of recycled aluminum demand for scenarios 1, 2, and 3*

Scenarios 1-3B have higher amount and share of recycled material flowing into the dMFA model compared to scenario 1-3A (Figs. 4.8-11). The main difference in recycling rate is related to the collection rate, rather than the recycling efficiency (Table 3.2). The recycling efficiencies of both lithium and aluminum are already high (95-99.9% depending on material and scenario). Consequently, making efforts in increasing these numbers will have a smaller impact on the absolute number of cells recycled and the amount of recovered material, than the collection rate. Although technical recycling process efficiencies are high, these processes are currently not used for all material collected due to their relatively high cost. The main improvements to be made for recycling processes relate to costs, as mentioned by Mao et al. (2022) and (Wang et al., 2022).

This implies that to reach a higher percentage of recycled material, companies need to increase the collection rate of batteries, as this is the limiting factor. Furthermore, even in the “high” scenario assumed by Zhang et al. (2021), the collection rate reaches only 50%. Increasing collection rates from 35% to 50% would increase in inflow of recycled lithium and aluminum by between 43% and 46% depending on scenario and material. The extra 440 ton lithium that can be harnessed from only increasing the recycling rate by 15% in 2050 would satisfy the battery cell need of 4320 rigs or roughly 1280 trucks or loaders. One way to reach a higher collection rate is for the manufacturer of mining equipment to maintaining ownership of the battery throughout the whole value chain and offer battery as a service, as described by Helander and Ljunggren (2023), and hence be responsible also for the collection and recycling of the batteries.

Relating the amount of recycled lithium flowing into the system each year to the annual lithium demand, scenario 1B achieves the highest percentage share of recycled material of 40%, whereas scenario 3A has the lowest share of 24% (Fig. 4.11). A peak in the percentage of the demand satisfied through recycled material is seen in 2024 (scenario 1A), 2025 (scenario 2A) and 2027-2028 (scenario 3A). This peak is attributed to the fact that recycling is assumed to be implemented in 2020 in the dMFA model and, as a consequence of the estimated battery cell lifetimes, the majority of the 2020 battery cell cohort reaches EoL in 2023-2025, resulting in a high inflow to recycling in these years. After this peak, the increase in the share of recycled material is estimated to increase slightly for the whole period under study but appears to slow down as it approaches 2050.

The share of lithium demand that can be supplied by recycled material approaches 28%, 27%, and 24% for scenarios 1A, 2A, and 3A, respectively. Similarly, the same decrease in growth can be seen in scenarios 1B-3B, although at higher levels (30%, 39%, and 35%, respectively). The reason for the decreased growth towards the end of the period is that the recycled material share of demand is approaching the maximal recycling rate possible of 33.95% and 34.65% for lithium and aluminum in scenarios 1A-3A, or of 49.50% and 49.95% in scenarios 1B-3B, corresponding to the “medium” and the “high” recycling rates in the two scenarios. As the recycled material share of demand seems to end up at the same level eventually in scenarios 1-3, having extended life should not be perceived as negatively affecting the recycling content in the long run. However, having extended life could make it more difficult to reach specific goals of high recycled content and some companies must weigh the trade-off between expanding their business model to include BESS or a faster supply of recycled materials to their machines.

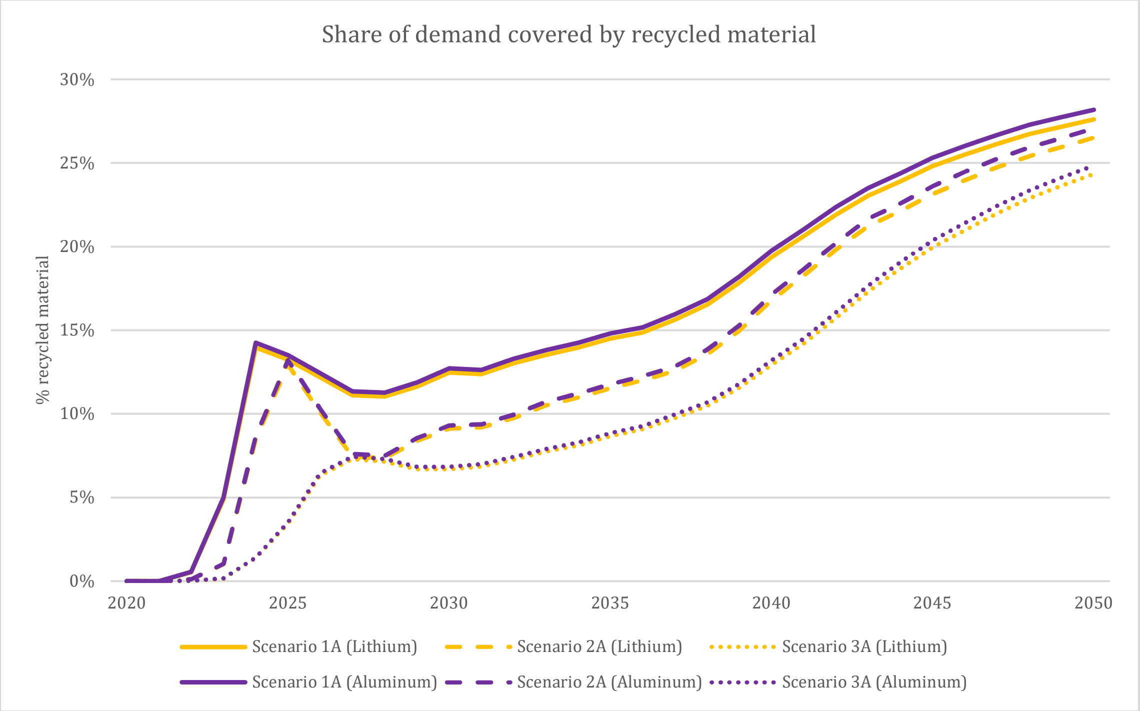

*Figure 4.11 share of material demand covered by recycled lithium.and aluminum respectively.*

Further noted from the results is that the primary material inflow is notably lower in scenarios 2A+B and 3A+B, the scenarios with life extension, compared to scenarios 1A+B, the scenarios without life extension (Fig 4.12). Between scenarios 1A and 2A, the difference in 2050 is 16.2 kton (17%). These figures point to a strong potential to reduce the demand for materials like lithium and aluminum through life extension applications. For example, universal standards and modularity of battery cells could allow for further extending battery life. With high levels of interchangeability and appropriately developed infrastructure, future solutions could potentially involve battery cells at EoL in rigs to be reused in even smaller machines with lower SoH demands. However, such solutions would reduce the SoH levels of batteries reaching BESS, a trade-off that must be considered.

For all scenarios, the primary material need shows a continuously increasing trend (Fig. 4.12). However, in scenarios 1A-3A, a decrease in primary material demand growth rate can be seen after an inflection point between 2035-2040. The same pattern exist for scenarios 1B-3B as this is a consequence of the recycling approaching its limits. Comparing scenario 2 and 3, however, shows that the primary material demand is only slightly higher for scenario 3, as a consequence of the above mentioned “delay” in

BESS. It is also worth mentioning that scenario 3 entails prolonged battery usage, extracting more value from the battery compared to scenarios 1 and 2. This clarifies why increased reuse leads to a heightened demand for primary materials.

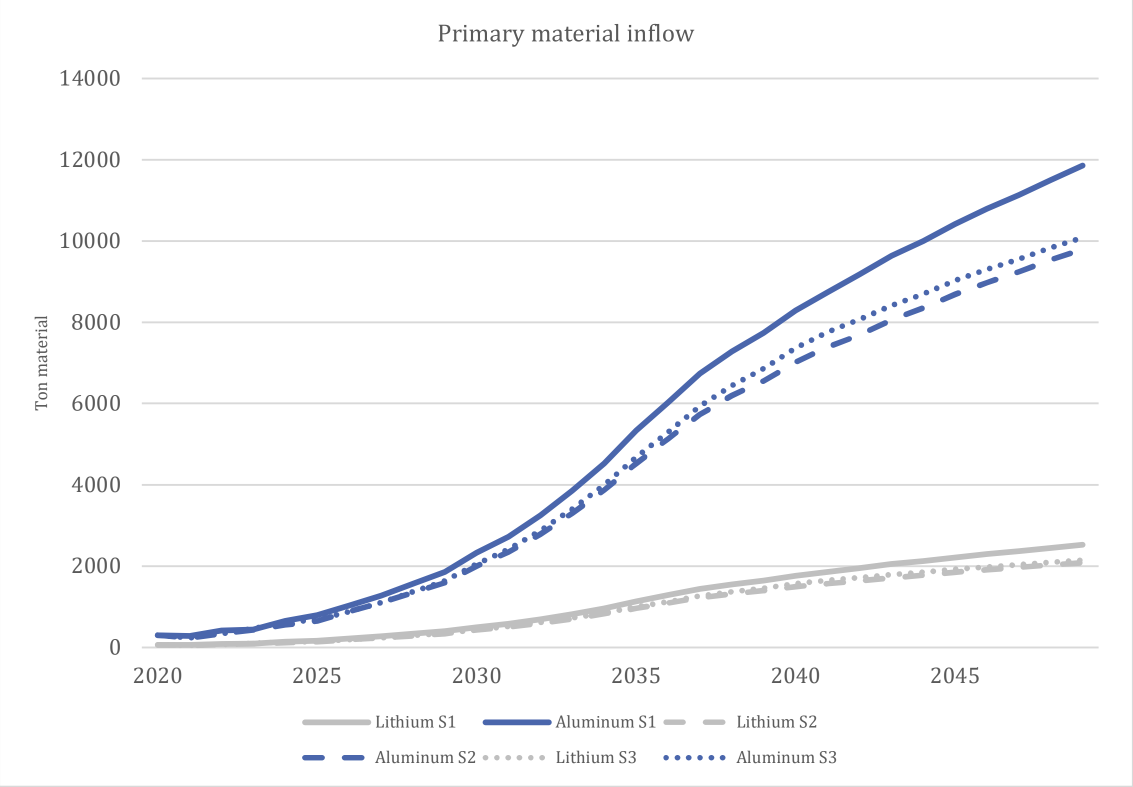

*Figure 4.12: Inflow of primary material for scenario 1, 2, and 3.*

## 4.4 Sensitivity analysis results

Based on the parameters identified in section 3.4 and summarized in Table 3.5, three different sensitivity analyses were performed to test the robustness of the results. The sensitivity analyses were performed for the medium recycling rate scenarios (1A-3A).

### 4.4.1. Life extension in rigs

Excluding the possibility for life extension in rigs is achieved in the dMFA model by setting the flows from trucks and loaders to rigs to 0. Battery cells from rigs are, however, still allowed to flow into BESS when reaching EoL in scenario 3A. Since there is no reuse in scenario 1, this section only accounts for the differences in scenario 2A and 3A (for a summary of the sensitivity analysis outcomes of life extension in rigs, see Appendix D).

Even when excluding life extension in rigs, the machine battery cell stock remains the same in all three scenarios since the MFA is performed with a stock-driven approach. However, scenario 3 has a higher total battery cell stock as it also includes battery cells in BESS, accounting for the 8% increase by 2050.

In scenarios 2 and 3, the inflow of primary battery cells in 2050 increases by 11.1% and 11.7%, respectively, as a consequence of excluding life extension in rigs (Fig. 4.13). In absolute numbers, this amounts to a reduction of 2.1 million battery cells in scenario 2 and 2.5 million cells in scenario 3, solely in the year 2050. This difference of 2.1-2.5 million cells would otherwise have been provided from previous use in other machines. Avoiding these extra cells likely constitutes an attractive prospect for mining equipment manufacturers and their customers as it has the potential of saving costs and decreasing primary raw material dependency.

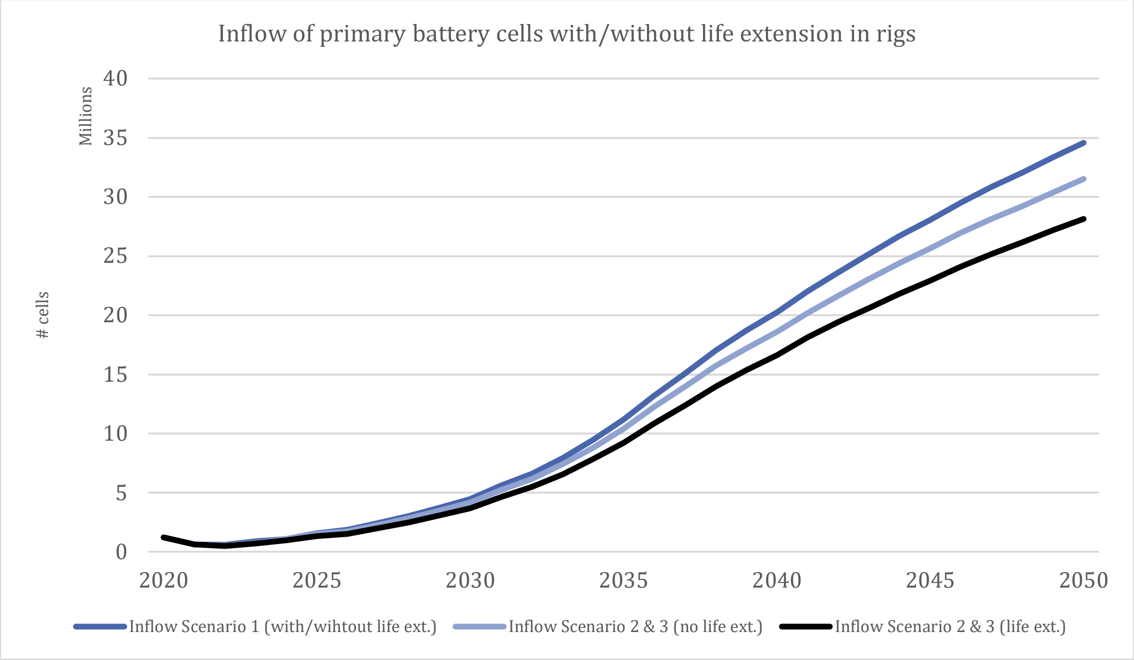

*Figure 4.13: Amount of primary battery cells in the cases of life extension in rigs / no life extension in rigs. Life extension not applicable for scenario 1, thus only scenarios 2 and 3 are considered.*

In scenario 3, the battery cell stock is roughly 8% larger without life extension in rigs compared to with life extension. This is because the BESS stock depends on the amount of battery cells flowing out and their SoH. In a scenario without life extension in rigs, more cells will be at a higher SoH when they flow into BESS and, consequently, these batteries will remain longer within this application. However, this creates a trade-off as both rigs and BESS need batteries according to the dMFA model projections (as the model is constructed, BESS has no stock need but receive the “leftover” battery cells from machine applications).

When life extension in rigs is not included, the inflow to 1st life extension applications decreases by over 42% in scenarios 2 and 3. This implies that the number of batteries flowing into 1st life extension in rigs is greater than the number of batteries flowing into 1st life extension in loaders, which can be explained by two factors. First, battery cells flow to rigs from both trucks and loaders, whereas for loaders, batteries only come from trucks. Second, drilling rigs have lower energy requirements for their duty cycle and can hence accept batteries at lower state of health compared to trucks and loaders.

Further, the share of battery cells in life extension applications is reduced from 27% to 9% in scenario 2 and from 24% to 9% in scenario 3. This brings an increase in the number of primary batteries and consequently in primary material. As shown in Appendix D, the primary material demand for both lithium and aluminum increase by about 12% when excluding life extension in rigs. In absolute numbers, this amounts to approximately 340 ton lithium and 1600 ton aluminum solely in the year of 2050 (Fig. 4.14). According to the World Economic Forum (2022), the global lithium demand from EVs in 2050 will amount to approximately 16 million tons, making the extra 340 ton lithium a small share of the total demand but could nevertheless be significant for the mining industry or specific companies given a future with increased competition over scarce resources.

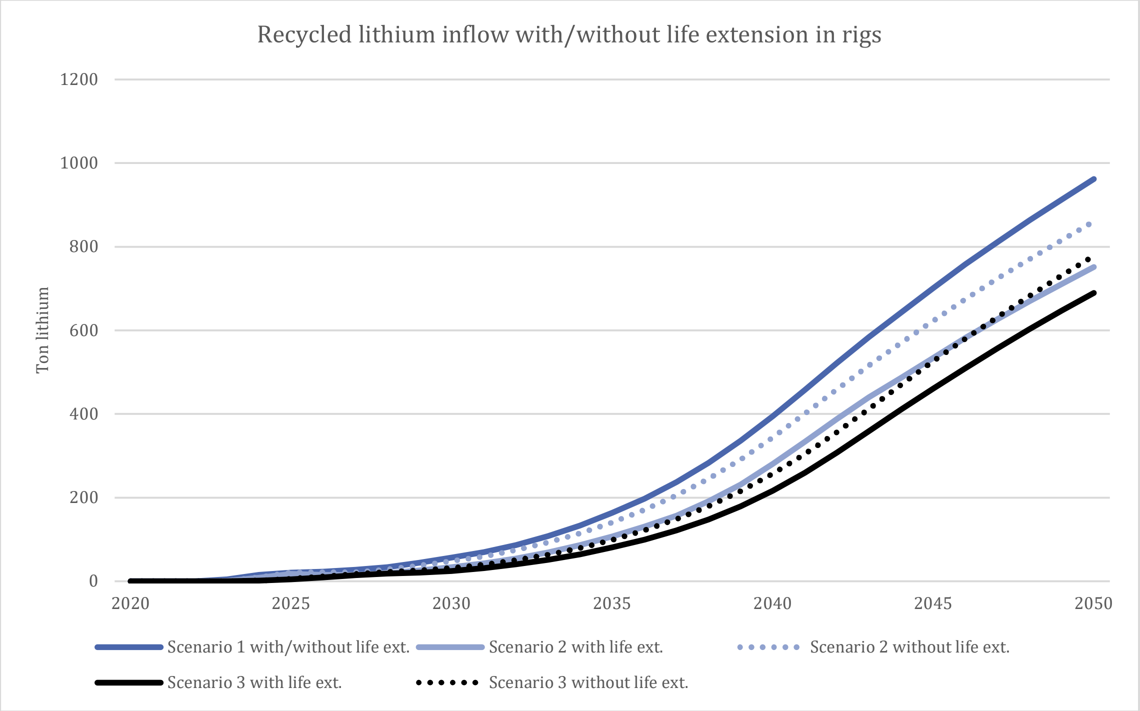

*Figure 4.14: Amount of recycled lithium in the cases with / without life extension in rigs.*

### 4.4.2 Battery cell lifetimes

To investigate the potential impact from technological improvements and account for the uncertainty in the assumed battery lifetimes, the lifetimes of primary batteries in trucks, loaders, rigs, and BESS were increased for the entire period of 2020-2050. Also, lifetimes for battery cells in use in life extension applications were increased by the same factor of approximately 40%.

The longer lifetimes lead to a decrease in the share of recycled cells in use in all three scenarios. This is expected, since longer lifetimes will result in a smaller amount of battery cells going into recycling and, consequently, a lower share of the total demand will be covered by the inflow of recycled material. Despite a general strive towards higher shares of recycled materials (Reck & Graedel, 2012), in this case, a lower level of recycled content is not necessarily a bad thing. Increased lifetimes also reduce the total inflow each year, leading to a lower need for production of primary cells.

The longer lifetimes lead to a decrease in the share of recycled cells in use in all three scenarios. This is expected, since longer lifetimes will result in a smaller amount of battery cells going into recycling and, consequently, a lower share of the total demand will be covered by the inflow of recycled material. Notably, the shares of primary and recycled inflow appear to converge when approaching 2050 (Fig. 4.15). This is likely because the system is approaching a steady state. In the dMFA model, recycling is introduced in 2020 and therefore the system is not in a stable state in terms of recycled inflows for the first couple of years. When increasing the battery cell lifetimes, it takes a longer time to achieve this balance as the material flows slow down and change occurs at a slower rate.

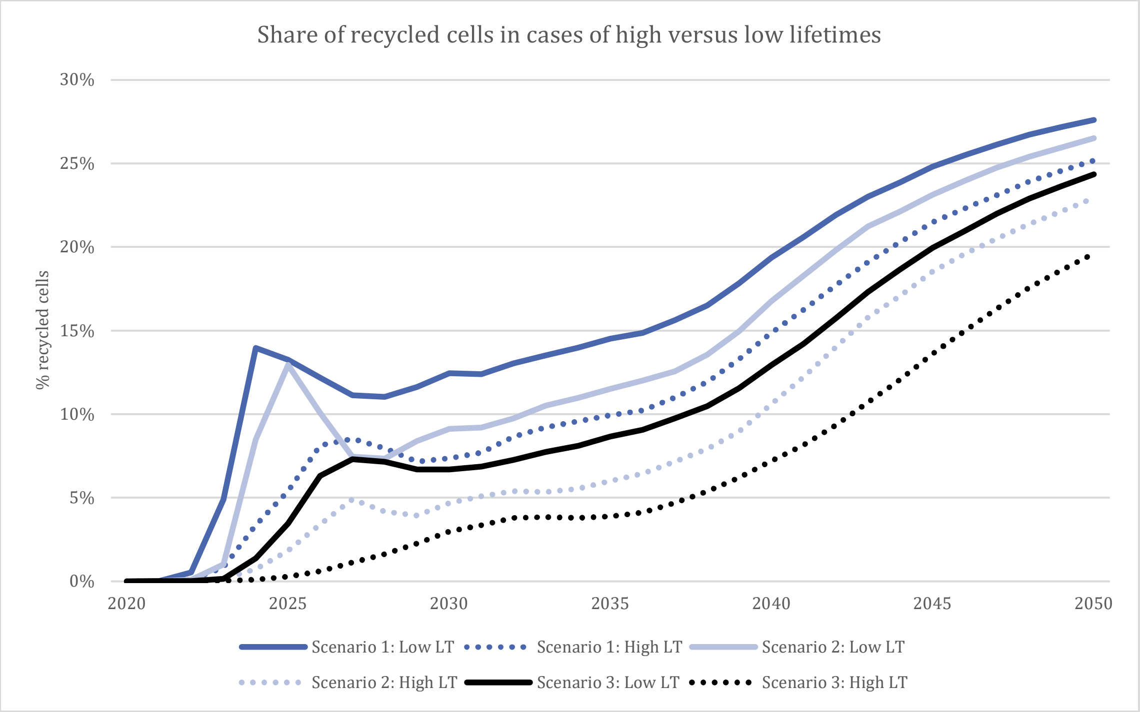

*Figure 4.15: Share of battery cell inflows made from recycled material in the cases of high versus low lifetimes.*

In Figure 4.16, the decrease in recycled lithium and aluminum inputs is illustrated as the change that occurs when going from shorter lifetimes to longer lifetimes. As can be seen, the decrease is the greatest for both materials in scenario 1 and differs only marginally between scenarios 2 and 3 although no scenario stands out significantly. For lithium, the longer lifetimes amount to a decrease of approximately 380, 350, and 340 ton in 2050 for the three scenarios, respectively. For aluminum, the trends are the same, but the longer lifetimes decrease the material need by 1810, 1660, and 1650 ton material, respectively. The reason for the decrease being higher (in absolute terms) for scenario 1 is because the overall flows are higher in this scenario than in scenario 2 and 3 due to the exclusion of life extension possibilities. Evaluating instead the percentual decrease, longer lifetimes result in -39%, -46%, and -50% lower inflows of recycled material. This can be explained by the material being bound in machines (or BESS) for a longer time in scenarios 2 and 3 due to life extension and, consequently, cannot be recycled as quickly. It again appears that scenarios 2 and 3 converge towards 2050 due to the system reaching a steady state.

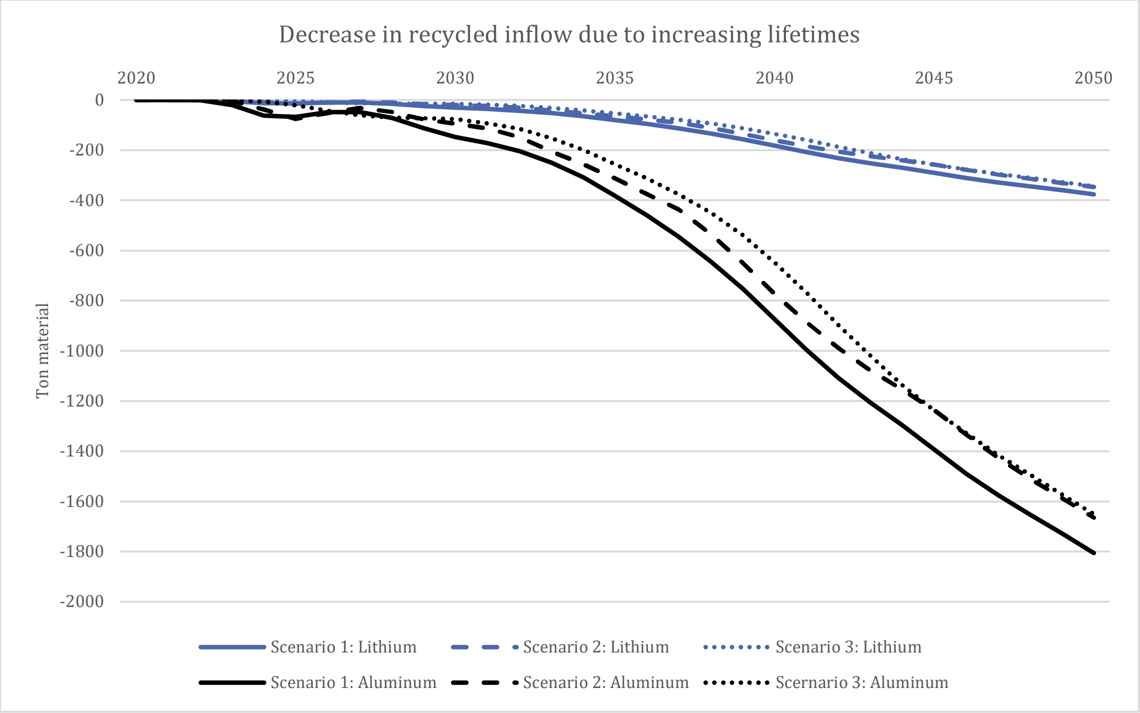

*Figure 4.16: Decrease in amount of recycled lithium/aluminum inflow from increasing battery cell lifetimes.*

### 4.4.3 BEV adoption rate

Due to its high uncertainty, the BEV adoption rate was altered in the final sensitivity analysis. This change could reflect, e.g., the introduction of legal requirements that mandate all mining vehicles to be battery-driven by 2050. Increasing the adoption rate from 65% in 2050 to 100% adoption in 2050 results in an increase of 6.2 million battery cells required in scenario 1 by 2050 (Fig. 4.17 and 4.18). Further, this increase corresponds to approximately 4.9% of the total demand in 2050 in this scenario. For scenario 3, the increase is 7.5 million battery cells, equaling a 4.7% increase when going from 65% to 100% adoption rate.

In relation to the increase from 65% to 100% BEV adoption rate in 2050, an increase in the inflow of only 4.9% in 2050 might appear low, but this is because the life extensions come into play. As the adoption rate is higher also in previous years, more material will have entered the system by 2050 with the higher assumed adoption rate. This, in turn, results in more material available for reuse, which decreases the primary material required in relation to the adoption of new BEVs.

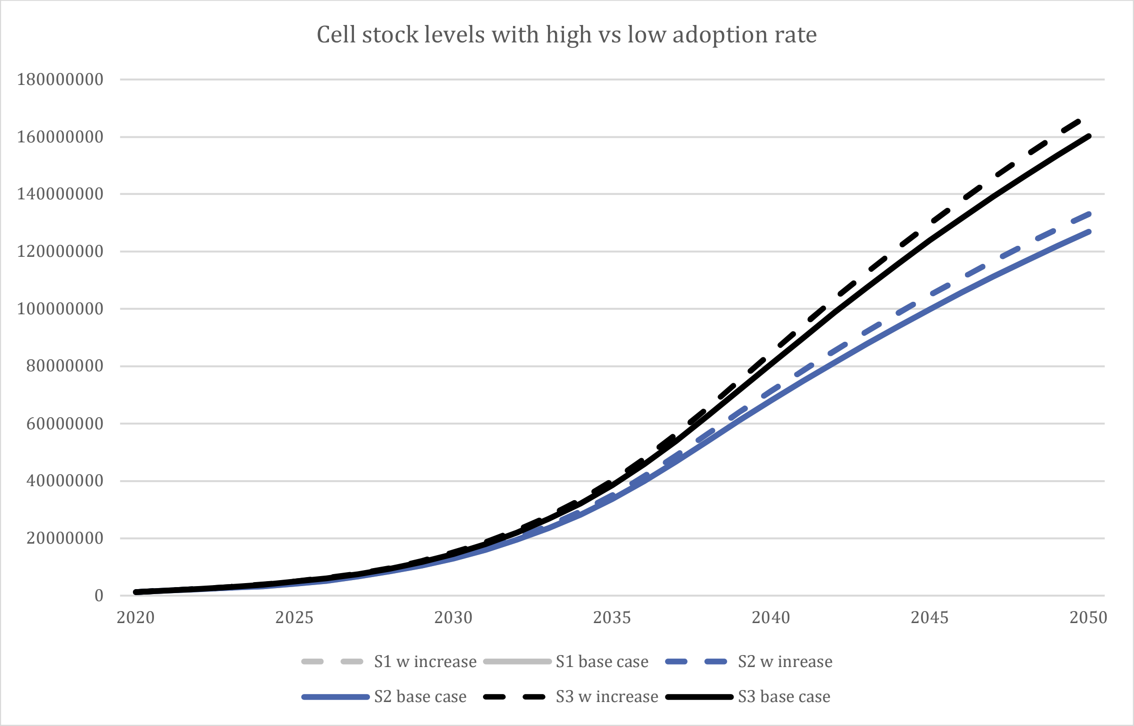

*Figure 4.17: Cell stock levels for battery cells with adoption rates of 65% and 100% respectively by 2050.*

The inflows of recycled and primary material are also impacted by the increased adoption rate (Fig. 4.18). As a result of the higher adoption, the increase of lithium amounts to 46, 34, and 31 ton extra for scenarios 1, 2, and 3 respectively. The corresponding increase for aluminum is 220, 161, and 152 ton in the three scenarios, respectively (Fig. 4.19).

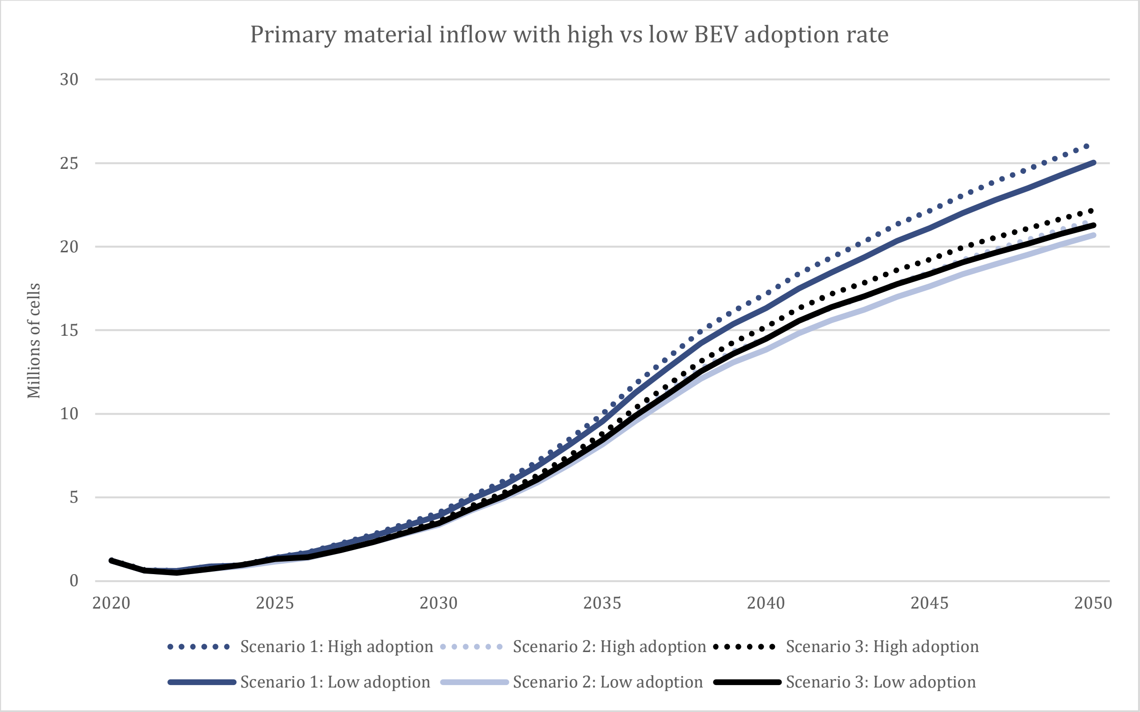

*Figure 4.18: Primary material inflow with high vs low BEV adoption rates in the three different scenarios.*

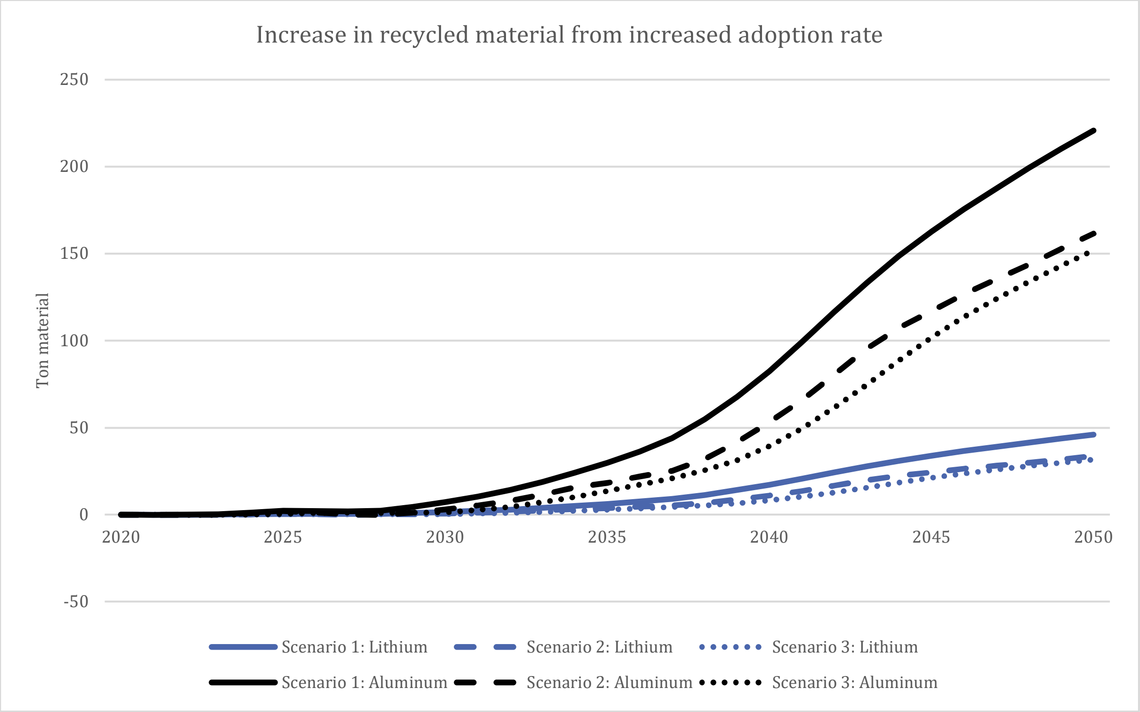

*Figure 4.19 Increase in amount of recycled lithium and aluminum from increased adoption rate*

The increase in inflows of recycled material due to the increase in adoption rate for BEVs is reasonable as a larger amount of BEVs will result in a larger number of cells recycled. The increase is higher in scenario 1 compared to scenarios 2 and 3 because when reuse is not possible, more material will be required and the total flows in scenario 1 are therefore larger compared to scenarios 2 and 3.

Finally, it can be mentioned that the dMFA model does not consider potential limitations in recycling infrastructure, which might limit how much material can actually be recycled. The model assumes the same collection rate for both low and high adoption rates, although the amount of material collected will differ in absolute numbers. Consequently, the share recycled material in the inflow will remain the same for each of the scenarios 1-3, regardless of the BEV adoption rate.

# 5. Conclusion

This thesis departed from three research objectives (ROs). First, a dMFA model for battery cells in mining equipment was developed to understand the dynamics of material flows within the context of electrified mining operations (fulfilling RO1). The model allows researchers and industrial actors (e.g., the case company) to simulate and assess the impact of reuse and recycling of bttery cells.

Second, the model was applied to simulate three scenarios with different life extension possibilities to investigate the flow of products and materials over time (fulfilling RO2). It was concluded that 13.5 million more cells flow into the machines in 2050 for scenarios 2 and 3 (with life extension), compared to scenario 1 (without life extension). However, only 27% of the total cell stock in 2050 can be satisfied by reused cells, meaning that that life extension contributes only to a moderate portion of the overall cell stock. This suggests that even with life extension, there will still be a considerable demand for new cells to meet stock requirements. Scenarios 2 and 3 further demonstrate a 19% reduced inflow need for cells in 2050 compared to scenario 1. This translates into a reduced need for the primary materials used in battery cells, in accordance with circular economy ambitions. Additionally, results from scenario 3 show that extending the cell life with BESS would enable the mining sector to contribute to the growing demand for batteries and primary materials in BESS. In this dMFA model, the flow of cells to BESS is a consequence of the battery cell outflows from machines, not of an additional stock need. Increasing demand for BESS application may drive actors to prioritize supplying BESS requirements over life extension in machines such as loaders and rigs.

Third, different recycling scenarios were considered (fulfilling RO3). A key assumption is that recycling processes for lithium and aluminum are efficient (97-99.9% recovery rate), so the impact from improving them is minor. However, this assumes that these recycling efficiencies are actually realized. Based on this assumption, the crucial factor is the collection rate and degree of utilization for these processes. Current collection rates indicate significant improvement potential and raising them from 35% to 50% can increase the inflow of recycled cells by 45-46%, depending on scenario. Provided sufficient recycling infrastructure is developed, the key challenge then lies in the high costs associated with these recycling processes, leading to low levels of utilization. Addressing this issue could initiate a virtuous cycle, where increased adoption yields economies of scale, which lowers costs, further boosting adoption. From a company perspective, enhanced recycling responsibility could be initiated by the OEMs, for example by adopting PSS. This approach could also reduce dependency on primary materials. Increasing collection rates and facilitating recycling adoption can also be promoted through regulatory initiatives, such as the EU Battery Directive.

From the sensitivity analysis, it can be concluded that life extension possibilities in rigs have approximately the same impact on primary material demand as increasing battery cell lifetimes. Both parameter alterations resulted in a difference in lithium demand by 340-380 ton and in aluminum demand by 1600-1800 ton. While life extension in rigs and increasing battery lifetimes both decrease the demand for primary material, increasing the BEV adoption rate from 65% to 100% in 2050 instead increases the demand for primary materials. However, this increase is relatively small (31-46 ton lithium and 152-220 ton aluminum, depending on scenario), but could have a substantial impact carbon emission reductions from the mining industry. Future research is recommended to assess the magnitude of the carbon dioxide emission reductions, e.g., using life cycle assessment, as well as quantifying the related surge in demand for recycling and life extension infrastructure. It would further be relevant to assess the generalizability of the conclusions made in this thesis to other industries that could benefit from including life extension solutions when electrifying their operations.

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# Appendix

## Appendix A - Interview guide: Business & Market Intelligence

**Introduction**

- Begin with a brief introduction of all attendees
- Clarify the purpose of the interview
  - Thesis background
  - Short presentation of model structure
  - Data input needed

**Section 1: Market size for mining equipment**

- Can you provide an overview of the current market size for mining equipment?
- How has the market size evolved recently and what factors have contributed to these changes?
- Are there any segments within the mining market that are experiencing notable growth or decline?

**Section 2: Growth trends**

- What are key growth trends observed in the mining equipment industry?
  - Are there specific technological advancements or innovations influencing the growth trends?
  - How does the current economic climate impact the growth trajectory of the mining equipment market?

**Section 3: Adoption rate of BEVs**

- How would you characterize the current adoption rate of BEVs in the mining industry?
- What are the main drivers behind the adoption of BEVs in mining operations?
- Are there any challenges or barriers hindering a more widespread adoption of BEVs in the mining sector?
- Can you share insights on how environmental regulations or sustainability goals are influencing the adoption of BEVs in mining?

**Conclusion**

- Summarize key points discussed in the interview
- Ask if there are any points we might have missed

# Appendix B - Interview guide: Global Data Market Intelligence

### Introduction

- Begin with a brief introduction of all attendees
- Clarify the purpose of the interview
    - Thesis background
    - Short presentation of model structure
    - Data input needed

### Section 1: Installed Base of Mining Equipment

- Can you provide an overview of the current installed base of mining equipment globally?
- How has the installed base evolved over the past few years, and what factors have contributed to these changes?
- Are there specific regions or countries with notable variations in the installed base of mining equipment?

### Section 2: Growth Rate

- What is the expected growth rate in the installed base of mining equipment globally until 2050?
- Can you share insights into the key drivers influencing the projected growth rate in the mining equipment sector?
- Are there particular mining equipment segments that are expected to experience higher growth rates?

### Section 3: BEV Adoption

- What is the current share of Battery Electric Vehicles (BEVs) in the installed base of mining equipment globally?
- Can you provide estimations or projections on the expected growth of BEV adoption in the mining industry until 2050?
- What factors are driving or inhibiting the adoption of BEVs in the mining equipment sector?

### Section 4: Regulations

- How do you foresee regulatory initiatives impacting the growth of the installed base of mining equipment globally?
- Are there specific regulatory trends or changes that could significantly influence the adoption rate of BEVs in mining operations?
- Can you discuss any regional variations in regulatory approaches and their potential effects?

### Conclusion

- Summarize key points discussed in the interview
- Ask if there are any points we might have missed

## **Appendix C**: Summary of key parameters from results

Table summarizing the main results from the six different scenarios. The most beneficial results from a circularity perspective are marked in green, the least beneficial in red.

| **Parameter** | **Medium recycling rate** | | | **High recycling rate** | | |
|---|---|---|---|---|---|---|
| | Only recycling (1A) | Recycling + life ext. (2A) | Recycling + life ext. + BESS (3A) | Only recycling (1B) | Recycling + life ext. (2B) | Recycling + life ext. + BESS (3B) |
| Demand for lithium (2050) | 3483 ton | 2834 ton | 2834 ton | 3483 ton (same as A) | 2834 ton (same as A) | 2834 ton (same as A) |
| Inflow of recycled cells (2050) | 9.5 M cells | 7.5 M cells | 6.9 M cells | 13.9 M cells (+46% compared to 1A) | 10.9 M cells (+45% compared to 2A) | 10.0 M cells (+45% compared to 3A) |
| Share of inflow recycled cells (2050) | 28% | 27% | 24% | 40% | 39% | 35% |
| Recycled lithium inflow (2050) | 962 ton | 751 ton | 690 ton | 1 402 ton (+45.8% compared to 1A) | 1 095 ton (+45.7% compared to 2A) | 1 005 ton (+43.4% compared to 3A) |
| Recycled aluminum inflow (2050) | 4 616 ton | 3606 ton | 3311 ton | 6 654 ton (+46% compared to 1A) | 5 198 ton (+44.2% compared to 2A) | 4 773 ton (+44.2% compared to 3A) |
| Share recycled lithium of demand (2050) | 28% | 27% | 24% | 40% | 39% | 35% |
| Share recycled aluminum of demand (2050) | 28% | 27% | 25% | 41% | 39% | 36% |
| Primary material inflow (2050) | 92.7 kton | 76.5 kton | 78.8 kton | 76.5 kton (-17% compared to 1A) | 63.9 kton (-16.5% compared to 2A) | 67.2 kton (-14.6% compared to 3A) |

## **Appendix** D: Sensitivity analysis outcomes – Rig extension possible/not possible

Outcomes from the sensitivity analysis in scenarios 2A and 3A from life extension in rigs being, or not being, possible. The most beneficial results from a circularity perspective are marked in green, the least beneficial in red. Values within percentages represents in comparison to the scenario with life extension.

| | **Scenario 2A** | | **Scenario 3A** | |
|---|---|---|---|---|
| | **With life extension in rigs** | **Without life extension in rigs** | **With life extension in rigs** | **Without life extension in rigs** |
| Primary inflow (2050) | 20.7 M cells | 23.0 M cells<br>(+11.1%) | 21.3 M cells | 23.8 M cells<br>(+11.7%) |
| Total cell stock (2050) | 126.9 M | 126.9 M<br>(+0%) | 160.2 M | 173.0 M<br>(+8.0 %) |
| Inflow 1st life ext. (2050) | 19.9 M | 11.5 M<br>(-42.1%) | 19.9M | 11.5 M<br>(-42.1%) |
| Share in ext. life (2050) | 27% | 9%<br>(-66.7%) | 24% | 9%<br>(-62.5%) |
| Lithium demand (2050) | 2834 ton | 3174 ton<br>(+11.9%) | 2834 ton | 3174 ton<br>(+11.9%) |
| Recycled lithium inflow (2050) | 751 ton | 860 ton<br>(+14.5%) | 690 ton | 778 ton<br>(+12.8%) |
| Aluminum demand (2050) | 13 328 ton | 14 927<br>(+12.0 %) | 13 328 ton | 14 927<br>(+12.0%) |
| Recycled aluminum inflow (2050) | 3 606 ton | 4 130<br>(+14.6 %) | 3 311 ton | 3 735 ton<br>(+12.8%) |

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